Optimizing tugboat emissions within port areas using data fusion

Mujal Colilles, A.[1]; Vigo, M.[2]; Borén, C.[3] Pla, N[2]; Nyiazi, L[3]; Ribet, J[3]; Martinez de Osés, X[3]; Castells-Sanabra, M.[3]

1. Serra Húnter Fellow. Department of Nautical Sciences and Engineering. UPC-BarcelonaTech. Barcelona, Catalunya
2. Department of Computer Sciences. UPC-BarcelonaTech. Barcelona, Catalunya
3. Department of Nautical Sciences and Engineering. UPC-BarcelonaTech. Barcelona, Catalunya

Abstract— **Maritime transport is essential for global trade but remains a major source of greenhouse gas and air pollutant emissions, especially near ports and coastal communities. Tugboats, which play a crucial role in vessel manoeuvres, are significant contributors but their emissions are poorly quantified due to the inadequacy of conventional estimation methods. This study develops a multidisciplinary approach to quantify and optimize tug-related emissions by integrating on-board field campaigns, interviews with tug crews, Automatic Identification System (AIS) data, and full-mission bridge simulation. Initial results from Spanish ports reveal that tugboats operate inefficiently, with more than half of their time spent below 25% engine load and extended waiting periods contributing to unnecessary fuel consumption. Logistic regression applied to AIS and observer data achieved 91% accuracy in identifying manoeuvre phases, while modified power–speed models outperformed the traditional cubic method for estimating engine power. These findings confirm that tug operations are oversized relative to their actual power needs, leading to avoidable emissions. The proposed methodology enables more accurate emission inventories and offers a framework for real-time monitoring and manoeuvre optimization, providing port authorities and policymakers with actionable strategies to mitigate local air pollution and improve sustainability in maritime operations.**

Keywords—green house gas emissions, emission control, tugboats, coastal communities

1 INTRODUCTION

Maritime transport is the pillar of economic growth as 80% of worldwide freight is carried by vessels (UNCTAD 2022). However, it is a substantial source of greenhouse gas emissions (GHG) causing a noticeable impact on air, water and biodiversity and, generating a social alarm particularly in coastal communities. Greenhouse gas emissions from shipping increased worldwide by 9.6% from 2012 to 2018, amounting to some 1076 million tonnes, accounting for 2.9% of global GHG emissions (International Maritime Organization, 2020). In global terms, the quantified SOx, NOx and PM2.5 emitted from shipping sector was 24%, 24% and 9% of worldwide emissions, respectively (European Maritime Safety Agency, 2021). A growth in global seaborne trade is forecasted in the near future because of the world's growing population, which will translate into an increase in air pollution from maritime transport (International Maritime Organization, 2020). In parallel, the growth on maritime transport and the pollutants emitted has created a social alarm on coastal communities that has to be addressed. Major concerns are related to the consequences of emissions on human health affecting respiratory system among others (Sofiev et al., 2018; Viana et al., 2014). As a consequence of the actual and predicted paradigm, the International Maritime Organization (IMO) has developed and adopted over the years more stringent regulations aimed at dramatically abating emissions from vessels (Raza, 2020). These air pollution regulations focus on the reduction of CO2, NOx, SOx and PM, since these are the main emissions from marine engines (International Maritime Organization, 2021). Focusing on shipping emissions, the list of parameters to take into consideration when theoretically assessing their environmental impact is boundless. The COP27, held in Egypt in November 2022, highlighted that the Mediterranean Sea is the second area more vulnerable to climate change, provoked by the GHG emissions, being the Arctic the first. Since nearly 70% of ship emissions are emitted from within 400 km of coast with intensive ship traffic and in-harbour activities, where emissions from harbour operations add further to the air pollution generated by ships imposing a potential threat to the local ecosystem and residents' health. Exhaust from large marine diesel engines contributes significantly to the anthropogenic burden, thereby affecting the chemical composition of the atmosphere, global climate, and air quality in coastal areas (Capaldo et al., 1999; Duce et al., 2008). Pollution emitted from ports comes from merchant ships constantly docking and undocking but also from other auxiliary port vessels working continuously throughout the year, like pilotage vessels, bunkering barges, vessel-generated waste collection services, mooring and unmooring services and port tugs.

