Chapter 10
Economic and Environmental Trade-Offs in Water Transportation

Thalis Zis, Panagiotis Angeloudis and Michael G.H. Bell

Abstract In recent years slow steaming has resurfaced as a fuel saving measure allowing ship owners to significantly cut operational costs. Reduced fuel consumption leads to lower levels of greenhouse gases and pollutant emissions. Port authorities have considered offering incentives to ship operators that significantly reduce sailing speed in the port proximity, as a means to improve local air quality. This chapter conducts a literature review on emissions modelling methodologies for maritime transport and develops a framework that allows the estimation of pollutant emissions under different sailing scenarios. The chapter presents existing regulations and port initiatives that aim to reduce maritime emissions. The merits of localised slow steaming near the calling port for various case studies including different ship size, trip distance, sailing speed and fuel policies in place are examined. An activity based methodology is used to estimate fuel consumption and emissions savings during lower sailing speed operation for machinery on-board. Fuel price and the value of time lost govern the extent to which slow steaming and local speed reductions can be effective. The economic and environmental trade-offs occurring at different sailing speeds are discussed from the perspective of both the ship operator and the port authority considering the implications of regulatory policies such as the expansion of Emission Control Areas (ECA). The chapter concludes with a set of guidelines to port authorities on designing attractive speed reduction programmes, and recommendations to shipping companies on improving fuel efficiency across their schedule when such programmes are available.

Keywords Shipping emissions · Emission control areas · Speed optimization · Environmental trade-offs · Speed limits

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10.1 Introduction

The transportation sector accounted for 22 % of world CO_2 emissions in 2010 (IEA 2012), while the shipping sector alone was responsible for 2.2 % of the global amount in 2013 down from 2.7 % in 2008 (IMO 2014). This figure is relatively low considering that maritime transport moves 80 % of the world's trade by volume (UNCTAD 2013) and supports the argument that shipping is the most efficient mode of transport. However, cargo volumes continue to increase and as a result the environmental impacts of maritime transport are expected to gain interest in the future.

In addition to the contribution of the sector to climate change through the release of CO_2, there are concerns about other pollutant species emitted through maritime shipping. Of particular interest are sulphur, nitrogen and particulate matter emissions. The shipping sector is responsible for between 5 and 8 % of the global anthropogenic SO_2 emissions (Eyring et al. 2005) whereas its share of NO_x emissions was estimated at approximately 8.5 % in 2000 (Koffi et al. 2010) although there are other estimates that this figure reaches 15 % (Corbett et al. 2007). In the latter study, it is also estimated that PM emissions from shipping accounted for 64,000 fatalities near European, East and South Asian coastlines in 2002, a number which could increase with the expected growth in shipping activity.

Over the last decades there have been many attempts to reduce the growth of total emissions from the sector, with the International Maritime Organisation (IMO) playing an active role in developing a number of regulations and policies covering a broad range of important factors that affect the footprint of each ship, including fuel quality, engine efficiency and hull designs. Research has been carried out on emissions at both the microscopic (i.e. focusing on specific ship elements such as engine, ship design etc.) and macroscopic levels (i.e. approaching the problem from a systems perspective such as fleet deployment). Regulations have been set up to address the environmental consequences of maritime shipping at the global level dealing with CO_2 emissions and at a more regional level addressing pollutant emissions near coastlines, inland waterways and ports.

This chapter commences with a review of the literature on shipping emissions, the main modelling methodologies used to estimate the sector's footprint and ways of reducing the environmental impacts of maritime transport. The existing regulatory framework that is concerned with air emissions from maritime shipping is presented and operational practices and technologies that affect fuel consumption are discussed. The chapter then expands on existing studies by highlighting the economic and environmental trade-offs that emerge when emission reduction measures are adapted by the relevant stakeholders (regulators, shippers, port authorities). It is shown that to design efficient emissions reduction measures the perspective of all stakeholders has to be accounted for. The chapter finishes by providing recommendations for further research on the trade-offs amongst different pollutants and on specific questions with regards to impacts of the coming regulation on sulphur content. The potential benefits of including the maritime sector in emissions trading systems are also discussed.

10.2 Literature Review

This section presents previous research on the environmental impacts of maritime shipping. The research spans from efforts to create global emission inventories for the sector to operational problems of optimising sailing speeds across particular routes and dedicated studies of monitoring pollutants in coastlines.

10.2.1 Shipping Emissions Modelling

Pollutants emissions are the result of fossil fuel combustion in vessel engines. Most modelling methodologies calculate the emissions generated either as a function of the ship activity or the bunker sales in a specific region and subsequently multiplying this figure with appropriate emission factors. The former type is known as a bottom-up approach while the latter is a top-down approach. The selection of which approach is most appropriate to model the fuel consumption of a given system depends on the available data; however there are examples where intermediate approaches are preferred. In each case it is important to use accurate emission factors to convert the fuel consumption to pollutant emissions.

