CO_2 EMISSION ANALYSIS FOR CONTAINERSHIPS BASED ON SERVICE ACTIVITIES

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ABSRACT

This paper considers the CO_2 emission estimation problem for containerships. As container shipping services are far more regular and standardized than other shipping sector, we argue that it is more appropriate to estimate its fuel consumption and CO_2 emissions using more detailed service activity data rather than the aggregated activity data that have been adopted in most existing literature. We will formulate the CO_2 emission problem for containerships by taking into account its unique characteristics. A detailed service activity-based method and two aggregated activity-based methods are presented to estimate the CO_2 emission index. A case study shows that the CO_2 emission index by the detailed service activity-based method could be significantly different from those by the aggregated activity-based methods. To obtain a more accurate estimation of CO_2 emission from the aggregated method, it necessary to select an appropriate ship speed in the calculation. The emission statistics for the current world containership fleet is then estimated using the aggregated method, and its sensitivity to ship speed and berth time is examined.

Keywords: CO_2 emission, container shipping, shipping service route, fuel consumption, load factor, empty container.

1. INTRODUCTION

Climate change has been one of the most important challenging issues facing the world today. It has been recognized that greenhouse gas emission (GHG) such as CO_2 are responsible for climate change. Among all sources of GHG, transport accounts for 13.1% of CO_2 equivalent emissions in 2004 (IPCC 2007). Although shipping is regarded as the most-energy efficient mode of transport, the rapid growth of international fleet has resulted in the substantial increase of its contribution to global GHG emissions. Container shipping is the fastest growing sector in the shipping industry. Both container traffic (demand side) and containership fleet (supply side) have maintained around two-digit growth rate in the last two decades. Containerships are by far the most important source of CO_2 emissions in the shipping industry (compared to other sectors such as dry bulk, crude oil, chemical, Ro-Ro), both in absolute and per tonne-km terms (Psaraftis and Kontovas 2009).

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol set binding targets for industrialized countries and the European community for reducing GHG emissions. Due to the difficulty of defining the nation or territory for international shipping and the lack of reliable emission data, shipping has so far not been covered by the Kyoto Protocol (Christodoulou and Giziakis 2009). However, International Maritime Organization (IMO), who is responsible for the shipping sectors, has proposed several projects to estimate the shipping GHG emissions and seek potential measures to reduce emissions.

The first IMO study of GHG emissions from ships used figures for 1996 and was published in the year 2000 (Skjølsvik et al., 2000). It underwent a general update and led to the full report of the Second IMO GHG Study 2009 using the world fleet data for the year 2007 (Buhaug et al., 2009). From these reports and other relevant literature (e.g. Corbett and Kohler 2004; Psaraftis and Kontovas 2009), it can be concluded that there are basically two main approaches that are used to estimate the CO_2 emission in shipping: based on fuel statistics (top-down approach) and based on activity data (bottom-up approach).

The fuel statistics approach uses marine fuel sales data and fuel-related emission factors. The main concern of this method is on the coverage, consistency of reporting and accuracy in various parts of the world, which presents a risk of errors and under-reporting in fuel statistics (Buhaug et al., 2009). The high level of uncertainty (unreliability) in the fuel statistics is the main reason that led to the discrepancy in many published estimates, e.g. Corbett and Fischbeck, 1997; Skjølsvik et al., 2000; Corbett and Köhler, 2003; Eyring et al., 2005; Endresen et al., 2003, 2007.

In the activity-based approach, the fuel consumption is estimated for individual ship categories (e.g. Corbett and Kohler 2004; Buhaug et al. 2009; Psaraftis and Kontovas 2009; Wang et al. 2008; Wang 2009). For example, the procedure in Buhaug et al. (2009) is described as follows: (i) the main engine (ME) and auxiliary engine (AE) fuel consumption of a ship category is estimated by multiplying the number of ships in each category with the average ME and AE power to find the installed power (kW) by category; (ii) the annual power outtake (kW•h) is then estimated by multiplying the installed power with a category-specific estimate of the operating hours of the engines and the average engine load factor; (iii) finally, the fuel consumption is estimated by multiplying the power outtake with the specific fuel oil consumption (SFOC) that is applicable to the engines of the given category (g/kW•h). Psaraftis and Kontovas (2009) adopted a similar procedure but used real fuel consumption data provided by ship operators for most of the fleet instead of using the SFOC factor. Wang et al. (2008) and Wang (2009) determined the ship fuel consumption using activity data including ship engine power, load, operating time, and the number of trips.

It was stated that the activity-based approach consistently predicts values of fuel consumption that are higher than those from the fuel statistics approach. These activity-based estimates share many common inputs and assumptions, and therefore are not fully independent. On the other hand, fuel statistical data may include apparent errors and other inconsistencies that could be expected to cause under-reporting of fuel consumption (Buhaug et al. 2009). It is therefore concluded that the activity-based estimates provide a more correct representation of the total emissions from shipping than what is obtained from fuel statistics. This indicates the importance of using activity data in estimating the fuel consumption and CO_2 emission from shipping. For example, Corbett and Kohler (2004) and Psaraftis and Kontovas (2009) emphasize the importance of using actual data by stating that "the importance of obtaining empirical and valid measures of vessel activity is also a point of agreement. These data are fundamental to understand engine load profiles, operating hours, and resultant fuel consumption."