There are extensive and multi-perspective ways to assess ship emissions based on methodologies that either combine fuel sales data with emissions (top-down methods) or are based on vessels' technical and operating conditions (bottom-up methods) (Castells-Sanabra et al., 2020). Bottom-up approaches are widely used because they are ship-specific. (J. P. Jalkanen et al., 2012; J.-P. Jalkanen et al., 2009) suggest a methodology for the evaluation of the exhaust emissions of marine traffic using the Automatic Identification System (AIS). The emissions are computed based on the relationship of the instantaneous speed to the design speed, and using the detailed technical information of the engines installed on-board. The estimation of fuel consumption (FC) is commonly based on the cubic speed–power relation as a bottom-up approach (Kristensen Hans Otto, 2017). The need to emission-control policies and regulations at ports is widely acknowledged as an active policy issued by maritime port authorities. It is also considered an answer of international and European regulations and depends on an accurate estimation of emission inventory in close-to-land and in-port (Yu et al., 2021). Port tugboats frequently sail between terminals (free sailing) and provide docking, undocking and removing merchant ships services. Port tugboats have powerful engines but they are not prepared for speeding and in most ports, between 40% and 70% of all free sailing is done at speeds where the fuel consumption is higher, often for no reason. (Murcia González, 2021) also reports that only 3.5% of the total time operation, tugs are required to give maximum power, and at only 0.5% of total manoeuvring time, the main engines have a maximum continuous rate of 81%, confirming that not as much propulsion power is needed during the manoeuvres of a tugboat, and smaller ones could be used. The traditional propeller-law-based method is not applicable to estimate the emissions during pushing and pulling operations, even during free sailing phases in tug speeds due to the characteristic engines these vessels are designed with (Chen et al., 2021). Very few researchers have considered port tugs emissions during pushing and pulling operations, while these two services may consume a large amount of energy (Chen et al., 2021; Jaramillo et al., 2025; Lee et al., 2021; Paulauskas & Paulauskas, 2011; Xie, G, 2014). (Xie, G, 2014) summarized the tug engine load during berthing and unberthing services, which provides empirical rules for emissions of port tugboats, but have not been systematically evaluated yet and therefore are not generally applicable. The empirical rules are based on the experiences of tug captains and operational guidelines, thereby providing a more accurate estimation of Main Engine (ME) load than the propeller-based method. However, these empirical rules face the emissions assessment considering real data of ME load during operations. An on-board analysis of each tug is expensive and inefficient for collecting ship emission data, being necessary to obtain a methodology to estimate the total emissions and characterize the spatial and temporal features of emissions distinguishing the operational modes of tugs and calculate the emissions according to the status of ship engines. In light of all the above, there is a need for urgent action on emissions mitigation and fleet technological and operational adaptation. There are different ways to reduce GHG emissions from design standards, retrofit technologies, and operational measures that improve ship energy efficiency. However, the high costs of investing in different technologies and associated infrastructure could imply a significant investment for the stakeholders in the adaptation of their fleets to new fuels and/or innovative technologies.

Our hypothesis is that the present research is that the current methods to estimate emissions are not suitable for in-port manoeuvres and in particular for tugs activity. Thus, the main goal of the proposal is to quantify and predict spatio-temporal behaviour of port tugs' emissions in order to assess their impact in close-to-land area and establish strategies to mitigate them through manoeuvre optimization

2 METHODOLOGY

The methodology follows a logical sequence of steps that are connected among themselves in order to optimize the usage of data: i) new multidisciplinary approach to define tug manoeuvres, ii) use of bottom-up approach to compute in-port fuel consumption and emissions through real-ship data, iii) multi-criteria assessment to identify the best methodology to estimate fuel consumption and tug-related emissions, iv) full mission bridge simulator use as a research tool to obtain tug manoeuvre characteristics and optimization.

