Well-to-tank carbon emissions from crude oil maritime transportation

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A B S T R A C T

International seaborne transport of crude oil takes place mainly on tankers, with annual seaborne crude flows totaling an estimated 12 billion barrels. To take into account the carbon footprint on crude oil from its international distribution segment, we utilize a micro-level dataset of more than 28,000 individual shipment samples to estimate each journey's carbon emissions. The unique detailed dataset enables us to aggregate carbon emissions at the country level for importers and exporters, by trade lane, and by vessel size categories. Our methodology provides a framework for crude oil consumers to dynamically account for the carbon footprint of the commodity which is transported via different trade routes and by different vessels (size and age). So far, this dynamic emissions accounting has been largely neglected by oil consumers who typically apply one single emission factor regardless its supply chain. Our results highlight the importance for importers to consider the origin and point-of-use of crude oil in order to have a comprehensive view of its carbon footprint. The quantitative analysis in this study can feed into well-to-tank fuel emissions factors for oil and oil products in order to adopt dynamic emissions factors in companies' carbon accounting. Finally, our research is important for the design of new environmental policies for the corporate Environmental Social Governance (ESG) reporting to include downstream logistics in the overall emission accounting of oil companies.

1. Introduction

The oil and gas sector is responsible for significant greenhouse gas (GHG) emissions. Emissions arise from both the extraction, processing, transportation, and distribution of fuel (often referred to as the well-to-tank phase of the fuel life cycle) as well as the eventual combustion of the fuel in various applications like energy, heat, and transportation (the tank-to-wheel phase) (El-Houjeiri et al. 2013; Greene and Lewis, 2019). Together, these stages form the well-to-wheel fuel life cycle. While tank-to-wheel emissions are the primary climate impact from the oil and gas, the other elements of the fuel life cycle are important to account for and monitor (Rahman et al., 2015; Di Lullo et al., 2016). This paper focuses on the carbon dioxide (CO_2) emissions from one of the most important elements of the well-to-tank stage: international maritime transport of crude oil. The primary mode of transport for intercontinental oil movement is by oil tanker, largely powered by marine diesel and heavy fuel oil (Jia, 2018).

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The maritime sector is an important element of the low carbon transition strategy and has been identified by the Energy Transitions Commission (ETC) as one of the most difficult sectors to decarbonize (ETC, 2018). The International Transport Forum (ITF) estimated that maritime transport made up 3% of global emissions and 27% of freight transport emissions in 2015, amounting to roughly 873 million tonnes of CO_2 per year (ITF, 2019). Oil tankers make up 13% of maritime emissions, or approximately 114 million tonnes of CO_2 (Olmer et al., 2017).

The International Council on Clean Transportation found that between 2013 and 2015, oil tankers as a class became more efficient mainly due to the continuous improvement of technical standards (Olmer et al., 2017). Speed reduction has a high potential to increase fuel efficiency (Corbett et al., 2009; Faber et al., 2012), but only if charterparty contractual terms allow (Jia et al. 2017), or if mandatory slow steaming measures are put in place (Rehmatulla and Smith, 2015). While reduction in carbon emissions has become a focus for the shipping industry and its many customers, the sustainability efforts in oil transport have focused on safety issues – namely avoiding oil spills (Poulsen et al., 2016; Smith et al., 2015).

The importance of well-to-tank emissions is becoming more prominent with the growing adoption of alternative fuels like biodiesel or hydrogen (Bouman, et al., 2017; Di Lullo et al., 2016; Ozawa, et al., 2017; Winebrake, et al., 2007), where emissions often lie primarily in the well-to-tank phase. Companies that are seeking to understand the true impacts of their activities and align with mandates from carbon accounting and the Science-Based Targets initiatives must include values for well-to-tank emissions (Greene and Lewis, 2019; SBT, 2018). Companies do this by using standard emissions factors to convert fuel use into greenhouse gas emissions (Greene and Lewis, 2019). Typically provided by government bodies or academic studies, emissions factors are generally presented as a static value for the well-to tank and tank-to-wheel emissions, or combined as well-to-wheel emissions, for diesel, gasoline, and other fuels (Edwards et al., 2014; DEFRA, 2019; and EPA, 2014). These factors are rarely provided based on the fuel's origin or place of use. In order to better understand variations within the carbon emissions from oil, this paper provides new insights on the well-to-tank phase of the oil life cycle by providing an in-depth analysis of emissions from the maritime transportation of oil.