10.2.1.1 Bottom up

The term bottom-up is used to denote the approach of examining the contribution of each individual actor to a system. In the context of emissions modelling, a bottom-up approach considers the fuel consumption of each engine operating in a ship at each phase of each journey (cruise, manoeuvring, anchorage and at berth) and adds this fuel consumption for all engines, vessels and journeys to estimate the system's performance and emissions contribution. The necessary data to build the emissions estimate of a particular system (fleet) involves the technical specifications of each vessel (engine power installed, hull efficiency) and the operating patterns (sailing speed at sea, manoeuvring profiles at each port, hours spent stationary at anchorage and turnaround time at each port) at each activity phase.

Notable applications of bottom-up studies include the updated global emissions from ocean shipping based on activity data and vessel information from the Lloyd's ship registry (Corbett and Koehler 2003), the construction of an emissions inventory for marine vessels operating within 200 nautical miles of the US shoreline and inland waterways (Corbett and Fischbeck 2000) and the energy use and emissions generation of vessel activity in North America (Wang et al. 2007). In an era where vessel activity can be retrieved through data of shipping companies, port authorities and Automatic Identification System (AIS) the use of bottom-up methodologies can provide realistic estimates of emissions generated through shipping.

10.2.1.2 Top Down

A top-down approach decomposes a system by reducing it to its compositional subsystems. Top-down approaches in emissions modelling use data on the overall fuel consumed within a system and then match this consumption to the expected activity that caused it. Many studies are based on fuel sales statistics where the underlying hypothesis is that the fuel sold has been consumed under typical conditions. Such approaches could be used for the construction of large scale emission inventories (large areas, fleets and periods examined) but one key weakness in the context of marine emissions are the poorly documented sources of fuel statistics and the lack of validation (Corbett and Koehler 2003). When a top-down approach is used to estimate the emissions contribution of a particular country, fuel sales data are not sufficient as vessels within the examined country may be using fuel bought elsewhere.

Corbett et al. (1999) have used a top-down approach to construct a geographically resolved inventory for sulphur and nitrogen emissions using fuel data from 1993 and accounting for vessels of registered gross tonnage above 100. It has been argued that top-down methodologies are less appropriate to construct emission inventories from international transport (Peters et al. 2009). Due to limited data on vessel activity from earlier years top-down methodologies could be used to estimate emissions generation in the past. Endresen et al. (2007) used fuel sales data spanning a period from 1925 to 2002 to model carbon and sulphur emissions from oceangoing vessels taking into account the technological progress during this period (higher fuel efficiency, sailing speed, improved fuel quality etc.).

10.2.2 Emissions Reduction

A number of studies where emissions inventories have been constructed have been presented. Another recurring theme in the literature is the potential for fuel consumption and/or emissions reduction through operational practices, technologies or regulation. The relationship between sailing speed and pollutant emissions has been extensively researched. Ship operators are reducing sailing speed at times of increased fuel prices, a practice commonly known as slow steaming which has re-emerged in recent years following the recession of 2008. Corbett et al. (2009) examined the potential of slow steaming for various containership routes and showed that carbon emissions could be reduced by up to 70 %. Cariou (2011) illustrated that slow steaming can have environmental benefits despite the increase in fleet size operating to meet demand at lower sailing speeds. Psaraftis and Kontovas (2010) examine trade-offs between operating costs and environmental benefits of slow steaming.

Speed optimisation to minimise operating costs also has environmental consequences through the fuel consumption reduction (Wang and Meng 2012). A sensitivity analysis on different slow steaming scenarios and the resulting savings per shipment in carrier costs and CO_2 emissions was conducted by Maloni et al. (2013). Hvattum et al. (2013) developed an algorithm for the vessel speed optimisation problem to minimise fuel consumption along a fixed sequence of port calls.

10.2.3 Relevant Regulation and Port Initiatives

In the past the majority of the shipping fleet used to run on bunker oil with sulphur content up to 4.5 % (Corbett et al. 1999). In recent years there have been many regulations forcing the use of low sulphur fuel in certain areas. The IMO has set the maximum allowed content of sulphur in fuel and established Emission Control Areas (ECA) where tighter limits apply (IMO 1997) progressively in the coming years. The first four ECAs were the North Sea, the Baltic Sea, the majority of US and Canada Coasts and the US Caribbean ECA. The latter two have set limits on PM and NO_x emissions forcing marine vessels with diesel engines on-board to comply with standards set by MARPOL VI of the IMO. Apart from including additional pollutant species in the regulated areas, existing ECAs could be expanded or new ones added.

In the European Union, vessels in inland waterways and ships at berth are mandated to use ultra-low sulphur content fuel (0.1 % sulphur) or alternatively use technology (e.g. cold ironing, use of scrubbers) that results in the same reduction of sulphur emissions (European Commission 2005). A similar policy is applied in California waters in a radius of 24 NM of the California baseline (CARB 2012) where all machinery must use ultra-low sulphur fuel. These regulations are summarised in Table 10.1.

