

Analysis of vessel traffic flows on a waterway bend

Marcin Przywarty¹✉, Jan Dzwonkowski²

¹ Maritime University of Szczecin, Institute of Marine Traffic Engineering
1–2 Wały Chrobrego St., 70-500 Szczecin, Poland, e-mail: {m.przywarty}@am.szczecin.pl

² Szczecin Pilot Station, Szczecin-Pilot Ltd
24 Światowida St., 71-727 Szczecin, Poland, e-mail: j.dzwonkowski@eragnet.pl
✉ corresponding author

Key words: vessel traffic flows, traffic intensity, fairway width, fairway bend

Abstract

This paper presents preliminary results of research to develop a method of analysis of chosen parameters of vessel traffic flows on a bend in a waterway. Assumptions within the model are based on the geometrical dependences and, for a significant part, on expert experience and real life manoeuvring tactics. The work is focused on the analysis of coordinates of a ship, reduced to its centre of gravity, for different input and assumed output parameters. The proposed method allows also for the analysis of other parameters that influence navigational safety such as rate of turn. The results confirm the possibility of assessment of traffic flow parameters with use of the developed method. In the next stages of the work, algorithms which are capable of accounting for human factors and external conditions can be implemented.

Introduction

Marine traffic engineering uses simulation or empirical (deterministic or deterministic-simulation) methods to evaluate minimum widths of waterways. The most reliable and complete results are achieved using non-autonomous simulation methods, but these are time-consuming and require engagement with experts (pilots, masters, officers) and the use of advanced full-mission bridge simulators: factors which result in high costs (Gucma et al., 2015).

For the above reasons, simulation methods are used only during the final, detailed design of waterways, as addressed in previous studies (Aarsæther & Moan, 2007; Analiza, 2014). Commonly, empirical methods are used in the preliminary design of waterways; however, in most cases they allow for evaluation of only the basic parameters such as width of the waterway. The proposed method assumes more detailed information about vessel traffic flows without entailing high costs.

Model assumptions

Development of the model is based on the simulation of multiple passes of a vessel, treated as a point (centre of gravity), through a bend of a waterway. Due to the fact that the ship is reduced to its centre of gravity, the model deals with the following movement parameters:

- Course over Ground – COG, which concerns the centre of gravity of the vessel;
- Rotation over Ground – ROG, which is an angular speed on the arc of a circle upon which the centre of gravity of the ship moves;
- Radius of the Rotation over Ground – rROG;
- Acceleration of the Rotation over Ground – aROG.

The parameters of the bend are established in accordance with PIANC recommendations (PIANC, 2014). The bend is a 90° part of the annulus divided into i sectors, where the end of each sector contains the initial parameters for the next one. The size of the sectors corresponds to a minimum time between master/pilot decisions. The pilot navigating the bend tries

to end the manoeuvre in an assumed position with an angular speed $ROG=0$. The assumed approach results from an 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 sectors are therefore numbered in reverse order with sector 0 referring to the position of the vessel at the end of the manoeuvre.

The model assumes that the transition between sectors occurs along arcs of circles whose radii depend on the longitudinal and angular speeds. The considered angular speeds assume maintaining the angular speed from the previous section or its maximum change (increase and decrease). The assumptions of the model result in a power law growth of the number of considered paths in each sector. Such a large number of scenarios allows for the movement of individual vessels to be treated as a traffic flow and for the variations in this traffic flow, both along and across the axis of waterway, to be investigated. Quantitative relationships may include traffic intensity, distributions of angular speed and course over ground. It should be noted that the considered paths do not include all possible paths that the centre of gravity could take but only its characteristic values; however, this does not affect the validity of the considerations because they concern a shape of waterway which is assumed to be passed over countless times instead of the passage of a single vessel.

Assumptions about the vessel's movement are as follows:

- ROG cannot be negative (opposite to the bend direction – this assumption is based on the expert knowledge and manoeuvring tactics accepted for a maximum number of vessels).
- The vessel's path cannot extend beyond the waterway boundaries in the next sector.
- Each path has its continuation in all subsequent sectors.

