Assessing and Reducing Tugboat Emissions: A Data-Driven Approach to Sustainable Port Operations

A. Mujal-Colilles
Serra Húnter Fellow. Department of Nautical Sciences and Engineering. UPC-BarcelonaTECH, Catalunya

M. Vigo, N. Pla
Computer Sciences Department. UPC-BarcelonaTECH. Catalunya

L. Niyazi, C. Borén, F.X. Martínez de Osés, J. Ribet, M. Castells-Sanabra
Department of Nautical Sciences and Engineering. UPC-BarcelonaTECH, Catalunya

ABSTRACT: Maritime transport constitutes a cornerstone of international trade, yet it remains a major contributor to greenhouse gas emissions and atmospheric pollutants, particularly in port areas and adjacent coastal communities. Within this sector, tugboats play an indispensable role in facilitating vessel manoeuvres; however, their emission profiles are insufficiently characterized due to the limitations of conventional estimation methodologies. This study presents a comprehensive, multidisciplinary framework designed to quantify and optimize emissions associated with tugboat operations. The proposed approach integrates on-board measurement campaigns, structured interviews with tug crews and Automatic Identification System (AIS) data analysis. Empirical evidence gathered from Spanish ports reveals notable inefficiencies in tug operations, with vessels operating below 25% engine load for more than half of their active time and exhibiting prolonged idle periods that contribute to unnecessary fuel consumption. A logistic regression model combining AIS and observational datasets achieved a 91% accuracy rate in identifying manoeuvring phases, while refined power–speed relationships demonstrated superior performance compared to the conventional cubic estimation model. These findings indicate that tug operations are frequently overdimensioned relative to actual power requirements, leading to avoidable energy use and emissions. The proposed methodology facilitates the development of more precise emission inventories and supports the implementation of real-time monitoring and operational optimization. Consequently, it provides port authorities and policymakers with evidence-based strategies to mitigate local air pollution and advance the sustainability of maritime port activities.

1 INTRODUCTION

Maritime transport is the pillar of economic growth as 80% of worldwide freight is carried by vessels (UNCTAD, 2020). 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. GHG 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). This figure is a small amount compared to the close to 3 trillion of CO2 tones in the atmosphere that represents 27% more than in the industrial revolution period (European Maritime Safety Agency, 2021). In this regard, CO2 is responsible for ocean acidification, temperature rise and sea level rise, contributing to climate change together with other greenhouse gases (GHG) such as methane or hydrofluorocarbons. 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 difficult decision is where to set the limit while keeping in mind accuracy, i.e. detecting the research constraints, deciding the assumption of determinate parameters, the use of general or more specific formulation, accept empirical results from literature as admissible, etc. Above mentioned issues corroborate that vessels are very complex systems to be analysed in terms of sustainability and huge efforts in improving data availability should be done as shipping emissions impacts directly affect climate change, economy, human health and environment. Therefore, initiatives that include a cost-effective, potential reduction in shipping emissions have to be strengthened. For instance, slow steaming, the use of contra-rotating propellers and propulsion efficiency devices, can deliver fuel savings and, thus, reduce emissions (Avgouleas & Sclavounos, 2014; Min Keh-Sik et al., 2009; Weissmann, 2010). Furthermore, other strategies are valuable in terms of mitigating emissions, such as the use of low sulphur fuels (Zhou et al., 2019), burning alternative fuels such as liquefied natural gas (LNG), the use of electric auxiliary propulsion during slow speed sailing (Sciberras et al., 2013) or the installation of abatement techniques such as scrubbers, inter alia. Bui. et al. (2020) proposed a multi-criteria decision-making method for the selection of technological alternatives for environmental regulatory compliance. 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. This is ascertained as the temperature raise in the Mediterranean area is 20% higher than the global average temperature increase. There are 500 million people living in the Mediterranean who are already being affected by the drought provoked by the climate change. Therefore, the Mediterranean Sea is especially vulnerable to climate change and urgent action on emissions abatement is required. 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 (Chen et al., 2021; Tang et al., 2022). 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.