In addition to the introduction of regulated areas, the IMO developed the energy efficiency design index (EEDI) which is a ratio of the CO_2 emissions per ton mile of transported cargo. In 2013 acceptable values of EEDI were introduced which varied depending on ship type and characteristics. Older vessels of lesser fuel efficiency that now need to comply with the EEDI may need to change their operating patterns to do so (for instance through slow steaming).

Table 10.1 Existing regulation on sulphur content for bunker fuel

Operation	Sulphur content (%)			
	2005–2012	2012–2015	2015–2020	2020–
Within ECA	1.5	1	0.1	0.1
Outside ECA	4.5	3.5	3.5	0.5
European port at berth and inland waterways	0.1			
California within 24 NM	NA	0.1		

10.2.4 Port Specific Policies and Initiatives

Most of the aforementioned regulations affect the emissions along the journey of a vessel or part of it. Emissions of maritime shipping near ports may be influenced by the sulphur content restrictions and the lower speeds near the port, but there are additional port-specific policies and initiatives that target marine emissions at the port. In 2008 the International Association of Ports and Harbors (IAPH) launched the Worlds Ports Climate Initiative which provides support to member ports in reducing their greenhouse gas emissions. In Europe the European Sea Port Organization (ESPO) has developed a set of soft measures that allow port authorities to monitor qualitatively their progress in improving their environmental performance.

Port authorities around the world have adapted agendas seeking to improve local air quality in the vicinity of the port. The port of Singapore is rewarding vessels that are using low sulphur fuel by offering discounts in the port tariff. A similar policy is present in the port of Rotterdam for vessels using LNG as fuel. The port authorities of Gothenburg and Antwerp have invested in technologies that reduce emissions such as cold ironing (e.g. the provision of electric power to vessels at berth for their hostelling demands). Perhaps the most notable examples of port authorities with environmental action are the port of Los Angeles (POLA) and the port of Long Beach (POLB). In addition to the regulations in place by CARB, they are offering monetary incentives to ocean-going vessels that cut their sailing speed to 12 knots in the proximity of the port (20 or 40 NM). This scheme is known as the Vessel Speed Reduction Programme (VSRP) and it was marketed as a NO_x emissions reduction measure by the Californian port authorities. Despite the program being optional, participation rates in the first years have surpassed 90 and 80 % in the 20 and 40 NM zones respectively. Participating ship operators have noted however that the monetary compensation offered by the ports is not sufficient to cover the costs of complying with VSRP (Linder 2014).

10.3 Methodology

This chapter adapts an activity based methodology that models fuel consumption at the different phases of a journey for each engine on-board each vessel. Necessary data include the technical specifications of a vessel and the journey details (sailing speed, time spent at berth). The methodology uses established emission factors to estimate the pollutant emissions generated.

10.3.1 Fuel Consumption Per Trip

Each vessel operates in one of three different modes during a trip; cruise, manoeuvring and in-port berth activity. Typically on-board vessels there are three types of engines: main engines, auxiliary engines and auxiliary boilers (Zis et al. 2014). The propulsion requirements during cruise are powered by the dedicated main engines. The main engines are switched off during manoeuvring and when the vessel is at anchorage or at berth. The auxiliary engines on-board cover the electric requirements during any phase of the trip (cruise or berth) and tend to have increased engine loads during manoeuvring.

The boilers are fired whenever the main engines are switched off in order to maintain the temperature of the fuel and the propulsion engines at the desired levels. The energy demands of boilers vary depending on the ship, the calling port and the weather. The fuel consumption FC_{trip} (kg) for a journey is given by Eq. 10.1.

$$FC_{trip} = FC_{cruise} + FC_{manoeuvering} + FC_{berth} + FC_{anchorage} \tag{10.1}$$

where D denotes the distance travelled (NM), FC_{cr} the fuel consumption (kg) per NM during cruise, FC_m and FC_b the fuel consumption (kg/hour) during manoeuvring movements and at berth respectively for periods t_m and t_b (hours).

The fuel consumption during cruise per NM can be estimated by Eq. 10.2.

$$\mathrm{FC_{cr}} = 10^{-3} \cdot \left(\mathrm{SFCO_{main}} \cdot \mathrm{ELl_{main}} \cdot \mathrm{EP_{main}} + \mathrm{SFOC_{aux,cr}} \cdot \mathrm{EL_{aux,cr}}\right) \frac{1}{\mathrm{V_s}} \tag{10.2}$$

where $SFOC$ stands for the Specific Fuel Oil Consumption of each engine (*main* denotes the propulsion engine and *aux* the auxiliary engine), EL refers to the fractional engine load (%) of the MCR of the engine and EP to the nominal power (kW) installed for each engine. $SFOC_{main}$ and EL_{main} are functions of V_s. The general rule of thumb used in the industry is that EL_{main} relates to V_s by a power law (known as the propeller law) as follows:

$$\frac{EL_1}{EL_2} = \left(\frac{V_1}{V_2}\right)^{\mathrm{n}} \tag{10.3}$$

The value of the exponent n depends on the ship type, weather and sailing speed. Frequently a cubic relationship is used (n = 3) but when greater accuracy is required the values of Table 10.2 should be used.

