GHG Marginal Abatement Cost and Its Impacts on Emissions per Import Value from Containerships in United States

Abstract:

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Recent effort has made it clear that the marine shipping is an important contributor to world emission inventories. Of all cargo vessels that produce those emissions from international shipping, containerships are among the most energy-intensive. I investigate the total CO_2 emissions from containerships that carry exports to United States with a large database of more than 200,000 observations and calculate the CO_2 emissions per dollar import in 2002. I identify more than 1000 routes linking one domestic port and one foreign port with more than ten thousand callings from international containerships in 2002. I aggregate commodities at two-digit Harmonized System (HS) and find that the emissions per kilogram import vary by more than 100% by commodity groups. Analyzing the trade volume by countries, I find countries with highest emission/import rate are not the ones that emitted the most. It implies that if a cap-and-trade system were imposed on international containerships, the export countries and exported commodities would be influenced unequally. I then apply fundamental relationships between speed and energy consumptions of containerships, and compute the emissions reduction effect by slowing the fleet. I find that 10% speed reduction from the designed speed can reduce CO_2 up to 15%. This translates to CO_2 reduction cost between $10 and $50. I also discuss the policy actions on CO_2 reduction and its potential influence on bilateral trade with United States.

INTRODUCTION

Climate change has been one of the most important challenging issues. It has been shown that anthropogenic greenhouse gas (GHG) such as CO_2 is directly linked with climate change. Among all sources of GHG, transportation accounts for 23.4% of CO_2 emissions in 2004 [1]. Although some international regimes such as Kyoto Protocol have been set up to regulate land-based domestic CO_2 emissions (with limited success), ship-based emissions did not attract much attention until recently.

It has been estimated that in 2007 ships emitted 1019 million tons of CO_2, or 3.3% of world CO_2 emissions, among which international shipping accounts for more than 90%, or 843 million tons [2]. Among all types of ships, containerships, which accounts for less than 4% of world tonnage, emitted more than 20% CO_2 in international shipping industry. With more voices urging shipping industry to be included in international CO_2 reduction regime, it is inevitable to cap CO_2 emission in international containership industry in the future.

There are many proposals to incorporate international containerships in a post-Kyoto agreement, but creating and implementing an efficient and equitable CO_2 allocation regime, however, proves controversial. Flag of convenience is so common in the international shipping industry that it becomes complicated to identify the real nationality and then allocate quotas to them. Fundamentally, international shipping is derived from international trade. Data from UNCTAD shows that over 80% trade in weight is intercontinental and therefore carried by marine transportation for long distances. Substantial cost reduction in marine shipping due to containerization, economy of scale, and other technological breakthroughs is one of the most important stimuli to propel international trade growth [3-5]. Therefore, requiring ships to eliminate CO_2 will impose extra cost to ships and may hinder the trade flow. Currently, many papers have focused on CO_2 embedded in international trade [6-8]. Few research projects, however, have investigated the cost increase effect on international containership transport cost albeit international trade flows.

BACKGROUND

Early inventory research of air pollution from ships focused on local and regional pollutants, such as oxides of sulfur (SOx), oxides of nitrogen (NOx) and particulate matter (PM) [9-12]. These inventories were of critical importance in informing policy makers who design mitigation framework to reduce the regional, environmental, and health impacts of such pollutants [13-17]. In the recent decade, policy options have been developed to include ships in emission mitigation commitments, including speed reduction, cap-and-trade [18], and index requirement for new ships [2].

Emission reduction, however, generates cost. CO_2 elimination cost from international ships will ultimately be transformed to final consumers (Corbett, Wang 2008). There have been many discussions on how transport cost influences international trade [19-22]. Most papers have reported 100% increase of transport cost reduces trade by 10% to 20% [23, 24]. It is unavoidable that carbon reduction cost will inflate transport cost and decrease international trade. In such case, shipping emission reduction is not only a policy issue in global maritime industry, but also a topic in international trade negotiation, especially for those countries that depend heavily on export. Yet, literatures calculating cost increase from potential carbon tax and its impact on global trade remain rare.