The remainder of the paper is structured as follows. Relevant literature review is presented in Section 2. Data and methodology are illustrated in Section 3, which is followed with results and discussions in Section 4. Section 5 concludes the paper.

2. Literature review

The international maritime sector has been under scrutiny due to the fact that the large international ocean-going vessels, which, until very recently (1 January 2020), have been mainly fueled by marine diesel oil and residual heavy fuel oil. The overarching government body in the shipping industry, International Maritime Organization (IMO) has implemented a series of regulations and operational practice guidance to reduce emissions from the industry. For instance, the most recent IMO 2020 low sulphur cap regulation that aims to tackle sulphur oxide emissions from ocean going vessels either through burning lower sulphur marine gas oil or equipping the vessels with abatement facilities. CO_2 emission reduction is achievable through improvements in operational practices such as slow-steaming (Psaraftis and Kontovas, 2013); vessel designs (see, Motley et al., 2012; Doulgeris et al., 2012); or the use of alternative fuels (Bengtsson et al. 2011; Balcombe et al. 2019) - with zero emissions as the ultimate goal. Cariou et al. (2019) also show that liner shipping companies can achieve CO_2 emission reduction through network design by reducing vessel-cargo travel distances. Energy Efficiency Design Index (EEDI) was introduced by IMO in 2011 and its aim is to set the minimum technical standards for vessels built in and after 2013 for compliance in energy efficiency, ultimately emission reduction (Devanney, 2011). However, improvements in the environmental performance are mainly driven by power relationships in the market (see, for instance, Jeppesen and Hansen, 2004; Ivarsson and Alvstam, 2010; De Marchi et al., 2012; Goger, 2013). Maritime transportation is a derived demand from international trades. Cargo owners, for instance, the oil companies, are the other important side of the play. In fact, emphasis should be given to the whole crude oil supply chain to consider the power dynamics in this system.

Previous work on crude oil life cycles have provided insights on the variable emissions along certain oil value chains. For example, El-Houjeiri et al. (2013) found that emissions from crude oil production can range from 3 to 30 g CO_2/MJ depending on processing techniques and rates of gas flaring at a particular well field. The California Air Resources Board (CARB) assessed the well-to-refinery emissions of crude oil processed by California refineries, observing differences ranging from $2 - 48$ g CO_2/MJ depending on the oil field of origin (CARB, 2019). In a study of China's oil supply, Masnadi et al. (2018) found that the well-to-refinery emissions varied by oil field, with values ranging from 1.5 and 47 g CO_2e/MJ. These studies showcase the variability within oil production processes, but, while they include oil transportation, they do not specify the share of these emissions related to the transportation of crude oil. Further, these studies do not use efficiency data for specific oil tankers, rather relying on industry average data for oil tankers.

The accuracy of well-to-tank emissions for all fuels can be improved by providing emissions factors based on the oil's origin and ultimate destination, as well as the specific equipment used to carry it. This research attempts to fill this gap by investigating the potential for refining the transportation component of well-to-tank values based on a unique dataset of oil shipments. Through this analysis, this paper aims to build on the work of Clean Cargo, a group that offers trade lane emissions values for container ships, by providing a similar set of information for oil trade lanes that can be used in carbon foot printing initiatives (Clean Cargo, 2019). This research also echoes the efforts from the member states in the IMO to reduce carbon emission by 50% by 2050 (IMO, 2018), but emphasize the awareness from a wider community.