Fuel consumption at berth per hour can be estimated through Eq. 10.4.

$$FC_b = 10^{-3} \cdot SFOC_{aux,b} \cdot EL_{aux,b} \cdot EP_{aux} + FC_{boilers} \tag{10.4}$$

Table 10.2 Variations of the propeller law

Ship	Exponent n
General (valid at low speeds)	3
Low speed ships (tankers, bulk carriers)	3.2
Medium-sized ships (feeder containerships, reefers)	3.5
Large high-speed ships (containerships)	4
Large containerships (extreme weather)	4.5

Source MAN Diesel (2009)

Table 10.3 Specifications of the examined containerships

Class	Capacity (TEU)	Nominal speed V_S (knots)	EP_{main} (kW)	EP_{aux} (kW)
Feeder	1000–2500	17.0	10,000	1900
Panamax	5000–7000	23.0	35,000	9000
New panamax	10,000–13,000	24.6	62,000	15,000
ULCV	15,000–18,000	25.5	80,000	23,000

Similarly, the fuel consumption during manoeuvring is

$$FC_m = 10^{-3} \cdot SFOC_{aux,m} \cdot EL_{aux,m} \cdot EP_{aux} + FC_{boilers} \tag{10.5}$$

This work assumes a universal average engine load of auxiliary engines during cruise and hoteling 30 and 23 % of the MCR respectively (Kontovas and Psaraftis 2009). For $EL_{aux,m}$ and $FC_{boilers}$ fixed values suggested in the emissions inventory of vessels calling in the port of Los Angeles are used (POLA 2013). Finally, the t_m is assumed fixed at 0.5 h during arrival and departure. The examined vessels are containerships of 4 different size-classes and their technical specifications are given in Table 10.3.

10.3.2 The Role of Sailing Speed

Propulsion engines are tuned to operate at the optimum level of efficiency (between 70 and 85 % of MCR) where the $SFOC_{main}$ takes its lower value as seen in Fig. 10.1. Figure 10.1 presents typical SFOC curves of a large 2-stroke engine in an ULCV and a smaller 4-stroke engine of a feeder vessel.

A significant speed reduction would result in lower EL_{main} and consequently fuel consumption despite the fact that the $SFOC_{main}$ would increase as seen in Fig. 10.1. The fuel consumption per NM of an ULCV is plotted for various V_S in Fig. 10.2.

It is evident that the total fuel consumption per NM is rapidly dropping at lower V_S. Figure 10.2 shows that at very low V_S the fuel consumption of the auxiliary engines can surpass that of the propulsion engines which is explained due to the longer time of operation per NM and the fact that the $EL_{aux,cr}$ is unaffected by the change in V_S.

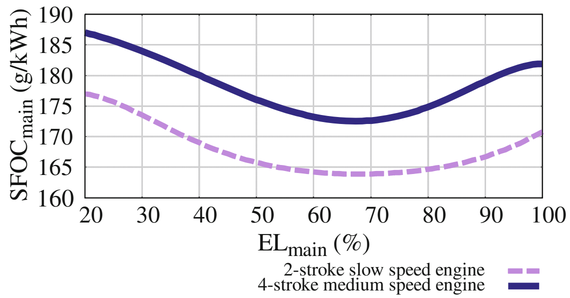

Fig. 10.1 SFOC curves as functions of engine load

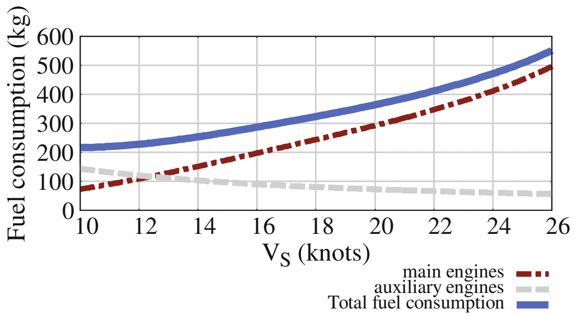

Fig. 10.2 Fuel consumption per NM at different V_S

10.3.3 Emissions Factors

Emission factors are ratios that are used to convert energy or mass to pollutant emissions. In maritime transport the emission factors are defined as ratios of mass of pollutant per mass of fuel burned and will be used as such in this chapter $\left(\frac{\text{gram of pollutant}}{\text{gram of fuel}}\right)$. The most common marine emission factors have been developed through a study of Lloyds Register Engineering Services during 1990–1995 when on-board data were collected for 50 representative sea vessels (Lloyds 1999). This study was expanded by Trozzi and Vaccaro (1998) who compared fuel consumption and emission factors used in the literature and proposed two activity-based methodologies for emissions estimation. A similar expansion to this methodology was conducted by ENTEC for the European Commission with increased importance in the role of the engine load to the main and auxiliary machinery (European Commission 2002). Finally, the Environmental Protection Agency (EPA 2000) has also set emission calculation standards and developed load correction factors for operation at very low loads.