Slowing speed provides a practical and relatively easy answer to mitigate CO_2, at least in the short run. Reducing CO_2 has been one of reasons CEOs of some major shipping lines declare why they cut their fleet speeds [25]. Because CO_2 emissions are directly related to energy consumption, the relationship between operational speed and fuel consumption suggests that slow speed operations may offer one effective way to control shipping CO_2 emissions [26, 27].

The main focus of this article is to investigate how potential CO_2 reduction cost will influence prices of different commodities from different countries. In section two, I perform a detailed analysis on the emissions from international containerships and commodities from ships that carried international trade between the United States and other parts of the world in 2002. In section three, I calculate price increase on different groups of commodities from various countries. In section four, I calibrate the marginal abatement cost to reduce CO_2 emissions by reducing fleet speeds. Based on the analysis, in section five, I consider the policy applications of this paper.

METHODOLOGY AND DATA

International shipping depends upon combustion of petroleum products for power and marine engines emit several types of pollutants such as SO_x, NO_x, PM, and CO_2. Like other pollutant emission rates, which are a function of the fuel properties and combustion conditions, CO_2 emissions are a function of the carbon content of the fuel, energy density of the fuel, and combustion efficiency with well-understood fuel-carbon ratio. This relationship allows me to estimate CO_2 emissions by adding and converting fuel consumptions from international containerships [28].

The total fuel consumption for a vessel-route (*ij*) pair as follows:

$$FC_{ij} = \left(\frac{kW_{ME,i} \cdot LF_{ME,i}}{\eta_{ME,i}} + \frac{kW_{AE,i} \cdot LF_{AE,i}}{\eta_{AE,i}} \right) \times \left(\frac{d_j}{s_{0i}} \right) \times \left(\frac{1}{EC_{ij}} \right) \quad \text{……………………… (1)}$$

where, FC_{ij} is the fuel consumption for vessel i on route j; $kW_{ME,i}$ and $kW_{AE,i}$ are the power ratings for the main engines (ME) and auxiliary engines (AE) in kilowatts, respectively;

$LF_{ME,i}$ and $LF_{AE,i}$ are the average load factors for the ME and AE rated at the ship design speed (base case), respectively; $\eta_{ME,i}$ and $\eta_{AE,i}$ are the engine efficiency of the ME and AE respectively; d_j is the route distance in nautical miles (nm); s_{oi} is the design speed (base case) for the trip in nautical miles per hour (nm/hr); and EC_{ij} is an energy content factor in kilowatt-hours (kWh) per kilogram (kg) fuel. $FC_{i,j}$ is determined using activity-based methods that consider the ship engine power, load, and operating time, and the number of trips [29]. Using the activity assumption from Wang et al 2007, I assume the SFOC to be 206 g/kwh; the average main engine load factor is 0.8 and the average auxiliary engine factor is 0.5.

Since FC_{ij} consists of main engine and auxiliary engine, we have the Equation 2:

$$Fuel_{i,j,k} = \sum_{i,j} (MEfuel_k \times (\frac{s_1}{s_0})^3 + AEfuel_k) \times \frac{d_{i,j}}{24 \times s_1} \quad \text{.................................... (2)}$$

In Equation 2 $MEfuel_k$ is the daily fuel consumption of the main engine for ship k, and is derived from kW_{MEi} and $LF_{ME,I}$; $AEfuel_k$ is the daily fuel consumption of the auxiliary engine for ship k, and is derived from kW_{AEi} and $LF_{AE,I}$; $d_{i,j}$ is the distance between the origin and the destination; $trip_i$ is the annual trips made by ships for each route in one year; s_1 is the operating speed; s_0 is the design speed.