Therefore, this research focuses in establishing cost effectiveness measures to mitigate emissions and is built upon the hypothesis that the current methods to estimate emissions are not suitable for in-port manoeuvres and in particular for tugs activity. This proposal is aiming to assess the environmental footprint of port tugs and give some insights on emission reduction operational port strategies to propose ways to reduce or significantly mitigate local air pollutants as a result of maritime activities at ports along with the harmful effects for the environment and the population health.

2 METHODOLOGY

The methodology follows a logical sequence of steps, organized in the tasks seen Figure 1: i) new approach to define tug manoeuvres, ii) use of bottom-up approach to compute in-port emissions through real-ship data, iii) multi-criteria assessment to identify the best methodology to estimate fuel consumption and tug-related emissions.

1. Intensive multi-disciplinary field campaigns: on-board observations to characterize emissions spatio-temporal characterization. The different operational modes of tugs according to the status of ship engine will be distinguished from preliminary interviews to stakeholders including tug masters, pilots and harbour management personnel. Field campaigns include real recording of emissions generated along with the engine orders given from the bridge.
2. AIS data to classify in-port manoeuvres: using raw AIS data to identify and classify tug in-port manoeuvres within a framework for high resolution spatial planning.
3. Estimate fuel consumption parameters for in-port manoeuvres: using data from engines and in-situ emissions.

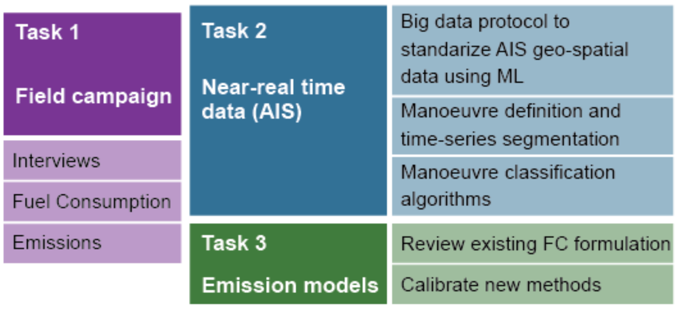

Figure 1. Tasks distribution of the methodology.

55 manoeuvres were monitorized with onboard observers in Azabra, a tugboat from the Port of Barcelona, from March to July 2024. Plus, the time series of the engine power used during 11 of these 55 manoeuvres were recorded. About 60% of the total manoeuvres with onboard observer, Azabra was the primary tug accompanied with a secondary tug (67% of recorded manoeuvres, see Figure 2). As per the service type, 57% were arrivals, 41% were departures and only 2% were shifting manoeuvres.

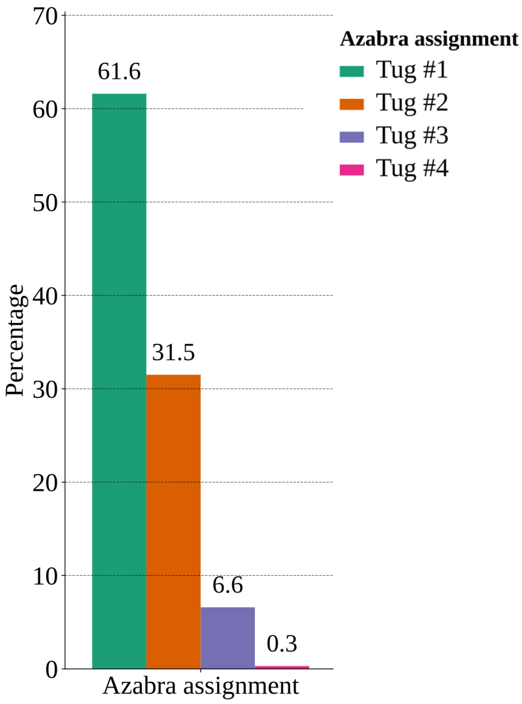

Figure 2. Percentage of recorded manoeuvres where Azabra tugboat was primary, secondary, third and fourth tug assisting the vessel.

Most operations required the assistance of two tugboats (71%), while only 20% were performed with a single tugboat. This campaign also enabled a more detailed characterization of trajectory sequences and supported the classification of tugboat operations together with the operational status of the tugboat, its position relative to the commercial vessel, and the engine order (idling, dead slow, slow, half, and full).