3. Data and methodology

3.1. Data and data processing

The basis for this study was a unique raw dataset of 70,000 oil shipments that took place between 2013 and 2016, which are provided by Clipper Data Ltd. and primarily derived from the Automatic Identification System (AIS) for vessel tracking and port agents for cargo information. Note that the most recent IMO 2020 regulation to switch the industry from burning high sulphur fuel oil (HSFO) to low sulphur fuel oil (LSFO) does not improve on CO_2 emissions. In fact, there have been suggestions that very LSFO (VLSFO) has even worse impact on black carbon emissions (Lloyds List, 2020). The vessel identification (name and IMO number) is then matched with Clarksons Fleet Registry database to get the vessel specifications, including the Energy Efficiency Design Index (EEDI). This dataset included information on the shipment origin and destination, shipment size, buyers and sellers of the cargo, and vessel information. In order to analyze the emissions from the shipments, the analysis of the data set involved various efforts to filter and categorize the data using Python, R, and Tableau, which are summarized below.

In order to ensure the accuracy of results, the raw dataset was cleaned by excluding duplicates, incomplete, or non-sensical shipments. For instance, a number of shipments that had a duration of more than 50 days or less than two days were removed. Shipments that had the same load and offtake country, as well as those with a travel distance of less than 100 km, were removed in order to keep the focus on international maritime journeys. Finally, shipments on the same vessel with multiple discharge ports along the same trade lane were identified and aggregated, so that the voyages with the largest cargo volume are kept.

The EEDI standard, which was a regulation adopted by the IMO in 2011, is to set minimum technical energy efficiency requirements for vessels built after 2013 (IMO, 2012). For older vessels that were built before 2013, commercial company RightShip back-calculated EEDI to the whole existing world fleet. The resulting Existing Vessel Design Index (EVDI) is a means to evaluate the carbon intensity (grams of CO_2 per tonne-nautical mile) of individual vessels based on a ship's design, manufacturer specifications, data from shipyards, industry publications, etc.

Though we recognize that the actual emissions will vary depending on operating conditions, e.g., speed and weather conditions, we chose the "design" index assuming vessels were operated at design levels (i.e. design speed and fair weather conditions) to provide a generalized picture of carbon footprint for crude oil seaborne transportation. Interested researchers can adjust the results based on specific information, for instance, average vessel speed by trade lane per time period.

3.2. Define trade lanes

Once the duplicative, conflicting, misrepresentative shipments, as well as domestic shipments (i.e. the same country for port calls in consecutive voyages) were removed, and the vessels were matched with their EVDI score, where available, the number of shipments reduced from 73,313 to 28,043. The shipments were organized into common trade lanes based on the most important flows between origin and destination regions, as shown in Table 1. In general, the trade lanes were categorized as major international trade lanes, intraregional lanes, and a catch-all category of other international, which includes all other low volume trade lanes not represented elsewhere. Shipments along these trade lanes include direct port to port shipments as well as ships that make multiple stops to

Table 1
Trade lane descriptions.

