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A kinematic method for the assessment of the safe parameters of a waterway bend

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Abstract
This paper presents an original kinematic method for the assessment of the safe parameters of waterway bends. The proposed method has been based on the analysis of the results obtained through the use of the developed simulation model which allowed for the examination of all the physically available paths of a ship's centre of gravity. The results of the simulation were divided into defined subsets that enabled the assessment of the safe parameters of waterway bends. This paper also presents the calculations that were carried out for the theoretical reference bend.

Introduction

One of the most important types of the research and studies carried out in marine traffic engineering is the assessment of the safe parameters of different types of waterways. These parameters are essential when designing new waterways as well as during the rebuilding and maintenance of existing ones. In most cases, for general calculations empirical methods are used. They are fast, inexpensive, and easy to use, but give only basic results, e.g. for a waterway bend – width and radius in most cases (PIANC, 2014). More detailed results can be obtained by using real-time simulation methods, which have been confirmed in many research projects e.g. (Artyszuk et al., 2016) or (Aarsæther & Moan, 2007). They are very precise, but time-consuming, and also require the engagement of experts and the use of advanced bridge simulators and for that reason are only used during the final, detailed design of the waterways (Gucma et al., 2015). The proposed kinematic method for the assessment of the safe parameters of waterway bends gives, in a relatively short time, detailed results without entailing high costs.

Assumptions of the kinematic model of the traffic flow on a waterway bend

To assess the safe parameters of a waterway bend a kinematic model of the traffic flow was developed. It was based on the simulation of multiple passes of a vessel through a bend of the waterway. For simplification reasons it was assumed that the bend was divided into sections and each section was divided into sectors (Figure 1), the number of sections and sectors can be freely adjusted to fit the size and shape of any waterway.

The vessel was treated as a point placed at her centre of gravity, therefore the movement parameters that were calculated, recorded, and analysed for each section were:

- COG and SOG – Course and Speed over Ground which concern the centre of gravity;

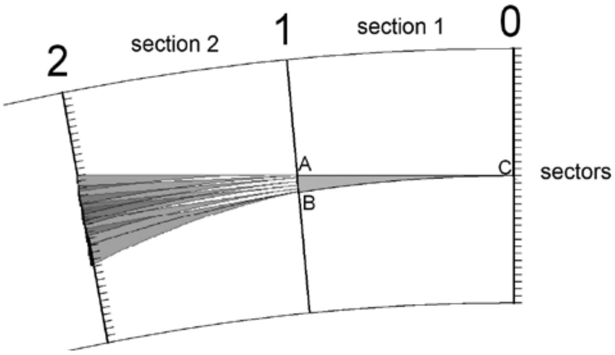

Figure 1. Sections of a waterway divided into sectors and the possible paths of a vessel

- *R* – distance from the centre of the bend (the position of the vessel is represented by the number of the section and the *R* value);
- ROG – Rotation over Ground which is the angular speed on an arc of a circle on which the centre of gravity of the ship is currently moving. Rotation over ground, ROG, should not be confused with the rotation of a vessel around its centre of gravity ROT. The ROG value can be calculated as $(\mathrm{COG}_{i-1} - \mathrm{COG}_i)/\Delta t_i$, where Δt_i is the passage time through the section i;
- *r* – radius of the circle on which the centre of gravity of the ship is currently moving.

It was assumed that the transition through the sections can be held in arcs of circles the radius of which depends on the longitudinal and angular speed. The angular speeds considered here assume the maintenance of the angular speed from the previous section or its maximum change (increase or decrease). It should be noted that the considered paths do not include all possible paths of the centre of gravity, but only its characteristic values. However this does not affect the validity of the considerations because they concern a shape of the waterway which is assumed to be passed over countless times instead of the movement of a single vessel.

It was also assumed that navigator passing the bend ends the manoeuvre in an assumed position with the COG of the next section of the waterway and with zero angular speed (ROG = 0). This approach results from the calculation algorithm, which answers the question: how should a vessel manoeuvre to achieve the assumed parameters (position, COG, ROG) at the end of the bend. The numbers of the sectors are therefore in reverse order to the order of their completion, starting from sector 0, meaning the position at the end of the manoeuvre (Figure 1).

