Intensity and severity of ship conflicts – An AIS based approach

VTI Working Paper 2023:12

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Abstract

There is a lack of standardized methods for socio-economic evaluations within the maritime transport sector. This paper presents a model for analysing and quantifying the intensity and severity of ship conflicts using AIS (Automatic Identification System) data and expert assessments. Also, a case study applying the proposed method to the Southern Gothenburg Archipelago is carried out. The goal is to contribute to cost-benefit analyses within the maritime transport sector by a better understanding of how different actions, such as the widening of fairways or new regulation, impact maritime safety. The importance of validating the model by comparing its results with independent sources of reported maritime accidents is emphasized, and the challenges of using existing accident statistics for this purpose is discussed. The basic model described in the paper can be built upon by differentiating parameters by region and vessel type, account for seasonality etc. Furthermore, a downstream consequence analysis model is needed to enable a monetary valuation of (the consequences of) identified conflicts. Finally, the same principles as laid out here for conflict analysis can also be adopted to the identification of groundings.

Keywords

Socio-economic evaluation, cost-benefit analysis, maritime safety, AIS, ship conflicts, geometric probability, probabilistic risk analysis.

JEL Codes

D61, R41, R42, C69

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1. Introduction

Cost-benefit analysis, which, in turn, rely on the effects and impacts of actions[1], is a crucial tool when deciding on actions within the transport sector. The purpose of such an assessment is to consider the costs and benefits that an action brings to society as a whole. There are guidelines in Sweden concerning socio-economic assessments within the transport sector issued by the Swedish Transport Administration (2023). However, standardized methods for conducting socio-economic evaluations are lacking when it comes to maritime transport (Vierth & Sjöstrand 2020; Swedish National Audit Office 2016). As a result, knowledge about how actions taken in the maritime sector affect maritime safety and to what cost is limited, presumably resulting in the most (cost)efficient actions not being the ones that are given priority.

To estimate how a certain action, such as the widening of a fairway or the introduction of new legislation, affect maritime safety, one needs reliable and detailed data on the probability of accidents. In Vierth och Sjöstrand (2020), we outline how CBAs are performed in the Swedish maritime sector. Effects and impacts of actions regarding maritime safety have been established primarily using expert assessments, accident statistics, and indirect methods where transport costs act as a proxy for maritime safety[2]. These approaches are associated with great uncertainties, and the understanding of how various actions (such as fairway improvements or new regulation) affect maritime safety is rather limited. Using a formal appraisal framework rather than depending only on expert assessment provides the advantages of improved traceability and outcomes that are less affected by the specific expert consulted. A major challenge when quantifying effects and impacts of actions on maritime safety is the relatively low number of accidents in the maritime sector, and the fact that the accident statistics is neither reliable nor comprehensive. However, a significant advantage compared to most other modes of transport is the fact that most ships are equipped with AIS (Automatic Identification System) transponders, providing high frequency data on vessel movements. This is utilized in this study, where a method for quantifying the conflict intensity and severity of ship conflicts is introduced.

[1] In Swedish it is referred to as “effektsamband” and is defined as the relationship between an action taken within the transport sector and the consequences for the actors directly affected by the action and the society at large.

[2] This refers to the so called PIANC method derived from recommendations regarding the size of vessels in relation to the width and depth of fairways. It builds on the assumption that the marginal increase in the cost of accidents when exceeding the PIANC recommendations is equal to, or greater than, the corresponding decrease in transportation costs.

2. Previous research

In Chen et al. (2019), the state-of-the-art regarding probabilistic risk analysis on collisions between ships is outlined, with a focus on quantitative methods in a macro perspective (meaning that measures taken for collision avoidance for individual ships is not discussed). It is shown how the approaches usually use geometric probability, and that a lot of the work emanates from Fujii och Shiobara (1971) and MacDuff (1974) where the following basic framework is applied:

$$P_{Collision} = N_{Candidate} \times P_{Causation}$$

This means that the probability of ship-ship collisions is determined by two elements, namely 1) the number of collision candidates, also known as geometric collision probability. This is to be understood as the number of ship encounters that could result in a collision, and 2) the causation probability, which is the probability of collisions due to causational factors such as fatigue, bad weather etc. With the introduction of new technologies such as AIS, this basic framework has been developed and made more sophisticated while building on the basic principles outlined above. As we will see below, also in our study the same basic principles form the basis for our analytical approach.

