Examining Trade-Offs in Port Emission Reduction Policies between Local and Global Benefits

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Abstract

In recent years port authorities have been developing green agendas in order to reduce pollutant emissions in their area and mitigate the effects to local air quality. Initiatives vary from rewards towards clean vessels to voluntary programs that provide monetary incentives to ship operators that participate and comply with the program guidelines. Typical examples of such programs include the promotion of the use of technologies such as cold ironing (provision of electrical power to ships at berth from the grid), the reduction of sailing speed near the port subject to monetary compensation and the use of low-sulphur fuel near and at the port. Such programs have been considered successful in reducing fuel consumption and subsequently emissions locally, however there are indications that participation to these programs from individual vessels may lead to increased absolute emissions through increased fuel consumption outside the policy areas and due to the energy consumption at the production facilities that power the cold ironing units. This paper examines ship activity near and at ports and compares local pollutant emissions (SO_2, NO_x and Black Carbon) benefits with global greenhouse gases penalties due to the additional fuel and energy consumption. Sensitivity analyses are conducted with regard to the following parameters: port-to-port distance, ship type, speed limit, port location, and grid emission factors. Recommendations for future work include refining the emissions generation model (particularly for Black Carbon emissions) as well as the considering pollutant dispersion in residential areas around the port as a means to further evaluate the impacts of potential savings through port policies.

Introduction

The impacts of maritime transport in climate change and pollutant emissions have been the subject of academic research over the last few decades. Regulatory bodies have been designing policies to reduce these environmental impacts. At the same time, shipping operators are keen to maximize their profits and reduce their operating costs which occasionally have environmental benefits due to lower fuel consumption per trip. Despite the progress in technology, the strict policies in place and the operators' efforts to reduce per trip costs, the environmental impacts of shipping are still expected to grow in absolute numbers due to the increase in throughput transport.

Maritime shipping has is widely considered the most cost-effective mode of transportation and moves about 90% of the world trade. The transportation sector currently accounts for 23% of the world's anthropogenic CO_2 emissions whereas maritime shipping is alone responsible for 2.7%. This would suggest that the environmental performance of maritime transport is excellent, however due to the poor quality of fuel used in marine engines, there are significant air pollutant emissions arising from shipping. These include SO_2, NO_x, particulate matter (PM), volatile organic compounds (VOC) and black carbon (BC) emissions, all of which pose risks to the health of affected population particularly close to coastlines and ports.

To reduce the impacts of shipping in specific areas there have been regulations that only allow the use of very good quality fuel within while at the same time port authorities have been designing green agendas that typically provide incentives to ship operators that promote good practice or comply with the guidelines of these programs.

This paper examines the effects of regulatory policies, operational practices and port authorities' initiatives to reduce pollutant emissions and contrasts their efficiency with the global environmental balance.

Effects of emissions reduction actions

The paper considers a set of case studies based on typical containership calls in typical container terminals and examines the environmental balance from the different emissions reduction strategies. The focus is on containerships of various sizes as this ship type is considered the most polluting (Psaraftis and Kontovas, 2013) and at the same time there is a requirement for high schedule reliability (Notteboom, 2006) which may be affected by some of the examined practices that could cause delays.

The central idea examined is that one emissions reduction action adapted in a specific area may affect another area in a negative way. This is illustrated in the schematic of Figure 1 where the global contribution of maritime shipping to emissions is depicted along with two ports within the system and their respective contributions.

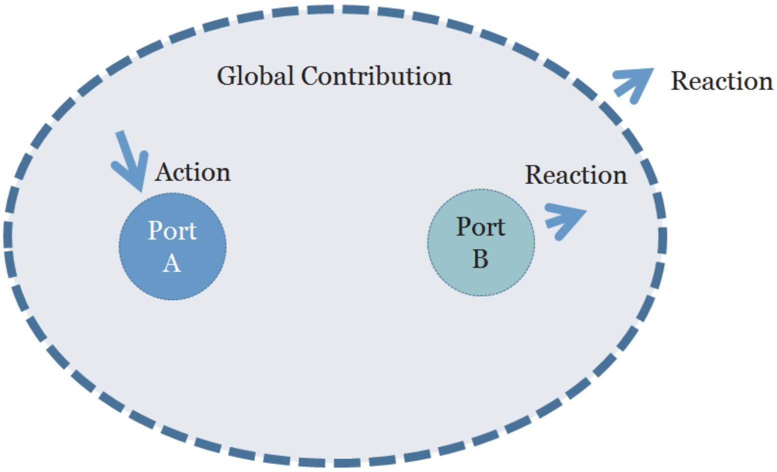

Figure 1: The global environmental balance of local emissions reduction actions

If the port authority of Port A designs a policy action that seeks to reduce the emissions generation within the local area by for example imposing a low sailing speed zone nearby, this may lead to increased sailing speeds outside this area and lead to additional emissions generation both globally and locally in port B through the respective reaction as seen in Figure 1. There are trade-offs between emissions, fuel consumption, fuel costs which vary for different combinations of port-to-port journeys, local and global emissions reduction actions and ship sizes. This paper presents a framework that allows the assessment of existing practices and help regulators design improved and more efficient policies with less negative environmental impacts in other areas.