For each passage the following rules were assumed:

- ROG cannot be negative (opposite to the bend direction – this assumption is based on the expert knowledge and manoeuvring tactics accepted for maximum vessels). The condition is not obligatory;
- The movement parameters at the end of one section become the initial parameters of the next section;
- The vessel path cannot go beyond the waterway boundaries in the next section;
- Each path has its continuation in all subsequent sections.

Taking into account the above assumptions, the calculations carried out in the model concern two main issues:

- Calculation of the position at the end of each section;
- Elimination of the paths crossing the boundaries of the waterway.

The model considered three possible movement scenarios (Figure 2):

- Rectilinear motion (ROG = 0);
- Motion when $R_{i-1} < r_i \cos\Delta C_{i-1}$;
- Motion when $R_{i-1} \geq r_i \cos\Delta C_{i-1}$.

A detailed description of the model, calculations, and dependences can be found in (Przywarty & Dzwonkowski, 2017).

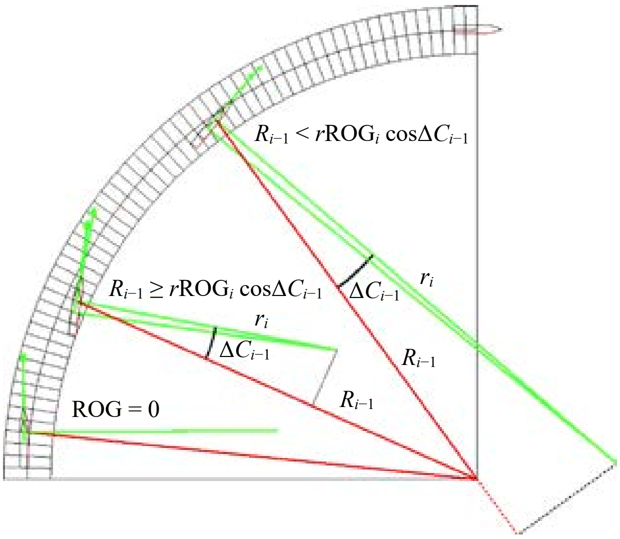

Figure 2. Geometrical dependences describing movement parameters (Przywarty & Dzwonkowski, 2017)

Proposed parameters of the waterway

The kinematic model developed for traffic flow enabled calculations for different sizes and shapes of bend as well as for different types and sizes of vessels with different manoeuvring parameters. The result of the simulation was a set of “manoeuvre events” defined as a path between the start and end of each section. Manoeuvre events that were part of the path passing through the entire bend were called successful manoeuvre events and were elements of the set $A_{\mathrm{in}\,R}$. Manoeuvre events that crossed the boundaries of the waterway were called unsuccessful manoeuvre events and were elements of the set $A_{\mathrm{out}\,R}$. The set of all the manoeuvre events A_R could be calculated as a sum of the sets $A_{\mathrm{in}\,R}$ and $A_{\mathrm{out}\,R}$. Each member of the set A_R can be described as:

$$A_R = \{\mathrm{ME}(R, \mathrm{COG}, r)\}$$

where: ME – manoeuvre event with the parameters *R*, COG, *r*.

In order to analyse the data provided by the kinematic model the following types of manoeuvre events were identified in each $A_{R,i}$ set:

- 3 possible paths in sector i+1 and 3 with continuation through entire bend (marked as 3/3 event);
- 3 possible paths in sector i+1 and 2 with continuation through entie bend (marked as 2/3 event);
- 3 possible paths in sector i+1 and 1 with continuation through entire bend (marked as 1/3 event);
- 2 possible paths in sector i+1 and 2 with continuation through entire bend (marked as 2/2 event);
- 2 possible paths in sector i+1 and 1 with continuation through entire bend (marked as 1/2 event).

The number of possible paths is a result of the assumption that a vessel can keep her present ROG or change it maximally, so there are 3 possible paths for all vessels except for those proceeding with a maximum or minimum ROG.