Trade Lane	Code	Description of Origin	Description of Destination
Arabian Gulf to East Asia	AG-EA	Basrah, Iraq, Al Ju Aymah and Ras Tarura, Saudi Arabia, and other ports in the Arabian Gulf	Ningbo and Qindao, China, Onsan and Yeosu, South Korea, Chiba and Kiire, Japan, and other ports in East Asia
Arabian Gulf to Europe	AG-EUR	Basrah, Iraq, Al Ju Aymah and Ras Tarura, Saudi Arabia, and other ports in the Arabian Gulf	Lavera, France, Europoort and Rotterdam, Netherlands, and other ports in Europe
Arabian Gulf to North America	AG-NA	Basrah, Iraq, Al Ju Aymah and Ras Tarura, Saudi Arabia, and other ports in the Arabian Gulf	Houston, Port Arthur, St. Rose, and other ports in North America
Arabian Gulf to Southeast Asia	AG-SEA	Basrah, Iraq, Al Ju Aymah and Ras Tarura, Saudi Arabia, and other ports in the Arabian Gulf	Sikka Jamnagar, India, Singapore, and other ports in Southeast Asia
Eurasia to East Asia	RUS-EA	Novorossiysk and Primorsk, Russia, and other ports in Eurasia	Ningbo and Qindao, China, Onsan and Yeosu, South Korea, Chiba and Kiire, Japan, and other ports in East Asia
Eurasia to Europe	RUS-EUR	Novorossiysk and Primorsk, Russia, and other ports in Eurasia	Lavera, France, Europoort and Rotterdam, Netherlands, and other ports in Europe
Latin America to North America	LA-NA	Puerto la Cruz, Venezuela and other ports in Latin America	Houston, Port Arthur, St. Rose, and other ports in North America
Latin America to Southeast Asia	LA-SEA	Puerto la Cruz, Venezuela and other ports in Latin America	Sikka Jamnagar, India, Singapore, and other ports in Southeast Asia
North Africa to Europe	NAF-EUR	Sidi Kerir, Egype, Arzew Bethioua, Algeria, and other ports in North Africa	Lavera, France, Europoort and Rotterdam, Netherlands, and other ports in Europe
West Africa to Europe	WAF-EUR	Ports in Angola, Nigeria, and other countries of West Africa	Lavera, France, Europoort and Rotterdam, Netherlands, and other ports in Europe
West Africa to Southeast Asia	WAF-SEA	Ports in Angola, Nigeria, and other countries of West Africa	Sikka Jamnagar, India, Singapore, and other ports in Southeast Asia
Intraregional	INT	Maritime trade lanes that operate within the Arabian Gulf, Latin America, or other regions.	
Other international	OI	Small volume trade lanes not included within those described above.	

Table 2
Average characteristics of various trade lanes.

Trade Lane	Avg. Distance (km)	Avg. Duration (days)	Avg Load Factor (%)	Avg. EVDI	Avg. sailing speed	Avg. design speed	Avg. DWT ('000 T)	Avg. YOB	g CO2 /t-nm	g CO2e / tkm	g CO2e / liter
Arab Gulf-East Asia	6023	26	65	2.620	9.90	15.71	294	2007	3.0889	1.668	15.997
Arab Gulf-Europe	5126	23	77	3.266	9.20	15.31	187	2006	3.9024	2.107	16.873
Arab Gulf-North America	9660	43	57	2.755	9.30	15.54	263	2008	3.3125	1.789	27.584
Arab Gulf-South East Asia	2244	11	66	3.222	8.40	15.19	204	2003	3.8183	2.062	7.089
Russia-East Asia	1276	7	87	4.077	7.30	15.10	109	2006	4.8255	2.606	5.078
Russia-Europe	1750	10	83	4.069	7.90	15.15	117	2007	4.8260	2.606	7.281
Latin America-North America	1623	10	62	4.147	7.60	14.99	103	2006	5.3269	2.876	7.259
Latin America-South East Asia	8950	40	82	2.745	9.40	15.73	277	2006	3.5419	1.912	27.119
North Africa-Europe	1287	7	77	3.805	8.10	15.11	125	2005	4.4887	2.424	4.843
West Africa-Europe	4141	17	76	3.371	10.20	15.26	152	2007	4.0596	2.192	14.430
West Africa-South East As.	7272	30	64	2.938	10.00	15.39	232	2007	3.4876	1.883	21.675
Intraregional	1046	6	74	4.146	7.70	14.93	116	2005	5.0191	2.710	4.766
Other International	3675	17	75	3.622	8.80	15.12	147	2006	4.3602	2.354	13.149
Overall Average	**4159**	**19**	**73**	**3.445**	**8.75**	**14.59**	**179**	**2006**	**4.4030**	**2.377**	**10.099**

discharge along the trade lane.

