The impact of regional environmental regulations on empirical vessel speeds

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Abstract

Economic theory suggests that the use of more expensive low-sulphur fuel within an Emission Control Area (ECA) should result in lower vessel speeds. The objective of this paper is to investigate empirically, for the first time, whether the introduction of an ECA affects vessel speeds. We utilize a dataset of observed vessel speeds derived from the Automated Information System (AIS) for nearly 7,000 ECA boundary crossings over a three-year period. Our results suggest that introducing stricter sulphur regulations inside the North Sea ECA from 1. January 2015 did not affect vessel speeds once changes in macroeconomic conditions are accounted for.

Keywords: AIS, emission control areas, vessel speed, fuel prices, green shipping

1. Introduction

The International Convention for the Prevention of Pollution from ships (MARPOL), specifically Annex VI, sets limits on sulphur oxide (SOx) and nitrogen oxide (NOx) emissions from ship exhausts. In 2008 the International Maritime Organization (IMO) agreed on the latest version, stipulating that global limits on the sulphur content in marine fuels of 3.5% would be reduced to 0.50% in 2020 or 2025 subject to an interim review in 2018. MARPOL further defines four Emission Control Areas (ECAs) with even more stringent limits on sulphur content in marine fuels: the Baltic Sea, the North Sea and English Channel, the North American coast and the US Caribbean coast. The latter two areas also regulate NOx and particulate matter (PM) emissions. In the current paper we focus on the implementation of the North Sea ECA regulations, which from 22. November 2007 limited marine fuel sulphur content to 1.5%. A lower limit of 1% came into force 1st July 2010, declining further to 0.1% from January 1, 2015. From a technical point of view, there are three ways to comply with these regional MARPOL regulations. The simplest and most common approach is a modification of a vessel's fuel tank system to enable switching from the standard heavy fuel oil (HFO) consumed outside ECAs to marine gas oil when sailing within an ECA. Other alternatives include natural gas-powered propulsion (LNG) and the installation of exhaust cleaning systems for SOx (scrubbers). Much recent research has been devoted to choosing the optimal compliance strategy (see, for instance, Lindstad et al, 2015; Yang et al, 2012; Balland et al, 2012, 2013; Brynolf et al, 2014; Jiang et al, 2014, Schinas and Stefanakos, 2012). In these studies, the alternatives are commonly assessed according to a number of criteria such as investment and operating costs, reliability and maintenance requirements. It is typically recognised that the optimal solution is subject to uncertain future price differences of alternative fuels as well as technological and regulatory uncertainty. A common weakness is the focus on cost minimization and failure to take into account that the inclusion of LNG propulsion or scrubbers will also affect a vessel's revenues. This is typically a result of a reduction in cargo-carrying capacity, either directly due to additional piping and larger fuel tank volumes, or indirectly by affecting a vessel's centre of gravity, for instance by placing heavy scrubber equipment high in the superstructure or LNG fuel tanks on deck for safety reasons. Moreover, as shown empirically in Adland and Strandenes (2007) for a perfectly competitive market, higher voyage costs merely increases the lower bound of the spot freight rate, passing increases in fuel prices on to the consumer of sea transport. From shipowners' point of view, this will favour compliance strategies that affect variable costs only (i.e. choosing fuel switching as opposed to additional investment in scrubbers or LNG retrofit). This important aspect is poorly understood in the literature on regulatory compliance.

A separate strand of the literature considers the impact that such environmental regulations should have on the operating patterns of vessels, notably as it pertains to speed choice and routing. The observation that the regulatory requirement to burn higher-priced low-sulphur fuel should influence speed stems from the classical research on speed optimization (see, e.g. Ronen, 1982). Because fuel consumption per time unit is approximately proportional to the cube of speed, it can be shown that the optimal (profit maximizing) speed in a one-period setting is approximately a function of the square root of the ratio between the freight rate and fuel price (Ronen, 1982). Accordingly, higher fuel prices, all else equal, should lead to reduced sailing speeds. Psaraftis and Kontovas (2013) provide a useful taxonomy and survey of the literature on speed models. Recent computational studies show, at least for the special case of liner shipping (Doudnikoff and Lacoste, 2014; Fagerholt et al, 2015) that a possible consequence of reduced sailing speeds within ECAs is that vessels must speed up outside to compensate for lost time, and that this will increase overall fuel consumption and CO2 emissions. Fagerholt et al (2015) also show that a likely effect of the regulations is that ship operators will choose to sail longer distances to avoid or reduce the sailing distances within the ECAs. Nevertheless, the main finding in the literature is that slow-steaming results in substantial reductions in carbon emissions (see, for instance, Corbett et al, 2009; Wang and Meng, 2012; Maloni et al, 2013, Zis et al, 2014, Ferrari et al, 2015).

We note that the literature on MARPOL compliance consists only of theoretical or computational studies, even though the North Sea ECA, for instance, has existed for nearly a decade. We seek to fill this gap in the literature by providing the first ever empirical study of vessel behaviour in regions affected by the ECA regulations. Specifically, the objective and contributions of this paper is to assess statistically i) whether vessels slow down, on average, when entering an ECA and ii) whether the introduction of the stricter ECA regulations on January 1st, 2015, affected speed patterns. We do this by building a unique and comprehensive dataset of high-frequency speed observations at the individual voyage level for ECA boundary crossings, derived from the international Automatic Identification System (AIS). The remainder of this paper is structured as follows: Section 2 describes the AIS data and our variable choices, Section 3 shows our empirical results and Section 4 concludes.

2. Data and variables

2.1. Introduction to AIS

Automatic Identification Systems are designed to automatically provide information about a ship and its location/course to other ships and coastal authorities, primarily with the goal of collision avoidance. Specifically, IMO regulation 19 of SOLAS Chapter V requires that AIS shall:

- Provide information – including the ship's identity, type, position, course, speed, draught, navigational status and other safety-related information – automatically to appropriately equipped shore stations, other ships and aircraft;
- Receive automatically such information from similarly fitted ships; monitor and track ships;
- Exchange data with shore-based facilities.

The regulation requires AIS to be fitted aboard all ships of 300 gross tonnage and upwards, engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships by 31 December 2004 (IMO, 2015).

