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Zoomed-Out Corridor-Level Shipping Emissions, Zoomed-In Ship-Level Causes, and Everything in Between

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Abstract: PIANC Task Group 234 concludes that the “path to decarbonization of inland waterway transport is different for different corridors and in different countries”. This calls for an approach that can consider large-scale differences as well as local influences when evaluating the emissions of inland vessels. This paper demonstrates the use of a so-called “event table” that allows corridor scale estimations of inland shipping emissions, while retaining the ability to identify the most important source mechanisms that produce these emissions. We considered three corridors in the Netherlands: Antwerp-Rotterdam, Antwerp-Duisburg and Rotterdam-Duisburg. Using the event table and four “pivoting perspectives”, we quantify large-scale emission patterns and investigate underlying mechanisms for these three corridors. Our study shows that despite their close vicinity, different mechanisms are responsible for observed emission peaks on these corridors. On the Antwerp-Rotterdam corridor, the most important contributions to emissions are slowly sailing vessels near the two locks that are on this route. It is furthermore shown that deeper fairway sections contribute to significantly lower emissions locally. On the Rotterdam-Duisburg corridor, we show that river currents significantly influence the emissions of vessels per travelled distance unit. The Antwerp-Duisburg corridor contains a combination of these factors.

Keywords: decarbonisation, inland waterway transport, emissions, event table

Introduction

In response to international agreements like the Green Deal, many initiatives have been started to investigate the required steps to reduce emissions. Specifically for inland shipping, two task groups (TGs) have been initiated by PIANC; TG 234 and TG 229.

PIANC Task Group (TG) 234 [1] had the objective to identify knowledge gaps and major challenges in achieving net-zero emissions for the operation of port and navigation infrastructure. A list of questions was formulated that are encountered by a waterway manager targeting to decarbonize the network. These questions evolve from the transportation demand and the state of the system (being both infrastructure and fleet), to the associated energy consumption and the alternative solutions to provide that energy. As such, they serve as a starting point for a structured approach to accomplish decarbonization of the network. The TG concludes that the “path to decarbonization of inland waterway transport (IWT) is different for different corridors and countries”. This calls for an approach that can consider local influences when evaluating a large area, consisting, for example, of multiple fairways or even corridors. Furthermore, actions for decarbonization are initiated both bottom-up, by vessel owners and bunker station operators, and top-down, by policy-makers. Consequently, an in-depth understanding of a network’s performance, both on a zoomed-in and a zoomed-out level, is required.

According to the TG, understanding the current performance of the IWT is needed, to identify effective solutions for decarbonization of the network. This study addresses two questions of the TG related to this, considering the state of the system and the associated energy consumption. Our objective is to provide insight into how the different characteristics of the corridors, both in terms of physical properties, as well as the type of activities that take place on them, influence the produced inland shipping emissions. Moreover, we answer to the desire to be flexible towards the evaluated scale, ranging from corridor level to the level of a single ship.

TG 229 [2] had the objective to develop guidelines for identifying sustainable performance indicators, indicating the environmental performance of individual ships and their subsequent contribution to the inland waterways system as a whole. In their report, the state-of-the art for environmental labels and indexes was given, including the OpenTNSim-Energy approach developed by TU Delft **Error! Reference source not found.**. The benefit of this approach was the fact that its output is dependent on the considered local conditions, “which qualifies well for specific stretch related assessments of CO2-production” [2]. For a conceptual study on bunkering infrastructure, Jiang [4] applied this approach to four abstract cases in a simulated environment. The current study implements the energy approach to real-world Automatic Identification System (AIS) data, including thousands of vessels, using realistic waterway properties, at a corridor scale.