Analogous to the work on identifying near-misses in the maritime sector, work has been conducted within the road transport sector to gain knowledge of near-misses, referred to as "the Swedish Traffic Conflict Technique" (STCT). Here too, the aim is to complement the data on actual accidents and to better understand effects and impacts of actions concerning road infrastructure features, regulations etc. (Laureshyn och Várhelyi 2018). Instead of waiting in order to have enough data on accidents, the data on near misses can be collected in much shorter time. But with no equivalence to AIS data, the traffic is instead observed either by trained personnel at site or by video monitoring. This act as an illustration of how AIS data facilitates the identification of conflicts and near misses within the maritime sector. *The International Association of Marine Aids to Navigation and Lighthouse Authorities*, IALA, has developed a software called IWRAP MK II, with the purpose of estimating the probability of ship collisions and groundings (IALA 2023a). By defining polygons for the relevant areas, determining the traffic composition based on AIS data, and specifying a so-called causation factor, probabilities for collisions and groundings can be estimated. The causation factor is the probability of the officer on the watch not reacting in time given that the ship is on collision or grounding course. This depends on various factors such as the safety level of the shipping company and how the fairway is designed. If the fairway is improved from a safety perspective, the causation factor can be assumed to decrease, meaning the probability of a person not acting correctly is decreasing. The software calculates the number of collisions and grounding in a scenario where every ship is staying the course without making any evasive maneuvers, which is then multiplied by the chosen causation factor. This leaves a lot to the user of the software, who must determine which causation factor to use. Alternatively, there is a default causation factor calculated by IALA using

Bayesian networks that can be used, with the caveat that this is not calibrated for the specific area in question.

A method that was recently developed in a Swedish context is the AutoMon approach (Bång et al. u.å), with the aim of developing real time traffic monitoring together with collision and grounding avoidance using a machine learning approach. The approach uses real time AIS data on ship movements and adds context information such as local weather data. The distance between ships and the direction sailed of ships in a certain area is then calculated. Subsequently, a series of algorithms for anomaly detection was developed, where the basic algorithm identified ships violating a pre-defined safety distance. A machine learning model was also created where ships with abnormal behavior are identified. Finally, an experimental algorithm using so called reinforcement learning was developed to automatically generate suggestions for evasive maneuvers for ships involved in a situation that could lead to a collision.

3. Method

3.1 Scope and outline

The vessel conflict analysis technique presented here shall be applicable anywhere in Swedish waters, given that GIS[3]/AIS data is available. This means that the method cannot be dependent on detailed, local calibration. Omitting local peculiarities means that the method must rely on structural, location-independent causal-effect relationships. This is an advantage when applying the method in a CBA context, where local infrastructure investments need to be assessed based on objective (location-independent) criteria.

Smaller vessels are not required to carry AIS equipment, meaning that not all conflicts arising in a study region are represented by corresponding AIS tracks. To avoid biased estimates, the method does not rely on the analysis of realized conflict situations (including evasive maneuvers). It instead relies on combinations of AIS trajectories observed at possibly different times.

The conflict analysis method is developed in the context of (and as a step towards) a broader approach to AIS/GIS-based naval safety assessment for cost/benefit analysis in Swedish conditions. Figure 1 provides an overview.