A good database of historical AIS data is a veritable treasure trove of high-frequency information on vessel behaviour. In principle, an accurate and complete dataset enables researchers to construct complete itineraries for any vessel or any fleet of vessels, with dynamic speeds and loading conditions, as well as detailed knowledge of the time spent in port, at anchorage or in repair yards. However, its application in academic research and commercial use has been hampered by the challenges in managing the extremely large volumes of data as well as varying quality and geographical coverage. As an illustration, the volume of raw data behind our study, as kindly provided by the Norwegian Coastal Authority (NCA) and collected since February 2nd 2005, is nearly 6,000 Gigabytes of data.

2.2. Defining the sample

The data consists of large files with one line per AIS raw message, which are decoded, joined and inserted into a database. Obvious errors, e.g., messages not conforming to the standard or vessels seemingly moving in excess of 100 knots, are discarded. The data collected by NCA has a varying degree of spatial coverage as time progresses. From early 2005 the network expanded with terrestrial base stations, and in 2010 with the addition of satellite coverage. The terrestrial base-stations have coverage along the Norwegian coast and 40 - 60 nautical miles into territorial waters. From a geographical point of view we focus on North Sea ECA boundary crossings (both inbound and outbound) at its northern borders, specifically latitude 62˚N west of Norway and north of Scotland (see Figure 1 for an illustration). We do not include data for the Southern boundary in the English Channel in our main analysis, since vessel speeds in such high-traffic-density areas will be strongly influenced by navigational constraints instead of economic optimization. However, the basic results for the English Channel ECA boundary are reported in Table 3A in the appendix for the sake of completeness.

We note at this stage that a large portion of the fleet is not relevant to the research question. This includes vessels that are not likely to adhere to economic optimization in the traditional sense (e.g. cruise/passenger vessels, tugs or fishing vessels) and, more importantly, vessels that always burn low-sulphur marine gas oil (MGO) or marine diesel oil (MDO). Because these distillate fuels have always been in compliance with even the strictest ECA limits on sulphur content (0.1% from 2015 onwards), ships that are fitted with engines built for MDO/MGO consumption only have not been affected by the regulations. Consequently, there is no reason for this part of the fleet to exhibit a behaviour that is contingent on regulatory changes and so it should be excluded from our sample in order to avoid a bias towards “no change”.

It follows that we want to further narrow down our sample based on the fuel type consumed by any given vessel. While this is a known parameter for many ships, the data is incomplete and so we must assess this indirectly based on other known vessel parameters, specifically vessel type and vessel size. Table A1 in the appendix shows a breakdown of fuel type by vessel type for the nearly 90,000 oceangoing vessels the Clarkson Research (2016) fleet database. With reference to this table, we note that vessel types defined as "cargo" (container, dry bulk and others) and "tanker" (crude tankers, products tankers and gas carriers) in the AIS system also correspond to those vessel types most likely to use HFO, while ships operating locally or on short-sea trades (dredgers, tugs, ferries, offshore) generally consume distillate fuels. Our study therefore disregards ECA crossings by vessels other than those defined as a tanker or cargo vessel under the AIS protocol. However, it is possible to refine our AIS-derived panel data sample further by also considering the relationship between vessel size and fuel type. We know from marine engineering that smaller vessels employed on shorter trades and spending relatively more time manoeuvring tend to be equipped with medium-speed 4-stroke engines that require high-grade fuels, while big deep-sea vessels are almost exclusively equipped with low-speed 2-stroke engines that burn standard HFO. The reason for this is the trade-off between the former's lower investment, smaller engine plant and ease of manoeuvring, and the lower running costs and greater power of the latter. Accordingly, we expect a high degree of correlation between vessel size and fuel type. Table A2 in the Appendix illustrates the percentage of all vessels by size category (based on overall vessel length) that burn HFO. The results suggest that we should disregard ECA crossings by vessels below 100m length as the majority of vessels in this size range use low-sulphur distillate fuels. We note that, in the case of tankers, 100m vessel length equates to a carrying capacity of roughly 5,000 DWT, as illustrated by Figure A1 in the Appendix. From the entire dataset, we therefore select only vessels matching the following filters:

- Vessel length being greater than or equal to 100 m
- Vessel type defined as either cargo or tanker
- Timestamp of message between 2013.01.01 and 2015.12.31

From this filtered dataset, we extract every ECA boundary crossing, keeping all position reports within a 48-hour window around each crossing. The cutoff time at 24 hours either side is chosen to be long enough to incorporate any acceleration or deceleration effects as a vessel approaches the associated fuel switching event. Our discussions with technical managers in the industry confirm that the actual fuel switching event usually takes place within a 6-12 hour window prior to entering the ECA[1]. Furthermore, some vessels will go into shore, e.g., at the Mongstad oil terminal on the west coast of Norway, shortly after crossing the ECA border, so we introduce an