- <u>Intensive multi-disciplinary field campaigns</u>: unprecedent on-board observations to spatio-temporally characterize emissions.
- <u>AIS data to classify in-port manoeuvres:</u> use raw AIS data to identify and classify tug in-port manoeuvres within a framework for high resolution spatial planning.
- <u>Composite methodology to gather manoeuvres data</u>: propose a composite methodology to systematically reproduce a manoeuvre through the full mission bridge simulator using AIS data.

The resulting data set enables a process based inter comparison of different data sources, improving the cross-validation among them (field, AIS and simulation data). The data is processed according to resolution and accuracy to derive integrated indicators for the manoeuvres (e.g. mean length and duration, engine load interval phases), fuel consumption (e.g. daily consumption) and emissions (e.g. gr of pollutant per working condition). The fusion of near-real time AIS data (vessel trajectories, navigational status, ship type), manoeuvre simulator (full bridge) and field data (fuel consumption, engine orders, pollutants emissions) provides a unique benchmark data set for demonstrating the capabilities of the shipping industry to reduce emissions with the appropriate available resources.

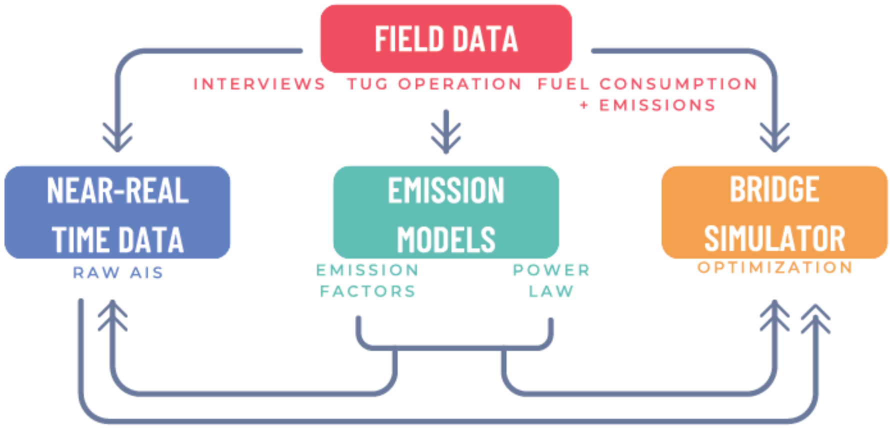

Figure 1. Workflow sketch of the methodology.

The workflow shown in Figure 1 summarizes the methodology presented. Extensive field campaigns are designed to obtain data from real manoeuvres. The campaigns include a set of interviews to tugboat skippers and chief engineers, onboard field campaigns collecting data from operations (call time, start of manoeuvre, time pulling/pushing or accompanying, etc…) combined with field campaigns including exhaust engines gas and engine load monitoring. The data collected feeds i) the near-real time AIS data to produce models capable of distinguishing the different operational phases of a tug manoeuvre, ii) the calibration of new emission models including the power-law and the emission factors and iii) the bridge simulator campaign to optimize manoeuvres based on the results from near-real time data, emission models and interviews. At the same time, the emission models are also used to incorporate the new models to AIS data to estimate near-real time emissions and be able to reduce them, as well as the bridge simulator to propose new manoevures minimizing emissions.

3 Results and Discussion

Initial field campaigns conducted so far have yielded interesting results. 17 interviews were conducted to tugboat skippers and chief engineers from 11 different ports in Spain which yielded unexpected responses. The interviewees emphasized the need to enhance traffic control to reduce unnecessary waiting times. They also pointed at the need to optimise manoeuvre planning to minimize the time spent with engines running at high power (Ribet et al., 2024).