3.3. Carbon emission density

EVDI measures the CO_2 emissions per tonne-mile for vessel i (Psarros, 2017; Jia, 2018):

$$EVDI_i = \frac{\sum P_i * C_F * SFC}{DWT_i * speed_i} \quad (1)$$

where, P_i is the energy consumption level of main and auxiliary engines (kW) for vessel i;
C_F denote conversion factor between fuel consumption and CO_2 emission;
SFC denote certified Specific Fuel Consumption (g/kWh).

Total CO_2 emissions for voyage j by vessel i is calculated as the total amount (tonnes) of CO_2 emitted during the voyage:

$$CE_{i,j} = S_{i,j} \cdot EVDI_i \cdot D_j \quad (2)$$

where, $CE_{i,j}$ is the total CO_2 emission for vessel i during voyage j;
$S_{i,j}$ is the cargo size on board vessel i during voyage j (tonnes);
D_j is the distance for voyage j (km).

To align with the scope 3 method in the GLEC Framework (Greene and Lewis, 2019) which applies to the whole supply chain, nautical miles in ocean distance are converted to kilometers. The resulting value from Eq. (2) is then scaled from CO_2 to CO_2e using the 2% conversion factors recommended by the GLEC Framework.

4. Results and discussion

4.1. Oil maritime transport emissions by trade lanes

Table 2 summarizes the characteristics of the shipments along each trade lane. The average distance oil was transported in this study was 4160 km. The trade lanes of Arabian Gulf to East Asia, Latin America to South East Asia, and West Africa to South East Asia have the highest average distance; it will be shown later on that this has an important effect on emissions. Dead Weight Tonnage (DWT) represents the measure of the capacity and size of a vessel. The average for oil tankers in this study was 179,000 DWT, falling into the category of Very Large Crude Carrier on the Average Freight Rate Assessment (AFRA) scale. It is noticeable that, in general terms, larger vessels are utilized for long distance shipments, whereas vessels with less DWT are more frequent in intraregional or short-distance trade lanes. For example, Latin America to North America operated the smallest ships, and Arabian Gulf to East Asia, the largest.

The average load factor of the ships, the ratio of shipment volume to ship capacity, represents the efficiency at which a ship is operating; higher load factors indicate more efficient shipments. The load factor varied by trade lane; the Arabian Gulf to North America trade lane had the lowest average load factor of 57% and Russia to East Asia the highest, at 87%. The average across all trade lanes, 73%, was similar to the average 70% load factor identified by Clean Cargo (2018) for container ships.

The average emissions intensity for oil transport along each trade lane is provided in several formats. Firstly, for each trade lane, we show the average EVDI of oil tankers, representing the efficiency of the fleets operating along that trade lane. Lower is more efficient, higher is less. EVDI value ranges from 2.6 for Arabian Gulf to East Asia, to 4.15 for Latin America to North America. We would like to point out that these values correspond only to the design efficiency of the ships; the actual operational performance, such as ship speed, is not considered in these results.

When the emissions are allocated to the shipment weight and distance, calculated based on the tonne-kilometers traveled by each shipment during the study period, the results are presented by CO2e/tonne-nm and CO2e/tonne-km (to be comparative to other transportation mode). The relative ranking across the trade lanes by CO2e/t-nm (CO2e/t-km) did not change materially comparing to EVDI measures. Namely, the average carbon intensity of the shipments, in CO2e/tonne-km along each trade lane, was lowest for Arabian Gulf to East Asia and highest for Latin America to North America. These values are useful for buyers of oil to estimate the carbon emissions of the maritime transportation of their oil purchases, such as for CDP reporting or product carbon footprint.