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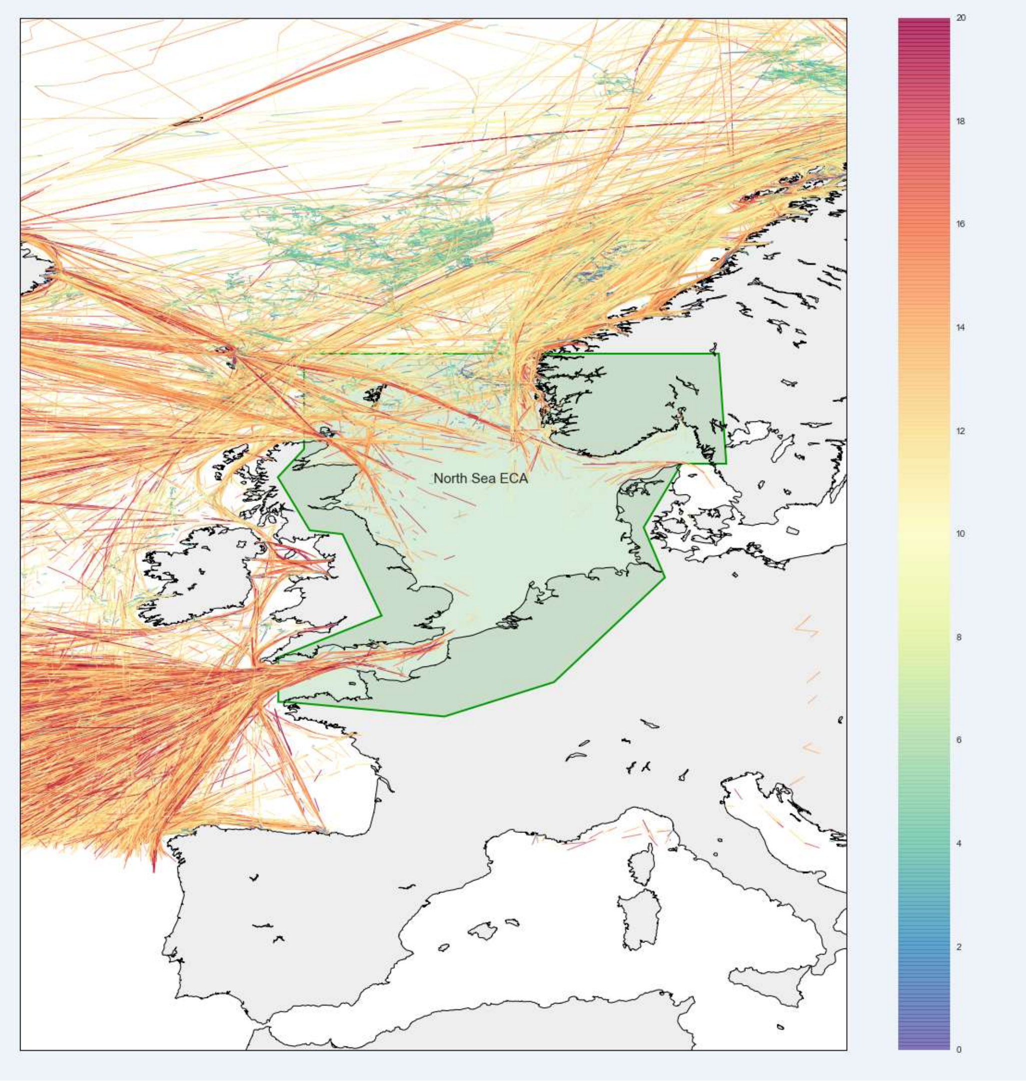
[1] From a regulatory point of view, the only requirement is that the remaining high-sulphur fuel in the engine and affiliated piping system from the fuel tanks has been flushed out by the time the vessel enters the ECA. Thus, the actual switching between fuels takes only a few minutes. Private communication with Mr. Reinertsen at SKS Tankers AS.

additional filter requiring all included vessels to maintain a speed above 10 knots at all times in this 48-hour window. This filter removes all vessels going into ports close to the ECA borders. Extending the observation window much beyond 24 hours, particularly for vessels sailing Southbound inside the North Sea, would induce "port proximity" effects for a greater part of the sample[2], with vessels adjusting speeds for non-economic reasons such as meeting a scheduled berthing time, maneuvering near shore, or decelerating towards an anchorage.

Figure 1 – Illustration of ECA boundary crossings in 2015 (vessel length > 100m)



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[2] The voyage from the ECA boundary at 62˚N to Hamburg at the sample average sailing speed takes 44 hours.

After the introduction of the speed restriction, the data is discretized into rows with one passing per row, containing one speed per whole hour starting from t =-24 to +24, and an indication of whether this vessel is entering or exiting the ECA zone (inbound/outbound passage). In hours with multiple data position reports, we use average speed and in hours with missing position reports we use linear interpolation (but no extrapolation). Each passing is further enriched with information on current draught, max draught observed, length, beam, ship type and IMO number. Our final dataset consists of 6971 individual crossings of the North Sea ECA border (excluding the English channel).

2.3. Other variables

The speed profiles of individual crossings make up only one part of our panel data set. In addition we want to be able to control for certain attributes of the vessels, directional and seasonal effects, as well as fuel and freight market conditions. The list below contains our chosen variables and our reasoning behind their inclusion. When it comes to technical vessel specifications, we purposely include only variables that are reported in the AIS feeds (i.e. main dimensions). While we could in principle use a vessel's IMO number to look up other technical specifications from the various fleet register databases available, this is a rather cumbersome exercise that does not add much value. We divide our variables into three main groups: macroeconomic, vessel-specific and voyage-specific as follows:

Macroeconomic variables

- Spot freight rate ($/tonne). For tanker vessels we proxy the spot freight rate by the daily TD7 Baltic index for Aframax tankers operating in the North Sea, converted from Worldscale to $/tonne using the applicable annual flat rate. For cargo vessels we use the daily C7 Baltic index for Capesize vessels in trans-Atlantic trade.
- Bunker prices ($/tonne). We use weekly prices quoted in Rotterdam for 380cst HFO, low-sulphur HFO and MGO.

Vessel-specific variables

- Length*Beam*Design_Draught. Using AIS-reported main dimensions, we use their cubic product as a proxy for the vessel's carrying capacity (DWT). As per graph A1 in the Appendix, this is a very good approximation. Design_Draught corresponds to the Summer DWT loading condition (maximum draught).

- Age_proxy. We use the AIS reported IMO number, specifically its first two digits as a proxy for when the vessel is built[3]. All else equal we would expect older vessels to sail slower due to deteriorating hull conditions over time.

Voyage-specific variables

- Ratio of AIS-reported draught to Design_draught gives an indication of the loading condition. A ratio of 1 suggests that the vessel is fully loaded, while a ratio around 0.5 suggests ballast condition. All else equal, we expect ships with low draught ratios to sail faster (a positive coefficient) due to reduced water resistance.
- Direction dummies (southbound or northbound). Because vessels sailing northbound will typically have left a port in Continental Europe and sailing towards open sea we expect higher speeds, on average, for this sailing direction.
- Season dummies (winter Q1 & Q4 vs. summer Q2 & Q3). Due to the harsh winter weather in the North Sea we wish to control for consistent seasonal speed differences (expectedly lower in the winter).