However, most of the existing studies using the activity-based approach are mainly based on the aggregated activity data for different ship sizes and types. There is a lack of consideration for more detailed service activities involved in the shipping, particularly for container shipping sector, which is far more standardized and regular. This research will formulate and analyze the CO_2 emission problem for containerships by considering its unique features and detailed service activity data.

The rest of the paper is organized as follows: in the next section, the characteristics of container shipping and the key performance index (KPI) of containership CO_2 emission are discussed. In Section 3, the methodology to calculate shipping CO_2 emission KPI is presented. This includes a detailed service activity-based method and two aggregated activity-based methods. In Section 4, the methods are firstly applied to an Asia-Europe shipping route to make a comparison. Then, the CO_2 emission statistics for the world containership fleet are estimated by applying an aggregated activity-based method. The sensitivity analysis is performed to investigate the impacts of ship speed reduction or ship berth time reduction on the CO_2 emission KPI. Finally, conclusions are drawn in Section 5.

2. CHARACTERISTICS OF CONTAINER SHIPPING AND KPI OF CONTAINERSHIP EMISSION

Container shipping has been the fastest growing sector in shipping industry in last two decades. The world container carrying capacity has grown up to 14.7 million TEU (twenty-foot equivalent unit) in 2009 from just 4.7 million TEU in 1999, which implied an average growth rate 12% pa. The carrying capacity of individual full containerships varies significantly from 62 TEUs to 14,000 TEUs (www.ci-online.co.uk). The maximum ship speed ranges from about 10 knots to 27 knots. Some studies (e.g. Psaraftis and Kontovas 2009) have shown that containerships are by far the most important source of CO_2 emissions among all shipping sectors, both in absolute and per tonne-km terms.

The deployment of containership is unique in many aspects compared to other shipping sectors. Usually, a set of containerships with similar sizes of capacity will be deployed in a fixed shipping route to provide a regular service, e.g. a weekly service. Although container shipping companies may adjust their shipping networks from time to time by adding or cancelling service routes, adding or removing ports in the existing shipping routes, and redeploying existing and new ships, the overall structure of the shipping networks is reasonably stable and the regularity of the shipping services is often maintained. For this reason, it is possible that more detailed and reliable data about containership service activities can be collected, which enable us to estimate the CO_2 emission more accurately.

More specifically, the following characteristics of the container shipping can be identified, which could significantly affect the calculation of the CO_2 emission for containerships:

- Containerships are often deployed in a specific service route with regular service frequency. Different service routes may have very different service activities. For example, ships deployed in trans-Pacific routes are often more highly utilised than those in trans-Atlantic routes;
- A service route consists of a number of ports with a fixed sequence of port-of-calls. The load factor differs in legs (here a leg is defined as the journey of two consecutive ports in the route). For example, east-borne legs of a trans-Pacific route have much higher load factors than west-borne legs due to the trade imbalance;
- The ship's sailing speed varies in legs depending on its published schedule, port traffic, and the physical distance of each leg. Therefore, a universal sailing speed used in the aggregated activity approach may over-simplify the calculation of the ship's CO_2 emission as the ship speed is a very important factor in calculating the fuel consumption;
- Usually both laden and empty containers are lifting on/off the ships at each port. The movements of empty containers will affect ship's service activity and utilisation, in particular, the ship's berth times at ports;
- Containerships sail voyage by voyage consecutively. Each voyage includes two directions of journeys, e.g. west-borne and east-borne. The sailing direction and weather condition may affect the vessel speed and fuel consumption.

The above discussion reveals that apart from the ship sizes and types, many other factors should be taken into account in estimating the containership CO_2 emission, e.g. load factor at each leg in the route, port to port laden container movements, port to port empty container movements, container handling rates at ports, castoff and moor times, ship schedule with arrival times, sailing distance in each leg, ship sailing direction and weather condition. The majority of these data are related to detailed service activities. Therefore, there is a need of research on analysing the CO_2 emission of containerships by considering more detailed service activities rather than only the aggregated activities.

In container shipping, the capacity and activities are often measured in terms of TEUs. A natural performance index to measure the CO_2 efficiency of a containership is the CO_2 emission per TEU per kilo-metre (Christodoulou and Giziakis 2009). As the amount of CO_2 emitted from a ship is directly related to the fuel consumption, the CO_2 efficiency index will also provide useful information on a ship's performance with regard to the fuel efficiency. The key performance index (KPI) of CO_2 emission for a containership can be defined as follows:

KPI = gram CO_2 / (laden TEUs * transport distance)

3. METHODOLOGIES TO CALCULATE CO_2 EMISSION KPI

The following notation is introduced in order to formulate the CO_2 emission problem for a containership deployed in a given shipping service route.