The remaining value, CO2e/liter, is related not to the GHG emitted to power the ship, but rather to the oil that was transported within the vessels as cargo. These values could be considered part of a product carbon footprint for crude oil. Here again we see wide variability based on the trade lane that doesn't necessarily correspond to the EVDI or oil tanker carbon intensity. In fact, a negative correlation was observed between CO2e/liter and EVDI; however, the correlation coefficient is very low (-0.203), which indicates that the EVDI of a vessel does not have a strong effect on emissions per barrel of oil transported. A weak correlation exists as well between these variables and load factor, which implies that the degree of utilization of the vessel's capacity does not have a big influence on total emissions either. On the other hand, a very strong correlation exists between these variables and distance (correlation coefficient $= 0.93$), showing that CO2e/liter is linearly related to distance, with $R^2 = 0.948$. This suggests that minimizing distance is a key level to

decreasing crude oil maritime transportation emissions.

4.2. Oil tanker emissions compared with well-to-wheel emissions

Companies tracking their GHG emissions use fuel emissions factors (g CO_2e/liter) to convert the amount of fuel burned to CO_2e. For most companies, a single emissions factor is adopted that represents the average emissions for an entire class of fuel, regardless of its supply chain. While it is impossible to know the percent of each fuel emissions factor that can be attributed to maritime transportation, we can still make several observations about a variance in well-to-tank emissions based on the origin and destination of fuel.

As Fig. 1 shows, emissions per liter of fuel were considerably lower for short trips, like from Latin America to North America, or from Russia to East Asia. Conversely, longer trips, like from the Arabian Gulf to North America, had higher emissions. Also high were emissions for oil shipped from Northern and Western Africa to Europe, likely due to the higher EVDI of oil tankers running on these lanes (see Fig. 2).

Comparing oil tanker emissions to GLEC well-to-tank fuel emissions factor (250 g CO2e/liter heavy fuel oil), our results indicate that the proportion of these factors that maritime emissions would comprise varies by the trade lane. Considering the case of heavy fuel oil, the least refined type of oil, shown in Fig. 3, if crude oil traveled from the Arabian Gulf to North America, maritime transport would make up 11% of well-to-tank emissions; whereas if the oil was transported from the Arabian Gulf to Southeast Asia, this number drops to 3%. Depending on the type of fuel, and its value chain, it's possible that companies could be over- or under-estimating their well-to-tank emissions by using generic industry average values.

5. Conclusion

Properly accounting for carbon emissions is becoming increasingly important to companies, governments, and international governing bodies as part of efforts to keep global temperatures below 2 degree celsius from pre-industrial times. These efforts need participation from various stakeholders to join force to achieve environmental improvements (see, for instance, Schleifer 2013; Hale and Roger, 2014; Abbott et al. 2015; Graham and Thompson, 2015; Raza, 2020). Consequently, companies in many industries are increasingly calculating, disclosing, and seeking to reduce carbon emissions along their value chains, including the production and distribution of the fuels they consume. This is reflected by the growing trend for the inclusion of well-to-tank emissions in carbon accounting standards and climate goal-setting.

In this study, we demonstrated the difference in oil tanker efficiency along key trade lanes based on micro-level oil seaborne shipment data. We also demonstrated how this affects the carbon footprint of the oil cargo being transported by these oil tankers, adding new dimensions to the work done by El-Houjeiri et al. (2013) and Masnadi et al. (2018) who consider oil life cycles using global industry average emissions intensity values for oil tankers.