The two methodologies of ENTEC and EPA were compared in the seminal paper of Dolphin and Melcer (2008) where it was shown that while the two are consistent, the EPA model fails to accurately depict the role of engine size, type and fuel type. The pollutant species modelled in the majority of these studies include CO_2, SO_2, NO_x, CO, volatile organic compounds (VOC) and particulate matter

(PM) emissions. In recent years there has been increasing focus on Black Carbon (BC) emissions from shipping due to its dual nature as a climate forcing agent and a local pollutant (Flanner et al. 2007).

This chapter will examine CO_2, SO_2 and NO_x emissions using values suggested by the IMO. A value of 3.17 is frequently used for CO_2 which is found by multiplying the carbon fraction of the fuel (86.4 %) with the relative molecular masses of CO_2 and C e.g. $\left(\frac{44}{12}\right)$. In a similar manner the SO_2 emission factor can be found by multiplying 0.02 with the sulphur content present in the fuel used. Nitrogen emissions vary depending on the engine speed and the IMO suggests a value of 0.087 for slow speed engines (large 2-stroke engines) and 0.057 for medium speed (4-stroke engines, auxiliary engines).

10.4 Analysis

The methodology of the previous section shows that there are significant fuel savings from sailing at lower speeds. This section will contrast the effectiveness of fuel switching and localised speed reduction schemes environmentally and economically.

10.4.1 Speed Reduction Near Ports

The following analysis assumes that each measure is compulsory and that the ship operator aims to minimise the cost of compliance without compromising the overall trip time. The critical parameters are the overall trip length D (NM) from port to port, the policy zone length z (NM), the nominal speed of each vessel V_S, the fuel cost and the speed limit V_l near the port.

10.4.1.1 Ship Operator Perspective

Considering that a ship operator would have to reduce V_S to V_l for the last z miles of an overall trip distance D, the time lost t_{lost} (hours) in the policy zone can be found by

$$t_{lost} = \frac{z}{V_1} - \frac{z}{V_s} \tag{10.6}$$

In order to ensure no time delay, the ship has to increase the sailing speed to V^* before entering the regulated area. If a maximum time delay t_{max} (hours) to the total trip time is allowed the necessary speed can be calculated as

$$V* = \frac{V_s \cdot V_l \cdot (D - z)}{V_1 \cdot D - z \cdot V_s \cdot V_l \cdot t_{\max}} \tag{10.7}$$

The necessary speed will increase for longer policy zones and stricter speed limits and decrease for very long journeys as there is additional distance to make up for the lost time. It should be noted that there is a maximum speed V_{max} that a vessel can sail at when the propulsion engines are working at the MCR.

$$V_{\max} = V_s \sqrt{[\mathrm{n}]}\frac{100}{EL_s} \tag{10.8}$$

The baseline conditions consider an ULCV travelling a distance of 1000 NM and entering a speed limit of 12 knots. A sensitivity analysis is performed for D, V_l, t_{max} and vessel type and $V*$ is plotted as a function of z in Fig. 10.4.

Figure 10.3 shows that different specifications of vessel speed reduction programmes near ports (policy length, speed limit) result in different behaviours for participating vessels (depending on port of origin and vessel specifications) and thus port authorities should consider tailoring such programs according to the visiting fleet and network connections.

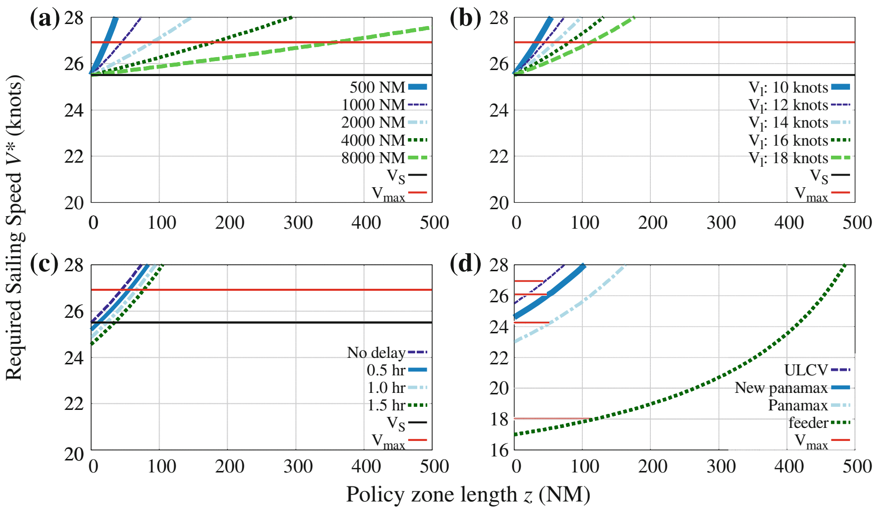

Fig. 10.3 Effects of policy zone length z (NM) to required vessel speed V^*(knots) for different: **a** trip distance D (NM), **b** speed limit V_l (knots), **c** allowed delay t_{max} (hours), **d** vessel type