CO_2 emission can be calculated by calculating the fuel's carbon fraction and a converting carbon to CO_2. The relationship is shown in equation 3.

$$CO_2 = 3.17 \times \sum_{i,j,k} \left\{ \left[MF_k \times \left(\frac{s_{1k}}{s_{0k}} \right)^3 + AF_k \right] \times \frac{d_{ij}}{24 \times s_{1k}} \right\} \quad \text{..(3)}$$

Unique ship information can be found at the US Entrance/Clearance dataset [30]. This dataset contains all international ships arriving at or leaving the U.S. ports. Their engine information comes from Lloyds 2002 registration data [31]. Trade distance, a key variable to determine fuel usage and CO_2 emission, can be obtained from Waterway Network Ship Traffic, Energy and Environment Model (STEEM) [32].

Upon finishing inventory calculation, the emission per import ratio (emission/import) can be calculated for different commodity groups and for different trade partners. Trade weight and value with the United States are first combined and then divided by the CO_2 emissions produced from transporting them. The Import data can be found at Import Dataset which is published by the U.S. Department of Commerce. The trade is classified by countries and by commodity groups. The commodity types are classified using 2 digits Harmonized System Codes (HS2).

One underpinning assumption in the study is that CO_2 emissions from containerships are proportional to trade weight, because in a containership, various commodities are packed in containers in one ship and transported. It is unlikely to distinguish which ships transport which commodity. Therefore, to calculate emission/import ratio, I first calibrate the total CO_2 emissions from international containerships from each country to the U.S; then I extrapolate the ratio by comparing the weight of each commodity type from one country with the total export weight from this country.

RESULTS

Baseline Inventories

Applying the U.S. Entrance/Clearance dataset, I identify near 10,000 international shipping arriving in or leaving U.S. ports in 2002 by containerships. Those ships emitted ~22 million tons CO_2 in 2002. Adjusting annual growth, it is within 5% of the Ocean Policy Research Foundation estimate for 2000 (Ocean Policy Research Foundation, 2008). In 2002, U.S. imported totaled 13.6 billion kg. With CO_2 emissions, that is 0.002 ton CO_2 emission for 1 kg trade. I define ton CO_2 emission per trade as unit emission.

Unit emission by country

There is a large amount of variation in unit emissions among countries. Table 1 and Table 2 show the top ten biggest CO_2 emitters from trade with the U.S, and the top 10 unit emitters. The total amount of emission is mainly influenced by total trade weight and trade distance. It indicates that major emitters in Table 1 were major trade partners with the U.S. Top unit emitters, however, are countries with few trade relationships with the U.S. (Table 2). They are singled out mainly because of small trade weight and old and inefficient ships. Comparing the average unit emissions with top emitters in Table 2 shows emission units are vastly different among countries by more than 100%. It again implies different emission/import ratios for countries.

Table 1 Top Emitters of CO_2

Top Emitters in CO_2 (tons)		Annex B
Japan	1936541	Yes
South Korea	736677	No
China Taiwan	526735	No
China Mainland	522934	No
Mexico	484057	No
Canada	445075	Yes
Venezuela	302723	No
Spain	300096	Yes
United Kingdom	277705	Yes
Hong Kong	262963	No

Table 2 Top Unit Emitters in CO_2

Top Unit Emitters in CO2 (ton CO2/kg Imports)		Annex B
American Samoa	1.05	No
Pacific Islands N.E.C.	0.75	No
St. Helena	0.58	No
Western Sahara	0.31	No
Eritrea	0.26	No
South Pacific Islands	0.18	No
Gambia	0.16	No
Kiribati	0.12	No