Methodology

This work builds on earlier methodologies that model emissions generation for CO_2, SO_2, NO_x and BC pollutants based on activity patterns of ships near and at ports under different operating conditions (Zis et al. 2014). Most vessels are equipped with main engines that are used for propulsion, auxiliary engines that provide energy for the electric requirements of the vessel (lighting, refrigerating and other on-board uses) and auxiliary boilers that are operating when the main engines are not working to maintain fuel and cylinder temperatures. During the various stages of the journey machinery on-board is operating at different engine loads requiring fuel which leads to emissions generation.

The fuel consumption *FC* (kg) of each engine during activity of time *t*(h) can be estimated based on its operating patterns through equation 1.

$$FC = 10^{-3} \cdot EP \cdot EL \cdot SFOC \cdot t \qquad (1)$$

Where *EP*(kW) denotes the nominal power of the engine, *EL*(%) is the fractional load at which the engine is operating and *SFOC* (g/kWh) is the specific fuel oil consumption.

Main engines

The main engines are designed to operate at loads of about 85% of the maximum continuous rating (MCR) and have their lower *SFOC* near this point of operation. The *EL* of the propulsion engine is heavily influenced by the cruising speed and typically a power relationship is used to connect the two. This is commonly known as the propeller law and is shown in equation 2 for a pair (annotated 1 and 2) of engine loads and cruising speeds.

$$\frac{{}^{1}EL}{{}^{2}EL} = \left(\frac{{}^{1}V}{{}^{2}V}\right)^{n} \qquad (2)$$

In the majority of studies found in the literature a cubic relationship is assumed, however in practice the exponent n varies for different ship and speed combinations as seen in Table 1.

Table 1: Variations of the Propeller Law (source MAN Diesel, 2006; Psaraftis and Kontovas 2013)

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

Therefore any policy actions that influence the sailing speed across the journey or part of will result in significant change in the fuel consumption at the same trip segment. In recent years the practice of slow steaming has resurfaced and ships are sailing at lower speeds in order to reduce operating costs. This is more common when fuel prices are high or the market is on the decline resulting in more ships available than the transport demand. The environmental benefits of this practice have been confirmed in a series of studies (Psaraftis and Kontovas, 2013; Corbett et al., 2009) and it has been shown that emissions savings occur despite an increase in journeys to meet demand at the lower sailing speeds (Cariou, 2011).

Auxiliary engines

The auxiliary engines are operating during all activity phases of a ship's journey. Their nominal power is much lower than that of propulsion engines and auxiliary engines tend to be less efficient in terms of SFOC. Auxiliary engines rarely operate at their optimal load and the point of operation typically depends on the ship type, cargo on-board (ships with many reefer containers on-board need more energy), weather and time of day (particularly for lighting demands). The energy demands of auxiliary engines are higher during the manoeuvring operations at the port while at all other phases (cruise, berth and anchorage hoteling) the requirements are ranging from 20 to 50% of the nominal power output.

Emission factors

This work uses fuel based emission factors to estimate pollutant *P* emissions $\varepsilon_{i,j}^{P}$ for each engine *i* generated during each activity *j* by multiplying the fuel consumption $FC_{i,j}$ calculated through equation 1 with the appropriate emission factor $EF_{i,j}$. The emissions generation during a journey can be estimated by summing over the emissions generation of each engine at each activity as in equation 3.

$$\varepsilon_{i,j}^{P} = \sum \ FC_{i,j} \cdot EF_{i,j}^{P} \qquad (3)$$

The emissions factors used in this work are summarised in Table 2.

Table 1: Emission factors (g pollutant/ g fuel) source: Dolphin and Melcer, 2008; Lack and Corbett, 2012

Pollutant P	EF^P	
CO_2	3.17	
SO_2	0.02*S%	
NOx	0.057 medium speed engines	0.087 slow speed engines
BC	$0.0008 \cdot (33.519 \cdot EL^{-0.754})$	

Where S% denotes the sulphur content in the fuel used. The NOx emission factor depends on the engine speed and typically large container vessels are using slow speed 2-stroke engines for propulsion. The BC emission factor depends heavily on the engine load at which the engine operates and this study uses derives these values based on the work of Lack and Corbett (2012) in modelling BC emissions.