For further analysis the following subsets were defined in the set $A_{R,i}$:

- Subset $A_{\mathrm{in}\,R,i}$ – containing successful manoeuvre events i.e. 3/3, 2/3, 1/3, 2/2, and 1/2 types in section *i*.
- Subset $A_{\mathrm{out}\,R,i}$ – containing unsuccessful manoeuvre events in section *i* leading to the crossing of waterway boundaries in this or the next sections. The number of set elements was equal to the sum of the 2/3 events, 2×1/3 events, and 1/2 events.
- Subset $A_{\mathrm{safe}\,R,i}$ – containing all safe manoeuvre events when the vessel could proceed with any ROG. The number of set elements was equal to the sum of 3/3 and 2/2 events.
- Subset $A_{\mathrm{unsafe}\,R,i}$ – containing manoeuvre events when the vessel, in order to stay on the waterway, could proceed with only one acceptable ROG. The number of set elements was equal to the sum of 1/3 and 1/2 events.

The defined subsets were the basis for distributions that were determined for each sector and have been presented in Figures 3, 4, 5, and 6. The legend of Figure 3 also refers to Figures 4, 5, and 6.

Analysis of the $A_{\mathrm{in}\,R,i}$ subsets was based on the estimation of the empirical distributions of the successful events as a function of the distance from the centre of the bend, represented by sector number (Figure 3) and median value (the distance for which there is the same number of events on both sides).

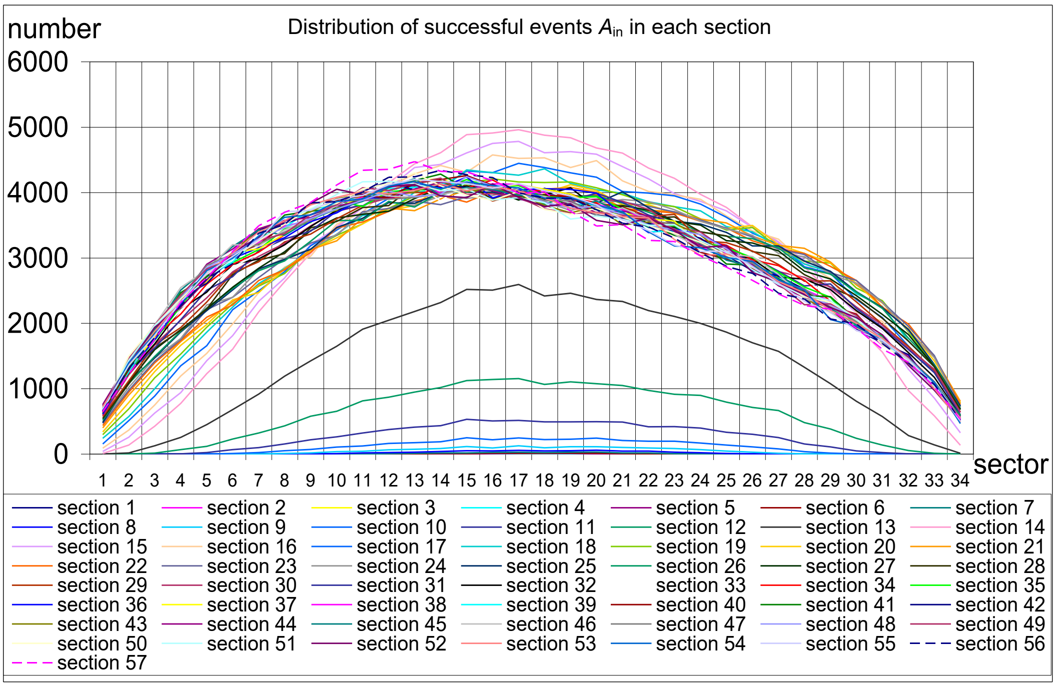

Figure 3. Exemplary distributions of successful maneuvering events A_{in} (each line represents the distribution in one section)