Materials

For the analysis, our most important data source is the Automatic Identification System (AIS). The data set used for this study was anonymised and provided by Rijkswaterstaat. It covered 3 months in 2019 (January, April and July). To overcome some unknowns related to the anonymised data, we combine this data source with information captured by the classification by the Conférence Europeénne des Ministres de Transports (CEMT) [5], whereby an estimate of the CEMT class was made based on the known vessel dimensions. Based on this categorisation, we assumed the installed engine power of the vessels. The CEMT classification was also used to assume a water depth on the fairway segments in our network. We also used data from the Dutch Fairway Information System (FIS), which was translated into a representation of the inland waterway network by means of a graph by [6]. Finally, we made use of an algorithm referred to as the energy module, that estimates the propulsion energy of vessels based on their speed, their main characteristics (dimensions, shape, loading condition), and the environmental conditions (water depth, current speed) [3][7].

Method

To combine all these (big) data sources into an integrated overview of the shipping emissions in the system, a structured approach is proposed. The central concept is the creation of a so-called “event table”, in which the described data sources are combined, while keeping the required level of detail to investigate causes at a local scale. To define the requirements for the event table, we consider four “pivoting perspectives”: scales, relations, behaviour, and dependencies. Thereby, we create awareness of which data should be kept available, at what level, upfront of the actual data analysis. In this section, we first define the concept of the “event table”, and subsequently, we describe the “pivoting perspectives” and how they are used to construct and evaluate the event table.

The definition of an event table and how to generate it for evaluation of inland shipping emissions, is described by [8]. The event table is inspired by two concepts: on the one hand, by process mining [9], where events are defined to assess how processes work, and on the other hand, by the concept of moving features [10], where keeping track of space of features is key. In an event table, each row represents one event, defined by a “case” and an “activity”. For the application to inland shipping emissions, a case is defined as a single vessel trip with a clear origin and destination. Hence, one vessel can execute multiple trips (cases), and changes in the vessel’s loading condition are reflected by a different case. An activity is defined as sailing or staying at a particular fairway section, which is represented by an edge in the FIS graph.

Table 1 Simplified example of an event table

Event	Case	Activity		Attributes		
		Edge	**Task**	**A1**	**A2**	**A3**
1	VA-T1	AB	sailing			
2	VA-T1	BC	sailing			
3	VA-T1	CD	sailing			
4	VA-T1	CD	pausing			
5	VA-T2	CD	sailing			
6	VA-T2	CB	sailing			
7	VA-T2	BA	sailing			
8	VA-T2	AZ	sailing			
9	VB-T1	KL	sailing			
10	VB-T1	LM	sailing			
11	VB-T1	LM	pausing			
12	VB-T1	LM	sailing			
13	VB-T1	MN	sailing			
14	VB-T1	NO	sailing			
15	VB-T1	NO	pausing			

Practically, this means that all events in the table with the same activity ID, represent all vessel trips that crossed the fairway section with that ID.

Hence, all events belonging to one case, represent the fairway segments that a vessel has crossed during one trip. Based on AIS data, the cases are constructed by determining the start and end points of each vessel, and subsequently categorising all samples into vessel trips. The activities are constructed by determining the nearest edge in the FIS graph for each sample. AIS samples with the same unique combination of case and activity, belong to the same event. In the event table, the case and the activity are specified in dedicated columns. The position coordinates of the samples that are part of each event are also stored in a table column, and similarly there are columns for the characteristics of the vessel, or its loading condition, and characteristics of the fairway section, like the water depth. These columns are referred to as ‘attribute’ columns, and they provide additional information about each event. A simplified example of an event table is given in Table 1. With this table as a basis, additional analyses can be performed, resulting in additional attribute columns in the table, like, in this study, all kinds of attributes related to the energy consumption and emissions for each event in the table.