A service is defined as the cycle starting from the initial call to the tug's final return to its base. If the tugboat receives a new call immediately after completing a job without returning to base, the end of the first service marks the beginning of the next. Services can be classified as: A1 Entrance; A2 Departure, A3 In-port shifting/escorting. The manoeuvre is defined as the segment of the trajectory where the tug is actually engaged in active actions with the towed vessels and the tug position can be classified as: B1 Pull from aft, B2 Pull from stern, B3 Push, B4 Stand By.

The type of service and manoeuvre depend on the aforementioned descriptions, but the trajectory can be sequenced regardless of the type of service and manoeuvre, showing 4 different phases plotted in Figure 3. The segment with free sailing conditions is identified at the beginning of the service, when the tug exits the base and arrives at the meeting point and at the end of the service when the manoeuvre has finished and the tug goes back to the base or heads to the next service.

Figure 3. General description of a tug manoeuvre. TS: time segment

A Python visualization app was designed to be able to plot time series along with geo-spatial location of the tugs and towed vessels. This app was a key tool to further analyse trajectories, phases of the total service and manoeuvre and the variation of AIS recorded data from both vessels and is still under review to be published in open channels.

3 RESULTS & DISCUSSION

Results are summarized based on the input data. 17 tug skippers, pilots and stakeholders from 10 different ports in Spain were interviewed (Ribet et al., 2024). The interviewees covered tugs with LOA from 27 to 33 m and power systems with more than 3000kW (the average power of tugs in Spanish ports). The main conclusions from the interviews can be summarized as follows:

1. False exits are more common than expected based on the interviewees experience.
2. Waiting times and maximum speed while free sailing shall be minimized.
3. Tugs are over dimensioned for typical daily services.

Moreover, the survey yielded interesting results regarding the power distribution of the tugs in the different Spanish ports. Figure 4 shows the dispersion of the tugs' power along the Spanish ports and no correlation between the capacity of the port and the maximum power of the assisting tugs. Thus, the three main ports, Algeciras, Valencia and Barcelona do not have the tugs with maximum propulsion capacity having Algeciras the widest range on tugs propulsion power.

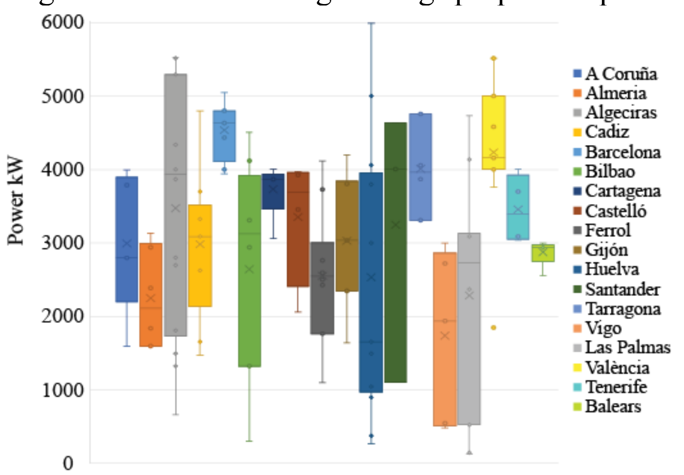

Figure 4. Power distribution of the tugs in the different ports of Spain.

The results obtained with the onboard observer during the field campaign provided detailed time-labelled data as shown in Figure 5.

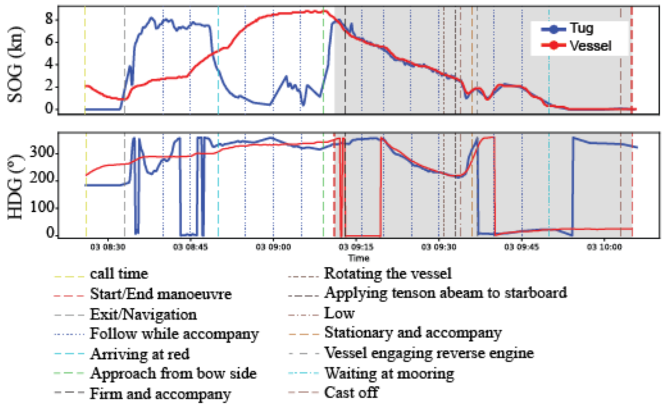

Figure 5. Example of an arrival with AIS data combined with onboard observer. Gray area highlights the time between the start and the end of the manoeuvre. Yellow dashed line sets the call time for the service to start.