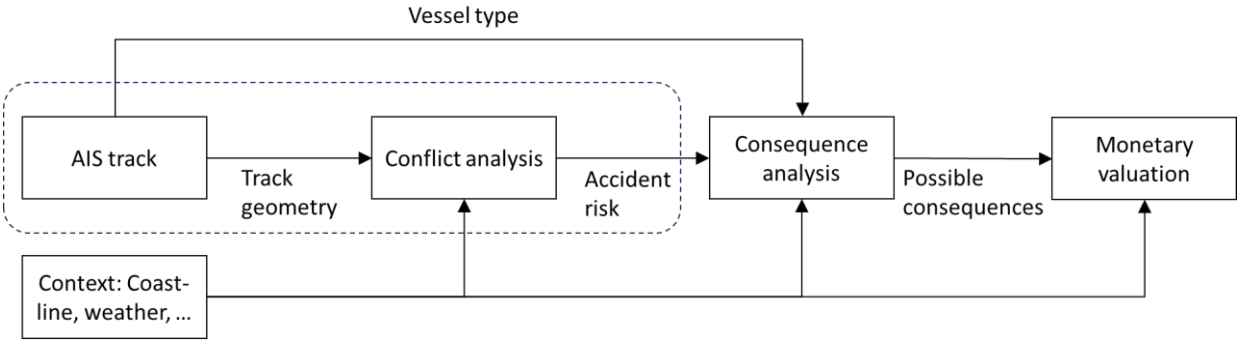


Figure 1. Overall method context

The dashed line delineates the work undertaken in the present project from the overall approach. Given a set of AIS tracks, their geometry is analyzed for possible conflicts. The analysis undertaken here only considers possible conflicts between two vessels with crossing paths. It computes, for each conflict, a measure of the risk that the conflict leads to an accident. *A conflict is defined here as a situation that could lead to an accident if no evasive maneuver is taken.*

The method quantifies accident risk in terms of two variables. Computing all possible conflicts in a region of interest (a "cell") yields the **cell conflict intensity**, which is directly related to the traffic intensity in the considered cell. Computing the risk of all possible conflicts in a cell yields a quantitative measure of how dangerous the conflicts in this region are, called the **cell conflict severity**.

[3] GIS refers to a geographic information system.

In other words: The cell conflict intensity represents the rate at which conflicts arise. The cell conflict severity represents an accident risk given that a conflict arises. The product of these two quantities then represents the overall accident risk in the considered cell:

cell accident risk = **cell conflict intensity * cell conflict severity**

Expressions of this type can be traced back to Fujii och Shiobara (1971). Being available for each cell in a study region, these quantities can be color-coded in a graphical representation of the spatial distribution of conflict intensities, severities, and accident risks. As elaborated on further below, the cell conflict severity is without further precautions prone to subjectivity in the expert assessment, which carries over to the cell accident risk.

3.2 Technical formulation

The study region is split into hexagonal cells. The size of these cells balances spatial (smaller cells yield higher spatial resolution) and statistical (larger cells contain more trajectories for analysis) precision. Figure 2(b) shows an example.

Assume that the available AIS data spans a time interval of duration *T*. Let *h* be the minimal safety distance between two vessels, and let *v* be a representative vessel speed. (Cell- and/or vessel specific parameters may be used.) The accident risk analysis is undertaken independently for each grid cell.

1. All AIS trajectories that enter and leave a grid cell are identified. Let J be the number of identified AIS trajectories in a considered cell.

2. The **cell conflict intensity** κ is computed as

$$\kappa = \frac{h}{v} \cdot \left(\frac{J}{T}\right)^2 .$$

   This represents the estimated number of conflicts arising per time unit. It is proportional to the safety margin *h* because a larger safety margin indicates a greater need for safety and, hence, evasive maneuvers. It grows with the square of the traffic intensity *J*/*T* because the considered conflicts may arise from all possible combinations of trajectories. It falls reciprocally with the speed v because the faster a vessel crosses the conflict zone, the less likely it is that it encounters another vessel during this traversal.