Energy requirement from cold ironing

Some vessels are able to receive alternative marine power (AMP) when at-berth at ports equipped with shore power facilities. In this case, the auxiliary engines are switched off and the only emissions generation at the port is occurring from the ship's boilers which are still operating. Cold ironing was first applied for military vessels (Paul and Haddadian, 2005) but in recent years civilian vessels started relying on shore power. Californian ports constituted the use of AMP mandatory for 50% of OGV from 2014 and will be forcing cold ironing for 80% of visiting vessels by 2020 (CARB, 2007). The main obstacle to the further expansion of AMP is the lack of a uniform voltage and frequency between ships and ports, as well as the different load requirements among different vessels.

The energy requirement of the vessel at berth is covered by the grid and can be calculated if the transmission and conversion losses are accounted as in equation 4.

$$E_{grid} = \frac{EL_{aux} \cdot EP_{aux} \cdot t_B}{\eta_t \cdot n_s} \qquad (4)$$

Where t_B denotes the time at berth, n_s describes the losses from the AMP unit to the vessel and n_t the efficiency of transmission from the power source to the AMP unit. To estimate the emissions generation at the source of energy it is necessary to know the energy mixture powering the AMP unit at the port. For most cases the emission factor from the grid is lower than the corresponding bunker fuel emission factor and therefore cold ironing can provide global benefits (Zis et al., 2014). However, for countries relying heavily on fossil fuel and coal for power generation this may not be the case, especially if low-sulphur regulations apply at berth.

Analysis

The emissions reduction actions examined at this work include slow steaming across the journey, speed reduction near ports, fuel regulations and provision of AMP. These actions are examined for a set of four containerships (feeder, panamax, new panamax, ultra large container vessel – ULCV) of different sizes and specifications as presented in Table 3 along with the fuel consumption under normal operation (sailing at nominal speed Vs, average auxiliary engine operation at berth). There are three areas considered for all port-to-port journeys examined; 40NM from the port of origin, 40NM from the port of destination and the high seas segment in-between.

Table 2: Containership specifications used in analysis

Class	***Capacity (TEU)***	**Nominal speed V_S (*knots*)**	***EP_m (kW)***	***EP_a (kW)***
Feeder	1500	17	9000	1800
Panamax	5000	23	36000	8000
New panamax	10000	24	60000	14000
ULCV	16000	25	80000	22000

Baseline scenario

In the baseline scenario the emissions generation for CO_2, SO_2, NO_x and BC emissions for a set of typical journeys is examined assuming the vessels are sailing at their nominal speed. It should be noted that in the last years many shipping lines were slow steaming; however for comparison purposes normal steaming is assumed as the baseline case. Table 4 summarises the fuel consumption at each trip stage at 40NM zones around the ports.

Table 3: Baseline scenario fuel consumption (kg)

Vessel type	*Total Distance (NM)*	*Origin Port*	*High seas*	*Destination Port*	*Berth at Destination*	*Berth duration (h)*
			Fuel consumption (kg)			
Feeder	200	3852	11555	3852	932	5
Panamax	1000	11643	267931	11643	6245	10
New Panamax	2000	18724	903075	18724	16537	15
ULCV	8000	25110	4965482	25110	32530	19

It can be noted that the larger vessels are far more polluting in absolute numbers; however they are more efficient if their TEU capacity is taken into account. Nevertheless, in the port proximity OGV are a significant environmental concern as they rely on larger engines and spend longer periods of time at berth.

Slow steaming

In this case study slow steaming across the full journey is examined for the vessels for three different speed scenarios; 10, 20 and 30% reduction from the nominal speed. The emissions change near the port (at 40 NM distance) is summarised for all scenarios in Table 5 assuming the use of 1% sulphur content fuel across the journey.

Table 4: Environmental benefits through slow steaming (kg of pollutant saved)

Vessel type	*Total Distance (NM)*	*0.9V_s*				*0.8V_s*				*0.7V_s*			
		CO_2	***SO_2***	***NO_x***	***BC***	***CO_2***	***SO_2***	***NO_x***	***BC***	***CO_2***	***SO_2***	***NO_x***	***BC***
Feeder	200	1564	9.9	28.1	-0.12	2864	18.1	51.5	-0.57	3871	24.4	69.6	-1.31
Panamax	1000	4514	28.5	123.9	-0.35	8244	52	226.3	-1.52	11073	69.8	303.9	-2.76
New Panamax	2000	7335	46.3	201.3	-0.6	13201	83.3	362.3	-2.52	17602	111	483.1	-4.57
ULCV	8000	9049	57.1	248.3	-0.9	16119	101.7	442.4	-3.6	21187	133.7	582.5	-6.45

The results show that slow steaming across the journey can also provide important environmental benefits to the proximity of a port. There is the notable exception of BC where an increase is observed that can be attributed to the lower operating loads as then the emission factor increases. In the next case study these environmental benefits will be contrasted to local speed reduction schemes with very low sailing speed requirements.

