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Vessel Behaviour under Varying Environmental Conditions in Coastal Areas

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Abstract: The planning and construction of offshore wind parks reduces the margin for error of nearby shipping activities. During the last couple of years, several incidents on the North Sea have raised the attention for the risk of ship-ship and ship-infrastructure collisions. Although often not the primary cause, environmental conditions play an important role in these incidents, and prevention and intervention measures, like the placement of emergency response vessels, are often deployed considering metocean conditions. To improve the design of risk-reducing measures, we need to understand better how vessels behave under varying environmental conditions. It is important to gain insight into risk patterns at system scale while retaining the ability to explain how these patterns are linked to underlying mechanisms. For this purpose we propose creating a so-called 'event' table, that couples ship behaviour data from Automatic Identification System (AIS) data to environmental data. The structure of the 'event' table, whereby events are defined as vessels sailing within a specific section of the system, allows appending analysis results and other data sources to the events. We show how the 'event' table adds important new perspectives to the analysis of nautical safety at sea.

Keywords: collision risk, shipping safety, environmental conditions, event table

Introduction

On January 31st, 2022, cargo vessel Jullietta D. was at anchor near IJmuiden on the North Sea. During the storm that day, the anchor broke loose, sending the vessel adrift. After colliding with another vessel at anchor, the ship drifted towards a wind park under construction, where it hit the foundation for a platform that was not installed yet. Although no severe injuries were caused by this incident, it raised the attention for the increased collision risk for ships due to the growing presence of wind parks (and other assets) in the North sea.

To facilitate the energy transition, more and more offshore wind parks are being constructed and planned on the North sea. As a result more assets are situated in close vicinity of shipping lanes and anchorage areas which leaves less space for current and future traffic to navigate, and puts further pressure on vessels in distress. The shorter distance to renewable energy infrastructure reduces the time available to intervene in case of incidents. Knowing under what circumstances larger risks may arise, and where, is the starting point for the design of appropriate measures, for example, to decide on where emergency response vessels should be located under given environmental conditions.

When investigating the causes of shipping incidents, vessel behaviour is usually assessed in combination with the environmental conditions that the vessels were situated in. For example, in the MSC Zoe incident in 2019, were the vessel lost 342 containers, unfavourable wave conditions in shallow waters played an important role [1]. The collision between two cargo vessels on the North Sea in 2023 was partially caused by poor visibility due to fog [2]. For the Julietta D., the stormy conditions were an important driver for the vessel running adrift and a complicating factor for the operation to tow the vessel into safe waters [3]. However, to use this knowledge for risk assessments is difficult, due to the limited number of occurrences of these incidents. Probability-based risk assessments therefore usually consider the probability on a collision by two independent components: the geometric probability and the causation probability [5]. The geometric probability considers the probability of a near miss [6], being encountering ships that have the potential to collide [7]. The causation probability considers human, organisational and technical factors that can lead to an accident.

Although often not the primary cause, environmental conditions clearly play an important role in these events, both for ship-ship collisions as well as for ship-infrastructure collisions. They may influence the probability of occurrence of an incident, as well as the likelihood that intervention measures are successfully implemented before the situation escalates. Moreover, they influence how vessels behave, as captains make different decisions under different environmental conditions. Despite the obvious relevance, however, environmental conditions are not explicitly incorporated as a contributing factor in most probability-based approaches on collision risks, since they are seldomly the primary cause of an accident [5]. Environmental conditions are considered in studies into 'not-under-command' cases. They are incorporated in the form of wind direction probabilities of occurrence, to estimate the probability of the drifting vessel colliding with an infrastructure object, like an offshore platform or wind turbine [8].

Given the influence of the environmental conditions on the entire chain of events that may or may not lead to a (severe) accident, ranging from adjusted vessel behaviour to the success rate of intervention measures and potential consequences, there is a need for a more detailed understanding of the role of the environmental conditions during ordinary shipping activities and during incidents. With this knowledge, improved decisions can be made for prevention and intervention measures, under varying conditions.

The objective of this study is to develop a framework that can serve as a basis to analyse collision risks at sea while considering environmental conditions. The approach facilitates a joint analysis of long-term and large-scale shipping data while connecting with underlying environmental conditions and shipping behaviours. The proposed framework contributes to the state of the art by enabling nautical safety analyses at an as yet unprecedented level of detail.

Materials
The study presented in this paper considers the North Sea spanning from the Dutch coast between IJmuiden and Rotterdam to approximately 40 nm offshore. It uses the following data sources as input:

- Automatic Identification System (AIS) data;
- Environmental data (ERA5);
- Geospatial data of designated areas and objects.