Simulations

Simulation experiments were carried out to verify the possibility of the use of the presented method for the evaluation of traffic flow parameters on a waterway bend. Assumptions about the experiment are as follows:

Vessel:

- bulk carrier type, $L_{oa} = 225$ m and $B_{oa} = 32.3$ m;
- speed over ground $SOG = 4$ m/s;
- ability to change the rudder position approx. every 12 s (value based on the experts knowledge and experience);

- minimum $ROG_0 = 0^\circ/\text{min}$, maximum angular speed acceleration approx. $31^\circ/\text{min}^2$, hence angular speed $ROG_1 = 7.84^\circ/\text{min}$, angular speed $ROG_2 = 15.68^\circ/\text{min}$, max angular speed $ROG_3 = 23.52^\circ/\text{min}$.

Waterway bend:

- bend radius $R_c = 1754$ m, waterway width calculated for centres of gravity $W = 126$ m, bend parameters were evaluated in accordance with PIANC recommendations (PIANC, 2014) for the presented bulk carrier;
- section width $\Delta\delta = 1.5^\circ$ giving approx. 44 m for the waterway axis.

It should be noted that ROG_1 corresponds to the nominal angular speed in the bend with radius 1754 m and for a ship moving with $SOG = 4$ m/s, confirmed by expert knowledge and PIANC recommendations concerning radius of bends and angular speeds.

Nominal angular speed depends on the bend radius and for the linear movement is equal $0^\circ/\text{min}$, hence for the observer in the reference system rotating with nominal angular speed $ROG_1 = 0^\circ/\text{min}$, $ROG_0 = -7.84^\circ/\text{min}$, $ROG_2 = +7.84^\circ/\text{min}$. For this reason it was assumed that $ROG_2 = 2(ROG_1 - ROG_0)$ and $ROG_3 = 3(ROG_1 - ROG_0)$. The model allows for reassessment of the initial parameters for different vessels, manoeuvring, waterway bends and external factors.

At the end of sector 1 (after the manoeuvre) the vessel has angular speed $ROG_{i-1} = 0^\circ/\text{min}$ and COG perpendicular to the waterway axis, i.e. for the assumption that $\alpha_{i-1} = 90^\circ$. Because $ROG_{i-1} = 0^\circ/\text{min}$ and the vessel cannot turn in the opposite direction to the bend, the straight line ($ROG_1 = 0^\circ/\text{min}$) and the curve corresponding to $ROG_1 = 7.84^\circ/\text{min}$ can begin at the end of sector 1. The intersections with the boundary of sector 1 of this straight line and curve give two points. Distances from the centre of the bend are $R_1 = 1754.6$ m and $R_1 = 1754.0$ m, COGs $\alpha_1 = 90^\circ$ and $\alpha_1 = 88.5^\circ$, $ROG_1 = 0^\circ/\text{min}$ and $ROG_1 = 7.84^\circ/\text{min}$. From these two points begin the next straight lines and curves. For $R_1 = 1754.6$ m two paths (as before a straight line and curve) and for $R_1 = 1754$ m three paths for $ROG_2 = 0^\circ/\text{min}$, $ROG_2 = 7.84^\circ/\text{min}$, $ROG_2 = 15.68^\circ/\text{min}$. From the five points at the end of sector 2, 13 paths can begin, one of which for $ROG_2 = 23.52^\circ/\text{min}$, because this is the maximum angular speed, from this point onwards only two new paths can be extended, $ROG_3 = 15.68^\circ/\text{min}$ and $ROG_3 = 23.52^\circ/\text{min}$ (Figure 1).

Calculations carried out in the model concern two main issues: calculation of vessel position and COG in each sector and elimination of paths that extend

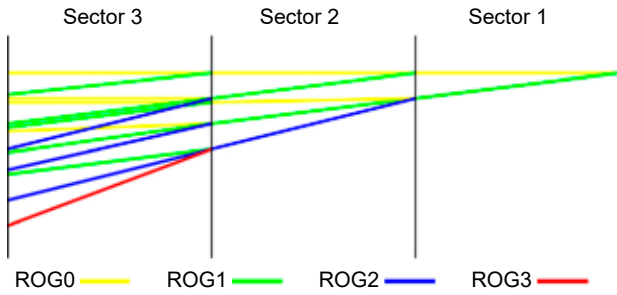


Figure 1. Scheme presenting the transitions of centres of gravity between the sectors for ROG0, ROG1, ROG2, ROG3

beyond the waterway boundaries. Position is given in the polar system, where the radius R_i is a distance from the centre of the bend and the angle is represented by a sector number. Values of radius R_i , course over ground COG_i , and the radius $rROG_i$ of the present course depend on the values within the previous sector, as described by the following relationship:

$$\begin{bmatrix} R_i \\ COG_i \end{bmatrix} = f \begin{bmatrix} R_{i-1} \\ COG_{i-1} \\ rROG_i \end{bmatrix} \quad (1)$$