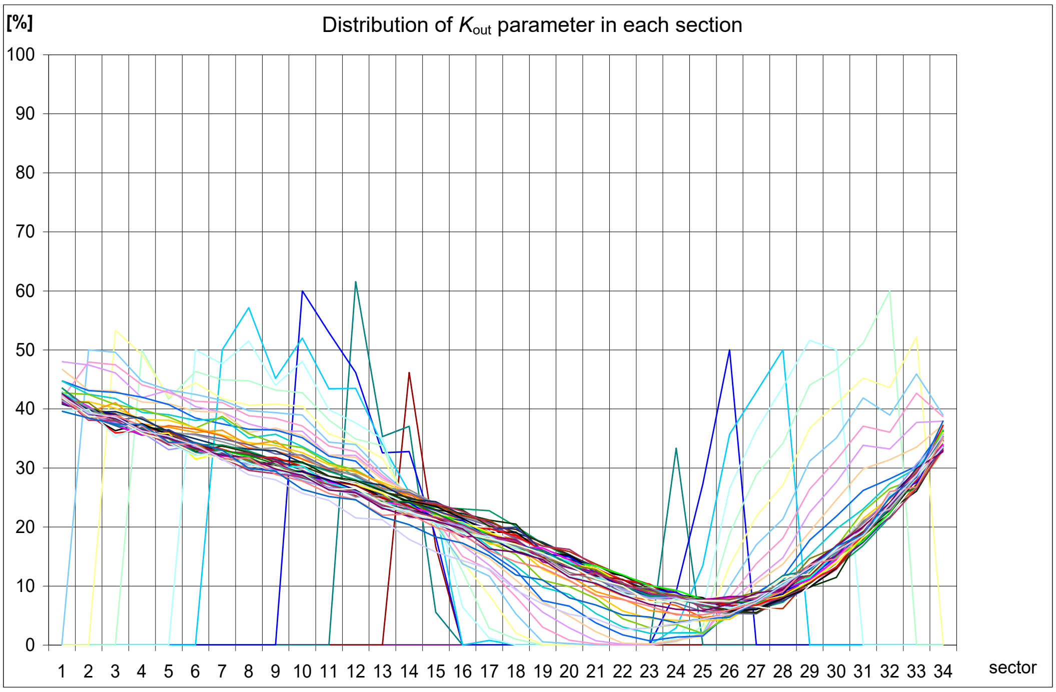

Figure 4. Exemplary distributions of the K_{out} parameter (each line represents the distribution in one section)

The calculated median allows for the determination of the area on the assumed K_{in} level. The proposed coefficient K_{in} is the percentage share of successful events and reflects the difficulty of a manoeuvre. From a practical point of view for captains/pilots even in difficult navigational conditions it is extremely rare for them to cross the boundaries of the area where the possibility of reaching the assumed final position is high. The value of the K_{in} parameter assumed for the determination of the recommended area should be confirmed by further analysis.

Analysis of the $A_{out\ R,i}$ subsets was based on the evaluation of the K_{out} parameter defined as the ratio of the number of unsuccessful events in a given sector and all the manoeuvre events in the set $A_{R,i}$ in a given sector. The distribution of the K_{out} parameter (Figure 4) enabled the estimation of the borders of the safe waterway which shouldn't be crossed by a vessel. On the basis of our own expert knowledge and experience it can be stated that the presented analysis is correct only for the outer side of the waterway. This is because actual manoeuvres at the internal part of the bend consist of either maintaining or decreasing the ROG, while the kinematic model of the traffic also generates events with an increased ROG that largely cross the waterway boundary and are not actually executed by the pilots or captains.

The analysis of the $A_{safe\ R,i}$ subset was based on the evaluation of the K_{safe} parameter which is defined as the ratio of the number of safe manoeuvre events (elements of $A_{safe\ R,i}$) and the number of successful manoeuvre events (elements of $A_{in\ R,i}$). The value calculated as $1 - K_{safe}$ is the percentage share of restricted manoeuvres i.e. manoeuvres requiring increased concentration. From the point of view of navigational safety, ships that are able to navigate through a given sector at any angular speed (ROG) have greater manoeuvring capabilities in case of unexpected events (navigational obstacles, temporary equipment failures, observation interruptions, etc.). At the same time they are less vulnerable to the influence of external conditions. From a practical point of view, in places with a large number of safe manoeuvring events, the number of commands issued by the pilot/captain decreases, reducing the likelihood of mistakes. The analysis of the distribution of the K_{safe} parameter presented in Figure 5 consists of determining the range of sectors containing an assumed percentage share of manoeuvre events.