An first on-board field campaign was conducted between March and July 2024 with an on-board observer enrolled in a tugboat from the Port of Barcelona, which included 55 different manoeuvres -58% departure, 38% arrival, 2% shifting berths and 2% false services-. In addition, most of the manoeuvres required 2 tugboats (71%), whereas only 20% required a single tugboat assistance. This field campaign also allowed to better describe the sequence of any manoeuvre and the classification of tugboat manoeuvres into three service types: Arrival, Departure and Shifting, combined with the situation of the tugboat (free sailing, waiting, manoeuvre and escorting); the position of the tugboat with respect to the commercial vessel (pulling, pushing and stand-by,) and the engine order (idling, dead slow, slow, half and full).

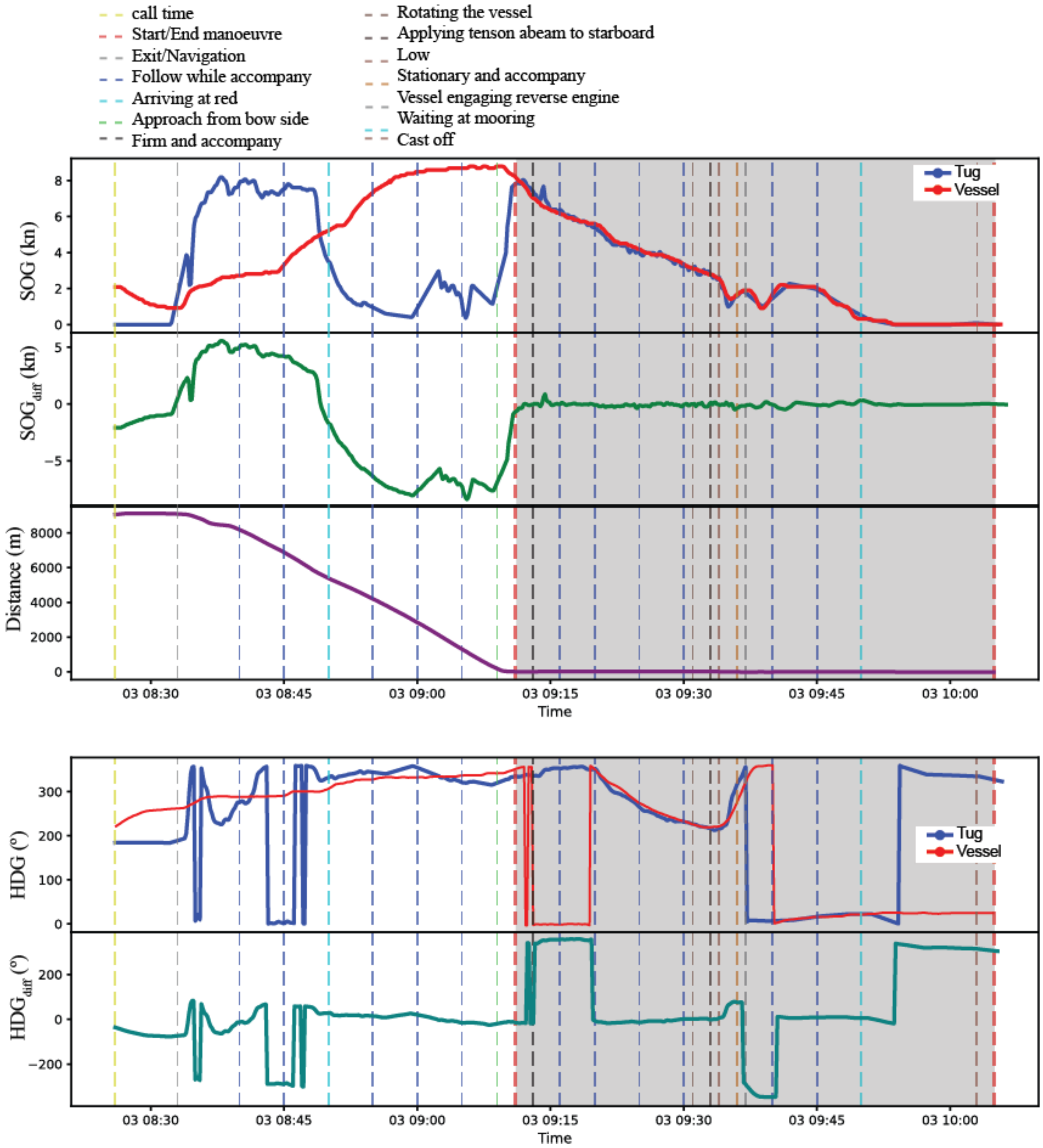

Figure 2. Example of an arrival with AIS data combined with onboard observer. Gray area highlights the time between the start and the end of the manoeuvre. Yellow dashed line sets the call time for the service to start.

The on-board field campaign was used to analyze AIS data in order to identify clear patterns (Niyazi et al., 2024). Figure 2 shows an example of an arrival with time evolution of Speed Over Ground (SOG) AIS-data from the tug and the commercial vessel and their differences as well as the evolution of the distance between tugboat and commercial vessel. Heading (HDG) was also considered interesting for pattern purposes along with HDG difference between both vessels. An interactive visualization tool was developed in order to ease the process of visually analysing all manoeuvres. This interactive tool allows to plot at the same time the geo-spatial map position, along with the variables of interest shown in Figure 2 with a time bar to locate each instant in time and space. At the same time, historic raw AIS data collected from the antenna has been made publicly available through a portal (Mujal-Colilles et al., 2025)