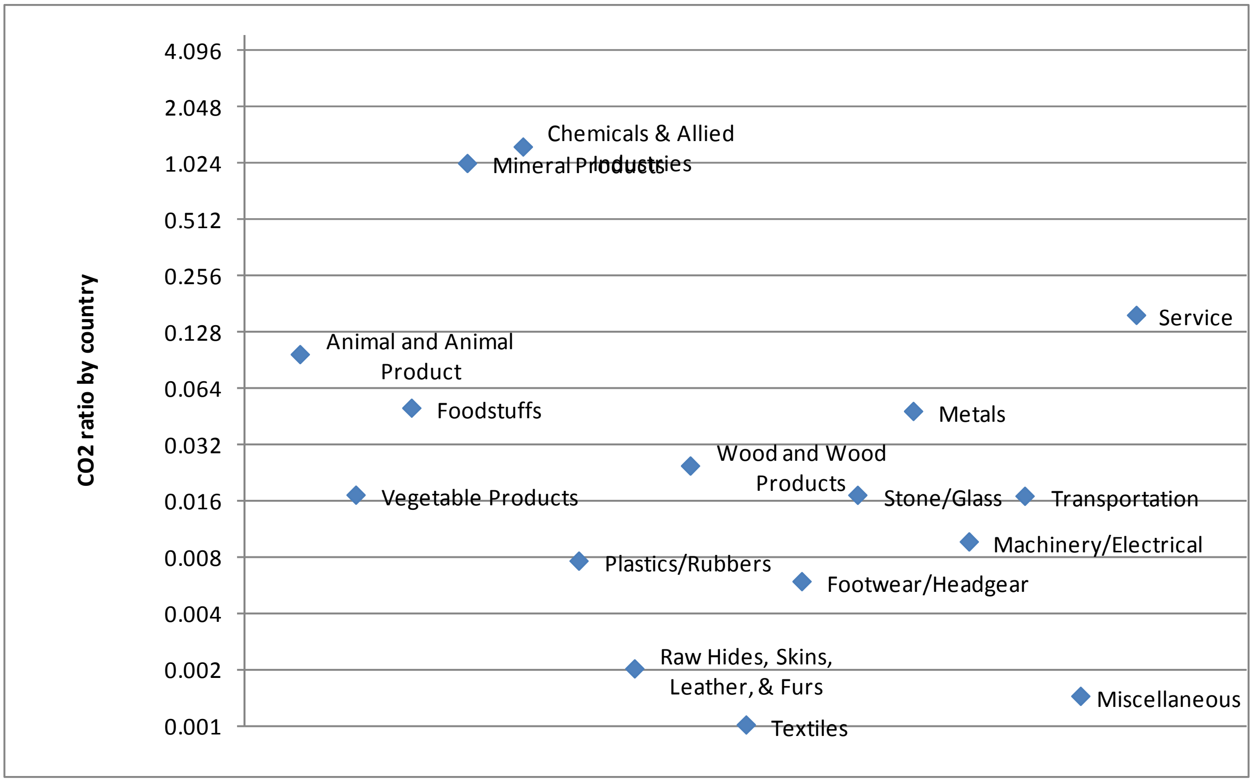
Cuba	0.08	No
Guam	0.04	No
Average	0.01	

Table 1 and Table 2 also show whether countries in the lists are Annex B countries in Kyoto Protocol, which are mandated to reduce CO_2 emissions in a binding agreement. The results show some heavy emitters are Annex B countries. But when it comes to the largest unit emitters, none is Annex B. In other words, it is those countries which would be most affected by a would-be binding CO_2 agreement that are most important to the success of a post-Kyoto commitment in international shipping.

Unit emission by commodity

I then compute the CO_2 emissions in different commodity types. Figure 1 shows 9 types of commodities that represent of 99 types of commodities classified by HS2. They again show a large variation among those commodities.

Figure 1 CO_2/Import ratio by industry



Unit CO_2 emissions embedded in international containerships are highest among heavy goods. The high emission/import rate is consistent with the real business since container can take far less heavy goods than light goods. Therefore, it requires more containers and energy to transport a certain value of heavy goods than light goods.

I then assume that a $50 per ton carbon levy is imposed to trade, and calculate the unit price increase (defined by value/weight). I choose three commodities: food, textile, and steel, representing basic living needs, labor intensive/light goods, and capital intensive/heavy goods. Table 3 reports the ten countries with most increase in unit price and the average price increase weighted by trade weight. Most countries in those tables are non-Annex I and small islands. Those countries are victims of GHG induced global warming, but when actions to mitigate CO_2 are made in the containership sector, those countries again become most vulnerable.