3. For any pair *i*, *j* of trajectories, let θ_{ij} be the conflict severity that arises when two vessels following these trajectories cross the considered cell simultaneously (the computation of θ_{ij} is described in section 3.3). The **cell conflict severity** σ is then computed as

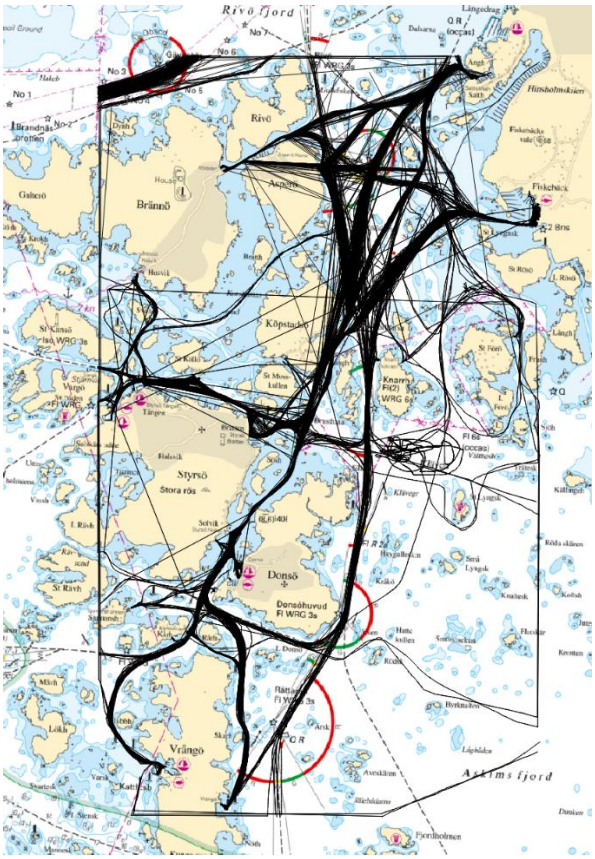
$$\sigma = \frac{1}{J^2} \sum_{i,j=1}^{J} \theta_{ij} .$$

This is the average severity over all possible conflicts that can arise by combining two observed AIS trajectories.

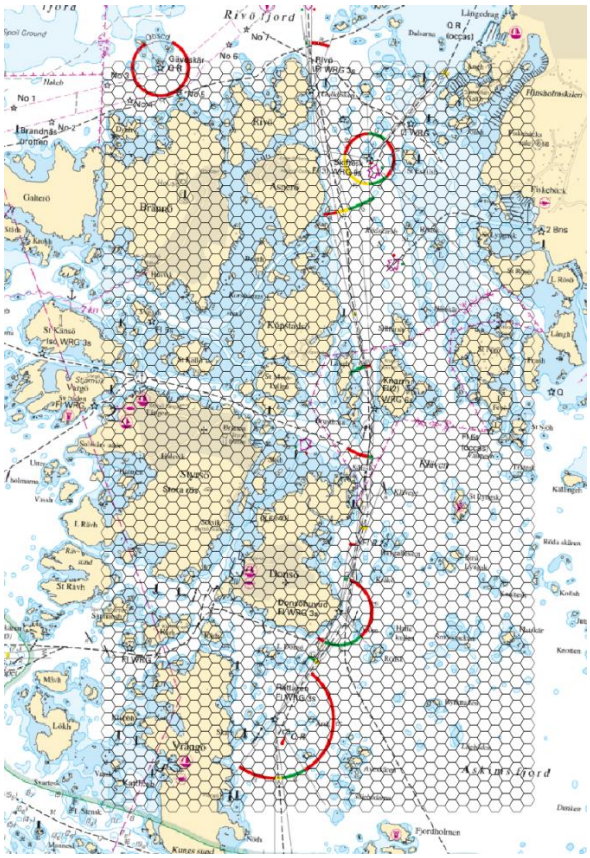
4. Multiplying intensity and severity then yields the **cell accident risk**

$$\alpha = \kappa\sigma = \frac{h}{v} \cdot \frac{1}{T^2} \sum_{i,j=1}^{J} \theta_{ij}.$$

