Transparent Monitoring: From AIS Data to Urban Environmental Intelligence

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Abstract: - Maritime transport is a major source of environmental pressure in coastal and port cities. It affects air quality, underwater noise, and, more broadly, urban ecosystems. Although Automatic Identification System (AIS) data is widely available today, its use for continuous and transparent environmental monitoring at the urban scale is still limited. This paper explores how AIS-derived port traffic data can be used in a more open and interpretable way to support what we refer to as urban environmental intelligence. The analysis combines high-resolution AIS data with environmental indicators to examine how vessel activity evolves and how it differs across vessel types and seasons. The study examines how these traffic patterns relate to potential environmental pressures. Attention is also given to transparency and data openness to make results understandable and usable beyond expert communities. The findings suggest that transparent AIS-based monitoring can help identify periods and areas of increased environmental pressure.

Key-Words: - AIS data analytics, data transparency, emission intensity, open science, sustainable maritime governance, port-city ecosystem resilience.

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1 Introduction

Maritime transport is essential for global and regional supply chains. However, its environmental effects are significant, most directly in port cities. In these cities, vessel activity takes place close to densely populated areas. Therefore, ecological footprints of these areas are fully affected by these ship emissions, port-related congestion and operational inefficiencies. These influence air quality, public health, and the resilience of urban ecosystems, [1]. As ports expand and maritime activity grows, the need for continuous and reliable environmental monitoring becomes increasingly important in enclosed seas such as the Mediterranean..

The Automatic Identification System (AIS) was originally introduced by the International Maritime Organization (IMO) for collision avoidance even though it is now used much more broadly to improve maritime visibility. It provides near real-time information on vessel position, speed, heading, and voyage-related details, which supports navigation, port operations, and, increasingly, environmental analysis, [2]. At the same time, AIS does not include direct measurements of fuel use, engine performance, or pollutant emissions. For that reason, environmental use of AIS data usually depends on additional assumptions, modelling choices, or the integration of external datasets.

Research has already shown that AIS data can be useful for estimating shipping emissions, examining congestion, and describing maritime traffic patterns, [3]. Closed datasets, proprietary tools, or highly aggregated indicators could be used as sources to many of these applications. Therefore, transparency can be reduced, reproduction can be more difficult, and wider use outside specialised communities is limited.. As a result, AIS-based environmental assessments do not always feed effectively into public debate, urban governance, or cross-sector policy discussions.

At the same time, the growing emphasis on Open Science and data transparency has changed expectations about how environmental knowledge should be produced and shared, [4]. Transparent monitoring systems are now seen as important for building trust, improving accountability, and supporting cooperation among authorities, researchers, industry actors, and local communities, [5]. This is particularly relevant in maritime transport, where activities are transboundary and environmental effects are often difficult to link to a single vessel category or operational pattern.

In this context, AIS data offers a useful basis for developing urban environmental intelligence, understood here as a data-informed view of how maritime activity affects urban ecosystems over time and across space. When AIS-derived traffic data is combined with environmental indicators through clear methods, it becomes easier to observe patterns of environmental pressure and identify areas where impacts may accumulate. Such insights can support earlier recognition of risks and more timely responses in port cities.

The present paper builds on this idea by examining how open and transparent use of AIS data can contribute to environmental intelligence in an urban port setting. Rather than treating AIS only as an input for emissions estimation, the analysis considers port traffic itself as an important driver of urban environmental dynamics. Particular attention is given to traffic composition, seasonal variation, and vessel operating profiles, since these factors shape both the intensity and the distribution of environmental impacts.

What this paper aims to show is that AIS-derived traffic data, when examined together with environmental indicators, can help identify environmental pressure patterns in urban port areas. It also suggests that transparent monitoring practices can turn AIS data into a more public-facing environmental intelligence resource, improving awareness and supporting accountability across the port-city interface.

