ARTICLE IN PRESS

Research in Transportation Business & Management xxx (xxxx) xxx

Contents lists available at ScienceDirect

Research in Transportation Business & Management

journal homepage: www.elsevier.com/locate/rtbm

Internalization of external and infrastructure costs related to maritime transport in Sweden

Inge Vierth, Axel Merkel *

Swedish National Road and Transport Research Institute (VTI), Sweden

ARTICLE INFO

Keywords:
Transport externalities
External cost
Climate change
Air pollution cost
Corrective taxes

ABSTRACT

The use of maritime transport is associated with external costs such as those related to greenhouse gas emissions and air pollution. If corrective taxes, fees or regulations are levied on the production of maritime transport services, these costs become internal and decision-makers will take into account the full social cost of transport. Shipping is subject to less incentive-based regulation than e.g. road transport, but Sweden represents a relatively unique regulatory case with its national system of fairway dues, which are differentiated according the environmental performance of ships. The central question posed in this paper is whether Sweden's internalizing national transport policy measures are in proportion to the societal costs generated by maritime traffic in Swedish waters. Using a dataset comprising all vessel movements in Swedish territorial waters during a year, we estimate the marginal external and infrastructure costs of maritime traffic and find that, depending on the set of unit values applied, the degree of internalization ranges between around 53% and 90%. We also evaluate the effects of a recent re-appraisal of CO2 in the Swedish official guidelines for cost benefit analysis and show that under the new recommendation the degree of internalization is significantly lower: 23–28%. Because the degree of internalization varies significantly between different shipping segments, a uniform increase of the charges currently in place is not recommended. Instead, we highlight that other, more appropriate instruments for internalization may be needed.

1. Introduction

Although maritime transport is typically viewed as a comparatively efficient mode in terms of CO_2 emissions per unit of transport work (Sims et al., 2014), the large growth of shipping demand associated with globalization has led to justified concerns about its environmental impacts. The European Commission (1995, 1998, 2001, 2008, 2011) has repeatedly called for internalization of the external costs for all modes of transport, meaning that all costs arising from the use of transport services and infrastructure should be passed on to the user through taxes, charges and regulations. This is in line with the Pigouvian tradition in economics, which instructs that a tax or a charge ought to be levied on an activity equal in amount to the marginal social cost generated. The demand for transport and its modal distribution is steered by price signals. Unless corrected to reflect the marginal social costs of any particular form of transport, these prices signals will likely result in an overuse of polluting technologies and distort competition between modes. Marginal social cost pricing, according to economic theory, yields an efficient amount and modal distribution of transport. Internalization can be said to be the realization of the popular 'polluter pays' principle of environmental policy.

The environmental costs of shipping can be internalized via international regulations, such as those imposed by the International Maritime Organization (IMO) or the EU. In addition, there are national and local measures that can be undertaken to steer the industry towards less polluting practices. The question pursued in this paper is to what extent national transport policy measures actually internalize the external and infrastructure costs of maritime transport. Following the Swedish government agency Transport Analysis (2019), we define all transport policy measures and regulations which impose taxes or charges that are variable with respect to the size of the external cost caused by maritime transport as internalizing measures. It follows from this definition that Sweden's fairway dues and pilot charges are viewed as internalizing measures. Due to the fact that fairway dues and pilot fees are determined and charged centrally by the government through the Swedish Maritime Administration, they function as transport policy levers and are subject to the politically determined principle (Proposition 2012/13:25, 2012) that taxes or charges levied through transport policy measures should

* Corresponding author.
E-mail address: Axel.merkel@vti.se (A. Merkel).

https://doi.org/10.1016/j.rtbm.2020.100580
Received 10 February 2020; Received in revised form 11 September 2020; Accepted 6 October 2020
Available online 16 October 2020

reflect the socioeconomic costs of transport activities. It is therefore relevant to expect the Swedish system of fairway dues and pilot fees to function in a 'corrective' way. Port charges, determined locally by port authorities are also to some extent functionally corrective in Sweden.[1] This paper focuses however solely on national internalizing instruments, leaving the calculation of internalizing charges levied by ports and port infrastructure costs in Sweden as a task for future research. While the exercise carried out in this study can in principle be replicated for other countries, the question of what fees, taxes or charges are to be considered as internalizing needs to be considered for each country.

Despite the stated interest in internalization at the European policy level, relatively little research has gone into establishing to what extent the infrastructure and external costs of maritime transport (including those related to greenhouse gas (GHG) emissions, air pollutants and traffic safety) are internalized by monetary disincentives. A recent study by van Essen et al. (2019a) assessed the current state of internalization for aviation, road, rail, inland waterways and maritime transport in the European Union. The study reported the interesting finding that the overall degree of external and infrastructure cost internalization, i.e. the ratio of total charges to total external and infrastructure costs, for maritime transport is very low: 4%. This can be compared to corresponding figures for rail transport, road transport and aviation, which were found to be 69%, 56% and 37% respectively. There are general difficulties inherent in the measurement of marginal social costs (Baumol & Oates, 1971) and there are specific difficulties related to assessing the external costs of shipping. Due to a lack of maritime traffic data at the EU level, van Essen et al. (2019a) focus on a set of 34 ports in the EU, in order to determine to what extent charges and fees in these ports internalize the external costs of a set of reference vessels carrying cargo over various hypothetical distances. Due to the admittedly uncertain information regarding port charges, as well as the lack of comprehensive traffic data in the EU study, further studies into the internalization of maritime transport are needed. In this paper, we present such a study at the national level in Sweden. Using a comprehensive set of data covering all vessel movements within Swedish territorial waters (see Fig. 6) during a year, including information about fuel consumption, we can estimate the total marginal social costs generated by maritime transport. We can also compute the degree of internalization by comparing these costs to the fees levied by the Swedish Maritime Administration in the form of fairway dues and pilotage fees, which are the instruments through which transport policy in Sweden can influence the degree of external and infrastructure cost coverage. This approach allows us not only to assess the extent to which maritime transport is bearing its social cost burden, but also to estimate the consequences of re-appraising the CO_2 unit value recommended in the Swedish guidelines for cost benefit analyses (CBA). The motivation for assessing such a scenario is that the Swedish Transport Administration (2020) recently raised its CO_2 valuation for use in CBA by a factor of six, which has large implications for our results and for transport infrastructure planning overall. The paper proceeds with a review of the available literature related to internalization in maritime transport. In Section 3 we provide a description of the relevant categories of external and infrastructure cost generated by maritime transport in Sweden and the current mechanisms in place to internalize them. In Section 4, we detail the methodology applied and describe our dataset. Section 5 contains our main results and findings and Section 6 is devoted to discussing these results and providing concluding remarks.

[1] Around 20 out of a total of 50 publicly owned ports apply environmentally differentiated port fees (Vierth, 2020). The extent of environmental differentiation is inconsistent among ports, as different benchmarking/scoring methods are used by different ports.

2. Internalization of maritime transport costs: Available evidence and challenges

There have been numerous research efforts aimed at uncovering the degree of internalization in transport (Gomes, Lopes, Martins, & Carvalho, 2010; Link, Nash, Ricci, & Shires, 2016; Santos, 2017), but very few of these focus on maritime transport. The state of knowledge is greater for land-based modes of transport than for maritime transport and aviation and the practices for estimating marginal costs in aviation and shipping are less well established (Nilsson et al., 2018).[2] A major reason for this is the fact that shipping and aviation are international by nature. It is not clear how to associate the costs of international transport with a particular state or other entity capable of enforcing corrective policies. The international nature of these industries also makes it more difficult to coordinate and consistently enforce regulation. A key difference between shipping and aviation is that shipping causes relatively low levels of externalities per unit of transport work but due to very large volumes and distances, it causes high levels of externalities in absolute terms. Aviation by contrast causes high levels of externalities per unit of transport work but deals with significantly lower volumes overall.

The Swedish governmental agency Transport Analysis annually compiles and publishes results regarding the degree of internalization in the transport sector. The report from 2019 (Transport Analysis, 2019) was based on analysis from Vierth (2018). The underlying study (Vierth, 2018) found that the degree of marginal social cost internalization in maritime transport is somewhere between 96 and 108%. The latter figure suggests that the fairway dues and pilot fees borne by maritime transport *more than covered* the marginal social costs generated for the period of study, which was 2017. Most of the external costs measured were related to GHG emissions and air pollutants, accounting together for around 70% of the total external costs. The study also considered infrastructure costs related to pilotage and icebreaking. The structure of fairway dues has since undergone change and the levied fees have increased by about 10% in total, which makes it relevant to re-evaluate the degree of internalization in Sweden.[3] In the report by Transport Analysis (2019) the results were similar although slightly different: the computed degree of internalization varies between 114 and 126% for maritime freight transport (which represents the major part of sea transport in Swedish waters) and between 64 and 77% for maritime passenger transport. The differences between the reports partly have to do with the segmentation into freight/passenger categories, which requires assumptions regarding the Ro-Pax factor (i.e. the share of external costs and fees attributable to cargo/passengers), as well as different (lower) estimations of the costs of icebreaking. Transport Analysis (2019) also used a later year (2018 rather than 2017, which was used by Vierth (2018)) to determine the fairway dues and pilot fees, resulting in a higher level of charges.

The finding that maritime transport in Sweden is more or less fully internalized is clearly very interesting and in contrast with the aforementioned finding by van Essen et al. (2019a), who reported that the degree of internalization in the EU is only at 4%. Apart from the fact that different geographical areas and markets are covered, there are important methodological differences between the studies. Vierth (2018) makes use of actual traffic data including all vessel-kilometers in Swedish territorial waters, while van Essen et al. (2019a) calculate external costs based on reference vessels corresponding to different sizes, cargo types, compliance with environmental standards and trip lengths. The revenue side considered by the two studies also differs.

[2] For instance, Hofbauer and Putz (2020) find in a literature review that the amount of research papers treating maritime transport external costs is roughly 5% of the amount of papers focused on road transport externalities and roughly 12% of the amount focused on rail transport externalities.

[3] For more detail on the fees and charges levied by the SMA, see section 3.3.