Onboard observers' data was used to feed a Logisitic Regression (Logit) algorithm in order to distinguish in geo-spatial data the real manoeuvre within the entire tugboat track. The accuracy of the model was 91%, and main errors occurred, as expected, during the transition phase that includes the waiting time, making fast the towing line, and the beginning of the manoeuvre, but also the last points of the manouevre -see Figure 3- coincident with the final actions.

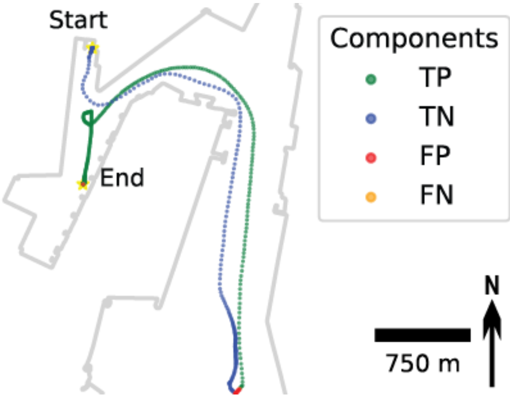

Figure 3. Example of the geo-spatial results obtained with the logit methodology to identify the manoeuvre within the segment of the track (TP: true positive; TN: true negative; FP: false positive; FN: false negative).

Current methodologies, based on the classical cubic formulation, are appropriate for merchant vessels operating at speeds close to their design conditions, but they are inadequate for tugboats, which typically work at lower speeds and under highly variable operating conditions. To assess the applicability of the power–speed relationship with an adjusted exponent for estimating the instantaneous power of tugboats, real data from field campaign were analyzed. The current methodology for power estimation, was compared against four alternative models where the exponent n was adjusted: constant, linear, quadratic, and power-law. The results show that the classical cubic correlation cannot be applied in the context of a manoeuvre, including the free-sailing track segment and models with an adjusted exponent significantly improve the accuracy of power estimation. This improvement enables a more precise estimation of pollutant emissions, which is essential for progressing towards more sustainable port operations.

At the same time, the data analysis shows that the tugboat operates most of the time at low engine loads, while higher loads occur only residually. This indicates that the engine reaches maximum power only during very specific moments of the manoeuvre. In fact, 55.03% of the time the tugboat operates below 25% of engine load, and 26.36% below 10%, conditions that are particularly inefficient. The higher engine orders totally account only about 5% of the total manoeuvre time, confirming that the system is clearly oversized.