AIS data has been widely used in earlier studies for traffic analysis and emissions modelling. However, many approaches still rely on complex modelling frameworks or limited datasets. This makes it more difficult to achieve transparency and reproducibility. This study follows a different path by placing openness and interpretability at the centre of AIS-based environmental monitoring. The focus is not only on estimating emissions, but also on showing how AIS-derived traffic indicators can be documented, interpreted, and communicated in ways that are useful for governance-oriented environmental monitoring in port cities.

The remainder of the paper is organised as follows. Section 2 briefly reviews the main background and the transparency-related issues that frame the study. Section 3 explains the methodological approach. Section 4 presents the empirical findings and discusses the main traffic patterns along with their environmental implications. Section 5 turns to the governance value of transparent AIS monitoring, and Section 6 closes with the main conclusions and directions for further work.

2 Research Background

2.1 AIS-Based Analysis of Maritime Traffic and Environmental Impacts

AIS data is widely used in maritime research to describe traffic intensity, vessel distribution, and operating patterns across different sea areas and ports. One of its main advantages is that it makes it possible to observe vessel movements in much greater detail, since it continuously records information such as position, speed, heading, and vessel type. This kind of information is not easily captured through conventional port statistics, and for that reason, AIS has become important in work on congestion, routing, and port efficiency, [6].

AIS data is often used to obtain an indication of shipping-related pressures, especially in relation to air emissions and ecological impacts in many environmental studies. Literature [7], [8], has explored how vessel activity derived from AIS can be linked with emission factors and ship characteristics to estimate pollutants such as nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter at a finer spatial scale. This is particularly relevant for port cities, where manoeuvring activities and short-sea shipping may have a stronger influence on local air quality and, in some cases, public health.

The literature on maritime emission estimation generally points to two broad methodological directions. One relies on detailed bottom-up models, where emissions are calculated using inputs such as engine characteristics, fuel consumption, and operational load factors, [9], [10]. When AIS trajectories and technical vessel data are added, these models can provide a fairly detailed picture of emissions. However, their use is not always straightforward, and access to the required data is often limited. Several modelling assumptions are needed, and as such, calibration steps can influence the outcome. For these reasons, such approaches may be less transparent and harder to reproduce, especially for non-specialist users.

The second direction uses activity-based indicators derived from AIS traffic patterns, for example, vessel counts, operational profiles, and traffic intensity, as proxies for environmental pressure, [11], [12]. These methods do not aim to produce exact emission inventories, but they are usually easier to interpret and explain. For exploratory monitoring and governance-oriented analysis, this is an important advantage. The present study, therefore, adopts this second direction, giving priority to transparency, reproducibility, and accessibility of indicators within a broader effort to develop open and interpretable AIS-based environmental intelligence for port-city systems.

2.2 Port Cities, Urban Ecosystems and Environmental Intelligence

Over recent years, urban sustainability agendas and environmental governance frameworks have increasingly treated ports as integral parts of the urban system rather than as isolated pieces of transport infrastructure, [13]. This shift has brought renewed attention to the port-city interface, where maritime operations generate effects that often extend beyond port boundaries. Addressing these effects requires not only regulation and technological intervention, but also reliable data infrastructures that can support decision-making, accountability, and environmental awareness at the urban level, [14].

Port cities bring together maritime operations, urban functions, and industrial activity in ways that are not always easy to separate systematically. In busy areas, vessel movements often take place close to densely populated zones, which can intensify environmental impacts. Ship emissions, congestion, and operational inefficiencies may therefore affect not only the port itself but also nearby urban areas. This suggests that infrastructure-centred approaches alone are not sufficient and that more integrated assessments are needed, taking environmental, social, and economic dimensions into account at the same time, [15], [16].

From this point of view, environmental intelligence can be understood as the ability to observe, interpret, and anticipate these pressures over time by using data to support better-informed decisions. AIS data is useful in this respect because it allows the monitoring of traffic variation, seasonal peaks, and changes in vessel composition, [17]. In urban contexts, such shifts can matter a great deal, since even short-term increases in maritime activity may lead to visible impacts, for example, in air quality or congestion. When AIS data is considered together with environmental indicators, it becomes easier to identify higher-pressure areas and to recognise emerging risks within the port-city interface.