N – the total number of port-of-calls in a single round-trip of the service route.
i – an index of port-of-call in a single round-trip of the service route, $i \in \{0,1,2,\ldots,N-1\}$. Here the index 0 refers to the first port-of-call in the whole journey, i.e. the home port.
$p(i)$ – the physical port that the index i refers to.
d_i – the distance in nautical miles from port $p(i)$ to port $p(i+1)$.
y_{ij} – the laden containers in TEUs from port index i to port index j carried by the ship.
x_{ij} – the empty containers in TEUs from port index i to port index j carried by the ship.
t_i^a – the ship arrival time at port $p(i)$ according to the schedule.
s_i – the ship's sailing speed from port $p(i)$ to port $p(i+1)$.
T_i^s – the ship's sailing time from port $p(i)$ to port $p(i+1)$.
T_i^p – the ship's berth time at port $p(i)$.
T – the ship's total journey time in a round-trip, i.e. $T = t_N^a - t_0^a$, where t_N^a represents the arrival time of the ship back to the home port after a round-trip.
R_i – the container handling rate at port $p(i)$ in TEUs per hour.
C – the ship's maximum carrying capacity in TEUs.
S – the ship's maximum sailing speed in nautical miles per hour.
w_i – the ship load factor from port $p(i)$ to port $p(i+1)$, which is the ratio of the number of laden containers on board to the ship capacity.

An example of shipping service routes is shown in Figure 1 (www.ci-online.co.uk), which consists of 11 ports (Busan (BUS), Xiangang (XIN), Dalian (DAL), Qingdao (QIN), Kwangyang (KWY), Shanghai (SHA), Bremerhaven (BRE), Hamburg (HAM), Rotterdam (ROT), Felixstowe (FEL), Tanjung Pelepas (TJP)). The indexes of port-of-calls are coded by {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10}. It should be pointed out that the number of ports in a general service route may be fewer than N because some ports in the service route may be called twice in a round-trip.

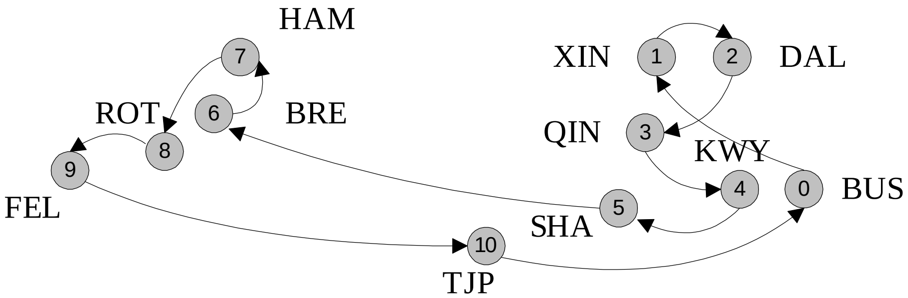

Figure 1. A container shipping service route

The fuel consumption for the ship consists of the bunker fuel consumption of the main engine at sea and the auxiliary fuel consumption at sea and ports. We present two types of methods to compute the fuel consumption, and afterwards to calculate the CO_2 emission. The first is based on detailed service activities along the shipping route. The second is based on the aggregated activities.

3.1 Detailed service activity-based method

As the ship travels along the shipping route, it unloads and loads both laden and empty containers at ports. The movements of empty containers will affect ship's berth time and ship utilisation. Since the load factor differs in legs and the ship's sailing speed varies in legs (which depends on the published schedule and the physical distance of each leg), it is therefore appropriate to compute the fuel consumption and CO_2 emission leg by leg, and port by port.

The total fuel consumption (FC) in a round-trip is the sum of fuel consumption in each leg and at each port, i.e.

$$FC = \sum_i F_m(s_i, C, w_i, T_i^s) + \sum_i F_a(C, T_i^s, T_i^p) \tag{1}$$

Where F_m represents the bunker fuel consumption of the main engine, which is a function of the following parameters: the ship sailing speed, the ship carrying capacity in TEUs, the load factor, the sailing time, and other ship related data (e.g. shaft power factor); F_a represents the fuel consumption of the auxiliary engine, which depends on the ship carrying capacity in TEUs, the sailing time at sea, and the berth time at ports. It should be noted that the fuel consumption in the next leg from port *i* to port *i*+1 is included in (1).

Apart from the ship carrying capacity, all the other parameters in (1) depend on the operational service activities along the shipping route, e.g. the berth time at a port depends on the handling time for both laden and empty containers, and the castoff and moor time; the ship sailing time depends on the departure time at the current port and the scheduled arrival time at the next port; the ship sailing speed is determined by the sailing distance between two port and the sailing time; the load factor depends on the actual number of laden containers on board. More specifically, those parameters can be determined as follows:

$$T_i^p = [\sum_j (y_{ji} + x_{ji}) + \sum_j (y_{ij} + x_{ij})] / R_i + \text{castoffMoorTime} \tag{2}$$
$$T_i^s = t_{i+1}^a - (t_i^a + T_i^p) \tag{3}$$
$$s_i = d_i / T_i^s \tag{4}$$
$$w_i = \left(\sum_{j=i+2}^{i+N} \sum_{k=i+1}^{j-1} y_{jk} \right) / C \tag{5}$$

From the fuel consumption (in tonnes), we can then estimate the CO_2 emission (in tonnes) by multiplying the emission factor (e.g. 3.17) regardless of the type of fuel. The emission factor 3.17 is an empirical mean value commonly used in CO_2 emission calculations based on fuel consumption (e.g. Endresen 2007; Psaraftis and Kontovas 2009; Wang 2009). According to the IMO2000 study (Skjølsvik et al. 2000), the actual value of this coefficient may range from 3.159 to 3.175. In the update of the IMO2000 study (Buhaug et al. 2008), a slightly lower coefficient is used, e.g. 3.082 for Marine Diesel and Marine Gas Oils and 3.021 for Heavy Fuel Oils (Psaraftis and Kontovas 2009). The use of different emission factors will impact on the estimation of the absolute value of the CO_2 emission, but does not affect much on the relative difference between different methods and the sensitivity of the results because it simply scales down or up the volumes with the same proportion.