Ideally, we would have liked to include the chartering status of every vessel as an explanatory (voyage-specific) variable. This is due to the expected dependence between who is in operational control of the vessel, cargo ownership and charter party clauses on the speed choice (Adland, 2013). For instance, the operator of a tanker vessel which is not under contract will have strong incentives to minimize the fuel bill, while the vessel will be subject to certain constraints on speed (e.g. meeting laycan) once it is fixed. Unfortunately, the fleet of tankers and cargo vessels in our filtered sample is very heterogeneous with regards to market transparency and the availability of market data such as fixtures. Specifically, the tanker segment here includes LPG and LNG gas carriers, crude, chemicals and products tankers, while the cargo segment encompasses container, general cargo and bulk carriers etc. Even for the most transparent sectors, public spot fixtures represent only a small fraction of the annual voyages undertaken by the global fleet. As an illustration, Clarkson Research (2016) reported 2,234 Panamax bulker spot fixtures during 2015 for a fleet of 2,453 vessels at year end, or less than one spot fixture per vessel per year. Consequently, as the purpose of our paper is to study the speed dynamics of the cross section of the entire fleet passing the borders of the North Sea ECA, it is not appropriate to substantially reduce the sample size and possibly introduce unknown biases by only selecting segments and voyages for which we can find public chartering information.

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[3] Between 1973 and 1991 the first two digits of the LR number were an indicator of the year of order, and after 1991 IMO numbers have been issued sequentially. For a detailed description of IMO number, please refer to Lloyd's Register Foundation Centre, Infosheet No. 45

However, we note that the loading condition of every vessel is captured by our draught ratio variable and that this may serve as a (weak) proxy for chartering status, as some vessels in ballast will be repositioning without contract.

3. Empirical results

3.1 Student-t tests

To assess whether the introduction of stricter sulphur requirements inside the North Sea ECA after 1st January 2015 had an impact on vessel speeds we consider first the Student-t test of the null hypothesis that the mean speed inside and outside the ECA are equal. The results are shown in Table 1 below. The null hypothesis of equal average speed inside and outside the ECA is rejected. The average vessel sailing speed in the sample is higher inside than outside the ECA though the mean difference is very small at around 0.2 knots. While this may seem implausible, we note that we are here effectively comparing the two populations of the 24-hour mean vessel speeds inside and outside the ECA and that such "daily" speeds exhibit low standard deviation, which translates into a low standard error of the mean estimates given the very large number of observations.

Table 1 – Student-t test of different mean speeds inside/outside ECA

t-test results with equal variances: H_0: two variables have the same mean ($\mu1=\mu2$)

		Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]	Pr(H_0: $\mu_1>\mu_2$)	Pr(H_0: $\mu_1=\mu_2$)	Pr(H_0: $\mu_1<\mu_2$)
μ_1	Speed_inside	6971	13.293	0.024	2.014	13.246	13.340	1.00	0.00	0.00
μ_2	Speed_outside	6971	13.092	0.023	1.945	13.047	13.138			
	by vessel type									
	vessel type=Cargo									
μ_1	Speed_inside ECA	4775	13.459	0.032	2.178	13.398	13.521	1.00	0.00	0.00
μ_2	Speed_outside ECA	4775	13.233	0.030	2.095	13.174	13.292			
	vessel type=Tanker									
μ_1	Speed_inside ECA	2196	12.931	0.033	1.541	12.867	12.996	1.00	0.00	0.00
μ_2	Speed_outside ECA	2196	12.786	0.033	1.525	12.722	12.850			
	by traffic direction									
	entering ECA									
μ_1	Speed_inside ECA	3111	13.131	0.036	2.003	13.060	13.201	0.969	0.062	0.031
μ_2	Speed_outside ECA	3111	13.086	0.035	1.926	13.018	13.154			
	exiting ECA									
μ_1	Speed_inside ECA	3860	13.424	0.032	2.015	13.360	13.487	1.00	0.00	0.00

μ_2	Speed_outside ECA	3860	13.097	0.032	1.960	13.036	13.159		
	by vessel length								
	vessel length 100 ~ 150m								
μ_1	Speed_inside ECA	3381	13.242	0.031	1.814	13.181	13.303	1.00	0.00	0.00
μ_2	Speed_outside ECA	3381	13.051	0.029	1.712	12.994	13.109			
	vessel length 150 ~ 200m									
μ_1	Speed_inside ECA	1691	13.565	0.054	2.240	13.458	13.672	1.00	0.00	0.00
μ_2	Speed_outside ECA	1691	13.306	0.053	2.194	13.201	13.411			
	vessel length 200 ~ 250m									
μ_1	Speed_inside ECA	1169	12.675	0.043	1.456	12.592	12.759	1.00	0.00	0.00
μ_2	Speed_outside ECA	1169	12.473	0.040	1.373	12.394	12.552			
	vessel length 250 + m									
μ_1	Speed_inside ECA	730	13.887	0.100	2.714	13.690	14.084	0.964	0.073	0.036
μ_2	Speed_outside ECA	730	13.779	0.099	2.683	13.584	13.974			
	by date									
	post 1 Jan 2015									
μ_1	Speed_inside ECA	2281	13.287	0.043	2.048	13.203	13.371	1.00	0.00	0.00
μ_2	Speed_outside ECA	2281	13.131	0.042	1.994	13.049	13.213			
	2013-2014									
μ_1	Speed_inside ECA	4690	13.296	0.029	1.998	13.239	13.353	1.00	0.00	0.00
μ_2	Speed_outside ECA	4690	13.074	0.028	1.921	13.019	13.129			

We furthermore see that both tankers and cargo vessles sail at an slightly higher average speed inside than outside the ECA. When we split the sample into vessels exiting or entering the ECA we find the same pattern - vessels sail at slightly higher speeds inside the restricted ECA area. But the result for vessels entering is not significant. We also split the sample in size classes and find that the speed inside the ECA is slightly higher on average than outside except for the largest vessels, above 250 m, where the result is not significant at the 95% confidence level.

Looking at the impact of sailing direction, Table 2 shows the student-t test results when we separate samples by sailing direction - inside ECA, outside ECA and overall, respectively. We note that the differences in mean speeds are statistically significant. This difference is also economically meaningful, with northbound vessels sailing around 0.133 knots faster. Interestingly, this result is driven by vessel operations inside the ECA. For observations of vessels speed outside the ECA we cannot reject the hypothesis that northbound and southbound vessels sail at the same average speed. We attribute the difference in average speed observed for vessels sailing in the ECA in part to the fact that northbound vessels are more likely to be sailing in ballast, with cargo flows (crude oil, natural gas and iron ore) being predominantly southbound from Northern Norway, North Russia or north of Scotland (e.g. the Sullum Voe oil terminal) to continental Europe. However, we are also back to the possible "port proximity effects" discussed earlier, where southbound vessels will be approaching a port in continental Europe or the UK, while northbound vessels are leaving a heavily trafficked area and heading into the open sea.