Speed reduction near ports

Speed reduction programs were first developed by Californian ports in an effort to reduce the NO_x emissions near the coastline from OGV (CARB, 2012). Vessels reducing their speed to 12 knots for the 20 or 40 NM around the port are eligible for a reduction in their port fees for their first day of dockage. In this case, there are significant trade-offs taking place as the ship operator may opt to increase sailing speed outside the policy zone in order to arrive at the expected time of arrival (ETA). The local benefits during the arrival at the port (40 NM) under a speed limit of 12 knots versus the global burden in increased CO_2 emissions are presented in table 6.

Table 5: Environmental trade-offs from port speed reduction programs

Vessel type	*Total Distance (NM)*	*Local benefit at 12 knots for 40NM (kg of pollutant saved)*				*Speed outside zone for same ETA (knots)*	*Global emissions change (kg of additional pollutant across journey)*
		CO_2	***SO_2***	***NO_x***	***BC***		***CO_2***
Feeder	200	3814	24.1	104.7	-1.25	18.97	4680
Panamax	1000	13289	83.8	364.7	-3.02	23.91	48008
New Panamax	2000	20281	127.9	556.6	-5.01	24.5	80664
ULCV	8000	22746	143.5	624.3	-6.59	25.14	26573

It is evident that should the total journey time remain constant, participation to the port program would result in a global increase of CO_2 emissions. In addition, there would be an increase in the other pollutants outside the policy zone including an increase in the pollutant emissions in the port of origin due to the increased speed. In case the ship operator would sacrifice journey time to participate in the program, then the same time could result in more global savings if it was invested in a lower sailing speed across the whole journey.

Cold ironing

A ship relying on AMP to meet its hoteling energy demands would only emit pollutants through its boilers. However, in the global scheme there would be emissions at the source powering the AMP unit at the port. Table 7 summarises the emissions savings at the port from switching off the auxiliary vessels for a ULCV and contrasts with the emissions released at the energy source for five different countries based on their average grid emission factors and accounting for energy losses due to transmission and conversions. It is assumed that the berth duration would be the same at all ports for comparison purposes.

Table 6: Comparison of AMP and at-berth emissions for a ULCV in different ports

	EF_{grid} *(g/kWh)*				**Emissions at the source from AMP (kg)**				**Emissions avoided from auxiliary engines (kg)**			
Country	CO_2 (kg/kWh)	SO_2	NO_x	BC	CO_2	SO_2	NO_x	BC	CO_2	SO_2	NO_x	BC
California	0.3	0	0.41	0.002	33918	0	46.4	0.22		55.17		
Germany	0.44	0.52	0.72	0.003	49746	58.8	81.4	0.34		55.17		
UK	0.47	0.36	0.76	0.003	53138	40.7	85.9	0.34	87453	55.17	2400.2	38.6
Australia	0.90	2.10	1.30	0.003	101754	237.4	146.9	0.34		1931.16		
Greece	0.80	0.18	1.28	0.003	90448	20.3	144.7	0.34		55.17		

The results show that cold ironing is in most cases preferable with regards to the total emissions released in the atmosphere. However, in countries which rely heavily on coal and fossil fuel there may be more CO_2 emissions from the grid. The same applies for SO_2 particularly when no low-sulphur fuel regulation applies. In European ports there is a requirement that vessels at berth use ultra-low (0.1%) sulphur fuel and as a result there are more SO_2 emissions from the grid.

Conclusions

This paper used an activity based methodology to estimate the environmental balance from ship emissions reduction actions. The effectiveness of such strategies heavily depends on the ship, journey and port characteristics. The improved air quality enjoyed at the proximity of a port may come at the expense of an increase in global emissions or a missed opportunity to invest in global emissions reduction actions. Provision of AMP appears to be beneficial from a global perspective in most countries; however some technological barriers must be overcome for a wider adaptation of this solution. It is recommended that ship operators, regulatory bodies and port authorities analyse the effects of any policies under consideration from both a local and a global perspective. Further work in this subject should be looking at additional emissions reduction actions and their impacts, and be performed for comprehensive datasets of shipping lines and port traffic data.

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