The dependencies comprise three possible scenarios: linear motion, motion for $R_{i-1} < r_i \cos \Delta C_{i-1}$ and $R_{i-1} > r_i \cos \Delta C_{i-1}$ (Figure 2).

For $ROG = 0$:

$$COG_i = COG_{i-1} \quad (2)$$

where: COG_{i-1} , COG_i – COGs at the end of the sections $i-1$ and i .

$$R_i = R_{i-1} \left(\frac{1}{\cos \phi} + \frac{\sin \phi \operatorname{tg} \Delta C_{i-1}}{\cos \Delta C_i} \right) \quad (3)$$

where:

R_{i-1} , R_i – line segment between centre of gravity and the centre of the bend for sections $i-1$ and i ;

ΔC_{i-1} , ΔC_i – difference between COG_{i-1} or COG_i and nominal courses at the end of sections $i-1$ and i i.e. $C_{\text{Nominal } i-1}$ and $C_{\text{Nominal } i}$;

ϕ – angle between sections $i-1$ and i .

For $R_{i-1} > rROG_i \cos \Delta C_{i-1}$

$$\begin{aligned} \beta_i &= \beta_{i-1} - \phi = \\ &= \left(\operatorname{arctg} \left(\frac{rROG_i \sin \Delta C_{i-1}}{R_{i-1} - rROG_i \cos \Delta C_{i-1}} \right) \right) \frac{180}{\pi} - \phi \quad (4) \end{aligned}$$

where:

β_{i-1} , β_i – angle between line segment S_{Rr} (joining centre of turning circle and centre of bend) and line segments R_{i-1} and R_i ;