The “pivoting perspectives” were introduced by Van der Werff et al. [7] and can be used to specify the requirements for the event table design, given an analysis goal for the performance of a system:

- *the scales perspective* – for analyses that aim to provide insight into the ‘where’ and ‘when’ of the quantified performance. By filtering the information based on space or time-related criteria and subsequently aggregating this information, one can essentially ‘zoom in’ on areas with good or bad performance or create an overview of performance changes through time or space;

- *the relations perspective* – for analyses that aim to identify what the (external) variables are that mostly affect the performance. By connecting system performance to underlying mechanisms and analysing the variations, potential causes for (under)performance can be uncovered;
- *the behaviour perspective* – for analyses that aim to link observed behaviour of individual vessels, to how the system as a whole performs. To understand a ship's behaviour, we need to examine its sequence of activities: how do the activities follow one another, and how much time do these activities take; and
- *the dependencies perspective* – for analyses that aim to uncover causal relationships, critical paths, and knock-on effect sensitivities within the entire system. While the behaviour perspective looks at the actions of individual agents, the dependencies perspective evaluates how activities of multiple agents depend on each other. By examining the sequence of events across all agents in the system, we can identify knock-on effects caused by interruptions, bottlenecks, or incidents in the system.

Following these pivoting perspectives, the requirements for the event table can be defined.

Viewing from the scales perspective, the zooming levels that we want to achieve, dictate the level of detail to be captured in the events. Potentially, the smallest detail could be a single interval between two AIS samples, however, that does not provide the possibility to aggregate. Therefore, an activity has been defined as one crossing of an edge in the FIS graph. Likewise, the furthest we want to zoom in on the case-side, is to distinguish between vessels and their varying loading conditions.

Viewing from the relations perspective, the quantified performance and the influencing parameters that we want to investigate, dictate which attributes need to be stored in the columns of the event table. For the current study, the most important parameters, therefore, are the emissions of each event. These are estimated using the energy module, for each event in the table, based on the exact path that a vessel has sailed during the event. The energy module [3]**Error! Reference source not found.** estimates a vessel's resistance through the water based on its main dimensions, draught and shape, and its instantaneous speed **Error! Reference source not found.**. Subsequently, the required power at the propeller until the engine is determined, using predefined transfer losses.

Emission factors related to the given power and the installed power are finally used to calculate the emissions. Furthermore, we want to be able to tie this quantified performance to underlying factors. Therefore, we store numerous intermediate outcomes and input parameters for each event. Examples are the vessel's dimensions, the engine age, which influences the emission factors, the overall speed of the vessel and the current, the mean power during the event, and the water depth at that location. As we did not have the current speeds on the rivers directly, we derived them based on the vessel speeds on the fairway segments. The speeds over ground in the event table were grouped by activity (hence, fairway segment) and time window of 12 hours. In tidal areas, a time window of 2 hours was used, and multiple fairway segments were considered jointly to have sufficient data. The 67-percentile values of these grouped speeds were used to derive the difference between vessels travelling in either direction, resulting in an estimate for the current speed.

From the behaviour perspective, our goal is to investigate sequences of events executed by vessels. This requires the event table to contain information on how events are connected to their predecessors and successors. This can be achieved by, apart from specifying the case each event belongs to, adding a time indication to each event, or by numbering the successive events within one case. When fulfilling this requirement, the behaviour perspective offers the possibility to investigate the sequence of actions of a vessel, for example, to see where it slowed down or sped up, or to compare multiple trips to find deviations from regular paths.

When viewing from the final perspective, dependencies, the ability to understand how certain events directly influence each other, puts a requirement on the event table of knowing the trigger, or initiation, of each event. In practice, this requirement is hardly possible to meet when only using observations. This knowledge can potentially be obtained from simulations, where it is easier to log how certain events were initiated. In the current study, this perspective is therefore not considered.

The four pivoting perspectives are to be considered in the prescribed order, thereby taking into account that their associated requirements for the event table are cumulative.