To calculate the KPI of CO_2 emission, we need to compute the total TEU-km in a round-trip for the ship,

$$\text{TEU-km} = \textstyle\sum_i (C \cdot w_i \cdot d_i \cdot 1.852) \tag{6}$$

Where the constant 1.852 is used to convert nautical miles into kilo-metres. Therefore, the KPI of CO_2 emission (in g/TEU·km) is given by

$$\text{KPI} = 3.17 \cdot FC \cdot 1000000 \,/\, \text{TEU-km} \tag{7}$$

In summary, the detailed service activity-based method can be illustrated in a flow chart in Figure 2.

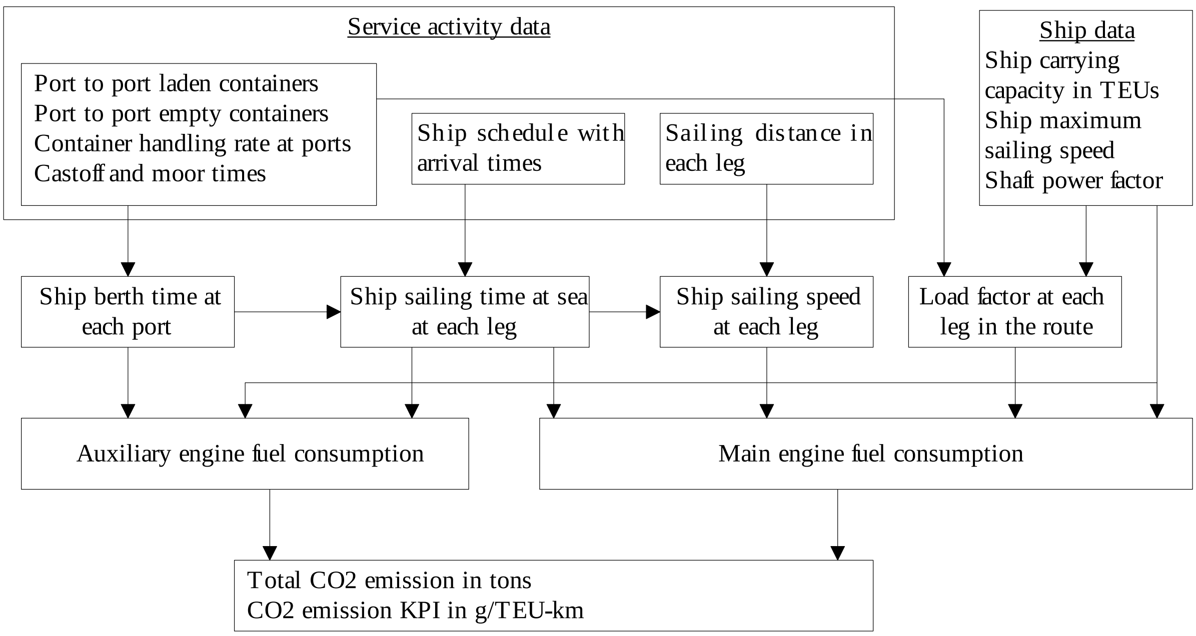

Figure 2. Detailed service activity-based method

3.2 Aggregated activity-based method

Many existing studies in estimating ship fuel consumption are mainly based on the aggregated activity data for different ship sizes and types. For each category of ships, a fixed ship speed and a fixed load factor are used. In many cases, a universal load factor is used for entire journey and even entire category of ships. The main reason for such simplification is the difficulty to collect the detailed service data, in particular the port handling time and the distance that the ship travelled. We present two aggregated methods for containerships, which depend on the availability of the distance information.

Firstly, let us assume that the total distance that the ship travelled is known, but the detailed port loading and unloading activities are unknown. The ship sailing time and ship berth time are derived from the fixed speed and the distance. Together with the attributes of the ship and some aggregated service activities, the fuel consumption and the CO_2 emission KPI may be calculated as follows:

$$FC = F_m(s, C, w, D/s) + F_a(C, D/s, T - D/s) \quad (8)$$
$$\text{KPI} = 3.17 \cdot FC \cdot 1000000 / (C \cdot w \cdot D \cdot 1.852) \quad (9)$$

Where *s* is an estimated fixed sailing speed, *C* is the ship's maximum carrying capacity in TEUs, *w* is the average load factor, *D* is the total distance that the ship travelled, and *T* is the total journey time of the ship including both sailing times and berth times. The method in (8) and (9) is called the aggregated method with speed and distance (AMSD).