Table 3 Price Increase due to CO_2 levy

HS19: Food		HS72: Steal		HS61: Textile	
Guam	366%	Guadeloupe	2769%	Guam	74%
Pacific Islands N.E.C.	366%	Belize	793%	Dominican Republic	39%
Kiribati	356%	Bahamas	538%	Sao Tome and Principe	3%
Fiji	14%	New Zealand	528%	Kiribati	2%
Georgia	4%	Panama	528%	Ivory Coast	0.9%
Panama	4%	Portugal	493%	Fiji	0.5%
French Guiana	3%	Ukraine	429%	New Zealand	0.4%
Albania	3%	France	407%	Greenland	0.3%
Cayman Isl	2%	Denmark	370%	Namibia	0.3%
Ivory Coast	2%	Korea	355%	Haiti	0.3%
Average	5%		3%		0.5%

Carbon marginal abatement cost by slowing ship speed

Speed reduction has been proven an effective method to mitigate CO_2 (IMO 2008). Equation 3 shows speed reduction can reduce fuel use and therefore CO_2 emissions. Using equation 3, CO_2 reduction effect due to different speed reduction rate can be calculated and listed in Table 4.[1]

Table 4 CO_2 saving by reducing speed

Percent Reduction in Speed	CO_2 saving (mt/yr)	Fuel usage (mt/yr)	CO_2 saving % change
10%	6,520,000	9,210,000	19%
20%	12,290,000	7,390,000	35%
30%	17,340,000	5,800,000	50%
40%	21,640,000	4,440,000	62%
50%	25,180,000	3,330,000	72%

However, speed reduction from optimal speed means less profits and more costs. The optimal speed is defined as the speed which yields maximum profits for a ship. When regulators mandate ships to slow their speeds, they deviate from ships' optimal speeds and produce costs.

[1] The same table was reported in J. J. Corbett, H. Wang and J. J. Winebrake, The Impacts of Speed Reductions on Vessel-Based Emissions from International Shipping, *Transport Research Board,* (Washington DC, 2009).

According to equation 3, however, the fuel usage and thus the CO_2 are reduced. The comparison between the loss of profits and the mitigation of CO_2 yields the CO_2 marginal abatement cost. Cobett et al [28] constructed an optimal speed function, which was primarily determined by fuel cost. The optimal speed can be calculated using the fuel cost and other ships' characteristic. The requirement asking for ships to reduce speed also produce cost since the required cost is less than optimal speed. By optimal speed function and profit function, the marginal cost can be computed.

The optimal speed function is given by:

$$s_1 = \left(\frac{(C_{tot} + P \times AEfuel) \times s_0^3}{2 \times P \times MEfuel}\right)^{1/3} \quad \ldots\ldots(4)$$