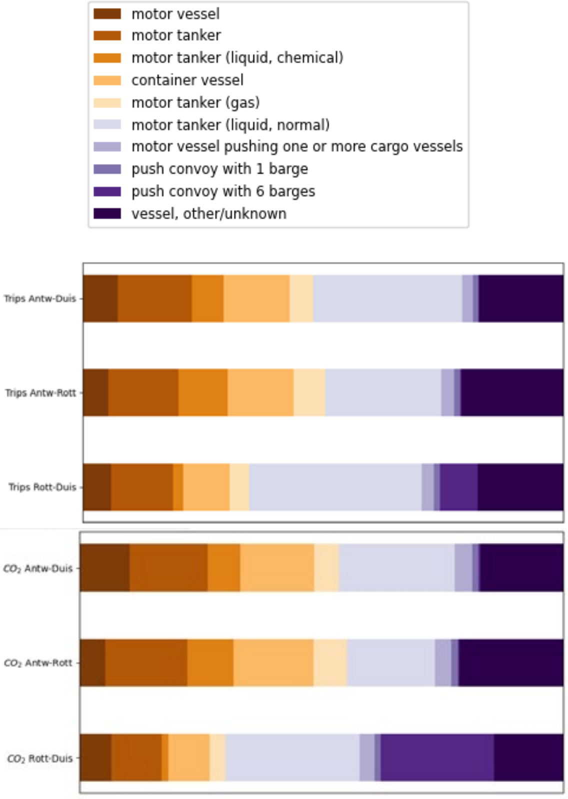

Figure 1 Vessel type distribution of executed trips for the corridors (top) and their contributions to the total CO_2 emissions on the corridor (bottom)

Scope

To increase the understanding of the different measures that are required on different corridors to reduce emissions, as stated by [1], we focused on three corridors in this study, being those between Antwerp and Rotterdam, between Antwerp and Duisburg and between Rotterdam and Duisburg, whereby we only evaluated vessel trips that have sailed the entire route between the respective ports. Note that our AIS data only covered the Dutch network, therefore, we only considered vessels sailing up to the German border near Lobith. Filtering vessel trips having origins and destination in accordance with the above-mentioned corridors, resulted in 1552 vessel trips on the Antwerp-Duisburg corridor, 2258 trips on the Antwerp-Rotterdam corridor and 4111 trips on the Rotterdam-Duisburg corridor.

Results

Based on the set scope, the created event table for the three corridors consisted of 664,504 events, that were defined by 7921 unique cases and 290 unique activities. Table 2 presents a high-level overview of the performance of the three corridors, whereby the CO_2 emissions are the mean emitted mass per sailed kilometre. It shows that the mean emissions are highest for the Rotterdam-Duisburg corridor.

Table 2 Overall comparison between corridors

Corridor	Trips (nr)	CO_2 (mean kg/km)	Distance (mean km)	Speed (mean km/hr)
Antw-Duis	1552	51.7	201.9	13.8
Antw-Rott	2258	46.3	97.7	13.1
Rott-Duis	4111	62.9	153.4	14.3

Furthermore, the table shows the mean distance the vessels covered, which depends on the exact starting and end point, and the mean speed over the entire trip, of all vessels sailing that route. The top bar diagram in Figure 1 shows the distribution of vessel types over the total number of executed trips. Only the most common types are shown explicitly, others are added to the last category (“vessel, other/unknown”). On all corridors, trips are made predominantly by motor vessels. Push convoys are nearly absent on the corridors from Antwerp, and are only seen on the Rotterdam-Duisburg corridor.

Again, following the pivoting perspectives, we will further explore the results and seek for influencing factors in the remainder of this section.

From the scales perspective, we explore the overall patterns. Figure 2 presents a map indicating the distribution of the quantified performance in space. It can be seen that the most of the high-concentrations of CO_2 emissions are in the West, on the corridor between Antwerp and Rotterdam. All of them coincide with the location of a lock. Furthermore, there is a stretch on this corridor that has relatively low emissions per sailed kilometre. The fairway sections on this stretch have been classified as deeper water. Water depth significantly influences a vessel’s the resistance, especially when the underkeel clearance becomes very small. In the Rotterdam area, there are multiple fairway sections having high emissions, as well as in the Eastern area, towards the German border. This is in agreement with the Rotterdam-Duisburg corridor having the highest mean emissions per vessel trip.