The full simulation bridge campaigns have been used to test the ability to reproduce AIS vessel tracks in order to obtain engine orders. The initial campaign included trials with 3 different experienced captains. First results using a reference vessel to reproduce manoeuvres show the clear need to use exactly the same model with exact ship particulars and engine configuration. Still, with an initial model differing less than 5% of the LOA, with the same engine configuration yielded similar AIS track with a high sensitivity on engine orders at specific times of the manoeuvre. In order to optimize maneuvres from an emissions reduction perspective, the following campaigns in the full simulation bridge are designed to reproduce free sailing and manoeuvre segments of the exact tug that is being used in the field campaigns.

4 CONCLUSIONS

With the ongoing research and the results obtained so far, we can conclude that:

- Optimization from the tug manoeuvre to reduce pollutants emissions will have to tackle waiting times and maximum engine power.
- AIS data is useful to identify the different phases of the track without the need of highly complicated machine learning models.
- The traditional model to estimate engine power as a function of the cube of the SOG does not work for the in-port tugboat operations.
- Full bridge simulations must be performed using the exact vessel model.

The needs to further develop the engine model and the AIS manoeuvre detection require deep research that it is currently ongoing.

5 ACKNOWLEDGMENTS

The authors would like to thank the following programs or institutions: i) the Serra Húnter Programme from the Generalitat de Catalunya; ii) the Spanish Ministery of Science, Innovation and Universities for the grant received to carry out this research as part of the R+D+I project PID2022-140497OB-I00 funded by MCIN/ AEI/10.13039/501100011033/; iii) P&O REYSER - SAR REMOLCADORES company for their collaboration and generously providing the field data used in this research; iv) The Barcelona Port Authority for their willingness to provide information and contacts to tugboat companies.

6 REFERENCES

Capaldo, K., Corbett, J. J., Kasibhatla, P., Fischbeck, P., & Pandis, S. N. (1999). Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. *Nature*, *400*(6746), Article 6746. https://doi.org/10.1038/23438

Castells-Sanabra, M., Borén, C., Meer, R. van der, Torralbo, J., & Ordás, S. (2020). Existing emission calculation methods applied to monitoring, reporting and verification (Mrv) on board. *Nase More*, *67*(2), 163–171. https://doi.org/10.17818/NM/2020/2.9

Chen, S., Meng, Q., Jia, P., & Kuang, H. (2021). An operational-mode-based method for estimating ship emissions in port waters. *Transportation Research Part D: Transport and Environment*, *101*, 103080. https://doi.org/10.1016/j.trd.2021.103080

Duce, R. A., LaRoche, J., Altieri, K., Arrigo, K. R., Baker, A. R., Capone, D. G., Cornell, S., Dentener, F., Galloway, J., Ganeshram, R. S., Geider, R. J., Jickells, T., Kuypers, M. M., Langlois, R., Liss, P. S., Liu, S. M., Middelburg, J. J., Moore, C. M., Nickovic, S., … Zamora, L. (2008). Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science*, *320*(5878), 893–897. https://doi.org/10.1126/science.1150369

European Maritime Safety Agency, E. (2021). *European Maritime Transport Environmental Report 2021*. https://www.eea.europa.eu/publications/maritime-transport/

International Maritime Organization. (2020). *IMO Fourth GHG report, MEPC 75-7-15.* (p. 46).

International Maritime Organization, I. (2021). *MARPOL Annex VI Revised. Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978*.