2.3 Transparency, Open Science, and Maritime Environmental Monitoring

At the same time, transparency has become increasingly important in transport systems. It influences not only the management of operations but also the credibility of the actors involved. This is especially relevant in maritime transport, which carries more than 80% of global trade by volume, [18]. Because shipping networks are complex, vessel categories are diverse, and the regulatory setting is fragmented, there is a strong need for data that is reliable, accessible, and understandable in practice.

Although AIS data offers significant analytical potential, many current applications are still constrained by limited access and low transparency, [19]. In many cases, environmental assessments depend on proprietary datasets, closed models, or highly aggregated indicators. This makes findings more difficult to reproduce and reduces their usefulness for public accountability and participatory governance, [20]. The issue is particularly important in maritime transport, where environmental impacts are diffuse, cross-border, and often difficult to assign to specific actors or practices.

The stronger emphasis on Open Science has renewed attention to transparency, reproducibility, and data openness as core elements of environmental research, [21]. Transparent monitoring systems support scientific scrutiny. In addition, they make it easier for policymakers, stakeholders, and citizens to understand environmental pressures and the trade-offs involved, [22]. In that sense, transparency is not just a technical feature. It also acts as a governance mechanism that helps build trust and legitimacy in environmental decision-making.

In maritime applications, a more transparent use of AIS data can improve accountability. Transparency can make vessel activity and traffic patterns visible in ways that go beyond expert circles. Open access to AIS-derived indicators can support comparisons across ports, facilitate monitoring over time, and allow independent checking of environmental claims. Clearer methodologies also reduce the risk of black-box assessments and strengthen the credibility of AIS-based environmental intelligence.

This paper addresses that gap by treating transparency and openness as enabling conditions for AIS-based environmental monitoring in urban port areas. The analysis focuses on port traffic composition and temporal dynamics as observed through AIS data and relates these patterns to environmental indicators.

3 Methodological Approach

The methodological approach contributes to operational environmental intelligence for port cities and connects AIS-based analysis with wider open science and sustainable governance objectives. In that way, the study extends beyond a purely technical assessment and moves towards environmental decision support for urban port settings.

More specifically, the study follows a transparent and data-oriented approach to explore how AIS-derived port traffic can support urban environmental intelligence. High-resolution AIS data is examined together with environmental indicators in order to understand traffic composition, temporal variation, and possible environmental implications in an urban port context. Throughout the process, emphasis is placed on clarity, reproducibility, and interpretability. AIS messages were retained if they passed basic quality-control checks. As such, duplicate messages, invalid positions, and incomplete vessel type information were removed. The processing steps were documented so that the dataset can be reused later for comparison or longitudinal analysis.

The approach also makes it possible to look both at overall traffic intensity and at changes in the relative contribution of different vessel categories. Monthly traffic composition offers a readable picture of how port activity changes through the year and where periods of higher pressure may emerge. Looking at the AIS data, vessel activity clearly varies by season. Traffic generally increases during summer, mainly because of passenger vessels, pleasure craft, and sailing vessels. Cargo and tanker traffic, by contrast, stays comparatively stable, reflecting the continuing role of commercial shipping in port operations. These differences matter because environmental impacts are not the same across vessel types or seasons.

AIS-derived traffic data is then used to explore possible environmental implications related to emissions intensity, congestion effects, and localised ecosystem stress. Traffic density and vessel counts indicate cumulative pressure on the urban environment, especially in relation to air quality and noise exposure. Seasonal increases in passenger and recreational traffic are examined as likely contributors to short-term environmental stress during peak tourism periods. Continuous cargo and tanker activity, on the other hand, is treated as a more persistent background source of pressure. Rather than producing absolute emission values, the analysis focuses on relative changes, temporal patterns, and potential hotspots. This makes the approach more transparent because it avoids overly opaque modelling assumptions and links observed traffic dynamics more directly to likely environmental effects.