Secondly, suppose we do not have information of the physical distance that the ship travelled. In this situation, the fuel consumption may be calculated using the aggregated sailing time at sea and the aggregated berth time at ports that can be obtained from the published schedules,

$$FC = F_m(s, C, w, T^s) + F_a(C, T^s, T^p) \quad (10)$$
$$\text{KPI} = 3.17 \cdot FC \cdot 1000000 / (C \cdot w \cdot s \cdot T^s \cdot 1.852) \quad (11)$$

Where T^s and T^p are the total sailing time at sea and the total berth time at ports respectively. Other parameters are defined as before. In many existing studies, a ship's sailing time and berth time are estimated from empirical data. For container shipping, they may be estimated from the ship schedule, which is reasonable since liner shipping provides regular services. The method in (10) and (11) is called the aggregated method with speed and time (AMST). It should be pointed out that many existing activity-based methods are generally in this line, although the sailing time and berth time may be estimated differently.

However, it is worth noting that both aggregated methods use the fixed ship speed *s*, which is assumed to be the maximum sailing speed or a close value. In reality, this aggregated speed could be quite different from the actual sailing speeds in individual legs of the service route.

4. APPLICATIONS

In this section, we first calculate the KPI of CO_2 emission for a containership in a given service route using the above methods and make a comparison. Secondly, we estimate the

CO_2 emission for the world containership fleet using the aggregated method, and examine its sensitivity to ship speed and berth time.

4.1 CO_2 emission for a containership in a specific service

Consider the Asia-Europe service route (Figure 1). Nine ships are deployed in this route to provide weekly service with the total round-trip time 63 days (i.e. T=63 days). The average ship capacity is 6600 TEUs. The maximum sailing speed S=25 knots per hour. The detailed sailing schedule and port distance (in nautical miles) are given in Table 1 (based on www.ci-online.co.uk).

We take one ship as an example. Assuming the castoff and moor time is 3 hours for each port. A reasonable trade demand scenario is assumed which yields a load factor for laden containers on board 0.8379 for the west-borne journey (from Asia to Europe) and 0.5250 for the east-borne journey (from Europe to Asia). The empty containers are repositioned in an optimal way such that the container flow-in and flow-out for each port are balanced (Song and Dong 2009).

Table 1. Schedule (days) and distance (nautical miles) of the shipping service route

Port	Arrives	Departs	Transit time	Distance
Busan	FRI	SAT	0	639
Xiangang	MON	MON	2	187
Dalian	TUE	TUE	3	238
Qingdao	WED	THU	4	388
Kwangyang	FRI	SAT	6	383
Shanghai	SUN	MON	8	10608
Bremerhaven	MON	TUE	30	117
Hamburg	WED	THU	32	305
Rotterdam	FRI	SAT	34	118
Felixstowe	SAT	MON	36	8212
Tanjung Pelepas	SAT	SUN	57	2504
Busan	FRI	SAT	63	

As the handling rate may vary quite significantly due to the efficiency of equipment, the number of gantry cranes, and the combination of twenty-foot boxes and forty-foot boxes. It is therefore necessary to examine the impact of the different handling rates on the CO_2 emission KPI. Figure 3 shows how the CO_2 emission KPI (g/TEU·km) responds to the change of the handling rate (from 80 TEUs/hour to 200 TEUs/hour) using the detailed activity-based method in (1) ~ (7).

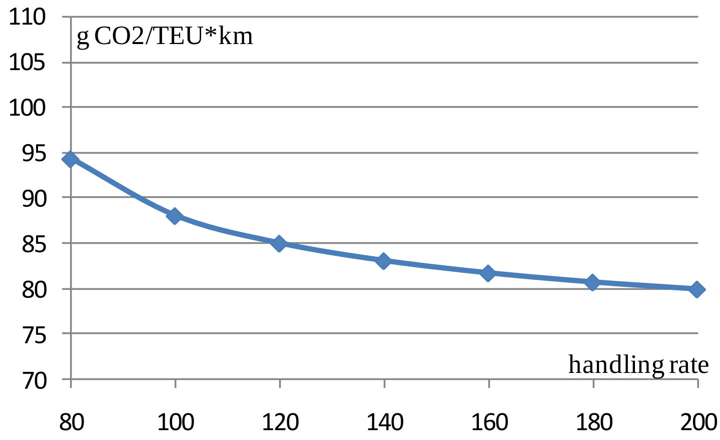

Figure 3. CO_2 emission KPI (g/TEU·km) under different handling rates

In many instances in the current shipping industry, three cranes may be used to serve the ship simultaneously and each may handle about 60 TEUs per hour. This gives rise to an average handling rate 180 TEUs/hour, which yields a CO_2 emission KPI being 80.70g CO_2/TEU·km.

From Figure 3, it is not surprising to see that the CO_2 emission KPI is decreasing as the port handling rate increases. This is due to the fact that higher handling rates lead to the reduction of the ship berth time at ports, and therefore enables to reduce ship sailing speeds at sea and save CO_2 emission. An interesting observation is that the improvement of the emission KPI is also decreasing as the handling rate increases by the same amount, e.g. increasing handling rate from 80 to 100 can reduce the emission KPI much more significantly than that from 180 to 200.