While Vierth (2018) uses the Swedish Maritime Administration's revenues for fairway dues and pilot fees from 2017, van Essen et al. (2019a) calculate the revenue from port charges in 2016 (assuming that 65% of total port revenues are from port charges) and fairway dues where applicable (ports in Estonia, Finland and Sweden). In estimating the costs related to traffic safety, both studies use a similar approach which consists of studying the frequency and types of accidents historically and assigning them a monetary value using previously established cost factors of fatalities and injuries. An important difference is related to the valuation of air pollutants. Vierth (2018) uses values from Nerhagen (2016), who applied the impact pathway approach to estimate the dispersion and damage to human health and ecosystems resulting from the emission of air pollutants from ships. The results imply for instance that the emission of a kilogram of nitrogen oxides (NO_x) in Swedish waters is on average associated with an external cost of roughly 0.5 euros (converted to 2018 level prices). In contrast, van Essen et al. (2019a) use values prescribed by the European Commission's Handbook on the external costs of transport (van Essen et al., 2019b), which are also based on the impact pathway approach but imply much higher monetary valuations of NO_x. The Handbook's values show that the average damage cost of emitting a kg of NO_x in the Baltic sea area is equivalent to 8.5 (2018-level) euros.[4] The valuation of air pollutants other than NO_x is similar across both studies. As we will show in the results section, the unit value applied to value NO_x emissions has a significant influence on the overall results.

While the external costs of road transport can be internalized through incentive-based measures such as fuel taxes, embedded carbon taxes or congestion charges (Santos, 2017), maritime transport is relatively free of such market-based environmental regulation. However, there are examples of market-based environmental regulation. One such example is the emissions trading scheme adopted by the State of California, which since 2001 includes emissions from marine sources and has led to ship engine modifications in order to reduce NO_x and SO_x emissions (Christodoulou, Gonzalez-Aregall, Linde, Vierth, & Cullinane, 2019). Another example is Norway, where a tax on NO_x emissions from industry (including maritime transport) was complemented by a NO_x fund, which is a non-governmental initiative. Entering into the fund, which is optional, means that firms are exempted from paying the tax and can instead pay a membership fee that is proportional to its emissions (Hagem, Holtsmark, & Sterner, 2012). The revenue gathered by the fund is subsequently delivered back to its members, through the financing of specific NO_x-reducing measures. Due to the international nature of maritime transport and the mobility of the tax base, it has largely avoided the imposition of charges such as those levied on road transport (Parry, Heine, Kizzier, & Smith, 2018). Rather, the regulation of maritime pollution has had to rely mostly on 'command and control'-type measures. A central climate change mitigation effort implemented by the International Maritime Organization (IMO) is the Energy Efficiency Design Index (EEDI), which has been in force since 2013 and sets ship-specific requirements on the carbon intensity of propulsion (expressed in terms of CO_2 per capacity-mile). This is accompanied with a set of emission standards, which are tightened every five years in order to attain overall improvements in the carbon intensity of ships. Ships entered into the fleet from 2025 and onwards are expected to achieve efficiency improvements of up to 30%, compared to ships built before the adoption of the EEDI (IMO, 2015). Another example of a command and control-type regulation is the setting of emission standards and the designation of emission control areas (ECAs). This is particularly relevant to the current study, since the Baltic and North seas and the English Channel constitute Sulphur Emission Control Areas (SECAs), where the limit of sulphur fuel content since 2015 is 0.1% mass by mass. Outside SECAs, the limit was tightened from 3.5% to 0.5%, effective January 1st, 2020. IMO's Tier regulations for NOx apply to new ships. Tier I and Tier II are mandatory worldwide while the stricter Tier III is applied in Nitrogen Emission Control Areas (NECAs). From January 1st 2021, the NECA comprising the Baltic Sea and the North Sea will come into force.

Regulations such as those mentioned above play a role in reducing the level of externalities caused by maritime transport. However, the role of economic instruments in creating incentives for emissions reduction – such as a carbon taxation scheme – remains an underutilized potential (Nikolakaki, 2013; Parry et al., 2018). According to an assessment by the IPCC, only a few countries utilize economic incentive schemes to reduce emissions from shipping (Kahn Ribeiro et al., 2007), and among these are Sweden and Norway.[5] Sweden has a system of environmentally differentiated fairway dues (to be further elaborated in Section 3.3.). Even if explicitly corrective fees and charges are quite seldom seen, vessels are charged fees for the use of maritime infrastructure and waterways and these fees thereby serve the purpose of making ship owners/shippers 'bear their own costs'. Schroten et al. (2019) calculate the maritime transport charges which are used by van Essen et al. (2019a) for assessing the degree of internalization. The method used is to find the sum of fuel charges, port charges and fairway dues payable by vessels calling at a set of 34 reference ports. Infrastructure costs related to pilotage were not included due to data availability (Schroten et al., 2019). Since energy products for use as fuel in maritime transport are exempt from taxation in the European Union (2003), this category of fees adds up to zero. In terms of port charges, the study only considers those charges levied by the port authority, meaning that service fees charged by third-party providers such as pilotage charges were not included due to a lack of available data. Most port charges were found to be differentiated with respect to vessel size, vessel type, type of services, number of calls and additional factors like the amount of cargo (un)loaded and the number of passengers. Based on the information regarding the level and structure of charges provided by the ports in question, Schroten et al. (2019) calculate applicable charges for a series of reference vessels and find for a container vessel with a carrying capacity of 2800 TEU that the applicable port charge varies between around 2000 euros and 20,000 euros depending on the port. In addition, three EU countries, Sweden, Finland and Estonia, charge separate fairway dues. These are calculated by Schroten et al. (2019) to range (for the same type of vessel) from 7000 euros to 11,000 euros per call. The task of calculating fees and charges is complicated when several countries and thereby several systems and practices need to be combined. In the aforementioned Swedish study of cost internalization, Vierth (2018) uses an approach specific to the Swedish setting, which is similar to the approach used in this study. This means that since pilotage and icebreaking services are provided by the government through the Swedish Maritime Administration, the marginal costs of supplying these activities and the fees charged for their provision can also be included in the assessment of internalization. Since the revenues from fairway dues and pilot fees correspond exactly to the actual dues and fees paid, using this information allows us to capture all discounts and price differentiation that is applied. As mentioned in the introduction, different countries have different policy tools available for internalizing the external costs of maritime traffic, which is an important aspect to consider when making cross-country comparisons.

[4] The previous version of the Handbook (Ricardo-AEA, 2014) prescribed a lower value of NO_x emissions in the Baltic sea area, corresponding to 5.8 euros using the same price level (2018).

[5] Schroten et al. (2019) also show that it is relatively common for European ports to offer rebated fees based on a vessel's score on the Environmental Ship Index, which covers NO_x, SO_x and GHG emissions.

3. Marginal infrastructure costs and external costs of maritime transport in Sweden

3.1. Infrastructure costs: Organization of pilot and icebreaking services

Transport activities cause damage in the form of infrastructure wear and tear, thereby hastening the need for maintenance and re-investment. When transport infrastructure is provided as a public good, transport users will not take these costs into account unless they are charged an amount equivalent to the marginal cost caused by their use of the infrastructure. In maritime transport, the wear and tear caused by ships is virtually negligible. However, the costs related to the provision of pilot and icebreaking services are non-negligible. While the costs of icebreaking are clearly classifiable as infrastructure costs, some clarifications can be made regarding the classification of pilotage costs. These are part of the infrastructure costs because there is a trade-off between safe fairways and the need for pilot services. The provision of pilotage services can therefore be seen as supplementing the state of infrastructure and lessening the need for additional investments in navigational safety.[6]

Depending on the type and size of a vessel and the fairway, the use of pilot services is mandatory in Sweden. This is regulated by the Swedish Transport Agency. Generally, vessels with dimensions exceeding 70 m in length and 14 m in width (or exceeding a draught of 4.5 m) are subject to mandatory pilotage. The Swedish Transport Agency issues roughly a thousand exemption certificates each year, which give the holder the license to operate without pilotage provided that the holder can prove that own staff onboard has the required competence. Pilot services are produced by the Swedish Maritime Administration, which serves as a monopolist. In 2017 it performed roughly 33,000 pilot operations (Swedish Maritime Administration, 2018a). The Swedish Maritime Administration's annual report states that its costs for providing pilot services in 2018 was roughly 59 million euros. It is important to note however that this figure differs from the policy relevant marginal costs of providing pilot services, i.e. the costs related to an additional pilot service being produced, including external costs caused by transport to and from the vessel. Relevant cost categories are labour costs, travel costs (to and from the vessels), voyage costs (fuel and wear and tear associated with the use of pilot vessels) and external effects of air pollution and GHG emissions. The total marginal costs of pilotage during 2014 were calculated by Vierth (2016) to be roughly 15 million euros, which means that the average marginal cost of a pilot operation was around 460 euros. In the following sections of this paper, we provide updated estimates of the marginal costs of pilot services for the year 2018.

As with pilotage, icebreaking services are regulated by the Swedish Transport Agency and produced by the Swedish Maritime Administration using a fleet of five own icebreaker vessels, which can be supplemented by leasing icebreaking resources from neighboring countries. During particularly harsh winters such as 2010 and 2011, up to half of all icebreaking operations were performed with contracted vessels. The demand for icebreaking during any particular year is heavily dependent on the weather conditions, which can vary significantly as is shown in Fig. 1. During 2018, the number of icebreaking assistance services produced was 1355, which can be compared to the previous year, during which 597 services were produced. This inherent variability of demand in some respects justifies the flexible strategy of contracting additional supply when needed. The Swedish Maritime Administration reports that its costs for providing icebreaking services amounted to roughly 31 million euros (Swedish Maritime Administration, 2018a). However, as with pilotage, the total *marginal costs* of icebreaking services are significantly lower. It has proven difficult to compute the marginal costs of icebreaking with a high level of precision, since there are a lot of uncertainties regarding which costs can accurately be treated as marginal. The previous approach in the Swedish internalization studies has been to construct a set of high- and low marginal cost scenarios. In the low-cost scenario in Vierth (2018), it is assumed that only the costs of fuel and lubricants, as well as the external costs of air pollution and GHG emissions can be classified as marginal. In the high scenario, the maintenance costs of the icebreaker fleet and the cost of contracting third-party icebreakers is also included. Previous assessments have found that the outcome of these scenarios is a range of total marginal costs related to icebreaking from 9 million euros to 16 million euros. This means that the average marginal cost per icebreaking assistance service produced is between roughly 6200 euros to 11,300 euros. In the following sections, we update these estimates and show how, depending on how the factors for air pollution and GHG emissions costs are selected, the marginal cost of icebreaking is most likely higher than previously assessed.