The analysis of the $A_{unsafe\ R,i}$ subset was based on the evaluation of the K_{unsafe} parameter which is defined as the ratio of the number of unsafe manoeuvre events (elements of $A_{unsafe\ R,i}$ subset) and the number of successful manoeuvre events (elements of $A_{in\ R,i}$). The value of the K_{safe} parameter shows the precision required to maintain the angular speed (ROG). The distributions of the K_{unsafe} parameter (Figure 6) enabled the determination of the internal boundary of the waterway which should not be crossed because of the high likelihood of the lack of possibility to reach, due to high angular speed, the

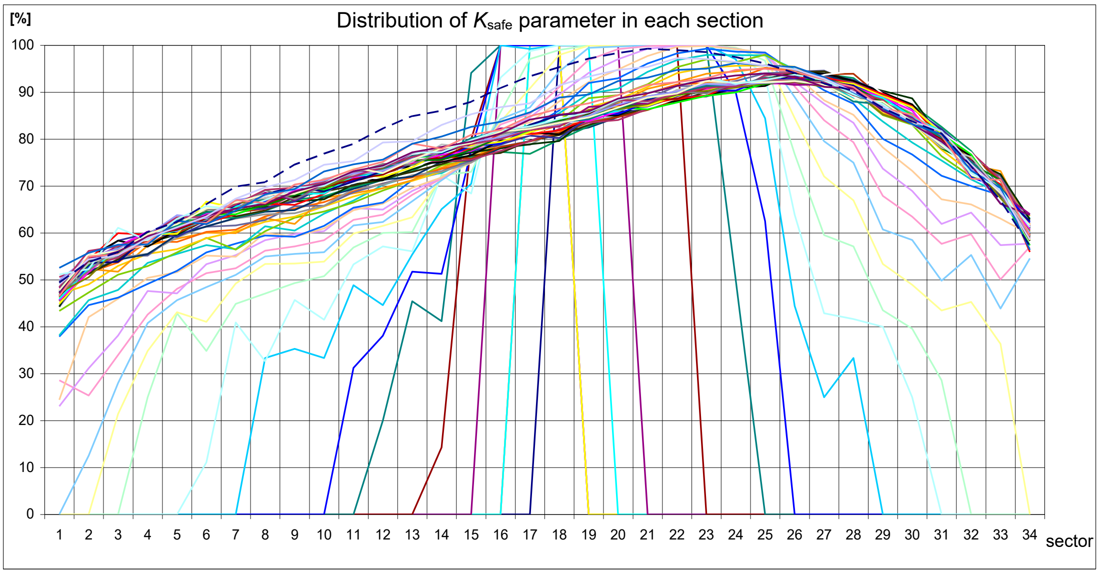

Figure 5. Exemplary distributions of the K_{safe} parameter (each line represents the distribution in one section)