Next we want to investigate the sensitivity of the results to the distance. Assuming that port handling rate takes 180 TEUs/hour, let sailing distances be -30, -20, -10, 0, 10, 20, and 30 nautical miles away from the actual distances in Table 1. Figure 4 shows how the emission KPI responds to the distance changes. The results indicate that the emission KPI is increasing as the distance increases. This may be explained by the fact that although increasing distance would increase the total TEU-km, it also requires faster sailing speed in order to keep the schedule, which has a cubic effect on the fuel consumption. Therefore, overall increasing sailing distance will incur higher emission KPI.

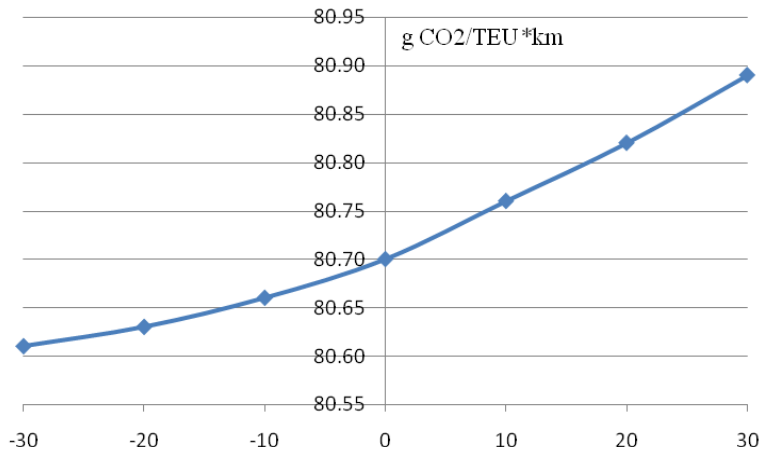

Figure 4. CO_2 emission KPI (g/TEU·km) under different sailing distances

For the aggregated methods, the average load factor is assumed to be 0.70, and a fixed ship speed *s* is used. In (8) and (9), the physical distance *D* is obtained from Table 1. In (10) and (11), the sailing time at sea T^s, and the berth time at port T^p are derived from the schedule in Table 1. The CO_2 emission KPI under the aggregated methods based on distance or time with different fixed speeds (from 0.80*S* to 0.96*S*) is shown in Figure 5.

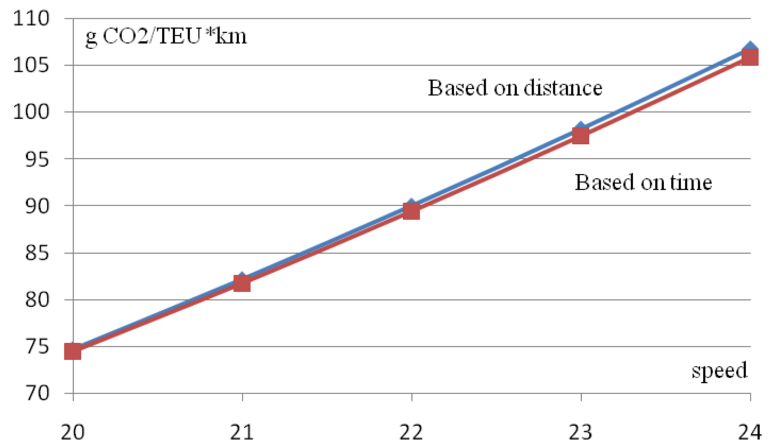

Figure 5. CO_2 emission KPI (g/TEU·km) under the aggregated methods based on distance or time

It can be seen from Figure 5 that the KPIs calculated from both aggregated methods are fairly close. This may be explained by the fact that both aggregated methods assume the same fixed sailing speed. More importantly, the fixed ship speed has a significant impact on the CO_2 KPI. Many existing studies use a fixed speed that is close to the ship maximum speed *S* (=25 knots/h), e.g. 24 knots/h for a containership with capacity 6600 TEUs. This leads to a CO_2 emission KPI, 106g/TEU·km, which is significantly higher than that calculated based on the detailed service activities (around 80g/TEU·km).

Therefore, the aggregated activity methods could well overestimate the CO_2 KPI compared to the detailed service activity-based method. The main reason for such difference is that the aggregated methods always adopt a universal fixed ship speed that is close to the maximum speed, which could well exceed the actual sailing speeds in many legs in the shipping route. Our research reveals that the detailed service activity-based method is preferred in estimating the CO_2 emission in container shipping.

On the other hand, the research findings indicate that it is important to select an appropriate ship speed in the aggregated methods, e.g. if a fixed speed 21 knots/h is selected, the CO_2 emission KPI (82g/TEU·km) would be reasonably close to the one obtained from the detailed service activity-based method. However, the problem may still remain because such speed is not easy to find without having sufficient information of operational activities.

4.2 CO_2 emission statistics for world containership fleet

The world containership fleet data (with capacity and speed) were collected from ci-online (www.ci-online.co.uk) in June 2009. The fleet includes total 4633 full containerships with total carrying capacity 12.5 million TEUs. The fleet is categorized into 7 groups with 2000 TEU as a separating gap. The number of ships, the total capacity in TEUs, percentage of each group out of the total capacity, and the average ship speed in each group, are given in Table 2.