3.2. The emission of GHG emissions and air pollutants

According to official statistics produced by the Swedish Environmental Protection Agency (SEPA, 2019a), domestic maritime transport accounts for some 4.5% of GHG emissions from the transport sector. These statistics also indicate that GHG emissions from commercial domestic shipping have increased by 63% since 1990. During the same period, GHG emissions from international maritime transport (emissions from ships bunkering in Sweden) increased by a factor of 3.5. Estimates of emissions from shipping were until recently produced based on a top-down approach, surveying oil suppliers regarding the amount of fuels purchased for the purpose of maritime transport operations (SEPA, 2019c). These statistics were fraught with significant uncertainty and the data exhibited fluctuations that were difficult to explain. A report by researchers at the Swedish Meteorological and Hydrological Institute (SMHI) instead showed, using a bottom-up approach based on Automatic Identification System (AIS) ship positional data that the fuel consumption of domestic shipping may have been twice as high as the official statistics suggested (Windmark, Jakobsson, & Segersson, 2017). Comparing the estimates for international traffic was less straightforward, since the official statistics covered all fuel consumed in international maritime transport legs originating or ending in Sweden, while the AIS method only considers fuel consumed within a confined geographical area. The official method for estimating maritime emissions and fuel consumption was changed as of the end of 2019 and currently incorporates the AIS modelling approach (SEPA, 2019c).

To combat the effects of airborne emissions from shipping such as acidification, eutrophication and damage to human health in coastal areas, the IMO included in its Annex VI MARPOL protocol the establishment of ECAs, including the SECA encompassing the Baltic and North seas. The tightened limit of 0.1% sulphur content in 2015 was met with a variety of compliance measures (Raza, Woxenius, & Finnsgård, 2019; Stalmokaitė & Yliskylä-Peuralahti, 2019). Raza et al. (2019) found that common compliance measures implemented by shipping companies in the RoRo and RoPax segment were a combination of switching to distillate fuels such as marine gas oil or ultra-low sulphur oil and in some cases installed scrubber systems or converted vessels to allow for the use of liquid natural gas (LNG) as fuel. It was hypothesized by some that the forced use of more expensive low-sulphur fuels could lead to higher freight rates and possibly an undesired modal shift 'back' from maritime to road transport (Notteboom, 2011). Ex-post studies of the modal shift effects following the more stringent sulphur regulation have shown that such effects, to the extent that they have occurred, appear to have been very limited (Transport Analysis, 2017a). Sulphur

[6] Note that there is a difference between the marginal costs of supplying a pilot service and the charge levied on a user for the same service. The former represents in our analysis the marginal *societal cost* of pilotage while the latter represents the user charge, i.e. the cost borne by the ship operator. In terms of calculating the degree of internalization, the charge is included in the numerator and the marginal societal cost is included in the denominator.

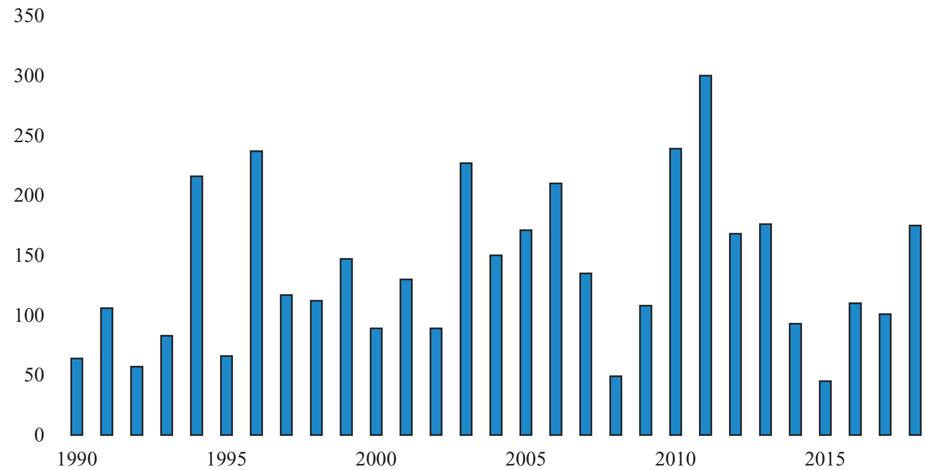

Fig. 1. Maximal extent of ice in the Baltic sea, measured in thousands of square kilometers. Source: SMHI (2019).

dioxide emissions from domestic maritime transport movements were reduced by more than 80% between 2014 and 2015, which can be seen in Fig. 2.

As of 2021, the North and Baltic seas will also enforce rules on the emission of nitrogen. All new vessels, including older vessels undergoing substantial modification or conversion, must then comply with the NO_x Tier III regulation. This is expected to lead to significantly reduced NO_x emissions, though the change will not be as immediate as with the SECA enforcement, since it applies only to new vessels. As shown in Fig. 3, NO_x emissions from domestic transport have gradually increased and are roughly 1.5 times higher today than in 1990, according to the new official statistics. Fig. 3 also shows a rather dramatic increase in NO_x emissions during 2018.[7] Costs associated with the emission of nitrogen oxides constitute a significant share of the total external costs of maritime transport, which makes the problem of valuing these emissions crucial.

3.3. The nature of Swedish fairway dues and pilot fees

The Swedish Maritime Administration constitutes the Swedish government's administrative body for handling most shipping-related matters. Apart from the pilotage and icebreaking services already mentioned, a main task for the Swedish Maritime Administration is to maintain the fairways and to implement corrective policies to lessen the impact of shipping on the environment and ensure traffic safety. At the same time, it is mostly financed by user fees and is therefore restricted to implementing changes to its charging structure that are more or less revenue neutral. Between 1998 and 2017, the fairway dues charged by the Swedish Maritime Administration were differentiated in the sense that discounts were given for vessels holding NO_x and SO_x certificates. These certificates were issued by the Swedish Maritime Administration upon confirming that the ships in question used low sulphur fuel (for the SO_x certificate) or had installed NO_x abatement technologies. For SO_x, the practice was discontinued in 2015 because the stricter SECA requirements entered into force. The maximum discount that a NO_x certificate holder could receive in 2017 was 0.29 euros per vessel gross ton (Lindé, Vierth, & Cullinane, 2019). In 2018, this system of environmentally differentiated charging was replaced with a new model. The new system, which was described and evaluated by Vierth and Johansson (2019), uses the Clean Shipping Index (CSI) score as a basis for determining environmentally motivated rebates. The CSI assigns scores between 0 and 150 (ascending with environmental performance) and is composed of the following parameters: CO_2 emissions, NO_x emissions, SO_x emissions and particulate matter (PM) emissions, chemical use and water/waste management (Clean Shipping Index, 2018). Performance in each category can give up to 30 points and the index is computed on the basis of individual ships. The early impact evaluation by Vierth and Johansson (2019) finds that while the CSI method succeeded in accounting for previously neglected environmental impacts, the new system might reduce incentives for NO_x reduction. Their study also shows that the total environmental rebates awarded during 2018 amounted to 3.5 million euros, which represents roughly half of the rebates given for NO_x alone during 2017, the last year of the previous system. The total value of environmental discounts given in 2018 represents 3% of the Swedish Maritime Administration's total annual revenues from fairway dues and pilotage charges, which indicates that the environmentally 'corrective' element of the tariff structure is rather small, reflecting that the NO_x-reduction incentives have been somewhat reduced under the new system.

The new tariff regime for fairway dues, which entered into effect on January 1st, 2018 is structured as follows. Ships are divided into 10 size categories by net tonnage (NT), where the smallest size category encompasses vessels with NT smaller than 999 and the largest category encompasses vessels larger than 100,000 NT. This category determines the level of charges. Firstly, there is a *call fee* (for the vessel), which varies both according to the size category of a vessel and the CSI score the vessel has received. A score above 125 (out of 150) is awarded an A, while scores between 100 and 124, 75–99 or below 75 get awarded B, C and D respectively. Vessels that lack a CSI score get awarded an E. Larger vessels pay higher call fees, while higher CSI scores translate into rebated call fees. Secondly, there is a *readiness fee*, which is only differentiated according to size: ships that belong to higher NT categories pay more. Thirdly, there is a *cargo fee*, which is differentiated according to whether the cargo is high- or low-value. Passenger ships instead pay a fixed *fee per passenger* since 2018. In addition to the call fee, the readiness fee and the cargo/passenger fee there are certain rebates that impact the actual fees paid. Ships that call more than twice in a month are eligible for discounted call fees and readiness fees. After more than six calls during the same month, the ship pays no additional call or readiness fees. This means that the total fairway charge is significantly reduced for vessels that are frequent customers, which heavily favors regularly scheduled traffic such as RoPax. There is also a deep-sea discount, which applies to vessels in the 7th size class or above ($NT > 15,000$) and a rebate for ships carrying transshipment cargo. The

[7] At the time of writing, the new statistics for the year 2018 were just released, and it is not entirely clear what has caused this large increase. The consumption of fuel does not seem to have increased as much during 2018, which indicates that the growth in NO_x emissions could be the result of an increased use of fuel with a higher NO_x factor, e.g. HFO, and a reduced use of diesel.

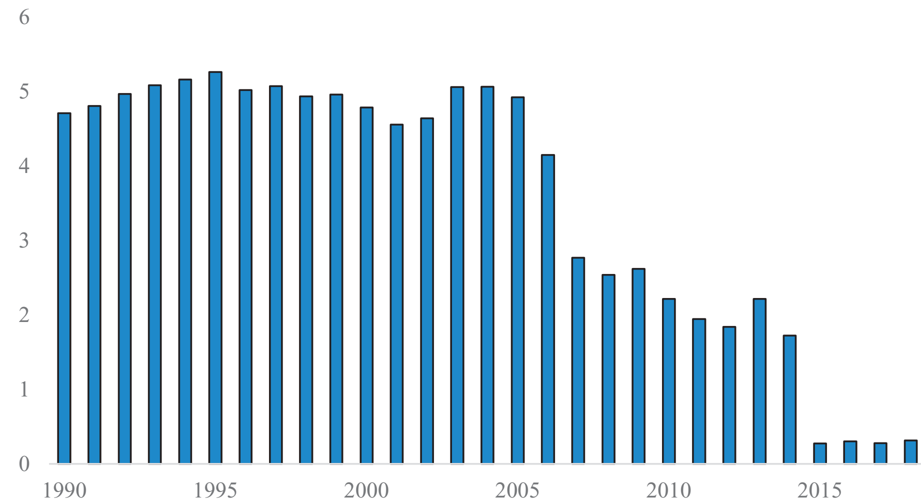

Fig. 2. Emissions of SO_2, measured in thousands of tons, from domestic maritime transport in Sweden. Source: Statistics Sweden (2019).