Table 2 – Student-t test of different inbound/outbound mean speeds

t-test results with equal variances: H_0: two variables have the same mean ($\mu1=\mu2$)

		Obs	Mean	Std. Err.	Std. Dev.	[95% Conf. Interval]		Pr(H_0: $\mu_1>\mu_2$)	Pr(H_0: $\mu_1=\mu_2$)	Pr(H_0: $\mu_1<\mu_2$)
μ_1	Speed_northbound	3860	13.269	0.030	1.844	13.211	13.328	0.999	0.003	0.002
μ_2	Speed_southbound	3111	13.136	0.034	1.872	13.071	13.202			
	Inside ECA									
μ_1	Speed_northbound	3860	13.424	0.032	2.015	13.360	13.487	1.000	0.000	0.000
μ_2	Speed_southbound	3111	13.131	0.036	2.003	13.060	13.201			
	outside ECA									
μ_1	Speed_northbound	3860	13.097	0.032	1.960	13.036	13.159	0.598	0.804	0.402
μ_2	Speed_southbound	3111	13.086	0.035	1.926	13.018	13.154			

3.2 Regression analysis: Speed determinants and the effect of regulatory change

The results in the previous section suggest that certain non-economic variables such as vessel – size and sailing direction (as a proxy for loading condition) may be key determinants of speed and speed changes. Hence, while this paper is not about the micro-determinants of vessel speed *per se* – rather, we care about the impact of regulatory changes - it is nevertheless useful to establish whether vessels speeds appear to be influenced by fuel prices and freight rates in a manner consistent with maritime economic theory.

To establish the determinants of the average speed V_i observed for ECA crossing i in our panel data set, we test various specifications of a multiple linear regression model using combinations of variables from Section 2. In particular, if we include all macroeconomic, vessel-specific and voyage specific variables, the most comprehensive model is:

$$V_i = \alpha_0 + \alpha_1 F_i + \alpha_2 B_i + \alpha_3 LBD_i + \alpha_4 Age_i + \alpha_5 U_i + \alpha_6 DD_i + \alpha_7 QD_i + \alpha_8 VD_i + \varepsilon_i \quad (1)$$

Where F_i is the spot freight rate, B_i is the bunker price, LBD_i is our DWT proxy, Age_i is our age proxy, U_i is our draft ratio measure of loading condition, DD_i is a dummy for the northbound direction, QD_i is a winter season dummy and VD is a dummy denoting observations post the introduction of the stricter sulphur regulation from 1. January 2015. Finally, ε_i is a random perturbation such that $E(\varepsilon_i) = 0$ and $V(\varepsilon_i) = \sigma^2$.

Following the recent literature on microeconomic analysis of vessel speeds and freight rates (see e.g. Adland et al, 2016 and Assman, 2015) we apply standard panel estimation methods, though note that other "inexact" methods such as neural networks may be suitable for analysing such high volumes of data. Specifically, we estimate Equation 1 on log-log format and use random effects (RE) or fixed effects (FE) models rather than pooled ordinary least squares estimation, as the latter does not account for the individual heterogeneity in ships that is constant over time. Such an omission would lead to biased and inconsistent coefficients (Verbeek, 2012). A random effects model takes into account variation both within and across observational units over time. However, it imposes a strict assumption that the individual unobserved heterogeneity is not correlated with the error term. The fixed effects model is less efficient than the random effects model, as it eliminates the unobserved heterogeneity by demeaning the variables. While the above assumption is redundant, this improvement comes at the expense of the FE model not being able to identify the effect of the variables that are constant over time. The choice between the random effects and fixed effects models is dictated by the variability in the data over time and the results of the Hausman (1978) test. The Hausman test is built around the null hypothesis that the coefficients estimated by the efficient RE estimator and the consistent FE estimator are identical. If the null hypothesis holds, then the RE estimator is preferable (Green, 2008).

Table 3 – Regression estimates for average vessel speed inside and outside the ECA

Dependent variable: logrithm of average speed

	(1)	(2)
log_Freight rate §	-0.002	
	-(0.350)	
	[0.73]	
log_Bunker price #	0.027	0.029
	(2.970)	(3.350)
	[0.00]	[0.00]
log_(L*B*D)	-0.040	
	-(1.380)	
	[0.17]	
log_age proxy	-0.017	
	-(0.230)	

	[0.82]	
log_draught_ratio	-0.012	
	-(1.280)	
	[0.20]	
Dummy_entering ECA	-0.021	-0.021
vs. Exiting ECA	-(9.050)	-(8.980)
	[0.00]	[0.00]
Dummy_post 1 Jan 2015	0.014	0.015
vs. 2013-2014	(1.960)	(2.200)
	[0.05]	[0.03]
Dummy_Winter	-0.018	-0.019
vs. (March-Nov)	-(3.150)	-(3.270)
	[0.00]	[0.00]
Constant	2.887	2.402
	(7.310)	(44.080)
	[0.00]	[0.00]
R-sq: within	0.0259	0.0255
: between	0.0024	0.0002
: overall	0.0000	0.0018
Fix effect	yes	yes
Hausman test chi2	0.000	0.000

note: Figures in [ ] are the *p*- values of H0: zero coeffecients; figures in ( ) are *t-stats*