The use of AIS is mandatory for larger vessels since 2000. By exchanging data on position, speed, vessel properties and identity in real-time, the AIS contributes to enhancement of nautical safety [4]. Historical AIS data can be used to analyse vessel behaviour and to improve shipping-related processes. In our study, AIS data spanning four months (January, April, July and October) of the year 2019 was provided in an anonymised form, by the Dutch Coast Guard and Rijkswaterstaat. Furthermore, hourly environmental data was used from the ERA5 dataset [9]. We considered waves (significant wave height, peak period), surface currents (decomposed speeds) and wind (decomposed speeds at 10m height) in our analysis. The resolution of the used reanalysis data is 0.5 degrees on a regular latitude-longitude grid. The wave-related data, however, does not contain valid data for all grid points in the considered area. Finally, we used geospatial data made publicly available by the Dutch government [10], including the vessel traffic separation scheme, anchor areas and designated wind energy areas.

Method: Event table
The key concept of our framework is the construction of a so-called event table, as described by [11], that connects aggregated output to the detailed underlying input data. The concept of an event table is inspired by two existing concepts: moving features [12] from which we adopt the ability to keep track of time and space, and event logs [13], from which we use the principle of defining events. Event logs are widely used to analyse and optimise processes in among others business, healthcare, or manufacturing. The ‘events’ are characterised by a ‘case’, indicating what process the event is part of, and an ‘activity’, a well-defined step in the process. In our implementation, the case is defined as a single journey of an individual vessel. The activity not only defines *what* the vessel is doing, e.g., sailing, anchoring, waiting, or loading, but also it specifies *where* this action is executed.

AIS data contain a vessel’s location at a given time. They do not, however, contain information about the local conditions. Also, the individual vessel positions are not easily aggregated to useful geographical units. To resolve this, we created a spatial representation of the North Sea by means of a grid, whereby its cells do not include boundaries of designated areas (shipping lanes, wind parks, anchoring areas). Therewith, one cell cannot overlap multiple designated areas. The *where* in an event’s activity can now be defined as the grid cell it is located in. Consequently, a single activity consists of a sequence of AIS position samples. Practically, data belonging to one case represent a single trip of a unique vessel that sails through multiple grid cells (activities). Data belonging to one activity (sailing through a grid cell) can be seen as the passages of all vessels through that grid cell. Data belonging to one event represents a single passage of a unique vessel through a specified grid cell.

Figure 1 visualises how these definitions materialise in practice, showing data belonging to the same case in the same colour in the left panel, and showing data belonging to the same activity in the same colour in the right panel. By structuring the data in this manner, it becomes possible to reconstruct multiple vessels following the same route, and aggregated information can be derived from all vessels that passed through the same grid cell(s). Additionally, all events related to a unique case, jointly represent the route sailed by an individual vessel.

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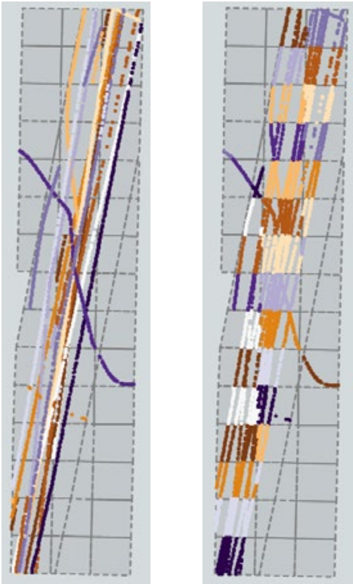

Figure 1 Visualisation of the definitions for 'cases' and 'activities', where the left panel indicates 'cases' by different colours, and the right panel indicates 'activities' by different colours, both for the same data.

An event is captured by one row in the event table and characterised by its case (the trip of a vessel) and its activity (the grid cell it sails through). The case and activity data are stored in specific columns in the event table. All further characteristics and details about the event are stored in attribute columns, being for example the travelled path in the cell (coordinates), the start time, duration, and speed of the vessel, but also characteristics of the vessel itself, or the designated area that coincides with the grid cell, for example an anchoring area or a shipping lane. A simplified example of an event table is given in Table 1.