A further aim of the methodology is to show how AIS data can be turned into a practical environmental intelligence resource through transparent monitoring. The analytical steps, from data cleaning and vessel classification to aggregation and visualisation, are designed to remain understandable and reproducible. Aggregated indicators are preferred over composite indices so that stakeholders can more easily connect observed traffic patterns with environmental concerns. The monthly composition analysis, therefore, serves as a communicable representation of port activity that can be integrated into environmental monitoring systems and policy dashboards. In this way, the method supports both reuse and independent verification, in line with open science principles and transparency needs in environmental governance.

It should also be made clear that the presented environmental indicators are not direct measurements from air-quality monitoring stations. The reported pollutant concentrations ($\mu g/m^3$) are proxy estimates derived from AIS traffic intensity and standard emission formulas found in the literature. Their purpose is not to provide exact atmospheric dispersion results, but to illustrate how changes in vessel activity and traffic composition may influence relative environmental pressure within the port-city interface. This allows the analysis to highlight temporal dynamics and possible hotspots while avoiding reliance on complex black-box emission models. The approach, therefore, gives priority to interpretability and reproducibility and presents AIS-derived traffic patterns as environmental pressure indicators that can support governance and policy discussions.

4 Empirical Results

4.1 Temporal Dynamics of Port Traffic

The analysis is based on AIS data from the Piraeus area (https://airos.imet-piraeus.gr/ais/), one of the main ports in the Eastern Mediterranean. It is also a key logistics hub. The data comes from an AIS station that operates continuously. It is also available through the AISHub network (Station ID: 3074). The station has been active since January 2025. It provides position data together with information such as speed, course, and vessel type.

Each month, the data is stored in an open repository. This allows access by researchers, authorities, and other users. The coverage is not limited to the port. It also includes nearby sea routes. Because of this, the dataset captures different types of activity, including cargo transport, ferries, cruise ships, and smaller vessels.

Looking at the data, vessel activity is quite dense. This is especially clear for cargo ships, tankers, and pleasure craft. This reflects the role of Piraeus as a major gateway. The data for 2025 shows a clear pattern. There is a stable level of commercial traffic throughout the year. At the same time, there are strong seasonal changes linked to tourism. In simple terms, regular operations continue throughout the year, while summer brings a clear increase in recreational traffic.

Cargo and tanker vessels form the industrial base of port activity. Their numbers remain relatively stable as shown in Figure 1 (Appendix). In most months, cargo vessels range between about 300 and 450. Tankers range between 200 and 300. In winter, these vessels represent a large share of total traffic. For example, in January, they account for just over half of all vessels. This remains similar in February and March. During this period, recreational activity is low.

As the summer season starts, the picture changes. The number of cargo and tanker vessels increases slightly, but their share of total traffic decreases. This happens because of the sharp rise in leisure vessels. In July, pleasure craft and sailing vessels dominate the traffic. Together, they represent more than half of all vessels. This does not mean that commercial activity declines. Instead, it shows that leisure traffic increases much faster.

After summer, this pattern reverses. The share of industrial vessels increases again. By October, cargo and tankers account for nearly half of total traffic. Across the year, the ratio between cargo and tanker vessels remains stable. Cargo vessels are usually about one and a half times more numerous than tankers. This reflects stable supply chain activity.

Pleasure craft and sailing vessels follow a different pattern. Their numbers are low in winter. From June onwards, they increase rapidly. The peak is observed in July and August. During this period, the number of pleasure craft exceeded 800 vessels. This almost doubles total traffic compared to winter levels. In January, leisure vessels represent a smaller share. In July, they become dominant. This seasonal increase leads to stronger interaction between maritime activity and the urban environment. It also creates local pressure, especially in summer. Passenger vessels and service vessels show more moderate changes. Passenger traffic increases during the tourism season, but not as sharply as leisure vessels. Service vessels follow the needs of larger ships.

Overall, two patterns can be observed. On one side, there is a stable commercial baseline. On the other hand, there is a strong seasonal increase in leisure traffic. This has practical implications. Port operations need to adapt during peak periods. Traffic management and environmental monitoring have also become more demanding.