Table 2. World containership fleet

Ship group (by TEU)	No of ships	Capacity (TEU)	Capacity % of total	Average speed
0-2000	2370	2451746	19.60%	16.75
2000-4000	1057	2980738	23.82%	21.32
4000-6000	781	3752791	30.00%	24.19
6000-8000	209	1384747	11.07%	24.84
8000-10k	187	1604960	12.83%	25.01
10k-12k	17	181376	1.45%	25.05
12k-14k	12	154664	1.24%	25.07
Total	4633	12511022	100%	

As it is difficult to collect the detailed service activity data for individual ships in the entire world fleet, the aggregated activity-based method is used to estimate the statistics of the fuel consumption and the CO_2 emission KPI. We start with max speeds as conventionally done and will do sensitivity test later on.

To apply (10) and (11), it is assumed that each ship is sailing at its maximum speed; the load factor is 0.70; the sailing time is 70% of its operational days; the ship berth time at port is 30% of its operational days; and the ship operational days per year is 320 days. The above data are mainly based on Psaraftis and Kontovas (2009). The statistics of annual fuel consumption (in million tons), annual CO_2 emission for each group (in million tons), CO_2 percentage of each group out of the total amount, annual TEU·km (in billions), and the CO_2 KPI (g/TEU·km) are given in Table 3. To have a clearer view, the CO_2 KPI for different containership groups is also shown in Figure 6.

Table 3. Statistics of emission of world containership fleet

Ship group (by TEU)	Fuel, yr (M-ton)	CO_2, yr (M-ton)	CO_2 % of total	TEU·km, yr (billion)	CO_2 KPI
0-2000	14.04	44.51	18.16%	301.25	147.76
2000-4000	18.68	59.20	24.15%	445.52	132.89
4000-6000	25.47	80.74	32.94%	634.07	127.34
6000-8000	8.60	27.28	11.13%	239.71	113.79
8000-10k	8.91	28.26	11.53%	279.73	101.03
10k-12k	0.91	2.88	1.17%	31.67	90.88
12k-14k	0.70	2.23	0.91%	27.02	82.68
Total	77.32	245.11	100%	1958.97	125.12

It can be seen from Table 3 that the total annual CO_2 emission is 245.11 million tons, in which the 4000-6000 TEU group accounts for the largest proportion (32.94%). It is not surprising to see that the groups with larger capacity proportions incur larger amount of CO_2 emission. However, it can also be observed that the groups with larger ships are more efficient in terms of CO_2 emission because their CO_2 emission percentages are lower than their capacity percentages. More clearly, the last column in Table 3 and Figure 6 reveal that the CO_2 emission KPI is steadily decreasing as the ship capacity increases.

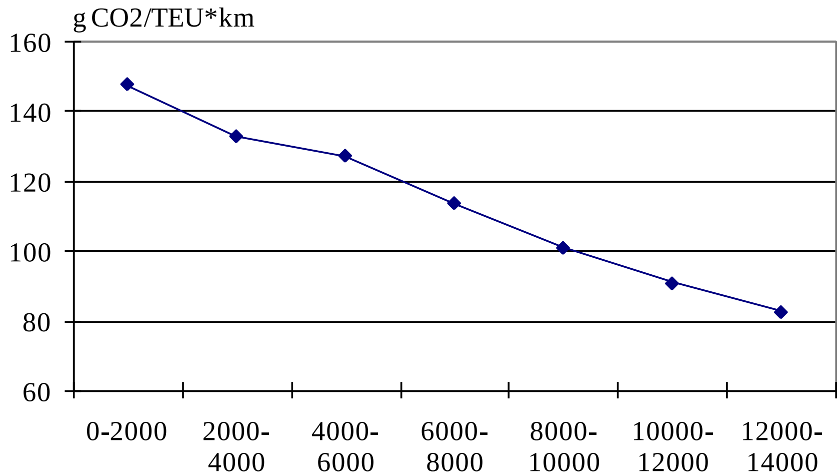

Figure 6. The CO_2 emission KPI for different containership groups

As we mentioned earlier on, the fixed sailing speed and the estimated berth time are two important factors to affect the CO_2 emission in the aggregated activity-based method. We therefore perform sensitivity analysis to investigate their impacts.

Firstly, let the ship sailing speed be reduced but all other parameters remain the same. The statistics for the world fleet is given in Table 4. The first row is the base case which is the same as that in Table 3. For the cases from the second row to the fifth row, the ship speed used in (10) and (11) is reduced by 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 knots per hour respectively. The fourth column gives the percentage of reduced CO_2 emission compared to the base case. The fifth column gives the total TEU·km that varies in ship speed because other parameters remain the same. It can be seen that the speed reduction significantly reduces the CO_2 emission, e.g. when the sailing speed is decreased by 1 knot from the maximum speed, the CO_2 emission can be reduced by 12.33% and the CO_2 KPI is reduced by 10.31 g/TEU·km.