The results show that the main driver of emissions is distance, despite optimized loads and more energy efficient oil tankers. This suggests that efforts to reduce these emissions should be first directed towards increasing local shipments, rather than improving EVDI or loading factors. New maritime routes may lead to a reduction in oil transport emissions by decreasing the distance shipments need to travel subject to naval and commercial feasibilities (ITF, 2019). Most significantly, the Kra Canal across the Malayan peninsula would shorten the Arabian Gulf to East Asia trade lane by 1,200 km. The Nicaraguan Canal and newly ice-free Arctic shipping routes may also

Fig. 1. Visualization of trade lanes Note: the width of the lines represents the approximate volume of oil that flows along the trade lane.
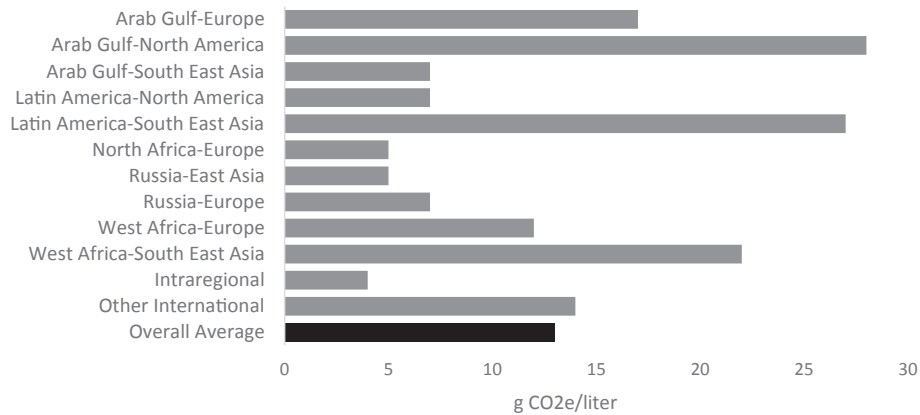
Fig. 2. The black segment represents the crude oil maritime transport's carbon footprint as a proportion the well-to-tank emission for heavy fuel oil according to the GLEC Framework 2019 fuel emissions factors.
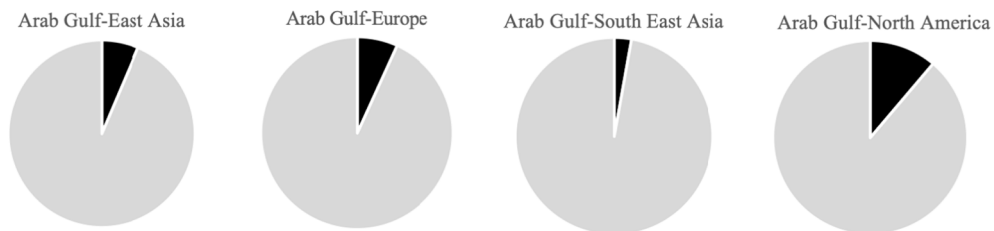

Fig. 3. The maritime transport carbon emissions per liter of crude oil shipped along various trade lanes.

have that same effect.

There is potential to use this study's CO_2e/liter emissions factors for oil maritime transportation to refine estimates for the well-to-tank emissions on a trade lane basis to more closely fit the emissions from oil consumed by companies. This work would contribute to a growing need to understand well-to-tank emissions, as alternative transportation fuels with emissions primarily lying in the well-to-tank phase begin to be used more widely. In additional, the CO_2e/tonne-km values build on the work of Clean Cargo, which offers trade lane factors for container shipping, by creating a similar trade lane dataset for oil tankers. There is also potential to leverage this information to inform fuel sourcing decisions by governments or companies based on the results, or as a factual basis for influencing oil transporters to reduce the emissions of their ships. Further work could be done to characterize the other transportation emissions that are also part of well-to-tank emissions, such as trucking, pipelines, or other shipping activities that invariably occur as the crude oil is further processed and distributed.

As companies and governments look towards their net zero and Paris Agreement goals, it's clear that the inclusion of transportation in the fuel life cycle based on the origin and destination is an important consideration that can help to refine emissions estimates and inform procurement strategies.

CRediT authorship contribution statement

Suzanne Greene: Conceptualization, Methodology, Writing - review & editing. **Haiying Jia:** Conceptualization, Methodology, Writing - review & editing, Funding acquisition. **Gabriela Rubio-Domingo:** Data curation, Software, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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