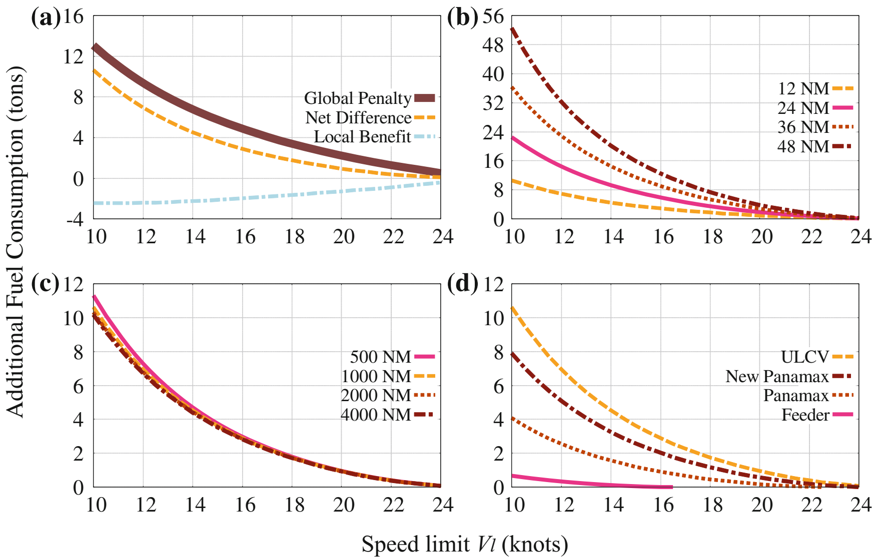

Fig. 10.4 Sensitivity analysis on difference in fuel consumption: **a** baseline scenario, **b** different zone length z (NM), **c** trip distance D (NM), **d** vessel type

10.4.1.2 Environmental and Economic Trade-Offs

The previous section examined the change in sailing speed along the journey caused by a speed reduction scheme near the port. The local benefits in emissions reduction enjoyed in the proximity of the port are offset by the additional fuel consumption due to the speed increase whilst at sea. The overall fuel consumption (from port to port) will increase and as a result assuming the same fuel price, the operating costs increase and there are more pollutants emitted globally.

The orange dashed curve gives the total additional fuel consumption for the baseline case (ULCV vessel in a trip of 1000 NM and a policy zone of 12 NM) for various speed limits. In Fig. 10.4a the local savings enjoyed in the proximity of the port are contrasted with the additional fuel consumption due to the speed increase outside the zone. The remaining graphs show that the policy zone length plays an important role in the additional fuel consumption globally, whereas the overall trip distance does not affect the global change as much. As expected, the larger ships complying results in additional emissions overall (but also more important local savings near the port) (Fig. 10.5).

Apart from the economic trade-offs of a complying decision, there are emission trade-offs occurring as well. As the localised speed reduction schemes aim to reduce NO_x emissions, which have more severe consequences in residential areas, it can be shown that NO_x savings in the port proximity are 'traded' with additional CO_2 released in the whole trip. For the baseline scenario of a policy zone of 12 NM, a

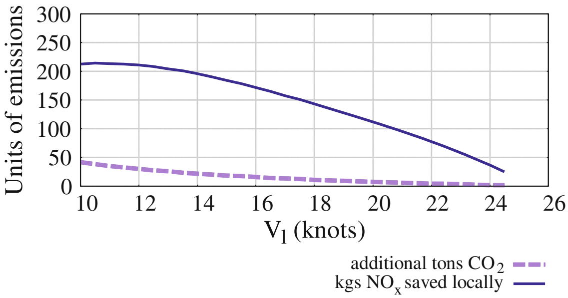

Fig. 10.5 CO_2 (tons) trade-off with local NO_x (kg) savings

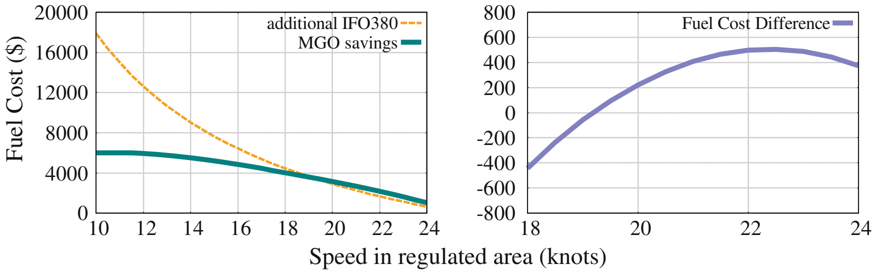

Fig. 10.6 Economic trade-offs and fuel price

trip distance of 1000 NM and a ULCV sailing normally at nominal speed the resulting trade-offs is plotted in Fig. 10.6.