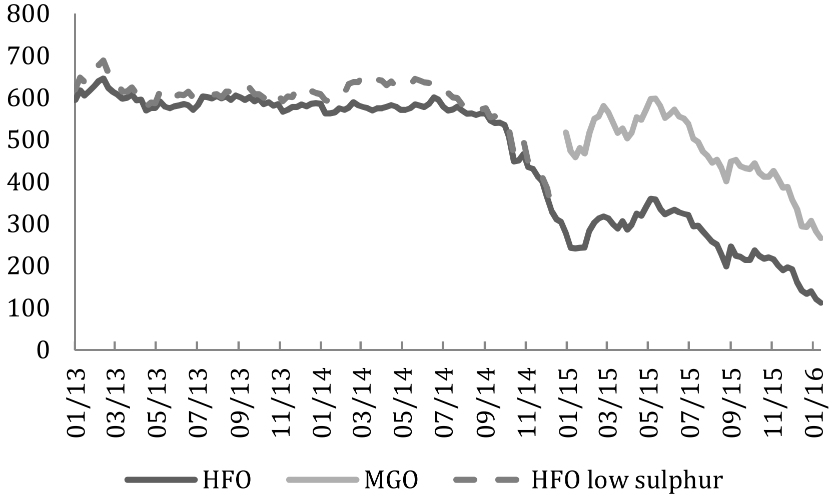
§ tanker freight rate is Baltic TD7 to $/tonne; cargo freight rate is C7.

bunker rate is taken as 380cst Rotterdam $/tonne

Table 3 shows the regression results for the log-log format of Equation 1 using the FE estimator. Specification 1 shows the results for the full model and in specification 2 we have dropped all the insignificant variables from the general specifications and re-estimated the parsimonious model. We can see that the freight rate does not affect the speed decision, whereas the bunker price has a minute positive effect on speed contrary to what classical maritime economic theory suggests. Instead, speed is mainly determined primarily by weather conditions (winter speeds are lower), the sailing direction (exiting ships sail faster) and the change in fuel sulphur content introduced 1st January 2015. (Vessels on average sail faster after the tighter restrictions came into force). The signs of the coefficients for weather conditions and sailing direction are as expected as per our discussion in Section 2.3. This is not the case for the sign of the change in regulation, however. The change in speed might follow from the steep reduction in fuel costs from 2014

(See Figure 2), but this explanation is contradicted by the slight positive effect on speed of bunker price indicated by the estimated positive coefficient for bunker price. Our findings support the results elsewhere in the empirical speed literature based on AIS data (see, e.g. Adland, 2013; Assman et al, 2015; Adland and Jia, 2016a,b) where the classical speed optimization theory is largely rejected.

Figure 2 - Bunker price ($/tonne) developments



Next, we modify Equation 1 slightly such that the dependent variable now is the change in average vessel speed for crossing i, $\Delta V_i = V_{\text{outside ECA}} - V_{\text{inside ECA}}$. We also introduce a dummy for tankers to assess whether the change in average speed differ for vessel type. The results of the log-log regression estimates are shown in Table 4 below. Once again we start with the most general specification (1) and then drop the insignificant variables to arrive at the most parsimonious specification (2). We note that the Hausman test suggests the use of the RE estimator.

The results are less straightforward to interpret once we consider speed differentials. Basically, a positive coefficient in Table 4 suggests that vessels slow down more when crossing into the ECA when the respective variable is increasing. Both coefficients for the freight rate and the bunker price have the correct sign, but neither estimates are significant. We note that the fuel price variable here refers to the price of ordinary high-sulphur HFO and not the price differential with low-sulphur or distillate fuel oil. Neither vessel size, the age of the vessel nor the draught ratio have a significant influence, but the direction dummy shows that the speed difference (relatively slower speed inside ECA) is greater for vessels entering than for vessels exiting, and tankers change their speed more than cargo vessels when crossing.

Importantly, the introduction of a stricter sulphur regulation inside the ECA from 2015 did not cause a significant change in vessel behavior. Principally, after the regulatory change, vessels crossing into the ECA did not adjust the average speed significantly. The bunker price does not have significant effect so we cannot contribute this to the reduction in bunker costs onwards from 2014.

Table 4 – Regression estimates for ECA boundary speed changes

Dependent variable: log Speed difference = log(speed_outside/speed_ inside)

	(1)	(2)
Dummy_post 1 Jan. 2015	0.011	
	(1.620)	
	[0.11]	
log_Freight rate §	-0.007	
	-(1.540)	
	[0.12]	
log_Bunker price #	0.014	
	(1.580)	
	[0.12]	
log_(L*B*D)	4.87E-04	
	(0.330)	
	[0.75]	
log_age proxy	0.007	
	(0.780)	
	[0.44]	
log_draught_ratio	-0.006	
	-(0.810)	
	[0.42]	
Direction_Dummy (Entering=1)	0.021	0.022
	(8.540)	(8.800)
	[0.00]	[0.00]
Season_Dummy (winter=1)	-0.005	
	-(0.800)	
	[0.42]	
VesselType_Dummy (cargo=1)	-0.005	-0.006
	-(1.780)	-(2.220)
	[0.08]	[0.03]
Constant	-0.121	-0.020
	-(1.800)	-(8.390)

	[0.07]	[0.00]
R-sq: within	0.0136	0.0121
: between	0.0150	0.0131
: overall	0.0128	0.0116
Fix effect	no	no
Hausman test chi2	0.102	0.401

Note: Numbers in [ ] are *p*- values of H0: zero coeffecients; Numbers in ( ) are *t-stats*

§ tanker freight rate is Baltic TD7 to $/tonne; cargo freight rate is C7.

bunker rate is taken as 380cst Rotterdam $/tonne

As a final check, we attempt to match the vessel names associated with the individual ECA boundary crossings in 2014 and 2015 with vessels that are reported as being on timecharter on the same date. The reason for creating such a sub-sample is the expectation that when charterers are in operational control of the vessel and pays the fuel bill directly, we may observe a greater sensitivity to the higher cost of burning low-sulphur fuel within the ECA. As expected due to the incomplete nature of public fixture data, the number of matches ends up very low, with only 23 large tankers and bulkers identified behind 36 crossings in 2014 and 2015. The t-statistics shown in Table 5 illustrates how chartering status does not appear to make a difference, as we are unable to reject the hypothesis of equal mean speed inside and outside of the ECA irrespective of how we slice the population (by vessel type, sailing direction, vessel size or crossing date). Once again, the prevailing tendency is for higher sailing speeds within the ECA.