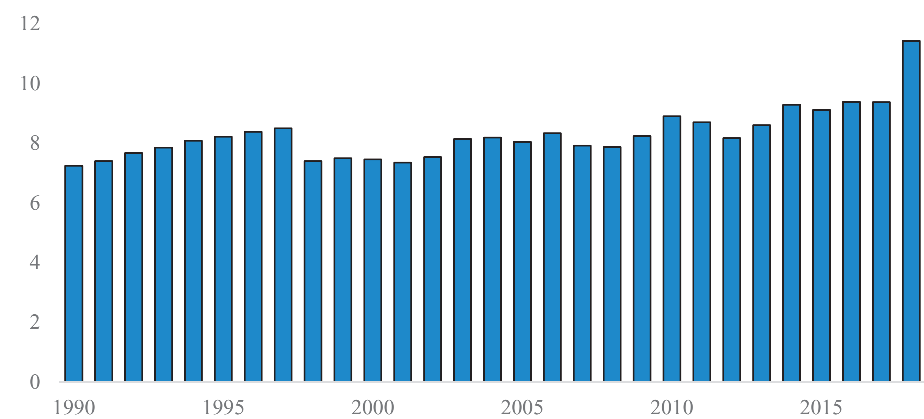

Fig. 3. Emissions of NO_x, measured in thousands of tons, from domestic maritime transport in Sweden. Source: Statistics Sweden (2019).

deep-sea discount is applicable to ships that regularly transport cargo on a deep-sea route. Vessels that qualify for the discount can receive a 75% reduction of their payable call and readiness fees. The deep-sea discount is motivated by the perception that maintaining cost-effective direct calls to other continents is important for the competitiveness of Swedish industry (Transport Analysis, 2017b).

Fig. 4 illustrates levels of total of the fairway dues components for five reference vessels: a small container ship with a capacity of 2800 TEU (assumed load of 2200), a large container ship with a capacity of 13,200 TEU (assumed load of 10,500), a small bulk ship with 18,000 GT, a large bulk ship with 104,700 GT (assumed load factor for both bulk vessels is 50%) and a Ro-Pax vessel with a capacity of 660 passengers and 2600 lane meters. The reference vessels and operational assumptions are the same as those used in Schroten et al. (2019). In addition to these fairway dues, pilot fees are charged separately. Pilot fees follow a two-way structure: a fixed cost is charged between around 400 euros and 2000 euros depending on the vessel's net tonnage size category. A variable cost is charged per half hour of service. This cost ranges from around 130 euros to 600 euros depending on the vessel's net tonnage.

An important note regarding Fig. 4 is that while these represent the chargeable fairway dues assuming no discounts, the average actual charge is significantly lower mainly due to the frequency discounts described above. This means that only a proportion of port calls (the first five each month for each individual vessel) are charged and among those charged only a proportion (the first two each month) are charged at full price. In total, 28% of approximately 79,000 vessel arrivals during 2018 were charged (Johansson, Vierth, & Bondemark, 2020). This proportion is lowest for the vessel category Ro-Pax, ferry and cruise ships, where only 9% of calls were charged. For this reason, the values in Fig. 4 should not be taken as an indication of how much a vessel is charged on average per port call, since vessels with a higher call frequency will end up paying significantly less.

Fig. 5 shows how the total amount of pilot fees and fairway dues (sum of vessel fees, readiness fees, cargo fees and passenger fees) actually paid during 2018 were distributed according to type of charge and vessel segment. For tanker vessels, bulk vessels, container vessels and general cargo ships, pilot fees accounted for the largest share of charges. The second largest fee (single largest for Ro-Ro and Ro-Pax, Ferry & Cruise) was the vessel-related part of the fairway dues (or call fee). As explained above, this charge is differentiated according to vessels' size and environmental performance, and the values presented in Fig. 5 show the total amount paid *after* such discounts were applied. The so-called readiness fee accounts for a small portion of total fees paid for all vessel segments, while cargo fees are substantial especially for tanker and bulk vessels. For obvious reasons, passenger fees are only paid by vessels in the Ro-Pax, Ferry & Cruise segment.

As mentioned in the introduction, fairway dues and pilotage fees in Sweden are internalizing transport policy measures since they impose monetary disincentives which are variable with respect to the external cost generated by transport operations. However, the description of these charging instruments in this section shows that they are far from perfect in terms of being proportional to external cost. Fairway dues are

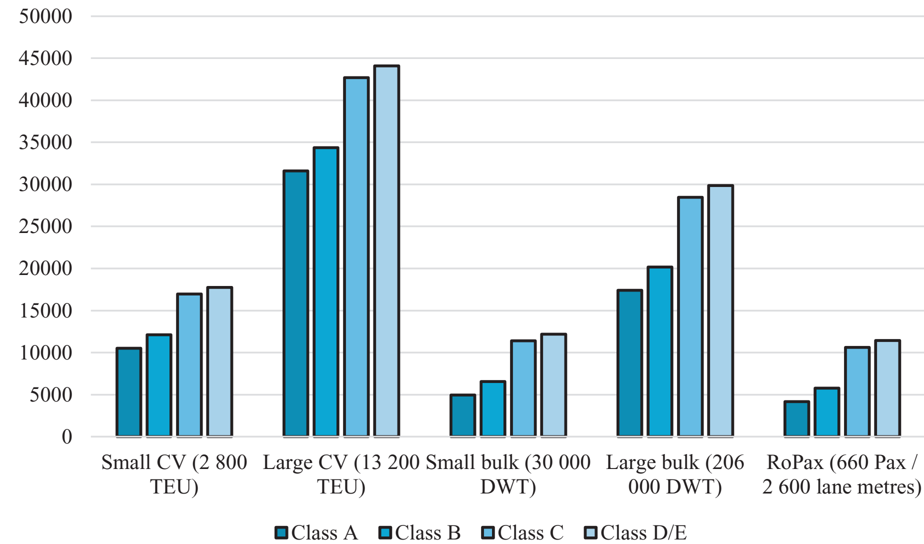

Fig. 4. Calculated fairway dues (in euros) per call for five reference vessels used in Schroten et al. (2019) using the tariff regime in force from 2018. The different classes illustrate how fees vary with vessels' environmental performance as measured by the Clean Shipping Index. Note that the calculated fees have not taken into account any discounts that might apply (including frequency discounts). Source: Own calculations based on the Swedish Maritime Administration (2018b).

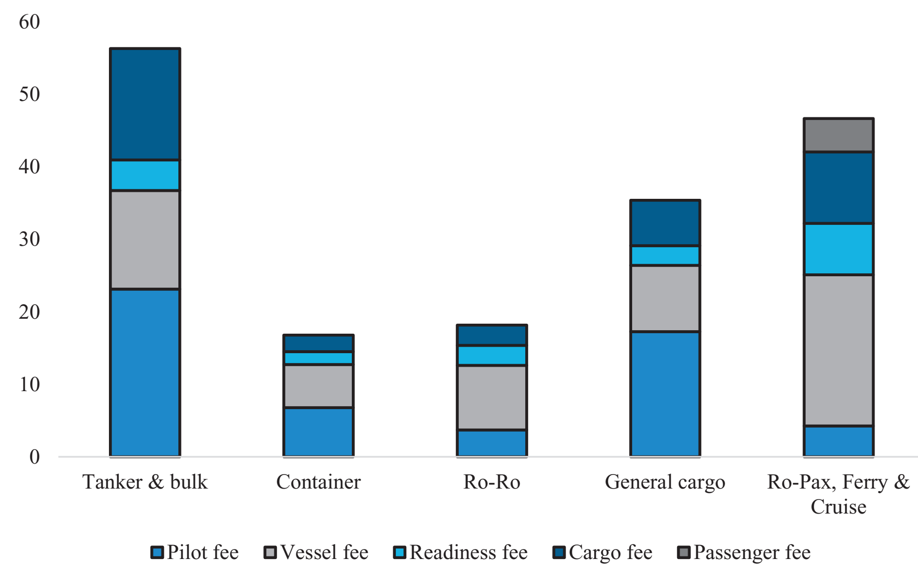

Fig. 5. Pilot fees and fairway dues paid in 2018 per vessel segment. Million euros expressed in 2018 prices. Segmentation done by Johansson et al. (2020).

on the one hand based on ship size and environmental performance, which is clearly related to external cost, but are not based on external cost-relevant factors such as distance sailed or fuel consumed. On the other hand, the frequency discounts in place imply that the average charge levied for port calls declines with each additional call, which is the opposite of a marginal social cost pricing principle. Pilot fees are based on size and time (duration of pilot service) which can be seen as a proxy for the distance the pilot boat is used. Pilot fees are effectively also differentiated according to whether vessels hold exemption certificates, which is presumably independent of the external cost generated. In summary, fairway dues and pilot fees are only weakly proportional to external cost.

4. Dataset and methodology for calculating the degree of internalization

4.1. Vessel movements and fuel consumption

There is no international consensus regarding the geographical area within which external costs should be counted as attributable to a country. One option, considered by Schroten et al. (2014) in a study of Dutch shipping's external costs, is to calculate the costs of half the distance between the country in question and the foreign destination. A drawback of this method is that it is not typically applied for road or rail transport, making the internalization of different modes difficult to compare. A second idea would be to calculate the external costs of the entire trip. This has the same drawback as the first method, and it could also lead to double counting of external costs. The method applied in this paper is instead focused on external costs arising from maritime transport in Swedish territorial waters. We acknowledge that the question of which geographical area to consider is difficult and open to discussion, but the relevance of considering only vessel movements within territorial waters is motivated by the fact that this is the primary area within which Sweden exerts any authority to levy corrective policies. Regarding its ability to influence emissions from international maritime transport, the government instead stresses the role of participating to promote such measures at the level of the IMO and the EU. Fig. 6 illustrates the extent of Swedish territorial waters.

The data regarding vessel movements is a collection of a full year's traffic for 2884 individual vessels performing a total of 1.3 million trips. The vessels counted in the dataset are those that called at a Swedish port, meaning that vessels that transited through the area were not included. The data was gathered by the maritime consultancy firm SSPA (2018), who quantified the total vessel-kilometers and fuel consumption for different vessel types with the help of AIS data and complementary inputs such as interviews with fuel suppliers and ship owners in order to determine the mix of different fuel types used. The calculation of vessel-kilometers shows an annual figure of 10.4 million vessel-kilometers within Swedish waters, whereof 5.1 million were domestic (Swedish port-to-port) trips. Fig. 7 illustrates the portion of kilometers carried out by different vessel types. The types of marine fuels considered to be in use are Heavy Fuel Oil (HFO), with subcategories corresponding to different sulphur content: High Sulphur Fuel Oil (HSFO) with 3.5% sulphur content, Low Sulphur Fuel Oil (LSHFO) with 1% sulphur content and Ultra Low Sulphur Heavy Fuel Oil (ULSHFO) with at most 0.1% sulphur content. In Sweden, vessels using HFO typically use ULSHFO as it satisfies the SECA requirements. Marine Gas Oil (MGO) with a maximum sulphur content of 0.1% (LSMGO) is also used. In addition, Marine Diesel Oil (MDO) with a sulphur content of max 0.001% is in use. Finally, some vessels use Liquified Natural Gas (LNG) as fuel, which principally contains no sulphur.