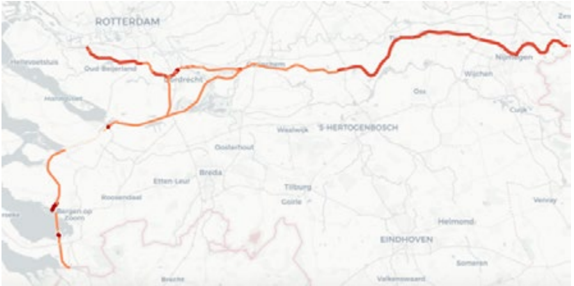

Figure 2 Overview map indicating large-scale patterns and hotspots of CO_2 emissions

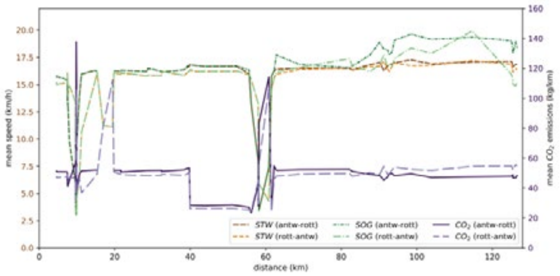

Figure 3 Vessel behaviour of all vessels travelling the Antwerp-Rotterdam corridor, with the speed through water in orange, the speed over ground in green and the produced emissions per km in purple.

From the relations perspective, we can investigate the contributions of the most common vessel types to the total produced emissions on the corridor. The bottom bar diagram in Figure 1 shows the composition of the estimated total emissions for the three corridors. The emissions are mostly proportional to the number of trips executed by the considered vessel type. Motor tankers seem to relatively contribute less to the total emissions on all three corridors. Furthermore, from the Rotterdam-Duisburg corridor, it seems that push convoys with 6 barges contribute much to the total produced emissions relatively to the number of trips executed with this vessel type, which can be tied to the large dimensions of these convoys.

From the behaviour perspective, we can further investigate how the behaviour of the vessel influences its performance, albeit under changing local environmental conditions. Figure 3 and Figure 4 present the behaviour of all vessels sailing between Antwerp and Rotterdam (or vice versa) and between Rotterdam and Duisburg (or vice versa), respectively. Using the concept of the event table, the behaviour of all vessels at the same point in space, e.g. the same fairway segment, could be evaluated. We have distinguished between the two sailing directions, but for direct comparison, the round trip was presented reversed, using the same horizontal axis. On the Antwerp-Rotterdam corridor, the emissions, presented in purple, are quite steady over the entire trip, and very similar for both directions (back and forth). This aligns with steady vessel speeds, again, without large differences between the travel directions, which is also supported by the fact that the speed over ground is very similar to the speed through water, indicating a negligible effect of currents. The only spikes in the emission patterns coincide with a fierce drop in the vessel speeds, and given the location of these phenomena, we can relate this to the passing of a lock. First, around the 10 km mark, vessels have to cross the Kreekrak locks, and next, around the 60 km mark, vessel have to cross the Volkerak locks.

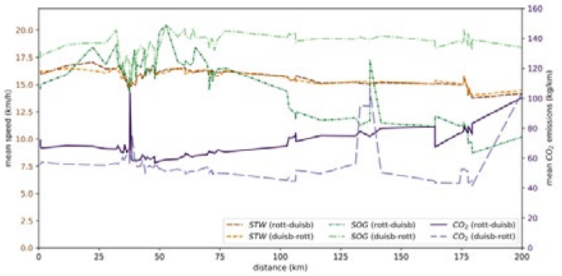

Figure 4 Vessel behaviour of all vessels travelling the Rotterdam-Duisburg corridor, with the speed through water in orange, the speed over ground in green and the produced emissions per km in purple.