4.2 Estimated Environmental Emissions Derived from AIS Traffic

Environmental indicators were estimated using AIS traffic patterns. These values are not direct measurements. They are proxy estimates based on vessel activity. Their purpose is to show relative changes, not exact concentrations. The results show seasonal variation in environmental pressure as presented in Figure 2 (Appendix). During winter, NO_2 and $PM_{2.5}$ remain relatively stable. This reflects the steady activity of cargo ships and tankers. In the first months of the year, NO_2 values remain around 35–40 $\mu g/m^3$. $PM_{2.5}$ follows a similar trend at lower levels.

O_3 behaves differently. It shows stronger seasonal variation. In winter, O_3 levels are relatively low. During the summer, they increase significantly. In July, O_3 reaches its highest level. This is linked to higher temperatures and stronger solar radiation. It is also related to increased vessel activity. This suggests that summer is a critical period for air quality. The interaction between emissions and weather conditions becomes more important.

During winter, NO_2 is the dominant pollutant. It accounts for about half of the total concentration. $PM_{2.5}$ and O_3 share the remaining part. In summer, the balance changes. O_3 becomes more important. NO_2 and $PM_{2.5}$ decrease in relative terms. This shows that environmental pressure is not constant. It changes with traffic patterns and seasonal conditions.

By autumn, the distribution becomes more balanced again. This reflects the reduction in leisure traffic and lower temperatures. These findings are important for policy. They show that different periods require different responses. A single approach may not be effective throughout the year.

Overall, the results highlight two types of pressure. One is the steady baseline from commercial traffic. The other is the seasonal peak linked to tourism. AIS data helps identify both. It shows when and where pressure increases. This supports more targeted environmental management.

5 Transparent AIS Monitoring as an Enabler of Urban Environmental Intelligence and Sustainable Maritime Governance

The empirical analysis shows that AIS-derived port traffic data can offer useful insight into how urban port systems operate, especially when it is interpreted together with environmental indicators. This type of monitoring can support environmental understanding and decision-making. It can also improve visibility and make underlying patterns easier to interpret.

5.1 From Traffic Data to Urban Environmental Intelligence

Urban environmental intelligence depends on having continuous information about environmental pressures and the factors that influence them. In port cities, maritime traffic is one of the main contributors to these pressures, although it is not always easy to observe directly.

In this context, AIS monitoring helps make vessel activity more visible. It allows traffic patterns to be followed over time and gives an indication of how these changes may relate to environmental conditions in the surrounding urban area.

Looking at the results, seasonal variations in traffic composition appear to be linked, to some extent, with changes in estimated environmental pressure. AIS-based monitoring makes these relationships easier to recognise and helps identify periods where impacts may become more pronounced. This is particularly relevant in urban environments, where even short-term increases in activity can influence air quality, noise levels, or congestion.

Another aspect that emerges here is the role of transparency. When indicators are clearly defined and the steps of the analysis are documented, it becomes easier for different stakeholders to understand how the results are produced. This improves trust in the findings and also supports their use in broader environmental monitoring processes.

5.2 Transparency, Accountability, and Trust in Maritime Governance

Maritime governance involves many actors. These include port authorities, operators, regulators, and local communities. For this reason, access to clear information is important. AIS data can support this. When it is used openly, it gives a common view of vessel activity. This can help reduce information gaps.

In port cities, impacts are often local. However, decisions may be taken at the national or international level. This creates a gap. AIS data can help reduce this gap by linking traffic patterns with environmental pressure. Transparency also supports trust. When methods are clear, results can be checked. This makes the analysis more reliable.

5.3 Supporting Evidence-Based and Adaptive Policy Responses

AIS data can support decision-making. It provides timely information about traffic patterns. For example, seasonal peaks can be identified. This allows authorities to take action in advance. Measures may include traffic management or support for low-emission vessels.

At the urban level, AIS data adds useful context. It shows how maritime activity relates to environmental conditions. This helps design better policies. The use of trends is also helpful. Even without exact values, patterns can be observed. This supports early action.

5.4 Towards Open and Integrated Maritime Environmental Governance

The findings indicate that AIS data can evolve from a mainly operational or surveillance-focused tool into a public environmental intelligence resource. However, this transition requires more than technical capacity. It also requires institutional commitment to openness, data sharing, and cross-sector collaboration.