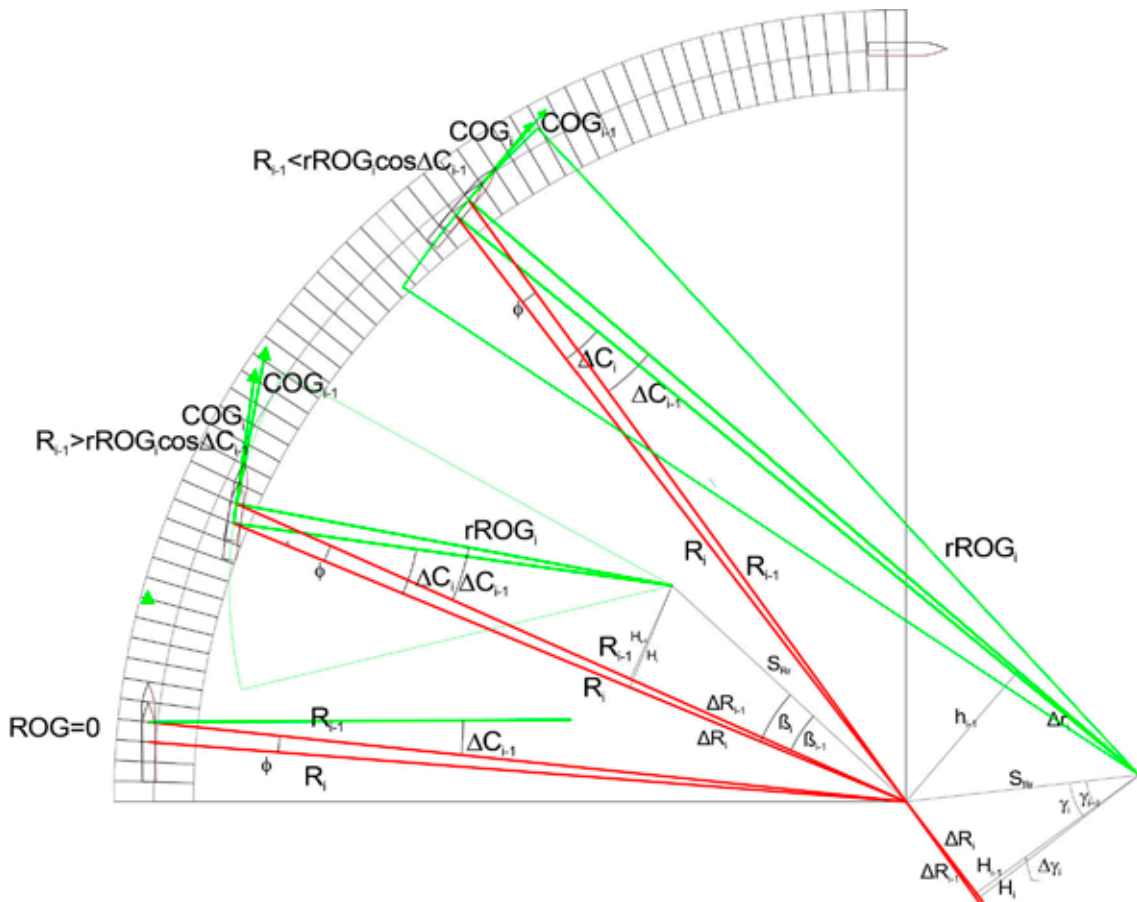


Figure 2. Geometrical dependencies describing movement parameters

$r\text{ROG}_i$ – radius of present circulation (circle described by arc of present course) in section i .

$$S_{Rr}^2 = R_{i-1}^2 - 2R_{i-1}r\text{ROG}_i \cos \Delta C_{i-1} + r\text{ROG}_i^2 \quad (5)$$

$$H_i = S_{Rr} \sin \beta_i \quad (6)$$

where: H_i – distance between R_i and centre of present circulation

$$\text{COG}_i = C_{\text{nomini-1}} - \phi + \left(\arcsin \left(\frac{S_{Rr} \sin \beta_i}{r\text{ROG}_i} \right) \right) \frac{180}{\pi} \quad (7)$$

$$R_i = \sqrt{r\text{ROG}_i^2 - H_i^2} + S_{Rr} \cos \beta_i \quad (8)$$

For $R_{i-1} < r\text{ROG}_i \cos \Delta C_{i-1}$

$$S_{Rr}^2 = R_{i-1}^2 \sin^2 \Delta C_{i-1} + r\text{ROG}_i^2 + 2R_{i-1}r\text{ROG}_i \cos \Delta C_{i-1} + R_{i-1}^2 \cos^2 \Delta C_{i-1} \quad (9)$$

$$\begin{aligned} \gamma_i &= \gamma_{i-1} - \phi = \\ &= \left(\arctg \left(\frac{R_{i-1}}{r\text{ROG}_i \sin \Delta C_{i-1}} - \text{ctg} \Delta C_{i-1} \right) \right) \frac{180}{\pi} - \phi \end{aligned} \quad (10)$$

where: γ_{i-1}, γ_i – angles between line segment S_{Rr} and lines containing segments R_{i-1} and R_i

$$H_i = S_{Rr} \cos \gamma_i \quad (11)$$

$$\text{COG}_i = (C_{\text{nomini-1}} - \phi) + \left(\arcsin \left(\frac{H_i}{r_i} \right) \right) \frac{180}{\pi} \quad (12)$$

$$R_i = \sqrt{r\text{ROG}_i^2 - H_i^2} + S_{Rr} \sin \gamma_i \quad (13)$$

In order to optimize the calculations, the paths that extend beyond the waterway boundaries are eliminated from the model. Calculations are performed to find the extreme value of COG for the distance R_i that remains within the waterway boundaries. The present angular speed and the time required to change from ROG0 to ROG4 is also considered.

For the inner boundary, ROG0 and ROG1, the minimum COG can be calculated as follows:

$$\text{COG}_{i \min} = \left(90 - \arccos \frac{R_{\text{inner}}}{R_i} \right) - i \cdot \phi \quad (14)$$

where:

$\text{COG}_{i \min}$ – extreme COG in vicinity of inner boundary of waterway;

R_{inner} – radius of inner boundary of waterway.