Fig. 8 illustrates the proportion of fuels consumed by the vessels in the dataset. The figures show that ULSFO and MGO are clearly the most used. The use of HSFO, which does not satisfy SECA regulations, can be explained by the use of scrubber technologies installed on some vessels. The calculations of fuel consumption are based on the movements recorded by AIS, including information about individual vessel and engines for propulsion as well as speeds. The fuel consumption at berth is not considered. The approach is based on calculating the energy required to pull the hull forward at a certain speed, taking account of propulsion efficiency, deep-water resistance, bottom topography and waves but excluding the effects of wind, streams, tides and shallow water (SSPA, 2018).

Fig. 6. Extent of Swedish territorial waters. Source: Swedish Maritime Administration (2019).

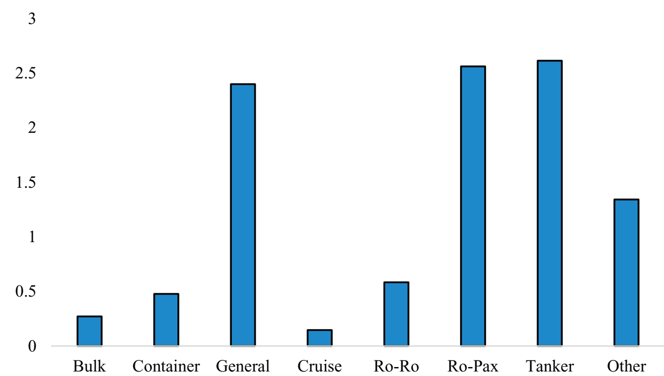

Fig. 7. Millions of vessel-kilometers in Swedish territorial waters by vessel type. Traffic from 2015. Source: SSPA (2018).

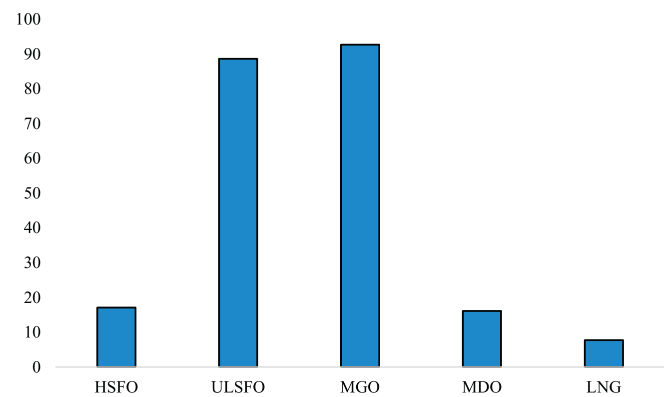

Fig. 8. Estimates of marine fuels consumed (thousand tonnes) in Swedish territorial waters in 2015. Source SSPA (2018).

4.2. *External costs (Costs of GHG emissions, air pollution and safety)*

CO_2-equivalents, a measure of the global warming potential of GHG, are calculated using emission factors from IMO (2015). The reason for focusing here on CO_2-equivalents, rather than just CO_2 emissions, is that excluding the small but still impactful emissions of methane (CH_4) and nitrous oxide (N_2O) would lead to an underestimation of shipping's impact on global warming. The conversion factors for CO_2-equivalents are shown in Table 1.

Using emission factors for various fuel types, as presented in IMO (2015), it is simple to compute the CO_2-equivalents emitted per tonne of fuel consumed. These emission factors, along with the calculated per-tonne CO_2-equivalent emissions are shown in Table 2.

The final row of Table 2 expresses that the amount of CO_2-equivalents emitted per ton of fuel consumed for HFO (ULSFO/HSFO), MDO/

Table 1
Conversion factors for CO_2-equivalents. Source: SEPA (2017).

Greenhouse gas	Global warming potential
CO_2	1
CH_4	25
N_20	298

Table 2
Emission factors, tonnes of emissions per tonne fuel consumed. Source: IMO (2015). CO_2-equivalents factor is calculated by multiplying the values in Table 1 through the factors in Table 2.

Greenhouse gas	HFO (ULSFO/HSFO)	MDO/MGO	LNG
CO_2	3.114	3.206	2.75
CH4	0.00006	0.00006	0.0512
N2O	0.00016	0.00015	0.00011
CO2-equivalents	3.16318	3.2522	4.06278

MGO and LNG is 3.16, 3.25 and 4.06 respectively.[8] Using these values leads to the conclusion that the annual traffic volume in the dataset gave rise to 719,560 tons of CO_2-equivalents. The question of how to value the emission of GHG is well-researched, though are varying answers (e.g. Nordhaus, 2017; Tol, 2009). The European handbook on the external costs of transport (van Essen et al., 2019a) recommends a central value of 100 euros per ton CO_2-equivalents in the short- and medium term. This is said to be based on the costs of limiting temperature rise to 1.5–2 degrees Celsius. This value is close to the value prescribed until recently in Swedish transport planning. The Swedish Transport Administration (2016) recommended a central value of 1140 SEK per ton, which is equal to 111.1 euros using the average currency exchange rate for 2018.[9] This value was not derived from any explicit damage or avoidance costs related to global warming, but was instead based on the politically decided Swedish CO_2 tax. The valuation was changed as of 2020, when a new valuation of 682 euros was made to be the new recommendation. The background for why this precise figure was chosen is a policy in Sweden in force since 2018 which mandates that fuel retailers must progressively increase the share of biofuels in petrol and diesel sold. The stated reasoning behind the reappraised CO_2 unit value is that it is to reflect the maximum fee that could be charged for selling petrol and diesel without including a mix of biofuels, i.e. failing to comply with regulations (Swedish Transport Administration, 2019). This value clearly deviates a lot not only from the previous Swedish recommendation, but also from international recommendations. In order to make our results comparable to international and Swedish previous studies, we will apply both the European and Swedish recommendations. In order to test the implications of the CO_2 re-appraisal for social cost internalization, we will also apply the new Swedish recommendation. The general method for calculating the monetary value of GHG impacts in this study can be described as

$$GHG\ impact = V_{CO2} * \sum_i F_i * E(CO_2e)_i \tag{1}$$

Where V_{CO2} is the valuation per ton of carbon dioxide equivalents, F_i is the amount of fuel type i consumed and $E(CO_2e)_i$ is the fuel-specific emission factor – how much CO_2e is emitted as a consequence of the consumption of a ton of fuel type i.

Calculating costs of other air pollutants requires both emission factors describing the relation between emissions and fuel consumption as well as monetary valuations of the individual pollutants. The emission factors for NO_x, VOC, SO_2 and PM are taken from the third GHG study (IMO, 2015). Given the information about the type and amount of fuel consumed in Swedish waters, it becomes possible to calculate the total amount of air pollutants. How to value them is an important question. As mentioned, the previous work on maritime external costs in Sweden (Vierth, 2018) used values from Nerhagen (2016), which indicate that the average cost of air pollution per ton of fuel consumed was 126 euros. Using instead the values from the European handbook, we can see that the cost per ton depends greatly on the type of fuel in use. The cost of air pollution associated with the consumption of a ton of ULSFO amounts to 799 euros, while the respective values for MDO, MGDO and LNG are 709, 785 and 115. The costs of air pollution arising from the use of LNG are by far the lowest, due to the very low NO_x emissions. As mentioned above, the difference between Nerhagen (2016) and the European handbook appears to be mostly attributable to very different valuations of NO_x. Both studies are based on an impact pathway approach, but some of the difference could have to do with the fact that Nerhagen (2016) calculates costs for a part of the Baltic Sea that is sparsely populated. For comparability, we use both values in the calculation of external costs. A limitation in this work is that we do not consider costs associated with noise or marine pollution. The general method for calculating the monetary value of air pollution impacts can be described as

$$Air\ pollution\ impact = \sum_j V_j \sum_i F_i * E_{j,i} \tag{2}$$

Where V_j represents the monetary per-ton valuation of air pollutant j, F_i is the amount of fuel type i consumed and $E_{j,\ i}$ is the amount of pollutant j emitted for every ton of fuel i consumed.

Another important set of inputs are those related to the valuation of safety. As previously mentioned, the European handbook and the Swedish guidelines offer different recommendations, which means that the marginal social cost of maritime traffic will differ depending on which guidelines are followed. Like with the above input factors, we apply both values in our calculations. The costs of accidents are calculated in the following way. First, we use the statistics compiled by Vierth (2016) on the total number of killed and injured people on passenger and freight vessels during 1985–2015. These number show that the average number of fatalities per year is 3.1, while the number of injuries sustained is 27.4. These average figures are then used as representative for a typical year. A drawback with this data is that we are unable to identify which injuries could be classified as serious injuries and which could be classified as slight injuries. Both the European handbook (van Essen et al., 2019b) and the Swedish guidelines for cost-benefit analysis (Swedish Transport Administration, 2020) differentiate between the cost of these two categories of injury. A notable difference is that the values prescribed by the Swedish Transport Administration are significantly higher than those recommended in the Handbook. For instance, the cost of a severe personal injury is roughly 1.32 million euros in the Swedish guidelines, while the European handbook prescribes a value of 0.5 million euros. The total external cost of a casualty prescribed by the handbook is 3.27 million euros, while the corresponding Swedish recommendation is around 4.5 million euros. Material damages incurred in accidents are assumed to be fully internalized through insurance and therefore irrelevant to the calculation of external cost. In order to deal with the fact that we cannot separate serious from slight injuries, we treat half the reported injuries as slight and half as serious.

4.3. Infrastructure costs (costs of icebreaking, pilotage)

As outlined in Section 3.1, The Swedish Maritime Administration's (2018a) cost of providing icebreaking services was roughly 31 million euros, however only part of these costs can be considered relevant. Based on data regarding emissions from icebreaking, the costs related to air emissions can be calculated. According to its annual report for 2018, the total CO_2-emissions from icebreaking vessels was 29,311 tons. Applying the emission factor for MGO from IMO (2015) and working backward, the total amount of fuel consumed is estimated to be around 9150 tons. From this information, the external costs of GHG-emissions and other air pollution can be easily found by applying the emission cost factors described above. Other marginal costs of icebreaking are related to the consumption of fuel and lubricants, maintenance and the renting of additional capacity. For these costs, values from Vierth (2016) are used.