Table 4. Impact of ship speed reduction (knots) on CO_2 emission

Speed reduction	Total fuel, yr (M-ton)	Total CO_2, yr (M-ton)	% CO_2 reduction	Total TEU·km, yr (billion)	CO_2 KPI
0	77.32	245.11	0.00%	1958.97	125.12
0.5	72.45	229.65	6.31%	1915.37	119.90
1.0	67.79	214.90	12.33%	1871.78	114.81
1.5	63.35	200.83	18.07%	1828.18	109.85
2.0	59.13	187.44	23.53%	1784.58	105.03
2.5	55.11	174.70	28.73%	1740.98	100.35
3.0	51.29	162.60	33.66%	1697.39	95.80
3.5	47.67	151.12	38.35%	1653.79	91.38
4.0	44.24	140.25	42.78%	1610.19	87.10

In the above experiments, we assume that the ship speed is reduced but other factors are the same. In reality, the speed reduction cannot be achieved without sacrificing other factors. For example, the number of containerships may be increased in order to maintain the same regularity. This obviously has counterproductive effect on fuel consumption. An alternative to reduce the sailing speed but still keep the schedule on time is to reduce ship berth time at ports, e.g. by using more efficient equipment, more gantry cranes, or better logistics management. In the next set of experiments, we assume that the ship berth time is reduced by 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% from the base case. The CO_2 emission statistics for the world fleet is given in Table 5.

Table 5. Impact of berth time reduction on CO_2 emission

Berth time reduction	Total fuel, yr (M-ton)	Total CO_2, yr (M-ton)	% CO_2 reduction	Total TEU·km, yr (billion)	CO_2 KPI
0%	77.32	245.11	0.00%	1958.97	125.12
5%	74.20	235.21	4.04%	1958.97	120.07
10%	71.26	225.90	7.84%	1958.97	115.32
15%	68.50	217.15	11.41%	1958.97	110.85
20%	65.90	208.90	14.77%	1958.97	106.64
25%	63.44	201.12	17.95%	1958.97	102.67
30%	61.13	193.77	20.95%	1958.97	98.91
35%	58.94	186.83	23.78%	1958.97	95.37
40%	56.86	180.25	26.46%	1958.97	92.01

As the ship berth time decreases, its sailing time is increasing and the sailing speed can then be reduced to keep the same service schedule. In Table 5, it shows that the berth time reduction can also significantly reduce the CO_2 emission, e.g. 10% of berth time reduction can save 7.84% of CO_2 emission and the CO_2 KPI is reduced by 9.80 g/TEU·km. The total

TEU·km in Table 5 is the same for different cases because the travelled distances are the same in those cases because the sailing time increase and the ship speed reduction cancel out each other.

Comparing Table 4 with Table 5, it can be observed that reducing speed and reducing berth time have similar impact on the CO_2 KPI for the given reduction scales, but they have quite different impacts on the absolute CO_2 emission amount. The former can reduce total CO_2 emission more significantly than the latter. This may be explained by the fact that the berth time reduction has less direct impact on the CO_2 emission because it achieves the reduction of speed through increasing sailing time. On the other hand, the speed reduction also reduces the total TEU·km, which offsets some of its impact on the CO_2 KPI.

5. CONCLUSIONS

This paper considers the CO_2 emission in container shipping sector. Taking into account the characteristics of container shipping, a detailed service activity-based method is proposed to estimate the CO_2 emission index of containerships. Two aggregated activity-based methods are also presented. A case study with detailed service data is used to make a comparison. The results show that the aggregated methods could well overestimate the CO_2 KPI compared to the detailed service activity-based method. The main reason for such difference is that the aggregated methods adopt a universal fixed ship speed that is close to the maximum speed, which could well exceed the actual sailing speeds in many legs in the shipping route. Another reason is that the formula to calculating the fuel consumption is nonlinear (e.g. it is a cubic relationship between the fuel consumption and the sailing speed), which may results in the underestimation of fuel consumption for the aggregated methods. The findings reveal that in order to make more accurate estimation of the CO_2 emission, either the detailed service activity-based method should be used, or an appropriate ship speed should be selected for the aggregated methods. The problem remaining for the aggregated methods is that it is not easy to determine an appropriate ship speed without knowing detailed operational information.

From this research, it could be argued that although the top-down approach might underestimate the CO_2 emission, the difference may be not as significant as claimed in the literature since the conventional bottom-up approach could overestimate the CO_2 emission.

For the world containership fleet, ideally we should apply the detailed service activity-based method to estimate total CO_2 emissions and the KPI. Due to the lack of operational data, the aggregated method is used, but we perform the estimation with a range of ship speeds. If the maximum ship speed is used, the world containership fleet will generate 245.11 million tons of CO_2 per year with the KPI 125.12g CO_2/TEU·km. On the other hand, if the speed is reduced by 4 knots from its maximum speed, then the total annual CO_2 emission will be 140.25 million tons with the KPI 87.10g CO_2/TEU·km. Note that simply reducing ship speed may cause delays and therefore disrupt the service schedule, an alternative is to reduce berth time which can effectively reduce the CO_2 emission amount and the CO_2 KPI without affecting the service schedule.

Further research includes the application of the detailed service activity-based method to the world containership fleet. However, the main challenge is to collect all the relevant operational data. Setting up an international database including detailed operational data from the entire industry sector could overcome current shortcomings. This may require the enforcement of new international policies under the name of IMO or UN. Alternatively, how to appropriately adjust the aggregated methods and improve its accuracy would also be interesting. Although this study is limited within the container sector, other shipping sectors may also have similar uncertainties in CO_2 emission estimation. It is therefore necessary to re-assess the CO_2 emissions for other shipping sectors by taking into account their unique characteristics.

ACKNOWLEDGEMENTS

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/E000398/1].

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