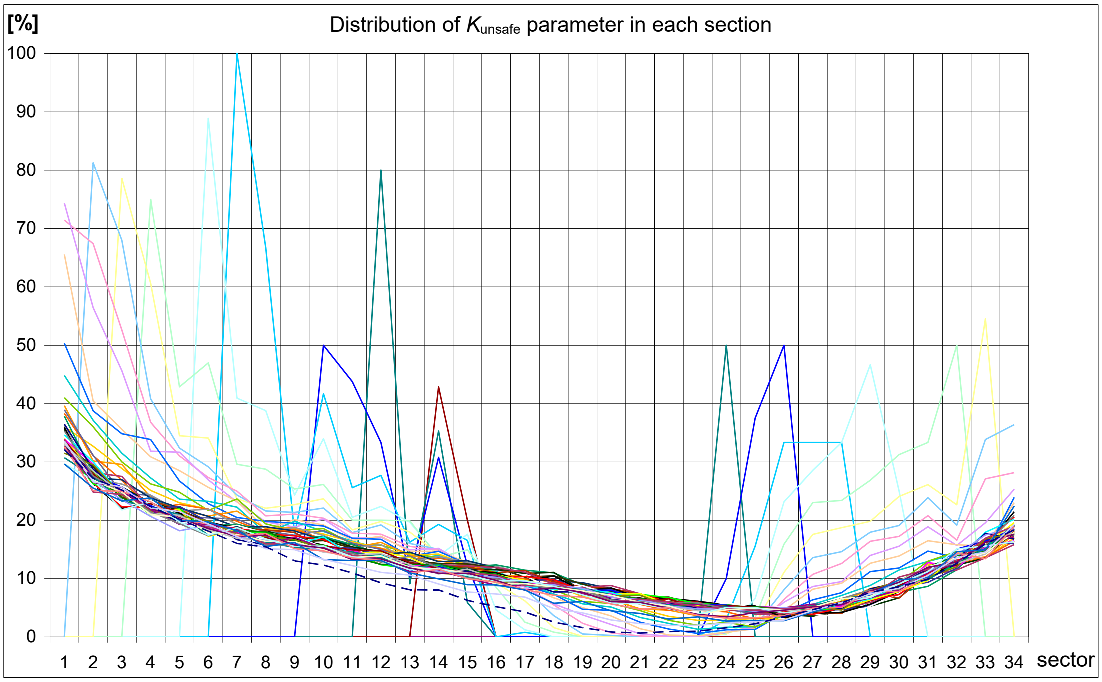

Figure 6. Exemplary distributions of the K_{unsafe} parameter (each line represents the distribution in one section)

assumed position and ROG = 0 after the manoeuvre. It is particularly dangerous in areas with insufficient navigation aids.

The safe parameters of the waterway can be evaluated as the position and width of a common part of the areas determined on the basis of the presented analysis of the parameters. As the waterway designers recommend passage in this area, it is further recognized as the recommended area. The proposed values of the parameters that provide a sufficient safety level that have been assumed for further calculations are as follows:

- K_{in} = 80% – what results in 80% of successful manoeuvre events between the boundaries;
- K_{out} should be calculated individually for a distance 0.4B (breadth of the vessel) from the inner boundary of the waterway on the reference bend;
- K_{safe} = 80% – what results in 80% of safe manoeuvre events between the boundaries;
- K_{unsafe} should be calculated individually for a distance 0.4B (breadth of the vessel) from the inner boundary of the waterway on the reference bend.

Assessment of the safe parameters for the given vessel on the given waterway bend is to compare each section width of the recommended area with the width of the recommended area on the reference waterway bend. The reference waterway bend is the bend with the assumed parameters according to the PIANC recommendations and is expected to be safe for the vessel under consideration.

Passage of the bend is hence considered as the safest if the centre of gravity of the vessel moves in the middle of the common part of the area described above. The width of the recommended area W_{recom} constitutes the safe parameters of the waterway bend.

Results for the reference waterway bend

In order to verify the results obtained by the proposed method, calculations were carried out for the 90 degree theoretical reference bend. Calculations were made using the software developed at the Marine Traffic Engineer Centre of the Maritime University of Szczecin. The bend parameters were chosen in accordance with the PIANC recommendations. The size of the ship for which the calculations were carried out was close to the maximum allowed for the assumed bend. Detailed data has been presented below.

Vessel parameters:

- Type – bulk carrier;
- L_{OA} = 195 m – overall length;
- L_{BP} = 185 m – length between perpendiculars;
- B = 29 m – breadth;
- T = 11 m – draft;
- m = 47,000 t – displacement, laden ship (corresponds to deadweight capacity of approx. 38,000 t);
- A_L = 1,200 m^2 – lateral windage area;
- propulsion: single-propeller; 8500 kW diesel engine; controllable pitch propeller, left-handed; conventional rudder; thrusters: none;
- rudder port to starboard 28 s.

Bend parameters:

- d_{COG} = 90 deg – angle of the bend;
- R = 1520 m – radius of the bend;
- W = 102 m – width of the bend.

The values of the possible rotation over ground (ROG) reflect the following assumption: the ship operator conducting the centre of gravity of the vessel on the waterway axis of the bend should have the equal possibility to change its position to each side of waterway. The middle value of rotation (ROG2) is a function of the bend radius and longitudinal speed, the lowest one (ROG1) is 0, so the highest value (ROG3) is equal to double ROG2:

- ROG1 = 0°/min;
- ROG2 = 9°/min;
- ROG3 = 18°/min.