[8] IMO (2015) include in their emission factors for LNG the effects of so-called methane slip. This refers to unburned methane being released from gas engines. See for instance Ushakov, Stenersen, and Einang (2019) for a more comprehensive discussion of the issue.

[9] This exchange rate is consistently applied throughout the paper.

Finding updated external costs of pilot services is not entirely straightforward. The average fuel consumption by pilot vessels in 2014 was 0.117 tons per service performed (Vierth, 2016). The Swedish Maritime Administration's annual report states that it performed 33,555 pilot services in 2018.[10] Assuming that the average rate of fuel consumption per service stayed roughly the same, the total amount of fuel consumed in 2018 amounts to 3930 tons. External costs of GHG emissions and other air pollutants can be found by applying the above described emission and valuation factors.

Having defined the features of the dataset (amount of traffic, vessel types, fuel consumption) and important assumptions and calculation inputs (emission factors, costs of GHG emissions and other air pollutants, cost of injuries), it is possible to calculate and compare the total marginal social costs of maritime traffic in Swedish waters with the total amount of fees charged in the form of fairway dues and pilot fees. In order to assess the sensitivity of the results to particular assumptions and to understand the differences between this study and that of van Essen et al. (2019a), we apply both the valuation factors used in their study and the those used by Vierth (2018). While the dataset regarding vessel movements is from the year 2015, we use fairway dues, pilot fees as well as estimated icebreaking and pilot costs for 2018 to calculate the degree of internalization. This is in order to reflect the current structure of charging in the Swedish fairway dues and pilot fees system.

5. Results

The main results regarding the internalization rates for maritime transport in Sweden are summarized in Table 3. Alternative A represents an updated version of what was reported in Vierth (2018). It is updated in the sense that more recent fairway dues and pilot fees (from 2018) are used, icebreaking and pilot costs were updated in accordance with the description in Section 4 and the most recent valuations of life and injury from the Swedish Transport Administration's guidelines were applied. Alternative B instead uses input values and valuations consistent with van Essen et al. (2019a). Specifically, this means that the CO_2-valuation is somewhat lower and that the valuation of other air pollutants (especially NO_x) is significantly higher. This affects not only the cost categories 'Other air pollutants' and 'CO_2-equivalents', but also the external costs of icebreaking and pilot services. The reason is that a fairly large share of these costs (10 to 25% for pilot services and 25 to 50% for icebreaking, depending on the valuation used) is due to GHG emissions and air pollutants from operating the pilot boats and icebreakers. Alternative C illustrates the impact of applying a CO_2-valuation of 682 euros per ton, while maintaining all other assumptions in Alternative A. Alternative D shows the effect of applying the same valuation while maintaining the set of valuations and inputs used in Alternative B.

The alternative that is most suitable for international comparison is B, since the valuations used are based on the European Commission's handbook on the external costs of transport. It is interesting to note that the degree of internalization yielded from using this approach is around 53%. This is notably closer to the computed degree of internalization by van Essen et al. (2019a) for road transport (56%) than their result for maritime transport (4%). The difference is quite striking and raises questions about what the state of play is regarding the external costs of maritime transport.

Clearly, some degree of difference is expected since different geographical areas with different population density are compared. Northern Europe including Sweden is subject to SECA regulations, which means that the marine fuel in use contains less sulphur. This translates into lower external costs than other parts of Europe covered by van Essen et al. (2019a). Sweden also has its national system of environmentally differentiated fairway charging, which is unique in an international context. The comparatively high degree of internalization found in this study could be taken as an indication that the fairway dues and pilot fees are an important part of achieving external cost coverage for maritime transport. There are also differences in the type of maritime traffic in Sweden compared to Europe as a whole: the Baltic Sea has a comparatively high share of passenger and Ro-Pax vessels. The structure of traffic is something that is likely to impact the degree of internalization. Still, the results also clearly show that, no matter the valuation method, the full extent of external costs of maritime transport in Sweden are not internalized by the fees levied by the Swedish Maritime Administration. This is partly due to the frequency discounts. In total, 28% of the calls during 2018 were charged; the share is lowest for the vessel category Ro-Pax, ferry and cruise ships (9%).

Updating the results of Vierth (2018) shows that fees and charges are close to covering costs (89.7%), but this is heavily influenced by a NO_x-valuation that differs from those recommended in the European handbook. Compared to Vierth (2018), we find for alternative A a slightly lower degree of internalization, which is mainly due to the use of new (higher) unit values for injuries and deaths. The total value of fees is also around 10% higher, which reflects the increase between the years 2017 and 2018. It is obvious that the much lower valuation of air pollutants in alternative A (based on Nerhagen, 2016) compared to that of alternative B (based on van Essen et al., 2019b) has a very large impact on the total marginal costs, and accordingly on the degree of internalization. The costs of air pollution are 6.2 times higher in alternative B compared to alternative A, highlighting a severe point of uncertainty.

No matter which method is preferred, the results in Table 3 show that the current system of charging does not adequately reflect the marginal social costs of shipping in Swedish territorial waters. The results of this paper are a useful update of previous research since we are able to compute the overall coverage of external and infrastructure costs for a full dataset of actual vessel movements without having to rely on hypothetical scenarios. Since we also have full information on the total fees and charges paid to the Swedish Maritime Administration, there is no need to assume or estimate charges.

It should be stressed that even if the results show that (using the current CO_2-valuation) the degree of internalization is at least 50% on average, this figure masks significant differences between different kinds of cost items. For instance, the results in Table 3 show that the pilot fees levied are at least twice the size of the total marginal costs involved in the production of pilot services. This means that if one were to assume that the costs of pilot services were internalized and leave them out of the calculation, one would run the risk of underestimating the degree of total external cost internalization (at least in Sweden). It should also be noted that there is a difference between external costs being internalized on average, and external costs being internalized at the margin. Even if the *total* marginal external and infrastructure costs were fully covered by fees and charges, this would not necessarily imply that the price signals in place yield an efficient modal distribution. This is because the relevant question is whether *an additional* vessel-kilometer, port call, unit of cargo transported, or other measure of marginal transport work, is charged for the costs it causes. What we have seen above is the extent to which the sum of external marginal costs is covered by the sum of fees charged. Whether or not these fees are functionally corrective depends on to what extent they internalize the costs of an additional unit of transport work at the level of the decision-maker. There are elements in the Swedish fairway charging system that are at odds with marginal cost pricing. An example is the frequency rebates given to vessels that call several times during a month. Each of these calls gives rise to external and infrastructure costs, and the frequency rebate means that charges are regressive with respect to the number of calls. The fairway dues also include marginal cost-related charges such as the differentiation of price with respect to environmental performance. However, because the environmentally differentiated fee is discounted with the frequency of port calls, the somewhat strange situation occurs that for each additional port call, the incentive

[10] For reference, the total number of vessel calls at Swedish ports during 2018 was 79,393.

Table 3
Computed degrees of internalization using inputs in four alternative valuation scenarios. All dues, fees and costs are expressed in 2018 euros. Alternatives A and B correspond to methodologies in Vierth (2018) and van Essen et al. (2019a) respectively. Alternatives C and D illustrate the impact of re-appraising the CO_2 valuation to reflect a much higher value. Final rows in bold show the sum of marginal costs and the degree of internalization (total fees divided by total marginal costs).

Alternatives for 2018	A: Updated Vierth (2018)	B: van Essen (2019)	C: Updated Vierth (2018) with high CO2	D: van Essen et al. (2019b) with high CO2
CO_2 valuation (€/tonne)	111.1	100	682	682
Fees (expresed in million 2018 €)				
Fairway dues	117.5	117.5	117.5	117.5
Pilot fees	56.1	56.1	56.1	56.1
Total fees	**173.5**	**173.5**	**173.5**	**173.5**
External and infrastructure costs (million €)				
Icebreaking	10.2	16.4	26.9	33.5
Pilot services	16.7	19.6	24.1	26.9
Accidents	44.4	18.9	44.4	18.9
CO2-equivalents	90.1	72.0	491.1	491.1
Other air pollutants	32.0	198.3	32.0	198.3
Total marginal costs	**193.5**	**325.1**	**618.5**	**768.7**
Degree of internalization	**89.7%**	**53.4%**	**28.1%**	**22.6%**

In accordance with both Swedish and European guidelines, prices have been converted to a new base year by correcting for both inflation and growth in GDP per capita.

to improve the environmental performance profile of a ship is reduced.

At first glance, the implication of the results in Table 3 might be that fairway dues and pilot fees ought to be uniformly raised. However, as illustrated in Fig. 9, the degree of internalization varies significantly by vessel segment. Using the breakdown of fees paid per segment provided by Johansson et al. (2020) and illustrated in Fig. 5, degrees of internalization can be computed separately per vessel segment. The results show that the segment Ro-Pax, Ferry & Cruise exhibits the lowest degree of internalization. This holds true regardless of whether the higher CO_2-valuation is applied. The degree of internalization after applying the higher valuation is more uniform across all other segments, averaging around 40%. A main reason why Ro-Pax, Ferry and Cruise vessels stand out as being worse is that the aforementioned 'frequency discount', i.e. the reduction in paid fairway dues per vessel call during a month, greatly favors ships that operate high-frequency schedules (Ro-Pax and ferries). A limitation should be noted about the analysis presented in Fig. 9. Importantly, the external costs of GHG emissions and air pollution have been calculated assuming the same fuel mix for each segment (in absence of specific information regarding what fuel is used by each segment). There are likely to be differences between segments both in terms of fuel used and in terms of other abatement measures such as scrubber use which might affect the results somewhat. Such uncertainties are however unlikely to change the result that the segment Ro-Pax, Ferry & Cruise is less internalized than others. Interestingly, Fig. 9 shows that the finding that maritime transport is under-internalized in column A of Table 3 is almost entirely driven by the low degree of internalization in this segment. It can be added that because a large share of these vessels operate short-sea routes, they spend a greater part of their operational lives within Swedish territorial waters. Since they therefore cause lesser external costs outside Swedish waters than vessels on deep-sea services, the preferential treatment illustrated in Fig. 9 may be seen as somewhat justified.