Table 5 - Student-t test of different mean speeds inside/outside ECA for vessels on timecharter

t-test results with equal variances: H_0: two variables have the same mean ($\mu1=\mu2$)

		Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]	Pr(H_0: $\mu_1>\mu_2$)	Pr(H_0: $\mu_1=\mu_2$)	Pr(H_0: $\mu_1<\mu_2$)
μ_1	Speed_inside	36	12.663	0.220	1.320	12.216	13.109	0.671	0.658	0.329
μ_2	Speed_outside	36	12.604	0.163	0.976	12.274	12.935			
	By vessel type									
	vessel type=Cargo									
μ_1	Speed_inside ECA	30	12.824	0.246	1.350	12.320	13.328	0.951	0.098	0.049
μ_2	Speed_outside ECA	30	12.619	0.182	0.996	12.247	12.990			
	vessel type=Tanker									
μ_1	Speed_inside ECA	6	11.859	0.340	0.834	10.984	12.734	0.087	0.174	0.913
μ_2	Speed_outside ECA	6	12.533	0.391	0.958	11.528	13.538			
	by traffic direction									
	entering ECA									
μ_1	Speed_inside ECA	12	11.962	0.390	1.350	11.104	12.819	0.093	0.186	0.907

μ_2	Speed_outside ECA	12	12.295	0.268	0.929	11.705	12.886			
	exiting ECA									
μ_1	Speed_inside ECA	24	13.014	0.241	1.180	12.515	13.512	0.954	0.093	0.046
μ_2	Speed_outside ECA	24	12.759	0.200	0.981	12.344	13.173			
	by vessel length									
	vessel length 200 ~ 250m									
μ_1	Speed_inside ECA	27	12.881	0.266	1.381	12.335	13.427	0.960	0.080	0.040
μ_2	Speed_outside ECA	27	12.659	0.201	1.043	12.246	13.071			
	vessel length 250 + m									
μ_1	Speed_inside ECA	9	12.009	0.294	0.883	11.331	12.688	0.122	0.244	0.878
μ_2	Speed_outside ECA	9	12.441	0.257	0.772	11.848	13.034			
	by date									
	post 1 Jan 2015									
μ_1	Speed_inside ECA	17	12.885	0.330	1.359	12.186	13.584	0.871	0.258	0.129
μ_2	Speed_outside ECA	17	12.659	0.240	0.988	12.151	13.167			
	prior to 2015									
μ_1	Speed_inside ECA	19	12.464	0.295	1.287	11.844	13.084	0.307	0.614	0.693
μ_2	Speed_outside ECA	19	12.555	0.227	0.990	12.078	13.032			

4. Discussion and future research

Overall, the results in our paper do not support the assertion that the introduction of stricter Sulphur regulation inside the Emission Control Areas affects vessel speeds in any economically significant manner. On the contrary, we show that vessel speeds are not generally determined by fuel prices or freight rates but rather by voyage-specific variables such as whether a vessel is heading towards or away from heavily trafficked areas or ports of call, whether it is a tanker or cargo vessel, and seasonal weather factors. For marine navigators this is presumably not a major surprise, but it is presumably disheartening for those seeking economic rationality and trying to apply complex and highly theoretical optimization models to the maritime supply chain.

However, one should be careful to dismiss such findings as signs of inefficiency or bounded rationality. There are several good reasons, many of them poorly understood in the academic literature, why speed optimization on the basis of changing fuel prices and freight market conditions are not likely to take place in practice. Firstly, there will always be external factors, such as safe sailing during poor weather or charter party clauses (e.g. cancelling dates) that take priority in practice. Secondly, fuel consumption as a function of vessel speed in the real seaway is an extremely uncertain function, with actual consumption easily surpassing nominal "flat water" consumption by 50% due to fouling, currents and weather conditions. With such high degrees of uncertainty, small theoretical gains in earnings from changing speed will soon be swamped by measurement errors. Thirdly, it is often forgotten that the level of the fuel price is not interesting *per se* – as long as there is a functioning freight market, freight rates will merely adapt such that owners of most ships will cover their voyage costs in full. This means that additional costs within ECAs, even with distillate fuel prices being substantially higher, *should not* affect optimal speeds materially. Hence, one should not be surprised that the stricter sulphur regulation inside the North Sea ECA from 2015, requiring vessels to switch to burning higher-priced marine gas oil, does not seem to affect vessels operations. Indeed, this should perhaps be the *a priori* hypothesis in the literature.

From a policy angle, our empirical results suggest that ECA regulations imposing the use of higher-cost marine fuels have not contributed to the expected change in vessel behaviour. Depending on the nature of commercial contracts and pricing power in the various shipping segments, the additional costs of low-sulphur fuels are borne by both consumers and vessel operators. This may lead to increased non-compliance from shipping companies. This would not only weaken the positive effect on emissions, it would also be a major competitive disadvantage for the companies that comply with the regulation. Consequently, strong enforcement of ECA regulations by relevant nations and authorities becomes crucial. In North America, there exists a set of inspection, investigation and enforcement procedures set by the US Environmental Protection Agency (EPA) and the US Coast Gard (USCG) with corresponding penalty policies. The US enforcement has led the way by focusing on checking relevant documentation, such as the bunker delivery note and the ship's log of fuel changeover timing and procedures, and taking fuel samples from ships to test for compliance (EPA, 2016). In Europe, the enforcement of emission regulations in ECAs is not as strong. The European Union adopted a strategic regulation covering Monitoring, Reporting and Verification (MRV) which focus on CO_2 and fuel efficiency. However, since the EU MRV is a regulation and not a directive, which means it does not need to be transposed into national law, it has already attracted criticism (Gemmill, 2015). Practical and robust enforcement is therefore required.

Future research should extend our empirical analysis to the North America ECA where stricter enforcement is in place. In addition, the sailing distance inside ECA in proportion to a vessel's total voyage distance is an important determinant in speed adjustment or optimisation. Therefore, speed changes should be considered in relation to the duration of the entire voyage (short-sea vs deep-sea shipping). Additionally, future research should investigate possible changes in ship routing as an alternative behavioural effect of ECA regulations.