For ROG2 and ROG3, the positions in sectors $i+1$ and $i+2$ are checked and the same procedure as was presented for ROG0 and ROG1 is followed.

For the outer boundary and for ROG3 and ROG2, the maximum COG is calculated as follows:

$$\begin{aligned} \text{COG}_{i \max} &= \\ &= 90^\circ - i \cdot \phi + \arccos \frac{R_i^2 - R_{\text{out}}^2 + 2R_{\text{out}}r\text{ROG}_{(1,2,3)}}{2R_i r\text{ROG}_{(1,2,3)}} \end{aligned} \quad (15)$$

where:

$\text{COG}_{i \max}$ – extreme heading in vicinity of outer boundary of waterway;

R_{out} – radius of outer boundary of waterway;

$r\text{ROG}_{(1,2,3)}$ – radius of present circulation for ROG1, ROG2, ROG3.

If the vessel in a sector proceeds linearly (ROG0) she can change her angular speed to ROG1 in section $i+1$ and next to ROG2 in section $i+2$ and finally to ROG3 in section $i+3$. The model checks whether the path extends beyond the waterway boundaries in sections $i, i+1$ and $i+2$ and for the next sections for ROG3. A similar approach is used for each section and for angular speeds ROG1, ROG2 and ROG3 (Figure 3).

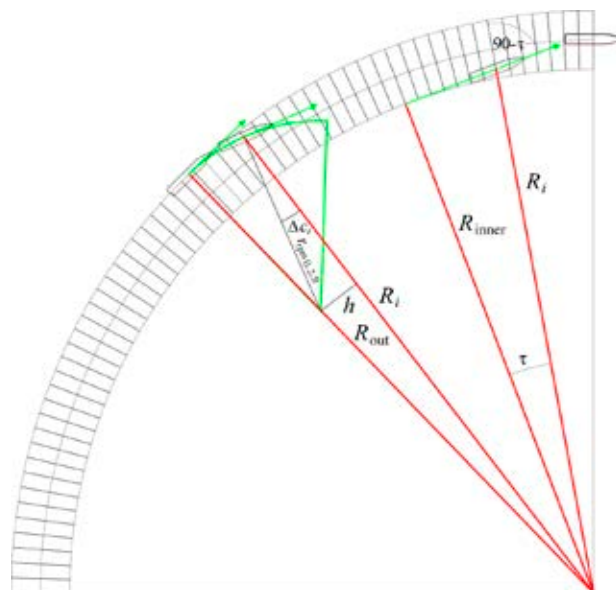


Figure 3. Elimination of paths extending beyond the waterway boundaries

Calculations were carried out for the 13 positions in sector $i = 0$ (every 10 meters in both directions from the axis of waterway) and for three COGs in section $i = 0$ $87^\circ, 90^\circ$ and 93° . The number of paths in each section was calculated for intervals of 3.5 m.

Elimination of paths affects all paths that go beyond the waterway boundaries either in the present sector or in subsequent sectors. This ensures

that the model considers only complete paths from the beginning to the end of the bend. Together with the elimination process, the number of paths where the navigator was forced to select a specific angular speed was evaluated.

Despite the elimination of paths extending beyond the boundaries of the waterway, their number increases greater than two-fold in each sector. Due to the computational capabilities of the applied software, the number of considered paths was randomly restricted to 50 000 in each sector.

Results

The results are separated into 3 categories. “Main stream” traffic with no restrictions to angular speed, “entire stream” traffic with and without restrictions and “restricted stream” traffic calculated as the difference between entire stream and main stream traffic. Analysis of traffic parameters can be carried out either in the direction of vessel movement ($i-0$) or in the opposite direction ($0-i$). The presented results are based on the analysis in the $0-i$ direction. To simplify interpretation of the results, the sectors are identified by their angles (e.g. sector 60 will be marked as 90°).