There are still things that can be improved in terms of the gathering of data relevant to calculating external and infrastructure cost coverage. An important point to reiterate is that we do not include port charges or the added effects of local air pollution in ports in our calculations. As mentioned in the introduction of the paper, port charges in Sweden are unlike fairway dues and pilotage fees in that they are not instruments of national transport policy and most ports' charges are not explicitly differentiated with regard to the marginal external costs caused by maritime transport. However, the omission of port charges and external costs in ports represents a shortcoming in this paper since any under−/over-internalization of external costs in ports through the levying of port charges will affect the main results. While it is theoretically possible to include port charges, there are problems. One problem is that unlike with the fairway dues and pilot fees, we do not have information

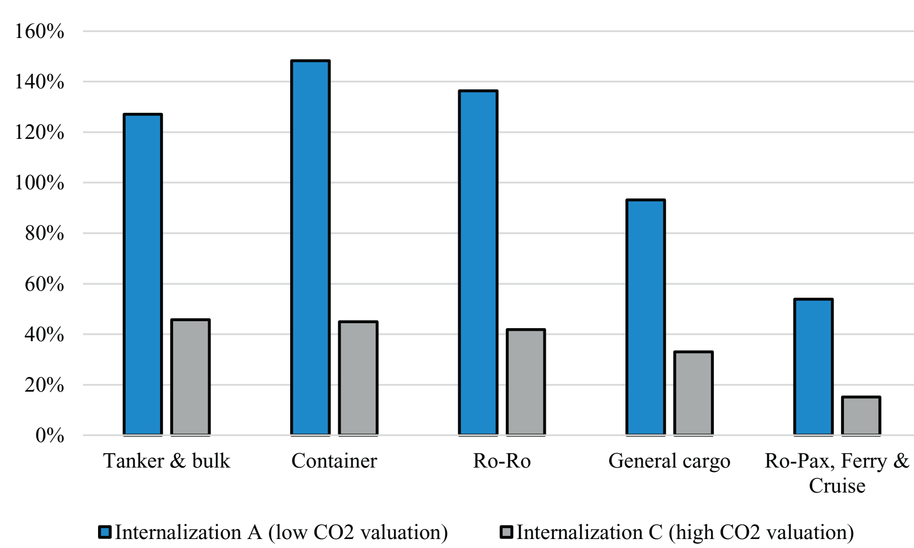

Fig. 9. Degree of internalization per vessel segment under the CO_2-valuation recommended until recently by Swedish cost-benefit guidelines (column A of Table 3) and under the recently reappraised CO_2-valuation (column C of Table 3).

regarding what port charges are actually paid. While most ports' tariff policies are available as published documents, it is ultimately difficult to know which ships have been charged at a full price and which have been given rebates. In addition, it is difficult to distinguish the portion of port charges which are simply payment for services and which portion ought to be viewed as internalizing. The benefit of the fairway dues and pilot fees is the transparency of the charging structure: we know exactly what total amount has been charged per call and per vessel. The structure of port charges is often complex, and it is not necessarily clear what charges are levied in order to cover past investment costs and what charges are levied to pay for port services.

A further limitation of our work is that we do not account for the increased cost of air pollution in port. Ship emissions at berth have significantly more impact on human health since they occur closer to dense centers of population. Since we do not have sufficient information about ships' laytime or emissions at berth specifically, this additional impact of local air pollution in addition to the regional air pollution that is addressed in our calculations is excluded from analysis. In addition to the higher impact of emissions at berth, we are also unable to account for the costs of marine pollution to water and noise. Both effects have been studied (e.g. Bermúdez, Laxe, & Aguayo-Lorenzo, 2019; Jägerbrand, Brutemark, Svedén, & Gren, 2019), but including valuations of such impacts would require more information.

Finally, a point that should be emphasized about the results is that they depend on the geographical delimitation of the study, which is Swedish territorial waters. If we were instead to expand the area within which external costs could be considered attributable to Swedish maritime transport, the degree of internalization would be lower. An alternative framework could be to count the external costs of half the journey to/from an international trading partner. This requires more in terms of data, since given our current dataset we do not have information regarding complete international movements originating and ending in Sweden. The approach used by van Essen et al. (2019a) is to calculate the degree of internalization for a set of hypothetical cases, calculating the external costs for vessel trips of up to 15,000 km. In absence of reliable data, this could be an appropriate method to supplement the state of knowledge regarding the internalization of international maritime transport. Still, with the increased availability of positional ship data and vessel movements using AIS, the approach used in this paper has the potential to be expanded to wider geographical areas in order to more precisely measure external costs.

6. Discussion and concluding remarks

Maritime transport in Sweden is subject to relatively strict regulation when it comes to emissions to air. It is since 2015 covered by the North Sea, Baltic Sea and English Channel SECA, which reduces the extent of SO_x emissions. Vessels calling at Swedish ports are also obligated to pay fairway dues. The vessel-related part of the fairway dues is differentiated according to emissions of CO_2, NO_x, SO_x and PM, as well as chemical use and waste/water management. This means that there is a monetary incentive to improve environmental ship performance in all of these categories, though early evaluations of the new system show that these incentives are not very strong – especially when it comes to the reduction of NO_x (Vierth & Johansson, 2019). This regulatory framework will be complemented as of 2021 by the introduction of a mandate that all new or newly modified vessels must comply with Tier III standards in the NECA comprising the North Sea and the Baltic Sea, which is expected to reduce the emissions of NO_x in the longer run.

To what extent does the Swedish national regulatory framework succeed in internalizing the external and infrastructure costs of maritime transport? Our results indicate that maritime transport in Sweden is under-internalized overall, meaning that it does not fully bear its social cost burden. The rate of internalization differs depending on some of the input values used in calculating external costs. As can be seen from Table 3, the combined use of valuation inputs for air pollution, GHG emissions and casualties/injuries in traffic from the European Commission's Handbook on the external costs of transport (van Essen et al., 2019b) implies a cost coverage ratio of around 53%. Using updated values from previous Swedish studies instead (Vierth, 2016, 2018) implies that the cost coverage is somewhat higher: around 90%. Both of these values differ significantly from the recent finding that the external costs of maritime transport in Europe are internalized to a degree of 4% (van Essen et al., 2019a). First, it should be reiterated that the scope of the studies is different – theirs covers international maritime transport in a set of 34 European ports while ours covers vessel movements in Swedish territorial waters. Still, the difference is interesting since the true degree of cost coverage has serious implications for the type and magnitude of economic disincentives that ought to be levied on ships in order to achieve a 'polluter-pays'-scenario. The value of the present study is to show that it is feasible to calculate the degree of cost internalization for maritime transport using actual traffic data, without having to rely on hypothetical reference scenarios.

The results presented in Fig. 9 show that a uniform increase of the current charges in place would not be a good way to achieve cost coverage, since the degree of internalization varies significantly between different shipping segments. A general problem with the current charging regime is that the costs it incurs on ship operators are at best approximately proportional to the harm generated by their operations. There are elements of the charging scheme, such as the frequency discounts, which are clearly at odds with the principle of marginal social cost pricing. At the same time, the charging of maritime transport requires a balancing act so that short-sea shipping services are not made uncompetitive vis-à-vis road transport solutions which may be worse from an external cost perspective. Proposing an alternative charging regime is outside the scope of this paper, but it is clear that the current system of charging does not adequately steer towards a 'polluter-pays' scenario. An improved system of environmentally differentiated charging in Sweden ought to seek harmonization between charging systems levied by ports and through national policy instruments, meaning that the method of benchmarking/rewarding environmental performance ought to be consistent. Expecting the system of fairway dues and pilotage fees to both raise sufficient revenue to finance the operations of a government agency and at the same time incur costs on maritime transport which are equal in size to the marginal social costs caused may be asking too much of these policy instruments. If both these objectives are to be achieved, other more appropriate instruments for internalization are needed. If the need for pilotage could be reduced in the future, e.g. through automation or a higher share of ships with exemption certificates, it would make little sense to keep charging high pilotage fees to cover other external costs. In terms of CO_2-emissions, monetary disincentives levied in an individual country are unlikely to have any significant effect on the industry-wide shift to less carbon-intensive propulsion. Acting at the international level, for instance by including CO_2-emissions from maritime transport in the EU emissions trading system, is likely to be more effective.

An interesting question for future research is how the Monitoring, Reporting and Verification (MRV) regulation for tracking CO_2 emissions, which has entered into force in the European Union (2015) can be applied in future analyses of policy measures to reduce emissions. The EU MRV regulation allows the monitoring of the type and amount of fuel consumed by ships, the total CO_2 emitted, as well as the total transport work produced. It applies to ships larger than 5000 GT calling at any EU port, and the first reporting period was 2018. A similar regulation is the IMO Data Collection System (DCS), which entered into force in 2018 and mandates the reporting of travelled distance and the amount/type of fuel consumed for ships larger than 5000 GT (IMO, 2018). The IMO DCS regulation applies globally. In parallel with this development is the increased use of AIS data for tracking vessel movements. The Swedish Environmental Protection Agency, which compiles the official statistics regarding emissions to air from shipping recently revised their method to incorporate AIS data. In summary, it seems that increased opportunities for data-driven analysis of maritime transport policies may be on the horizon. A recent example of research utilizing AIS data for the purpose of analyzing policy-relevant issues in maritime trade is Heiland, Moxnes, Ulltveit-Moe, and Zi (2019), who study the size and distribution of welfare effects following the expansion of the Panama Canal.

The Swedish parliament passed legislation in 2017 to increase its ambition in reducing GHG emissions and adhering to the Paris agreement. The sectoral goal for domestic transport is to cut emissions by 70% by 2030 compared to 2010. While emissions from domestic transport did decrease by about 18% between 2010 and 2017 (Statistics Sweden, 2019), the pace of reduction needs to increase if the target is to be met. It is likely that even with greater internalization of the climate change-related costs of transport, the amount of emissions reductions will fall short of the 70% rate that was decided. *Re*-appraising the valuation of CO_2 used in transport planning to reflect these high ambitions could therefore be a way of bridging the gap between cost coverage and target fulfilment. The new valuation, made the official recommendation in 2020, means that CO_2-emissions will carry six times more weight in the appraisal of transport system interventions. As shown in Table 3, this means that the rate of internalization will be much lower.

There are still aspects of the methodology for determining the internalization rate of maritime transport that could be improved. One aspect that deserves emphasis is that there is little consensus on how to value other environmental externalities than emissions to air. Another aspect is the differentiation of air pollution from ships at berth, where the proximity to urban areas means greater impacts to human health. Finally, an improved understanding of how different policy instruments contribute to the internalization of external costs is needed to more fully appraise the degree to which maritime transport actors are charged for the external costs they give rise to.