Structuring the data in the form of the described event table has three major advantages, both on the data processing side, as well as on the outcome interpretation side. First, coupling the AIS data in the event table to other information sources becomes straightforward, when defining their spatial distributions by the same grid. Second, we gain flexibility to investigate multiple aspects of the system based on this data structure in a relatively straightforward manner. Examples of such aspects are the 'total system', 'a particular area', 'a particular subset of vessels', and 'a particular time frame' that can also be defined by particular weather conditions. The third advantage is the predictability of the outcomes that can be achieved with the data that we have available. Depending on the analysis goal, the requirements for the input data may differ. By connecting input and output, the event table helps identifying upfront what information should be included to reach the defined analysis goal.

Table 1 Simplified example of an event table

Event	Case	Activity		Attributes		
		Cell	Task	A1	A2	A3
1	VA-T1	5	sailing			
2	VA-T1	6	sailing			
3	VA-T1	7	sailing			
4	VA-T1	7	anchoring			
5	VA-T2	7	sailing			
6	VA-T2	6	sailing			
7	VA-T2	5	sailing			
8	VA-T2	4	sailing			
9	VB-T1	9	sailing			
10	VB-T1	3	sailing			
11	VB-T1	3	dredging			
12	VB-T1	3	sailing			
13	VB-T1	9	sailing			
14	VB-T1	8	sailing			
15	VB-T1	8	dredging			

Method: Pivoting perspectives

For an event table application to the issue of 'emission footprint assessment', Van der Werff et al (2024) [11] derived a categorisation of system performance aspects that can be considered. They distinguished the following 'pivoting perspectives', that are related to the set analysis goal:

- *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.

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Each of these pivoting perspectives pose different requirements to the event table and subsequently to the input data that is needed. However, multiple pivoting perspectives can be considered for a single case, system, or problem. With each additional perspective, additional data requirements come into play.
As part of the *scales* perspective, we could aim to visualise areas (and times) of high shipping intensity, high-collision-risk areas, or hotspots. An important consideration is: how far do we want to be able to zoom in? Do we want to indicate hotspots of several hundreds of meters in size, or do we roughly need to distinguish between areas of several kilometres? This poses requirements to the refinement of the grid, and consequently to the definition of an activity in the event table. A coarse grid results in fewer different activities than a fine grid, but a finer grid might require more computational capacity and data storage space. For the analysis in this paper, we used a maximum grid size of 1 km, whereby additional splits were made at boundaries of designated areas like wind parks and anchoring areas. Consequently, the overall grid contains 16,832 cells with an average area of 0.785 km^2. Figure 2 shows how the large-scale intensity patterns are still recognizable on this grid, when compared to a heatmap based on raw AIS-position samples.

The pivoting perspective of *relations* aims at finding the most important variables influencing the performance. Where the rows of the event table indicate the events, the columns of the table contain all sorts of information that is attributed to each event. What we store in these columns, determines the relations that we can investigate. For example, if we are interested in the relation between the (average) vessel speed and the wave height, we must make sure to incorporate both attributes for each event as columns in the table. Attributes can be strongly related to the event's 'case' (vessel trip), for example the vessel characteristics, to the event's 'activity' (grid cell passed), for example the environmental conditions in a grid cell at the time of crossing, or to both (event-specific), for example the covered distance or average speed of a single vessel passage in a single grid cell. So, the relations we want to investigate determine the attributes we have to incorporate for each event in the table. In this study, we want to identify underlying mechanisms, whereby we primarily focus on the environmental conditions. For this reason, the attributes of the event table consider characteristics of the vessel behaviour, being the travelled (cumulative) distance, the covered distance (distance between first and final sample in the cell), the duration, the average vessel speed, and the course (determined between first and final sample in the cell). We also included time series of the position coordinates. Regarding the environmental conditions, wind (velocity in u- and v-direction at 10m height), wave (mean direction, peak period, and significant wave height), and precipitation conditions were incorporated.

Behaviour of vessels can be influenced by external factors, but it may also influence the performance of the overall system. This is what the *behaviour* perspective considers. For example, weather conditions can influence the vessel's timeliness or energy use, because it may sail against currents and winds, or because it adjusts its speed to cope with unfavourable wave conditions. The most important requirement to evaluate the system from this perspective, is to know the sequence of events that were part of a single case, in the right order. This is simply achieved by adding timestamps to each event. This evaluation may furthermore consider the routes taken for a given origin-destination, and potential deviations from the ordinary.

Figure 2 Spatial grid with colour indicating shipping intensity

The final pivoting perspective, *dependencies*, considers the triggers for events: can we identify causes for things to happen in a certain way? This perspective is the most complex one, and the required information, the initiation for each event, is impossible to retrieve from observed data only. The AIS data allows us to visualise vessel behaviour, but it does not contain information on how the behaviour of one vessel might have triggered the behaviour of another. For analyses where such dependencies are important, data may be supplemented with simulations, whereby the relation between causes and effects can be further investigated. In this study, we do not incorporate simulations or other sources to obtain this information about each event, therefore, the dependencies perspective is not further evaluated.