Field campaigns reveal that slightly more than 50% of the total service time is dedicated solely to the assist the towed vessel. The rest of the time is spent in free sailing (~40% of the time in departure services and ~30% of the time in arrival services), and waiting for the towed vessel to arrive (~10% of the time) at the meeting point as shown in Figure 6. The main differences between departure and arrival services come mainly from the dispersion of each segment of time, since median values are comparable; arrivals show less dispersion in the percentage values of each time segment.

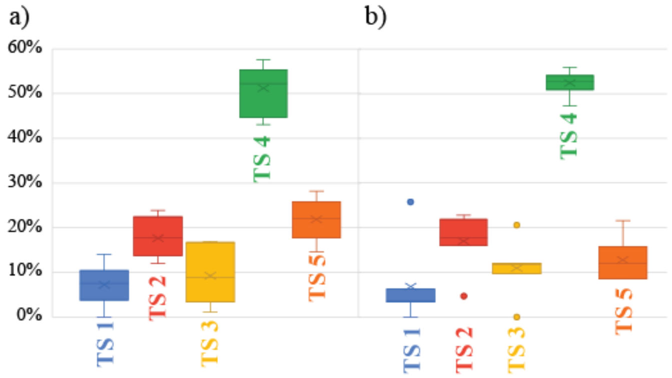

Figure 6. Distribution of percentage of time spent in the different phases of the manoeuvre during a) departure and b) arrival services. TS: time service based on definitions shown in Figure 3.

AIS data obtained from a public database (www.ais-fnb.upc.edu) from tugs and towed vessels during the on-board observer's field campaign was pre-processed to calibrate a model capable of distinguishing the manoeuvre within the total service trajectory. The pre-process was based on initial noise removal based on (Mujal-Colilles et al., 2020) and a more in-deep analysis to synchronize, at a 10s frequency, tug and towed-vessel trajectories to further compare them (Niyazi et al., 2024). Data obtained from the pre-process was the initial input for the visualization app which helped identify the main variables distinguishing the manoeuvre from the whole trajectory service.

The main variables identified using the visualization app and confirmed with a feature importance analysis describe the distance between tug and towed vessel and the relative Speed Over Ground (SOG) between vessels. Likewise, variables such absolute SOG of the tug and the towed vessel as well as relative Heading (HDG) and Course Over Ground (COG) were discarded due to a minimal impact on the model improvement.

A Logistic Regression (LR) model was trained with labelled data from on-board observers and AIS data from both vessels. The model was trained using service trajectories as the training unit and providing an input of 75% of the labelled trajectories. Points within a trajectory were classified as manoeuvre/not manoeuvre, where the former includes only TS4 from Figure 3 and the latter includes the remaining time segments (exit, free navigation and waiting times).

Figure 7 shows the confusion matrix of the LR based on the single points in each trajectory providing a total accuracy of 0.91. Regardless of the high level of accuracy achieved by the LR model, the main source of inaccuracies comes from the false positives, FP, (1875 out of 22.000 points), this is points labelled by the model as manoeuvre, which were, in fact, part of other TS.

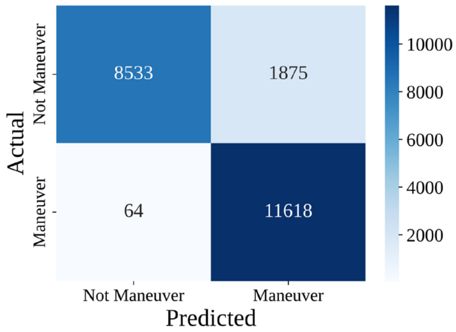

Figure 7. Confusion matrix from the LR model. Colormap is based on the single points label

As an example, Figure 8 plots the geo-spatial sequence of the results provided by the LR model in an arrival service. FP are usually labelled wrongly during the last part of the waiting time, and this is consistent with FP of the rest of the services. Also, the end of the manoeuvre can be wrongly labelled as manoeuvre when, according to the on-board observed data should be labelled as not manoeuvre. However, this FP can be corrected with a post-process algorithm selecting individual points surrounded by True Negatives, TN.