Acknowledgements

The authors are grateful for the comments and suggestions provided by two anonymous reviewers. The authors have no conflicts of interest to declare.

References

European Commission. (1995). *Towards Fair and Efficient Pricing in Transport – Policy options for internalizing the external costs of transport in the European Union*. COM (1995) 691 Brussels.

European Commission. (1998). *Fair Payment for Infrastructure Use: A phased approach to a common transport infrastructure charging framework in the EU*. COM (1997) 466 Brussels.

European Commission. (2001). *European transport policy for 2010: time to decide*. Com (2001) 370 Brussels.

European Commission. (2008). *Strategy for the internalization of external costs*. COM (2008) 435 Brussels.

European Commission. (2011). *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*. COM (2011) 144 Brussels.

Swedish Environmental Protection Agency [SEPA]. (2017). Sveriges rapportering till FN: s klimatkonvention Agency. https://www.naturvardsverket.se/Miljoarbete-i-samhallet/EU-och-internationellt/Internationellt-miljoarbete/miljokonventioner/Klimatkonventionen/Sveriges-rapportering-till-fns-klimatkonvention/.

Clean Shipping Index [CSI]. (2018). Methodology and Reporting Guidelines. https://www.cleanshippingindex.com/methodology/. Retrieved 2019a.12.05.

Statistics Sweden. (2019). Statistical database. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/. Retrieved 2019.12.05.

Swedish Maritime Administration. (2018b). Sjöfartsverkets nya avgiftsmodell presenterad som en prislista utifrån gällande föreskrifter för år 2018. http://www.sjofartsverket.se/pages/1615/Prislista%202018.pdf. Retrieved 2019c.12.05.

IMO. (2018). Data collection system for fuel oil consumption of ships. http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Data-Collection-System.aspx. Retrieved 2020a.01.02.

Proposition 2012/13:25. (2012). Investeringar för ett starkt och hållbart transportsystem. https://www.regeringen.se/49bbbe/contentassets/ea84b67fcac94bf8b5071c6e3c8db672/investeringar-for-ett-starkt-och-hallbart-transportsystem-prop.-20121325. Retrieved 2020b.08.07.

Swedish Maritime Administration. (2019). Sjöterritoriets gräns i havet. https://www.sjofartsverket.se/sv/Maritima-Tjanster/Havsgranser/Sjoterritoriets-grans-i-havet/. Retrieved 2020c.08.10.

European Union. (2003). Council directive 2003/96/EC. In *Official Journal of the European Union, L 283/51*.

European Union. (2015). Regulation 2015/757 of the European Parliament and of the Council on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, and amending Directive 2009/16/EC. *Official Journal of the European Union, L 123/55, 58*, 55–76.

Gomes, P., Lopes, M., Martins, H., & Carvalho, J. (2010). Internal and external costs of transport in Portugal. In *CITTA 3rd Annual Conference on Planning Research: Bringing City Form Back Into Planning*.

Johansson, M., Vierth, I., & Bondemark, A. (2020). *Evaluation of the Swedish Maritime Administration's new system for fairway dues and pilot fees – A model comparison for the period 2017 to 2019*. VTI report 1034.

Ricardo-AEA. (2014). *Update of the Handbook on External Costs of Transport*. Ricardo-AEA/R/ED57769.

Swedish Environmental Protection Agency [SEPA]. (2019a). Växthusgaser från inrikes transporter. https://www.naturvardsverket.se/Sa-mar-miljon/Statistik-A-O/Vaxthusgaser-utslapp-fran-inrikes-transporter/. Retrieved 2019.12.16.

Swedish Environmental Protection Agency [SEPA]. (2019c). Ny metod visar högre utsläpp för inrikes sjöfart. https://www.naturvardsverket.se/Nyheter-och-press meddelanden/Ny-metod-visar-hogre-utslapp-for-inrikes-sjofart/. Retrieved 2020.01.02.

Swedish Maritime Administration. (2018a). *Årsredovisning 2018 [Annual report]*.

Swedish Transport Administration. (2016). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 6.1 (Version 2018-04-01)*.

Swedish Transport Administration. (2020). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7 (Version 2020-06-15)*.

Swedish Transport Administration. (2019). *Åtgärder för ökad andel godstransporter på järnväg och med fartyg*. TRV 2018/93627.

Transport Analysis. (2017a). *Överflyttningseffekter inom SECA – regionala utvecklingsmönster av sjöfarts- och lastbilsgods mellan 2001 och 2015*. Rapport 2017:13.

Transport Analysis (2017b). Miljökonsekvenser av nya farledsavgifter. PM 2017:9.

Transport Analysis. (2019). *Transportsektorns samhällsekonomiska kostnader*. Rapport 2019:4.

Baumol, W. J., & Oates, W. E. (1971). The use of standards and prices for protection of the environment. In *The economics of environment (pp. 53–65)*. London: Palgrave Macmillan.

Bermúdez, F. M., Laxe, F. G., & Aguayo-Lorenzo, E. (2019). Port sustainability in Spain: The case of noise. *Environment, Development and Sustainability*, 1–18.

Christodoulou, A., Gonzalez-Aregall, M., Linde, T., Vierth, I., & Cullinane, K. (2019). Targeting the reduction of shipping emissions to air: A global review and taxonomy of policies, incentives and measures. *Maritime Business Review, 4*(1), 16–30.

van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Schmidt, M., Brambilla, M., … Andrew, E. (2019a). *State of play of internalisation in the European transport sector*, 194K83.071a. Delft.

van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Brambilla, M., … Parolin, R. (2019b). *Handbook on the external costs of transport. 18.4K83.131. Delft*.

Hagem, C., Holtsmark, B., & Sterner, T. (2012). *Mechanism design for refunding emissions payment*. Statistics Norway Research Department Discussion Papers. (No. 705).

Heiland, I., Moxnes, A., Ulltveit-Moe, K. H., & Zi, Y. (2019). *Trade from space: Shipping networks and the global implications of local shocks*. CEPR Discussion Paper 14193.

Hofbauer, F., & Putz, L. M. (2020). External costs in inland waterway transport: An Analysis of external cost categories and calculation methods. *Sustainability, 12*(14), 5874.

IMO. (2015). Third IMO greenhouse gas study 2014. *London*.

Jägerbrand, A. K., Brutemark, A., Svedén, J. B., & Gren, M. (2019). A review on the environmental impacts of shipping on aquatic and nearshore ecosystems. *Science of the Total Environment, 695*, 1–13, 133637.

Kahn Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D., Lee, D. S., … Zhou, P. J. (2007). Transport and its infrastructure. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Lindé, T., Vierth, I., & Cullinane, K. (2019). Evaluating the effects of Sweden's environmentally differentiated fairway dues. *Transportation Research Part D: Transport and Environment, 70*, 77–93.

Link, H., Nash, C., Ricci, A., & Shires, J. (2016). A generalized approach for measuring the marginal social costs of road transport in Europe. *International Journal of Sustainable Transportation, 10*(2), 105–119.

Nerhagen, L. (2016). Externa kostnader för luftföroreningar – Kunskapsläget avseende påverkan på ekosystemet i Sverige, betydelsen av var utsläppen sker samt kostnader för utsläpp från svensk sjöfart. *VTI notat*, 24–2016.

Nikolakaki, G. (2013). Economic incentives for maritime shipping relating to climate protection. *WMU Journal of Maritime Affairs, 12*(1), 17–39.

Nilsson, J.-E., Isacsson, G., Haraldsson, M., Nerhagen, L., Odolinski, K., Swärdh, J.-E., … Österström, J. (2018). *The efficient use of infrastructure – Is Sweden pricing traffic on its roads, railways and airways at marginal costs?*. CTS Working Paper 2018:2.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences, 114*(7), 1518–1523.

Notteboom, T. (2011). The impact of low Sulphur fuel requirements in shipping on the competitiveness of roro shipping in northern Europe. *WMU Journal of Maritime Affairs, 10*(1), 63–95.

Parry, I., Heine, D., Kizzier, K., & Smith, T. (2018). *Carbon taxation for international maritime fuels: Assessing the options*. IMF working paper WP/18/203.

Raza, Z., Woxenius, J., & Finnsgård, C. (2019). Slow steaming as part of SECA compliance strategies among RoRo and RoPax shipping companies. *Sustainability, 11* (5), 1435.

Santos, G. (2017). Road fuel taxes in Europe: Do they internalize road transport externalities? *Transport Policy, 53*, 120–134.

Schroten, A., Scholten, P., van Wijngaarden, L., van Essen, H., Brambilla, M., Gatto, M., … Coulon, A. (2019). *Transport taxes and charges in Europe – An overview study of economic internalization measures applied in Europe*. Delft: CE Delft.

Schroten, A., H P van Essen, S. J. A., Verhoef, E. & Knockaert, J. (2014). Externa en infrastructuur-kosten van verkeer - Een overzicht voor Nederland 2010, Delft: CE Delft.

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari, 2014: Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

SMHI. (2019). Årlig maximal isutbredning i Östersjön. https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-havsis-1.20049. Retrieved 2019.12.05.

SSPA. (2018). *VTI - Bränselförbrukning av olika bränslekategorier*. Gothenburg: SSPA.

Stalmokaitė, I., & Yliskylä-Peuralahti, J. (2019). Sustainability transitions in Baltic Sea shipping: Exploring the responses of firms to regulatory changes. *Sustainability, 11* (7), 1916.

Tol, R. S. (2009). The economic effects of climate change. *Journal of Economic Perspectives, 23*(2), 29–51.

Ushakov, S., Stenersen, D., & Einang, P. M. (2019). Methane slip from gas fuelled ships: A comprehensive summary based on measurement data. Journal of Marine Science and Technology, 1-18.

Vierth, I. (2016). *Sjöfartens policyrelevanta samhällsekonomiska marginalkostnader*. VTI Report 908.

Vierth, I. (2018). *Organization of pilot and icebreaking in the Nordic countries and update of the external costs of sea transports in Sweden*. VTI Report 988A.

Vierth, I. (2020). *Policies and measures to reduce air emissions from shipping: Recommendations for Swedish stakeholders*. VTI notat 24A-2019.

Vierth, I., & Johansson, M. (2019). The impact of alternative environmentally differentiated fairway dues systems in Sweden. In *World of shipping Portugal, an international research conference on maritime affairs, 21–22 November, Carcavelos, Portugal*.

Windmark, F., Jakobsson, M., & Segersson, D. (2017). *Modellering av sjöfartens bränslestatistik med Shipair*. SMHI, Rapport nr 2017-10.