The environmental data was coupled in space and time to the event table based on the AIS data and the spatial grid. For each event, the closest point in time (hour) in the ERA5 dataset was selected with respect to the starting time of the event, and the centroid of the grid cell was used to determine the closest available data sample in the ERA5 dataset for each variable. It was found that some events had a long duration, specifically for anchoring vessels this could be up to several days. For a proper alignment with the environmental conditions, a recommendation for improvement would be to limit the duration of one event, to an hour.

Results and discussion

The final event table consisted of 6.75 million events. The Planetary Computer [14] was used to process the data from all sources into this data structure, that can be used for several analysis perspectives, according to the pivoting perspectives.

What could be considered as part of the *scales* perspective, was already indicated in Figure 2: viz. a spatial distribution of shipping intensities. The event table allows to zoom in to a particular area or even to a single grid cell, to investigate which vessels passed it, what their characteristics are and what their trajectories looked like. Similar images could be generated based on the mean vessel speeds or courses. An example of the *relations* perspective is given by Figure 3 and 4, showing how the event table can be used to investigate how vessels adjust their speed in response to the environmental conditions they encounter, in this case for two crossings of the main shipping lanes. From the event table an aggregated extraction was generated based on the hourly time stamps whereby the mean vessel speed in these crossings was calculated. Next to the average vessel speeds, a moving average of the vessel speed was calculated over 12 windows, e.g. 12 hours, to evaluate the trends. Figure 4 shows that the mean vessel speed in northbound direction (green area in Figure 3) varies over time, which can be related to variations in vessel sizes and correlated design speeds. Figure 4 also shows that when the significant wave height peaks, the average vessel speeds decrease. From the *behaviour* perspective, we could evaluate this further, refer to Table 2, presenting multiple trips of a single vessel crossing the sections in Figure 3. The same speed reduction can be recognized, as observed in Figure 4. By looking from this perspective, other factors, like the vessel draught or its relative heading with respect to the waves can be considered.

Figure 3 The evaluated crossings in the main shipping lanes indicated in red and green

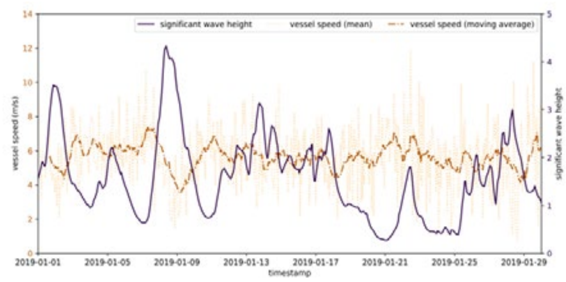

Figure 4 Hourly time traces of ERA5 significant wave height and northbound vessel speeds (mean and moving average) for the evaluated crossings

Table 2 Behaviour of a vessel evaluated

bound	dir (deg)	speed (m/s)	draug ht (m)	swh (m)	rel wave dir (deg)
north	38	7.5	5.0	0.5	11.7
	40	7.3	5.0	0.4	19.8
	38	7.6	5.0	0.5	171.1
south	219	3.0	6.6	3.6	72.0
	220	6.1	6.2	0.5	73
	220	6.3	6.2	1.6	173

The above examples show how the ‘event’ table concept can assist in improving the insight into various key aspects of nautical safety at sea. The scales perspectives show where and when safety risks occur (Figure 2). The relations perspective shows how vessel behaviour is related to specific local environmental conditions (Figure 3 and 4). The behaviour perspective shows how individual vessels adapt their behaviour under its own and environmental conditions (Table 2).

Besides the presented examples, specific studies into the behaviour of vessels in anchoring areas may be performed, providing a better understanding of the decisions that are made onboard under certain conditions. Adding further analyses to the available data in the event table, encounter behaviour can be investigated, or the table can support anomaly detection. Furthermore, details about other objects that are in the vicinity of the vessel can be indicated, like other vessels, wind turbines, or platforms. Using the presented approach, a starting point is created for further strategic (collision risk estimation) and operational (identification of the most optimal locations for support vessels, predicting drift paths) analyses, that contribute to creating space for sustainable energy sources, while keeping shipping operations safe. The construction of the event table ensures that the potentially very large amount of data, needs to be processed only a limited number of times, while facilitating the extraction of a large range of results and insights. This can save great amounts of computational and processing time.

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