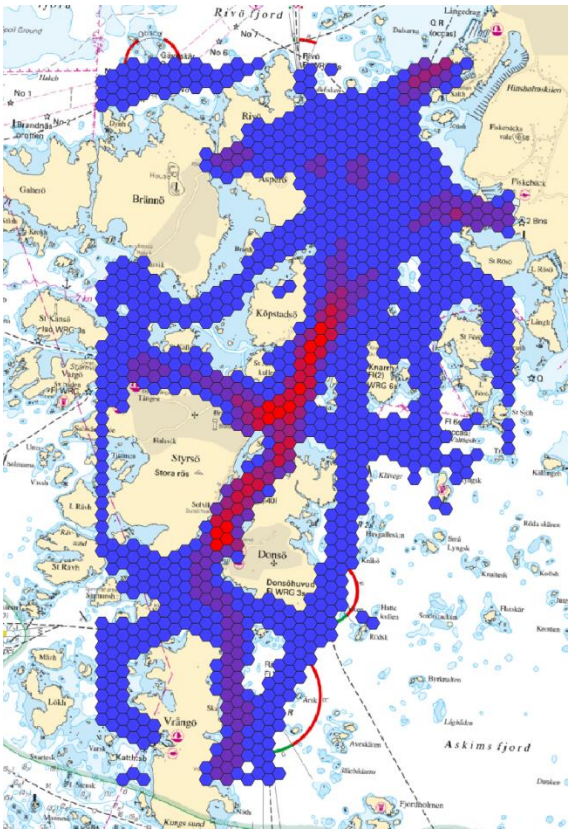
These formulations are based on basic geometric reasoning about the relative trajectories of two vessels. They may be obtained as reductions of the more complicated formulations of IALA (2023b) in that (i) uncertainty about lateral vessel locations is represented through a uniform distribution, and (ii) the severity of different conflict configurations is not based on geometry but on representative expert assessment (explained further below). The simplicity of what is described here stems from the need to operate on (combinations of) individual AIS trajectories rather than actual conflict situations, and to account for the fact that the individual trajectories are likely to be observed in a conflict-free situation, meaning that the conflict assessment must not depend on conflict-specific (e.g., evasive) vessel maneuvers.



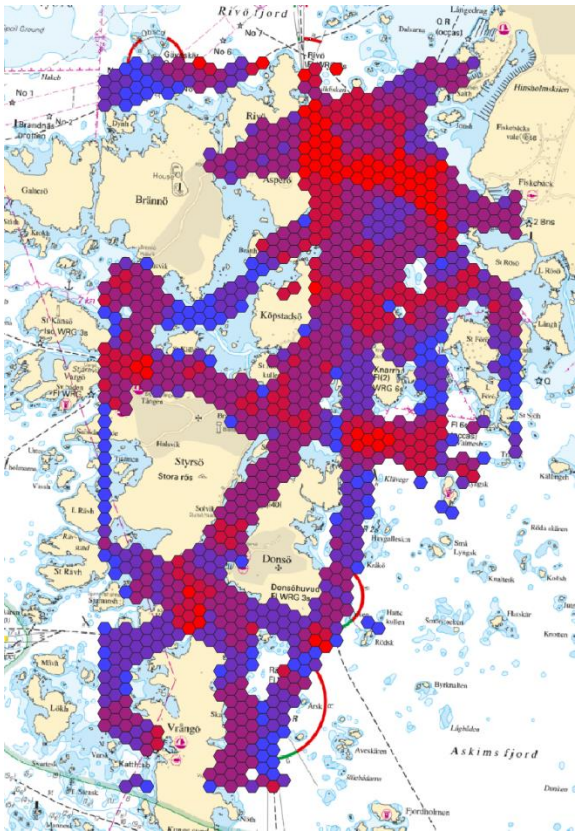
(a) Study region and AIS data



(b) Hexagonal grid



(c) Conflict intensities (blue=low, red=high)



(d) Conflict severities (blue=low, red=high)

Figure 2: Study region and analysis results

3.3 Computation of individual conflict severity θ_{ij}.

This is based on expert assessments of representative conflict situations. All possible conflict geometries of two vessel trajectories with entry/exit angles in $\{0°, 90°, 180°, 270°\}$ are enumerated, omitting redundant rotations. The expert assigned to each situation a representative severity value, using the following self-chosen criteria regarding when and how vessels must act to avoid accidents:

1 = Normal low risk. No vessel must act. Standard attention needed.

2 = One vessel must act but not the other.

3 = Both vessels must act away from each other.

4 =Both vessels must act towards each other.

5 = One or both vessels must act towards each other with same destination.