Compared with Figure 3, Figure 4 shows much more variations over the route for both the vessel speed through the water and the produced emissions. Especially in the right-hand part of Figure 4, a significant difference is observed between the AIS-based speeds over ground of the vessels travelling upstream (Rotterdam to Duisburg), of about 12 km/hr, and the vessels travelling downstream, of about 19 km/hr. When taking into account the effect of the river currents, the speed through the water is very similar for both directions. Still, the emissions per kilometre are higher for vessels travelling upstream. This is caused by the longer travel duration these vessels have to cover the same amount of distance, thereby producing the same amount of emissions per time unit, but a higher amount of emissions per distance unit.

Conclusion and discussion

The comparison between inland vessel emissions on different corridors shows that it is important to consider the characteristics of the infrastructure, as well as the fleet and the environmental conditions at the water, when designing emission-reduction measures. Different corridors have different challenges, as can be concluded from the presented study. This affects both the implementation of regulations, as well as the planning of new bunker infrastructure, for example. Following the methodology in this study allows incorporation of local effects in the evaluation of what is considered the performance indicator, the produced emissions by the inland vessels. Practically, following this approach helps minimizing the number of iterations needed to process the data, which, given the very large amount of data involved, can reduce the computational time drastically, even when having large computational power at your disposal.

Using the created event table, we can generate results at a zoomed-out level resulting in maps that indicate traffic intensities or emission levels in space, including hotspots and fleet composition in terms of types or sizes. Additionally, detailed results can be extracted from the table, indicating typical behaviour of ships in a particular area or fairway section, like their speed or the influence that local water depth has on the required propulsion energy. When linking these scales, the most important causes of emissions can be investigated, showing what part of the emissions is either caused by fast or slow sailing vessels or how much influence local effects, like water depth or currents, have on the produced shipping emissions. These insights form an important step on the path towards decarbonization of the IWT as outlined by the PIANC TG 234 [1], as they contribute to closing the knowledge gap on the current state of the system and the associated energy consumption, while being transparent about the mutual relations between them, at a local and a global level.

References

[1] Van Koningsveld et al., 2023, PIANC InCom TG 234, Infrastructure of the Decarbonisation of Inland Waterway Transport

[2] Visser et al., 2024, PIANC InCom TG 229, Guidelines for Air and Carbon Emissions Performance Indicators for Inland Waterways

[3] Jiang, M., Segers, L., van der Werff, S., Baart, F., van Koningsveld, M., 2022. Opentnsim. Software. URL: https://zenodo.org/record/6390276, doi:10.5281/ZENODO.6390276.

[4] Jiang, M., Baart, F., Visser, K., Hekkenberg, R., Van Koningsveld, M., 2023. Corridor Scale Planning of Bunker Infrastructure for Zero-Emission Energy Sources in Inland Waterway Transport. In: Proceedings of PIANC Smart Rivers 2022. PIANC 2022. Lecture Notes in Civil Engineering, vol 264. Springer, Singapore.

[5] Conférence Européenne des Ministres des Transports, 1992. Resolution no. 92/2 on new classification of inland waterways

[6] de Jong, J., Baart, F., Zagonjolli, M., 2021. Topological network of the dutch fairway information system. Zenodo. doi:10.5281/ZENODO.4578289.

[7] Segers, L., 2021. Mapping inland shipping emissions in time and space for the benefit of emission policy development. Master's thesis. Delft University of Technology. Van Koningsveld et al., 2021

[8] Van der Werff, S.E., Baart, F., van Koningsveld, M., 2024, Effective policy design requires linking system-scale emissions to detailed vessel behaviour, in prep.

[9] van der Aalst, W., 2012. Process mining. ACM Transactions on Management Information Systems 3, pages 1–17. doi:10.1145/2229156.2229157.

[10] Asahara, A., Hayashi, H., Ishimaru, N., Shibasaki, R., Kanasugi, H., 2015. International standard "OGC moving features" to address "4Vs" on locational BigData, in: 2015 IEEE International Conference on Big Data (Big Data), IEEE. pp. 1958–1966.

[11] Holtrop, J., Mennen, G., 1978. A statistical power prediction method. International shipbuilding progress 25, 253-256