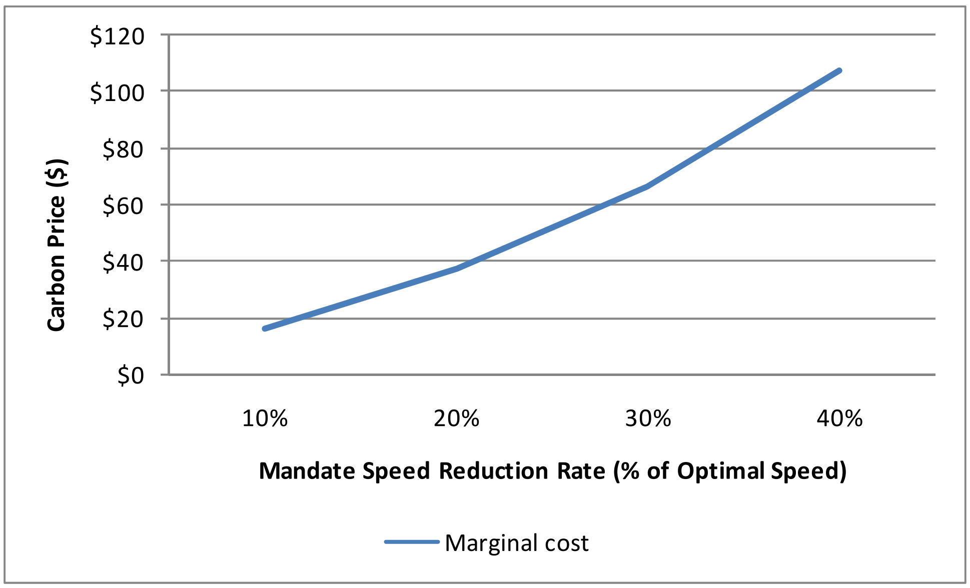
Where s_1 is the optimal speed; C_{tot} is the daily operational cost; P is the fuel cost; *AEfuel* and *MEfule* are fuel consumption of auxiliary engine and main engine respectively; s_0 is the designed speed.

In this part, I use Corbett et al function and choose the $300 per ton fuel price in this study as baseline, and assume all ships to operate at optimal speed, which is determined by equation 4. I then assume IMO mandates speed reduction for all ships. The profit losses can be calculated by adding all ships up. When ships reduce their speeds, the CO_2 emissions are reduced too. The marginal cost curve is reported in Figure 2. As ships continue to cut their speeds, the marginal abatement cost is increasing, showing the marginal benefit of losing profits to reduce emissions is decreasing, a classic marginal diminishing return.

International Maritime Organization (IMO), the international body for maritime industry, proposes a 10% speed reduction to mitigate CO_2 from shipping, the finding in this paper shows CO_2 marginal abatement cost is near $20 per ton under the baseline fuel price. Figure 2 also shows when the baseline fuel cost is $300 per ton and speed reduction is near 25%, the carbon price is near $50 per ton, which is consistent with my arbitrary carbon price levy. However, when baseline fuel price changes, the equation 3 and 4 shows that the carbon price at 25% speed reduction rate will not be the same. Such sensitivity analysis proves that the time choose for speed reduction mandate is of great importance.

Another canvet is that when ships reduce their speed by too much, they are unable to fulfill their business commitment. Therefore, more ships are required to maintain the frequency. That means more ships are added in the lineup, which discounts CO_2 reduction effect. I reserve this effect for future research, but it is more practical to reduce less than 10% speed in order to reduce CO_2 while avoiding more ships.

Figure 2 CO_2 Marginal Abatement Cost



CONCLUSTION

From a policy perspective, international community seems determined to reduce CO_2. This paper shows, CO_2 levy produces emission/import ratio among different countries with large variation by more than 100%. The unit cost increase varies by more than 100% among different commodities too. In other words, the reduction cost produces winners and losers automatically. In such fields as international community, where international cooperation is highly valued, policy makers need to consider compensating countries whose interests are severally influenced. Otherwise it is hard to win their supports, especially when such exports are of crucial importance for those countries' foreign exchange and economic development.

The paper also shows that the commodity types matter too. Heavy goods will be influenced in particular since they take more containers than other goods. Emission levies will severely influence those industries. Such industries in import countries will be "protected" to some degrees. Countries that heavily depend on such industries in export will be harmed and thus opposed to such levies, not only under IMO framework, but also under the World Trade Organization.

The result indicates that speed reduction is one of useful measures to reduce CO_2. Unlike unilateral carbon tax, it allows ships to choose either reducing speed or purchasing credits. It also provides certainty. Given one ship and fuel price, the marginal abatement cost is given. From a policy perspective, 10% speed reduction is both useful in CO_2 reduction and applicable in real shipping business. However, the timing for policy makers to start the mandate speed reduction is important since carbon marginal abatement cost is sensitive to the baseline fuel price.

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