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APPENDIX

Table A1 – Fuel type by vessel type

	MDO/MGO	HFO/IFO	Unknown	Total
Crude tankers	0	1837	1	1838
Product tankers	718	3260	3643	7621
Chemical tankers	175	2202	1065	3442
Specialised tankers	89	183	383	655
Bulkers (>10K dwt)	6	10172	195	10373
Containerships	25	4898	190	5113
MPP	591	2188	445	3224
Ro-Ro	164	651	441	1256
General Cargo	2433	1838	11405	15676
LPG	62	877	343	1282
PCC	6	740	24	770
Reefers	197	570	642	1409
Offshore	5886	506	4297	10689
Dredgers	355	141	1415	1911
Tugs	6409	337	10048	16794
Cruise	38	188	135	361
Ferries	2595	466	3090	6151
Total	19749	31054	37762	88565

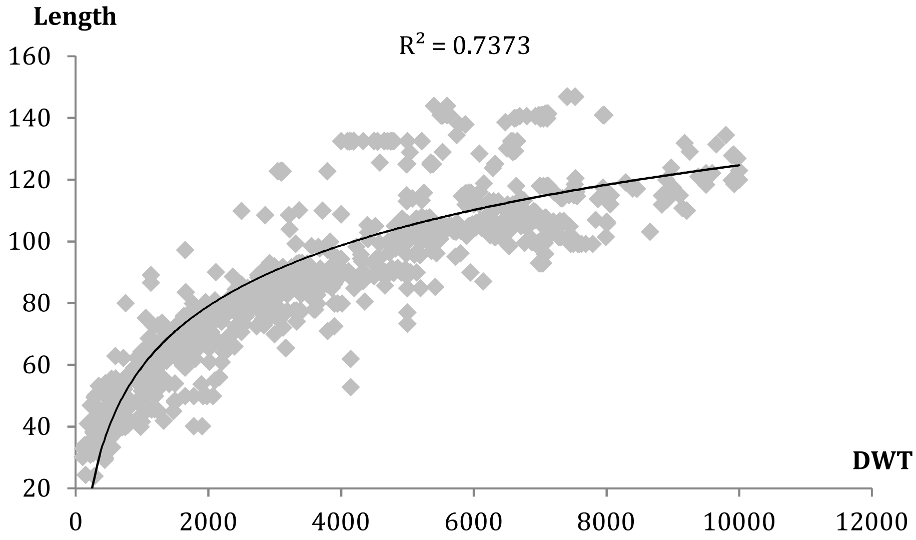
Source: Clarkson Research (2016) and author calculations

Table A2 – Fuel type by vessel length

Vessel length (LOA)	HFO/IFO	MDO/MGO	Unknown	HFO% (of known)
< 40	1.3%	42.7%	56.0%	3.0%
40-60m	2.1%	32.3%	65.7%	6.0%
60-80m	7.4%	25.2%	67.4%	22.6%
80-100m	24.5%	25.8%	49.6%	48.7%
100-120m	54.4%	14.5%	31.1%	79.0%
120-140m	69.1%	11.6%	19.3%	85.6%
140-160m	86.4%	2.9%	10.7%	96.7%
above 160m	95.5%	0.7%	3.8%	99.3%

Source: Clarkson Research (2016) and author calculations

Figure A1 – Relationship between DWT and vessel length (small tankers)



Source: Clarkson Research (2016) and author calculations

Table A3 Student t-test of different mean speeds inside and outside ECA for vessels in the English Channel.

t-test results with equal variances: H_0: two variables have the same mean ($\mu1=\mu2$)

		Obs	Mean	Std. Err.	Std. Dev.	[95% Conf. Interval]		Pr(H_0: $\mu_1>\mu_2$)	Pr(H_0: $\mu_1=\mu_2$)	Pr(H_0: $\mu_1<\mu_2$)
μ_1	Speed_inside	8124	14.940	0.032	2.847	14.878	15.002	1.00	0.00	0.00
μ_2	Speed_outside	8124	14.746	0.031	2.760	14.686	14.806			
	by vessel type									
	vessel type=Cargo									
μ_1	Speed_inside ECA	6159	15.435	0.038	2.949	15.361	15.508	1.00	0.00	0.00
μ_2	Speed_outside ECA	6159	15.302	0.036	2.835	15.231	15.373			
	vessel type=Tanker									
μ_1	Speed_inside ECA	1965	13.390	0.040	1.759	13.312	13.468			
μ_2	Speed_outside ECA	1965	13.003	0.034	1.514	12.937	13.070	1.00	0.00	0.00
	by traffic direction									
	entering ECA									
μ_1	Speed_inside ECA	3074	14.954	0.051	2.845	14.853	15.054	0.999	0.002	0.001
μ_2	Speed_outside ECA	3074	14.849	0.052	2.882	14.748	14.951			
	exiting ECA									

μ_1	Speed_inside ECA	5050	14.932	0.040	2.849	14.853	15.011	1.00	0.00	0.00
μ_2	Speed_outside ECA	5050	14.683	0.038	2.681	14.609	14.757			
	by vessel length									
	vessel length 100 ~ 150m									
μ_1	Speed_inside ECA	1430	14.045	0.061	2.324	13.925	14.166	1.00	0.00	0.00
μ_2	Speed_outside ECA	1430	13.696	0.059	2.224	13.581	13.812			
	vessel length 150 ~ 200m									
μ_1	Speed_inside ECA	3234	14.685	0.047	2.648	14.593	14.776	1.00	0.00	0.00
μ_2	Speed_outside ECA	3234	14.432	0.044	2.480	14.347	14.518			
	vessel length 200 ~ 250m									
μ_1	Speed_inside ECA	1178	14.352	0.077	2.649	14.201	14.504	1.00	0.00	0.00
μ_2	Speed_outside ECA	1178	14.024	0.075	2.565	13.878	14.171			
	vessel length 250 + m									
μ_1	Speed_inside ECA	2282	16.167	0.065	3.107	16.039	16.294	0.100	0.200	0.900
μ_2	Speed_outside ECA	2282	16.221	0.062	2.939	16.100	16.341			
	by date									
	post 1 Jan 2015									
μ_1	Speed_inside ECA	3203	14.796	0.049	2.763	14.700	14.892	0.922	0.155	0.078
μ_2	Speed_outside ECA	3203	14.747	0.048	2.741	14.652	14.842			
	2013-2014									
μ_1	Speed_inside ECA	4921	15.034	0.041	2.897	14.953	15.115	1.00	0.00	0.00
μ_2	Speed_outside ECA	4921	14.745	0.040	2.772	14.667	14.822			