The expert was asked to assume the same conflict region size in all scenarios but was not given information about region or vessel size other than that the conflict region was assumed to be larger than the minimal safety distance between the vessels. The rationale behind this is that the resulting evaluations are supposed to represent relative (to each other) values rather than totals (of, in this study, unspecified units). Section 5 elaborates on ways to refine this representation.

Figure 3 provides several examples.

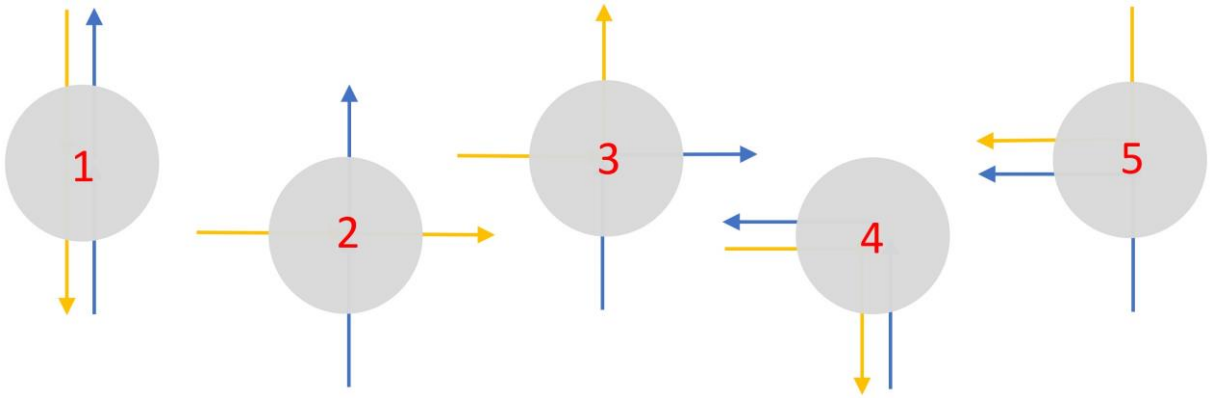


Figure 3: Examples of representative conflict situations

This classification accounts not only for the angle between two trajectories but also for the type of maneuver they are undertaking. As formulated here, it is only possible after complete trajectories (including their exit from the conflict zone) have been observed. This is suitable for the type of planning analysis motivating this work but is not applicable to (here irrelevant) real time applications where not yet completed trajectories are observed. This may be compared to Bång et al. (u.å), who process AIS trajectories for real-time traffic monitoring, using a machine learning approach.

U-turns within the conflict zone were excluded from this analysis because they were deemed not representative of regular vessel operations. Vessels moving along the same path through the conflict region are assigned a severity of zero; this may be changed if the possibility of vessels overtaking each other is to be accounted for.

The conflict severity θ_{ij} of any two given AIS trajectories i, j is computed in two steps:

1. Computation of similarity between the considered trajectory configuration and each representative situation. With $r = 1, \dots, R$ indexing the representative situations, let w_{ij}^r be the similarity between representative situation r and the trajectories i, j. It is, apart from rotation and switching trajectories, a falling function of the difference between the entry/exit angles of representative and given situation. Figure 4 provides an illustration.

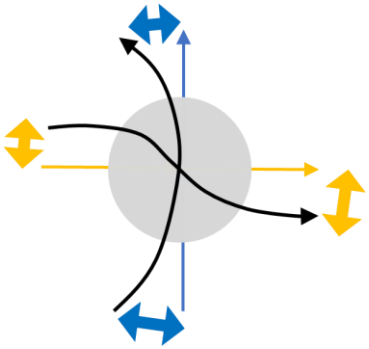


Figure 4: Matching of representative situations and a pair of AIS tracks

2. Computation of individual conflict severity as a similarity-weighted sum of all representative situations. With θ^r the conflict severity of representative situation r, this becomes

$$\theta_{ij} = \frac{\sum_{r=1}^{R} w_{ij}^r \theta^r}{\sum_{r=1}^{R} w_{ij}^r}.$$

The expert assessment-based approach described here can be extended.