Table 1. Calculated safe parameters of the waterway bend

	Sections					
	26–56	25	20	15	10	5
K_{out} [%]	27.64	29.63	29.64	38.69	58.21	0.00
K_{unsafe} [%]	16.16	21.34	23.68	32.90	60.00	0.00
R_{in} [%]	51.47	53.43	54.63	55.99	56.39	53.55
W_{in} [B]	2.03	2.03	1.79	1.64	1.05	0.22
R_{safe} [%]	50.00	50.00	52.11	53.92	51.78	52.94
W_{safe} [B]	2.13	2.01	1.82	1.60	1.26	0.40
R_{recom} [%]	51.61	53.62	53.70	54.61	55.59	54.31
W_{recom} [B]	2.03	2.00	1.72	1.55	1.03	0.22

The results of the analysis for the chosen characteristic sectors have been presented in Table 1, Figure 7, and Figure 8. The coordinates of the centre lines of the areas determined have been given in the percentage of the width of the waterway from the inner boundary. Widths of the areas have been given in vessel breadth.

On the basis of the results achieved for the assumed theoretical bend it can be stated that the distributions of the manoeuvre events had a symmetrical shape. The centre line of the determined recommended manoeuvring area started almost in the middle of waterway, next it ran on to the outside part of the waterway, about 5% of the width of the waterway from its centre. The width of the recommended manoeuvring area decreased from c.a. $2B$ for sections 56–26 to $1.5B$ for section 15 and finally $0.2B$ for section 5. It should be underlined that the calculated widths concern the position of a vessel that has been treated as a point, which should be considered in the final analysis of the results. The small values for the last sections were caused by the assumption that after the manoeuvre the vessel was in the centre of the waterway with ROG = 0.

Conclusions

The original proposed method based on the kinematic model of traffic flow has enabled the assessment of the safe parameters of waterway bends. It has given more detailed results than the existing empirical methods and is not as time-consuming and cost intensive as simulation methods. For the assumptions presented in this paper the duration of the numerical calculations was about 1 hour. This is comparable to the duration of one manoeuvre performed with use of the non-autonomous simulator.