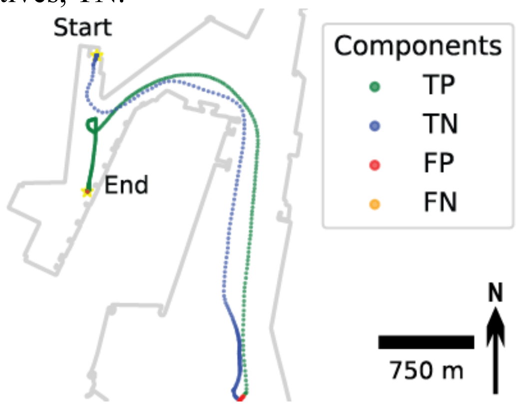

Figure 8. Trajectory example of the LR model results. TP: True Positives; TN: True Negatives; FP: False Positives; FN: False Negatives.

Finally, the data from engine's power use was used to check the best power vs SOG fit for the tug in-port manoeuvres. Data needed a pre-processing procedure to both synchronize it with AIS data providing the SOG and acquisition frequency (set at 60 s, the frequency of the engine data). In addition, trajectory segments with SOG < 2 kn were removed from the initial analysis due to significant variances in the power results. Two different models (linear model with n = 1, and cubic model with n = 3) were tested based on the equation of power:

$$P = k \cdot SOG^n \quad \text{Eq. (1)}$$

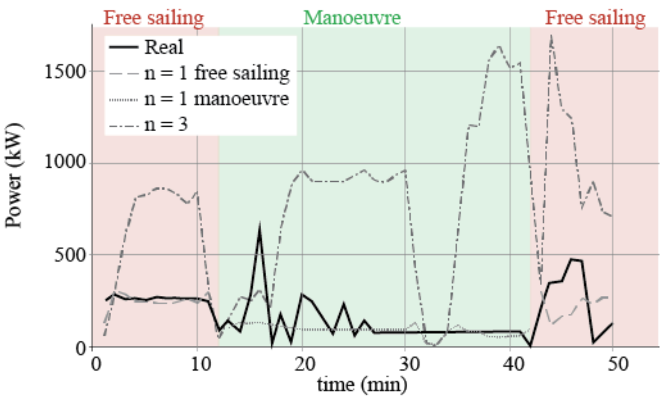

Figure 9. Time evolution of the engine power.

Constant, k, coefficient was calibrated using 10 kn as design speed. Figure 9 plots the best results obtained from the 11 manoeuvres analyzed. It is worth mentioning that exit and waiting times have been removed from the analysis. Results in Figure 9 show how, the traditional cubic law to estimate engine power clearly overfits the real measurements while a linear relation between power and SOG yields better fits both during the free sailing and the manoeuvre.

4 CONCLUSIONS

The ongoing research presented in this contribution provides new and promising insights on the in-port tug manoeuvres. Interviews show that stakeholders identify the tugs to be over dimensioned based on the majority of the manoeuvres carried out so far. Moreover, they also suggest that minimizing waiting times could provide a decrease on emissions generated by these type of port services.

However, the analysis of time spent in each TS reveals that free-sailing is as important as manoeuvre with respect to the total time spent. This may affect the total emissions produced since the SOG at which the vessel sails during free-sailing TS might be far from the engine optimal working point.

On the way to produce a model capable to estimate tug emissions during services, LR model yields good results to distinguish between manoeuvre and not-manoeuvre while some post-processing shall be needed to reduce the FP. Afterwards, linear models to express the power used during each TS of the service based on AIS broadcasted SOG can provide better results than the most commonly used cubic power law.

Overall, the initial analysis presented herein suggests several recommendations that can be used by port authorities to reduce emissions:

1. Reduce power capacity demand of the tugs.
2. Reduce speed during free-sailings which will also reduce waiting times.

To provide a more in-deep analysis of tugs' emissions and their potential reduction, further analysis is needed aiming to provide more detail of the emissions produced during the manoeuvre segment itself.

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