Transparent AIS monitoring aligns with broader open-science and open-data initiatives that seek to widen access to environmental information and encourage collaborative knowledge production. In port cities, this kind of openness can support coordination among maritime authorities, environmental agencies, urban planners, and local communities, helping to promote more integrated sustainability approaches.

Transparent AIS-based monitoring cannot replace direct environmental measurements or formal regulatory instruments. However, it can provide a valuable complementary layer of intelligence. For this reason, more visible and interpretable maritime activity and its environmental implications are needed. Transparent monitoring also supports more informed, accountable, and sustainable management of the port-city interface.

6 Conclusions

This paper looks at how AIS-derived port traffic can support urban environmental intelligence. It also explores how this can contribute to more sustainable maritime governance in port cities. The analysis combines AIS data with environmental indicators. This makes it possible to observe how traffic composition and seasonal changes relate to environmental pressure.

The results show a clear pattern. Port activity is based on two main components. There is a stable level of commercial traffic, mainly from cargo ships and tankers. At the same time, there is a clear seasonal increase linked to passenger vessels and recreational activity. These two patterns affect the environment differently. Commercial traffic is more stable. Seasonal increases, mainly in summer, create short-term peaks. These are often connected with higher congestion and air quality issues. The environmental indicators show similar behaviour. In winter, pollution levels remain more stable. In summer, changes become more visible. Ozone becomes more important during warmer periods, while NO_2 is more dominant during the rest of the year.

Another important point is transparency. The approach used in this study avoids complex models and focuses on simple and interpretable indicators. This makes the results easier to understand and to use. In this way, AIS data can be more than a technical tool. It can support communication between different actors, including port authorities, policymakers, and local stakeholders. The results also suggest that environmental management in port cities needs to be adaptive. Different periods require different responses. Identifying peak periods can support more targeted actions.

More generally, AIS data can support earlier identification of environmental pressure. It can help detect areas and periods where impacts increase. At the same time, AIS data does not replace direct environmental measurements. It should be seen as a complementary source of information. AIS could be combined with other data sources to improve understanding of environmental impacts.

Future work can extend this approach. This may include combining AIS data with real measurements, weather data, or socio-economic information. It may also include comparisons between different ports. Overall, it is presented that AIS data can support a more transparent and practical approach to environmental monitoring in port cities. It can also help improve understanding and support better decision-making.