Under the hypothesis that no time is to be lost, it is clear that the local savings in pollutant emissions near the port come at a significant cost due to the additional fuel required and higher greenhouse gas emissions. Finally, if a local speed reduction zone is to be adapted by a port authority and does not have a compulsory character, the analysis conducted allows the calculation of a monetary incentive that would convince ship operators to participate under different scenarios of z, D and V_l and ship calling.

10.4.2 Trade-Offs from Fuel Switching

There are areas where the use of low sulphur fuel is mandatory. The resulting SO_2 emissions are proportional to the sulphur content and therefore the emission savings are easily calculated. However, low-sulphur fuel is more expensive and therefore the SO_2 savings come at a high cost. Ship operators that seek to minimise costs may resort to speed differentiation in the different areas. For example, considering the CARB requirement of using fuel with 0.1 % sulphur in the last 24 NM of a journey the ship operator may choose to reduce the sailing speed for this distance and offset the delay with a speed increase earlier. The overall fuel consumption will increase due to the change of speeds; the ship will burn less of the expensive fuel. Considering again a baseline case of a trip of 1000 NM and fuel costs of $650 per ton of Heavy Fuel Oil (HFO—380) and $1200 per ton of Marine Gas Oil (MGO) the total fuel cost per trip is plotted in Fig. 10.6 for various sailing speeds in the 24 NM regulated area.

In the examined scenario depicted in Fig. 10.6, it is clear that it is in the economic interest of the ship operator to reduce its speed within the regulated area from 25.5 to 22.5 knots for fuel savings of $510 per trip. It is also seen that despite the increasing savings in MGO for very lower speeds, beyond 19.2 knots the increased fuel consumption of HFO during the trip is larger and thus leads to losses. Considering that in California the VSPR have a speed limit of 12 knots, it is clear that the overall fuel costs of the trip would increase and thus the ships complying with both regulations would be worse off. With different fuel prices, trip distance, policy zones and vessel types the optimal sailing speeds at the different segments would change.

10.5 Conclusions and Recommendations for Further Research

This chapter examined the economic and environmental trade-offs occurring when emissions reduction measures affect part of the journey in maritime transportation. The results highlight that there cannot be a universal policy/measure that is optimal for each vessel, port of origin and port of destination combination. The global environmental balance is sensitive and can be offset by one action that improves the air quality in the proximity of a coastal area or a port. The framework presented can be applied for the estimation of local savings in pollutant emissions for different values in the key parameters of the policy. The methodology considers the ship operator's perspective and the necessary changes in operation that allow the ship to arrive on time and at the minimum fuel costs while complying with the policy in place.

The overall trip distance does not significantly affect the additional emissions generated for arrival without time penalties and compliance to the scheme. Very large policy zones increase absolute emissions significantly and port authorities should carefully consider the length of the zone depending on the number of residents affected at each distance. Larger ships should be targeted primarily due to the bigger overall distance involved (allowing greater flexibility in sailing schedule) and the greater quantity of pollutants per call.

This work can be expanded by considering a shipping network where some of the proposed measures are compulsory and assessing the environmental impact. For example, the environmental benefits enjoyed in the regulated areas could be contrasted with the globally induced burdens due to increased sailing speeds. The impact on a more local scale near other ports where no such measures are forced could also be investigated. The next steps in this work involve the comparison of the local savings in the regulated areas with the global savings that would be enjoyed if the time lost for compliance in the regulated area was instead invested in slow steaming across the whole journey.

One of the weaknesses of the current model is that the economic analysis is very narrow and only considers the view of the ship operator. A thorough economic analysis can greatly enhance the suggested methodology by including the social costs and benefits of emissions reduction in residential areas and by considering the implications of the maritime and port sectors entering emissions trading schemes. Finally, the potential modal shift from maritime to other modes of transport due to the additional costs of emissions reduction measures and policies has to be considered as this would negatively affect the environmental balance given that shipping is the most fuel efficient mode.

References

California Air Resources Board. (2012). Ocean-going vessels—Fuel rule. Accessed July, 2013, from http://www.arb.ca.gov/ports/marinevess/ogv.htm.

Cariou, P. (2011). Is slow steaming a sustainable means of reducing CO_2 emissions from container shipping? *Transportation Research Part D: Transport and Environment, 16*, 260–264.

Corbett, J. J., & Fischbeck, P. S. (2000). Emissions from waterborne commerce vessels in United States continental and inland waterways. *Environmental Science and Technology, 34*(15), 3254–3260.

Corbett, J. J., & Koehler, H. W. (2003). Updated emissions from ocean shipping. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *108*(D20).

Corbett, J. J., Fischbeck, P. S., & Pandis, S. N. (1999). Global nitrogen and sulfur inventories for oceangoing ships. *Journal of Geophysical Research: Atmospheres (1984–2012), 104*(D3), 3457–3470.

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment, 14*(8), 593–598.

Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: A global assessment. *Environmental Science and Technology, 41*, 8512–8518.