- The integer risk values between one and five have no meaning beyond being comparable with each other. A more meaningful risk quantification would aim to reflect relative accident probabilities, in that a doubled risk value would correspond to a doubled probability of an accident occurring.
- Vessel speeds may affect the severities and are possible to include as additional parameters.
- The approach is expected to be transferable to the classification of grounding situations. In this setting, the expert would be given representative situations of single vehicle trajectories over a sea depth map, with the risk assessment now considering the likelihood of trajectory deviations into (too) shallow waters.

Relying on the expert assessment of representative scenarios is remotely related to “the Swedish Traffic Conflict Technique” for analyzing road intersection safety (Laureshyn och Várhelyi 2018). A major difference is that the present approach collects expert assessments of abstract (and hence transferable) situations rather than on observations of realized conflicts in real settings.

3.4 Model validation

A final step would be to validate the calculated conflict severity in different locations with an independent source of reported maritime accidents. A major challenge with this approach is both that the number of (reported) accidents is relatively low and the low spatial quality of existing accident statistics. Validating a model against accidents therefore presents a unique set of challenges, particularly when dealing with underreporting, the low geographical resolution and potential bias of the reported accidents.

A key issue when using accidents to validate the model is the low geographical resolution of the statistics. Since accidents and near-misses are reported manually through submitted reports, the geographical resolution of the incident is often low. This makes it difficult to connect a reported accident to a specific cell in the hexagonal grid. Reported accidents in maritime statistics include collisions between ships, groundings, machinery failures, among others (Transportstyrelsen 2023). Since this model focuses on incidents arising from interactions between vessels, only a subset of the reported accidents is relevant for this validation.

To address this, the proposed method of validation involves a stepwise aggregation process. The process starts with the initial hexagonal grid that predicts accident risk for each individual cell. For each cell, the accident risk is correlated with the number of reported accidents inside the cell. In the first step, most cells will have no reported accidents. Given the coarse positioning of these accidents, the next step is to aggregate the cells into larger units.

This aggregation is performed in a stepwise procedure in which the cells are combined into progressively larger geographical units at each stage. After every stage of aggregation, the correlation between the average accident risk and the number of reported accidents in each area is calculated. The hypothesis is that as the areas become larger, the correlation between the model's predictions and the reported incidents should improve, thereby compensating for the low resolution and positional inaccuracies in the accident data.

This approach aims to overcome the challenges posed by underreporting and biased geographical resolution. By dynamically adjusting the aggregation level, the method seeks to align the model more closely with the realities of reported accidents, thereby providing a more accurate and reliable validation of the model's capability to predict the risk of accidents.

4. Case study

4.1 Study region and available data

We consider the Southern Gothenburg Archipelago. The study uses approximately 3 million AIS data points which form around 370 trajectories, collected between April 8 and April 21, 2019. The time period was chosen so as to avoid the effects of ice formation and an abundance of recreational crafts, factors that the model at the current stage is not designed to handle. Also, 2019 was chosen to avoid getting a limited sample due to Covid-19. The AIS trajectories were preprocessed to reduce the number of meaningless trajectories with too long spatial or temporal distances between adjacent points; still, some artifacts remain. Study region and data are shown in Figure 2(a). The hexagonal grid overlaying the study region is displayed in Figure 2(b).

4.2 Metod application and results

AIS trajectories were analyzed per cell, as explained above. A limitation particular to this case study is that the data preprocessing reduced trajectories to their entry and exit points per grid cell, discarding possibly available information about trajectory shapes within the cells. Since the chosen grid was relatively fine compared to AIS trajectory curvature, all trajectory segments within a cell were hence treated as if they were straight lines. This means that, even though the functionality of the method is clearly demonstrated, the added value of accounting for trajectory shape during a conflict could not be demonstrated.

Visualizations of the resulting conflict intensities resp. severities are shown in Figure 2(c) resp. Figure 2(d). Since the model is not calibrated against any ground truth conflict data, only relative values are of interest. The color-coding thresholds were identified automatically to visually work out spatial variation, with blue representing low values and red representing high values.