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APPENDIX

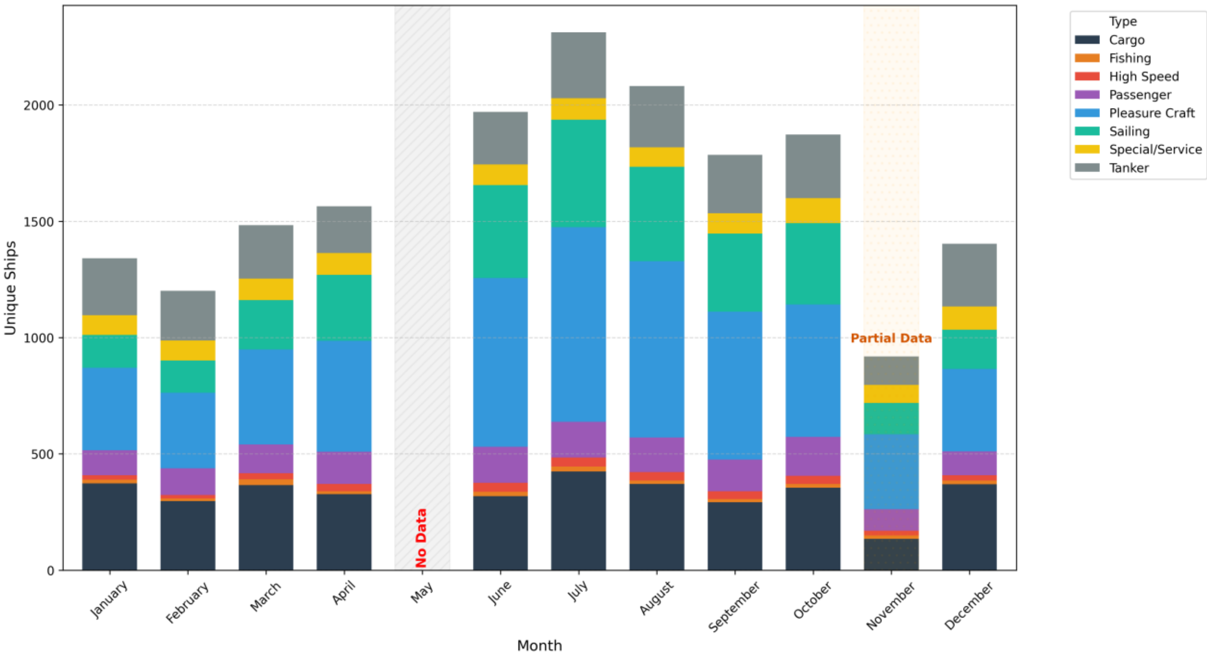

Fig. 1: Port Traffic Composition per Month (2025)
Source: created by the authors

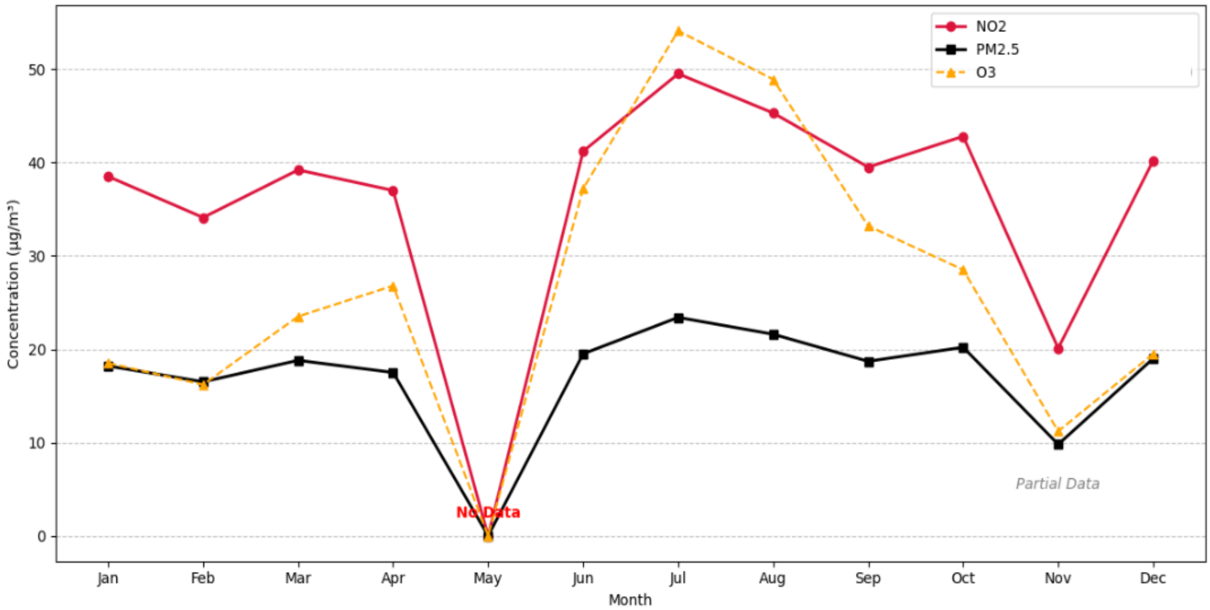

Fig. 2: Estimated Environmental Emissions per Month (2025)
Source: created by the authors

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

- Afroditi Anagnostopoulou focused on the overarching research goal and the examination of how transparent AIS monitoring supports urban environmental intelligence.
- Xenophon Kitsios managed high-resolution AIS data streams, including processing temporal and compositional vessel patterns and creating port traffic composition charts.
- Vassilis Kappatos provided a critical review of the integration of environmental indicators and the assessment of traffic dynamics in relation to localised ecosystem emissions.

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