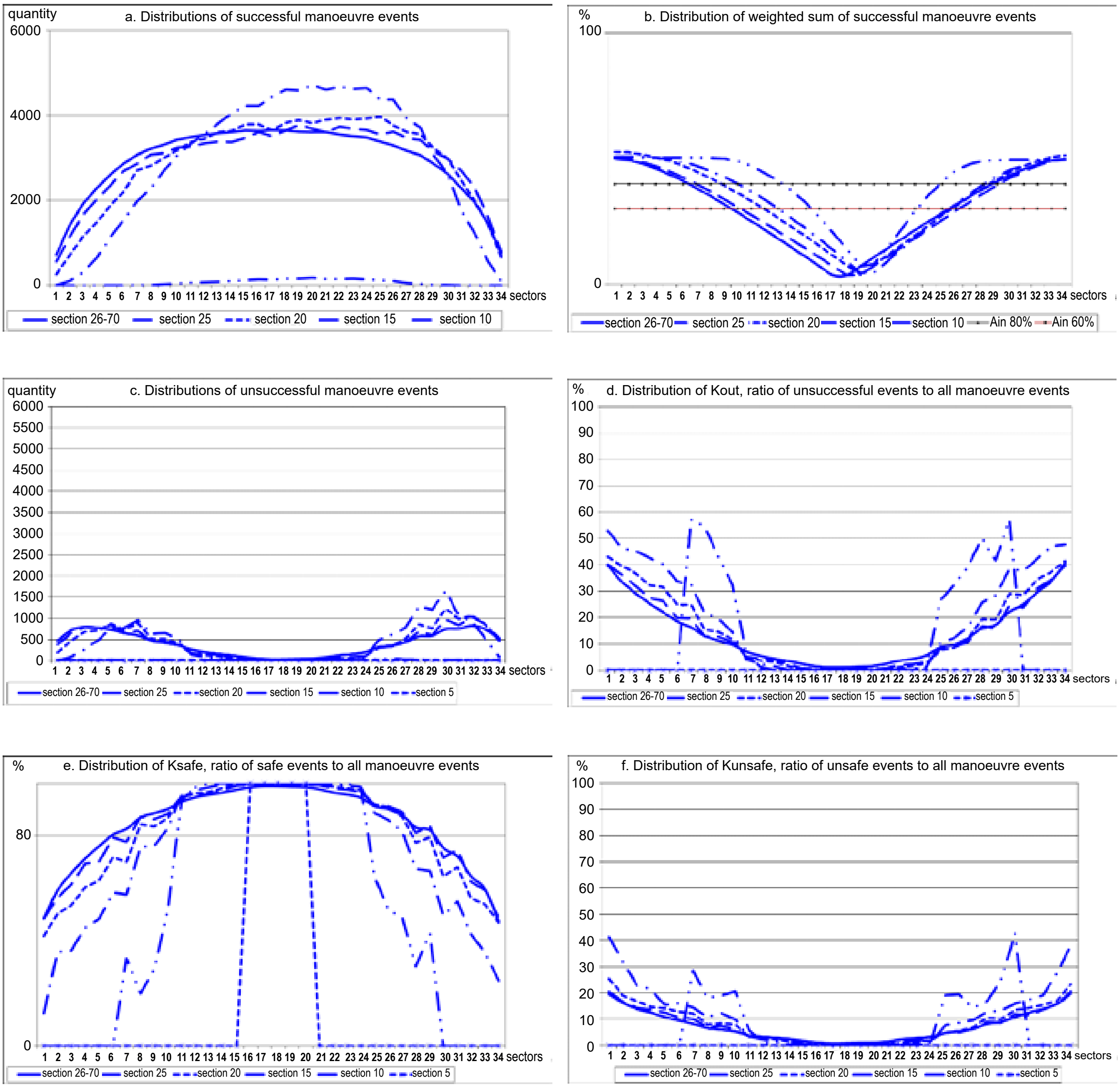

Figure 7. Distributions of manoeuvre events on the waterway bend designed with the assumed parameters according to the PIANC recommendations

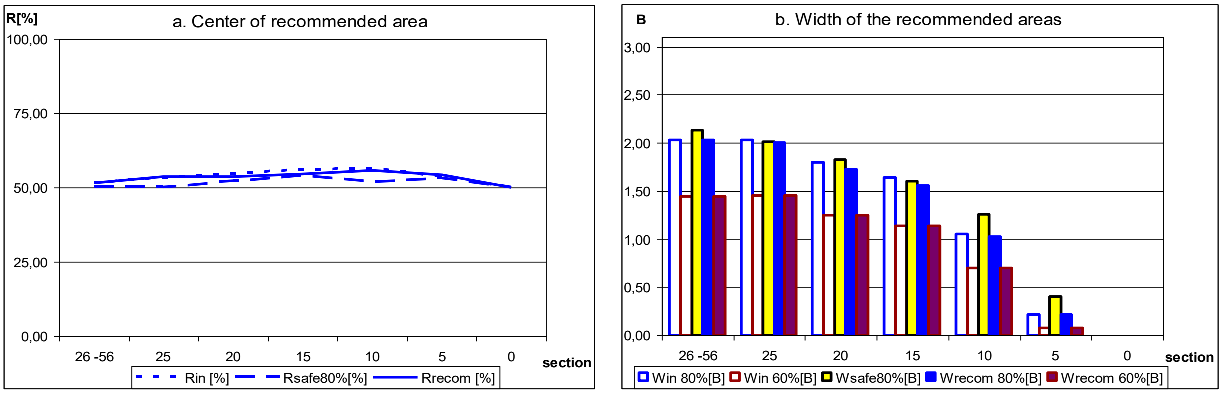

Figure 8. Widths and location of the centre line of the areas determined. Width is given in the ship's breadth, location in the percentage of the width of the waterway

the test reference bend confirmed the utility of the proposed method. A more detailed model of vessel movement, including e.g. the influence of currents, could be implemented and is being considered.

Acknowledgments

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