Conflict intensity: One observes in Figure 2(c) a clear concentration in the centra north/south channel between Styrsö and Donsö. Revisiting Figure 2(a), this can be explained by the narrowness of this channel in combination with the large number of trajectories using it. The north/south traffic going East of Donsö, clearly present in Figure 2(a), has in relative terms no visual effect; these trajectories are less and more spread out. The conflict intensity in the northern region between Asperö and the mainland is also relatively low; traffic is here as well too spread out to lead to frequent conflicts.

Conflict severity: The picture in Figure 2(d) is very much different. The largest and most severe conflict region is in the diffuse traffic area between Asperö and the mainland. Trajectories often cross each other in this region, which (by expert assessment, see above) is considered more dangerous than encounters in the same or opposite direction. Interpreting the waterbody between the islands as a system of channels, one further observes that conflict severity is largest at channel intersections, which also is consistent with expert assessment.

Multiplying intensity and severity yields a map that is visually difficult to discern from the conflict intensity map. Visually more insightful analyses may be expected once conflict severities are translated into physically/economically interpretable valuations of conflict consequences (such as the expected societal cost an oil spill given the amount of oil onboard a vessel of a particular size).

5. Summary and outlook

This document describes a vessel conflict analysis technique for strategic planning and cost benefit analysis. The method is constructed to be applicable anywhere in Swedish waters, given that basic GIS/AIS data is available. The method operates on a spatial hexagonal grid and computes conflict intensity and severity measures per grid cell. The basic approach is (i) to receive expert assessments of the severity of a limited number of representative vessel conflict situations, (ii) to match the conflicts extracted from an AIS dataset against these representative situations, (iii) and aggregate this into a conflict severity measure per spatial analysis.

The method relies on combinations of AIS trajectories observed in the same region but at possibly different times. The method hence creates hypothetical vessel encounters and postulates possible conflicts to be situations that could lead to an accident if no evasive maneuver was taken. This renders the method insensitive to a lack of realized and observed conflict situations, but it also excludes an account of conflict-specific vessel maneuvers as would be of interest in a real-time traffic monitoring setting. Being by design independent of detailed, local calibration, the method operates on a relatively coarse level of detail when compared to alternative techniques on vessel conflict detection.

The basic structures described in the present document can be built upon in various directions. Model parameters may be differentiated by spatial region and vessel type. This may affect both the identification of conflicts (for instance by making the geometric reasoning dependent on vessel size or by considering overtaking in the case of non-uniform vessel speeds) and the assessment of conflict severity (for instance a geometrically fixed conflict situation becomes the more severe the lower the maneuverability of the involved vessels is). Seasonality (separate analysis for winter/summer, day/night, calm/storm) may as well be accounted for.

Being dependent on realized AIS data, the method is policy sensitive when complemented with a model predicting possible vessel trajectory changes resulting from policy actions (for instance traffic spreading out after widening of a fairway), as well as in situations where the considered action does not change vessel trajectories.

The present model identifies conflicts but not their consequences, even though these differ vastly depending on, for instance, type of vessel, type of load and environment. A downstream consequence analysis model is hence needed to enable the monetary valuation of (the consequences of) identified conflicts. This would have to rely on a more differentiated assessment accounting for conflict implications (such as damage to vessel, personal injury and loss of load, also in dependence on vessel types and speeds) than just assigning numbers one to five that have no context specific meaning.

The same principles as laid out here for conflict analysis can be adopted to the identification of groundings: (i) receive expert assessments of the severity of a limited number of representative

maneuvers in/near shallow waters, (ii) to match a given AIS dataset against these representative situations, (iii) and aggregate this into a grounding severity measure per spatial analysis. Here as well, a subsequent severity analysis would enable a monetary evaluation.

Acknowledgements

This research was funded by the Swedish Transport Administration. The authors are grateful to Ulf Svedberg at the Swedish Maritime Administration for providing crucial knowledge about ship conflict situations, and to Chengxi Liu at the Swedish National Road and Transport Research Institute (VTI) for reviewing and providing helpful comments on an earlier version of the manuscript.

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