Dolphin, M. J. & Melcer, M. (2008). Estimation of ship dry air emissions. *Naval Engineers Journal 120*(3), 27–36.

Endresen, Ø., Sørgård, E., Behrens, H. L., Brett, P. O., & Isaksen, I. S. (2007). A historical reconstruction of ships' fuel consumption and emissions. *Journal of Geophysical Research: Atmospheres (1984–2012), 112*(D12).

Environmental Protection Agency (EPA). (2000). *Analysis of commercial marine vessels emissions and fuel consumption data*. Accessed March 2012, from http://www.epa.gov/oms/models/nonrdmdl/c-marine/r00002.pdf.

European Commission. (2005). Directive 2005/33/EC amending Directive 1999/32/EC as regards the sulphur content of marine fuels. Accessed May 2013, from http://www.ops.wpci.nl/_images/_downloads/_original/1264149906_2005eudirectivesulphurcontentofmarinefuels2005_33.pdf.

European Commission and ENTEC UK Limited. (2002). Quantification of emissions from ships associated with ship movements between ports in the European Community. European Commission, DG ENV.C1, Rue de la Loi, 200, B-1049: Brussels.

Eyring, V., Köhler, H. W., van Aardenne, J., Lauer, A. (2005). Emissions from international shipping: 1. The last 50 years. *Journal of Geophysical Research: Atmospheres*, 110(D17).

Flanner, M. G., Zender, C. S., Randerson, J. T., & Rasch, P. J. (2007). Present-day climate forcing and response from black carbon in snow. *Journal of Geophysical Research: Atmospheres (1984–2012), 112*(D11).

Hvattum, L. M., Norstad, I., Fagerholt, K., & Laporte, G. (2013). Analysis of an exact algorithm for the vessel speed optimization problem. *Networks, 62*(2), 132–135.

International Energy Agency. (2012). Electricity/Heat by Country /Region, OECD Member Countries. Accessed July 2014, from http://www.iea.org/stats/prodresult.asp?PRODUCT=Electricity/Heat.

International Maritime Organization. (1997). Annex VI prevention of air pollution from ships (entered into force 19 May 2005).

International Maritime Organization. (2014). Third IMO GHG Study 2014.

Koffi, B., Szopa, S., Cozic, A., Hauglustaine, D., & Velthoven, P. V. (2010). Present and future impact of aircraft, road traffic and shipping emissions on global tropospheric ozone. *Atmospheric Chemistry and Physics, 10*(23), 11681–11705.

Kontovas, C. A., & Psaraftis, H. N. (2009). An online ship emissions calculator as a decision-making aid and policy evaluation tool. In *13th Congress of International Maritime Association of Mediterranean IMAM* (pp. 12–15).

Linder, A. J. (2014). Explaining participation in voluntary vessel emission reduction programs at the ports of los angeles and long beach. *In Transportation Research Board 93rd Annual Meeting* (No. 14-1158).

Lloyds Register Engineering Services (1999). 'Marine exhaust emissions quantification study—mediterranean sea', *Report 99/EE/7044, Lloyds Register Engineering Services*, London: UK.

Maloni, M., Paul, J. A., & Gligor, D. M. (2013). Slow steaming impacts on ocean carriers and shippers. *Maritime Economics and Logistics, 15*, 151–171.

MAN Diesel A/S. (2009). Low container ship speed facilitated by versatile ME/ME-C engines. Accessed May 2013, from http://www.mandieselturbo.com/files/news/filesof8410/5510-0038-04.pdf.

Peters, G. P., Marland, G., Hertwich, E. G., Saikku, L., Rautiainen, A., & Kauppi, P. E. (2009). Trade, transport, and sinks extend the carbon dioxide responsibility of countries: An editorial essay. *Climatic Change, 97*(3–4), 379–388.

Port of Los Angeles. (2013). Inventory of air emissions—2012. Accessed March 2014, from http://www.portoflosangeles.org/pdf/2012_Air_Emissions_Inventory.pdf.

Psaraftis, H. N., & Kontovas, C. A. (2010). Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D: Transport and Environment, 15*(8), 458–462.

Trozzi, C., & Vaccaro, R. (1998). Methodologies for estimating air pollutant emissions from ships. *Techne report MEET RF98*.

UNCTAD (2013). Review of maritime transport 2013. Accessed November 2014, from http://unctad.org/en/PublicationsLibrary/rmt2013_en.pdf.

Wang, C., Corbett, J. J., & Firestone, J. (2007). Modeling energy use and emissions from north american shipping: application of the ship traffic, energy, and environment model. *Environmental science & technology, 41*(9), 3226−3232.

Wang, S., & Meng, Q. (2012). Sailing speed optimization for container ships in a liner shipping network. *Transportation Research Part E, 48*, 701–714.

Zis, T., North, R. J., Angeloudis, P., Ochieng, W. Y., & Bell, M. G. H. (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics and Logistics, 16*(4), 371–398.