Jalkanen, J. P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., & Stipa, T. (2012). Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmospheric Chemistry and Physics*, *12*(5), 2641–2659. https://doi.org/10.5194/acp-12-2641-2012

Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., & Stipa, T. (2009). A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. *Atmospheric Chemistry and Physics*, *9*(23), 9209–9223. https://doi.org/10.5194/acp-9-9209-2009

Jaramillo, J., Gutiérrez, J., & Masip Macia, Y. (2025). Comparative Analysis of Carbon Intensity Indicators Applicable to Harbor Tugboats. *Sustainability*, *17*(4), 1706. https://doi.org/10.3390/su17041706

Kristensen Hans Otto. (2017). *Energy Demand And Exhaust Gas Emissions of Marine Engines. Project No. 2016-108: Update of Decision Support System for Exhaust Gas Emission Calculations. Report No. 05*.

Lee, H., Pham, H. T., Chen, M., & Choo, S. (2021). Bottom-Up Approach Ship Emission Inventory in Port of Incheon Based on VTS Data. *Journal of Advanced Transportation*, *2021*(1), 5568777. https://doi.org/10.1155/2021/5568777

Lin Tang, Martin O. P., Ramacher, Jana Moldanová, Volker Matthias, Matthias Karl, Lasse Johansson, Jukka-Pekka Jalkanen4, Katarina Yaramenka, Armin Aulinger, & Malin Gustafsson. (2020). The impact of ship emissions on air quality and human health in the Gothenburg area – Part 1: 2012 emissions. *Atmos. Chem. Phys.*, *20*, 7509–7530. https://doi.org/10.5194/acp-20-7509-2020

Mujal-Colilles, A., Castells-Sanabra, M., & Fonollosa, J. (2025). *AIS maritime traffic data from the Barcelona School of Nautical Studies (FNB-UPC)* [Dataset]. https://doi.org/10.34810/data2026

Murcia González, J.-C. (2021). Analysis and measurement of SOx, CO2, PM and NOx emissions in port auxiliary vessels. *Environmental Monitoring and Assessment*, *193*(374). https://doi.org/10.1007/s10661-021-09145-4

Niyazi, L., Vigo, M., Pla, N., Murcia, J. C., Castells-Sanabra, M., & Colliles, A. M. (2024). Characterizing the AIS data of Port Tugs in the Port of Barcelona. *Maritime Transport Conference*, *10*. https://doi.org/10.5821/mt.13177

Paulauskas, V., & Paulauskas, D. (2011). Research on Work Methods for Tugs in Ports. *Transport*, *26*(3), 310–314. https://doi.org/10.3846/16484142.2011.623825

Raza, Z. (2020). Effects of regulation-driven green innovations on short sea shipping's environmental and economic performance. *Transportation Research Part D: Transport and Environment*, *84*, 102340. https://doi.org/10.1016/j.trd.2020.102340

Ribet, J. A., Castells-Sanabra, M., Boren, C., Osés, F. X. M. de, & Mujal-Colilles, A. (2024). Characterization of tugboats activity within spanish ports. *Maritime Transport Conference*, *10*. https://doi.org/10.5821/mt.13191

Sofiev, M., Winebrake, J. J., Johansson, L., Carr, E. W., Prank, M., Soares, J., Vira, J., Kouznetsov, R., Jalkanen, J. P., & Corbett, J. J. (2018). Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nature Communications 2018 9:1*, *9*(1), 1–12. https://doi.org/10.1038/s41467-017-02774-9

UNCTAD. (2021). *United Nations Trade and Development Report 2021: Review of Maritime Transport*.

Viana, M., Hammingh, P., Colette, A., Querol, X., Degraeuwe, B., Vlieger, I. de, & van Aardenne, J. (2014). Impact of maritime transport emissions on coastal air quality in Europe. *Atmospheric Environment*, *90*, 96–105. https://doi.org/10.1016/J.ATMOSENV.2014.03.046

Xie, G. (2014). Engergy savings in port pilot. *China Water Transport 6*, *6*(52–54).

Yu, H., Fang, Z., Fu, X., Liu, J., & Chen, J. (2021). Literature review on emission control-based ship voyage optimization. *Transportation Research Part D: Transport and Environment*, *93*, 102768. https://doi.org/10.1016/j.trd.2021.102768