The results achieved for the $0-i$ analysis of the entire stream, for end positions in the centre of the waterway and shifted 30 m in both directions (Figure 4), allow for the following conclusions to be drawn:

1. From sector 90° to 18° , main flow covers half of the waterway width and its percentage share is 3–5% for each 3.5 m segment.
2. From sector 90° to 30° side flow covers half of the waterway width and its percentage share is ca. half of the main flow share.
3. In all cases, entire stream traffic is similar between sectors 90° and 42° and is shifted to the inner boundary of the waterway. The maximum percentage share is at 16 m from the waterway axis, the median is 7 m from the waterway axis.
4. Visible differences between results for each end position start from ca. sector 36° . Streams leading to an end position of +30 m (30 m from the axis of waterway in the direction of the outer waterway boundary) start to decline in section 36° . Streams leading to an end position of -30 m (30 m from the axis of waterway in the direction of the inner waterway boundary) start to decline in ca. sector 27° .
5. From sector 27° to 18° , main flow traffic with a percentage share 3–5 % for the streams leading

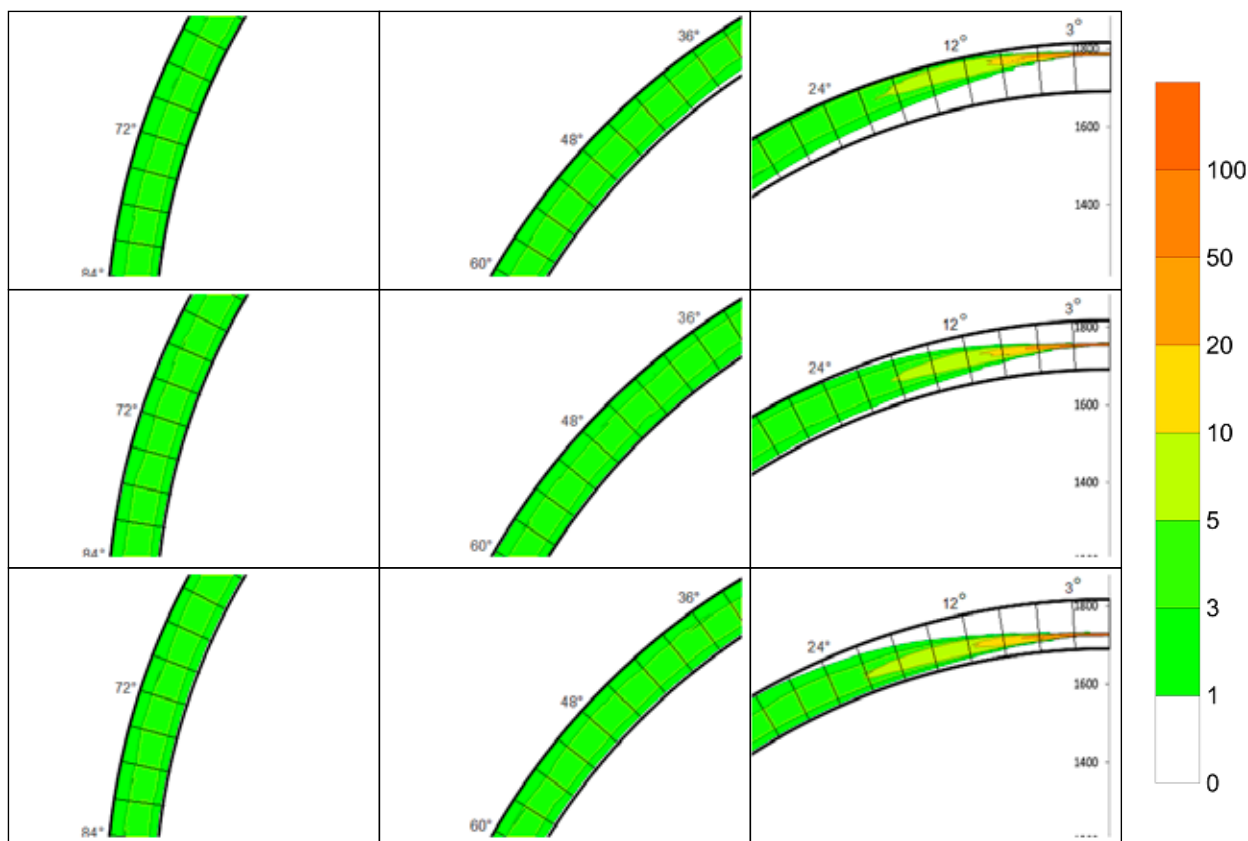


Figure 4. Density distribution of the entire stream in each sector for end positions in the centre of the waterway and shifted 30 m in both directions

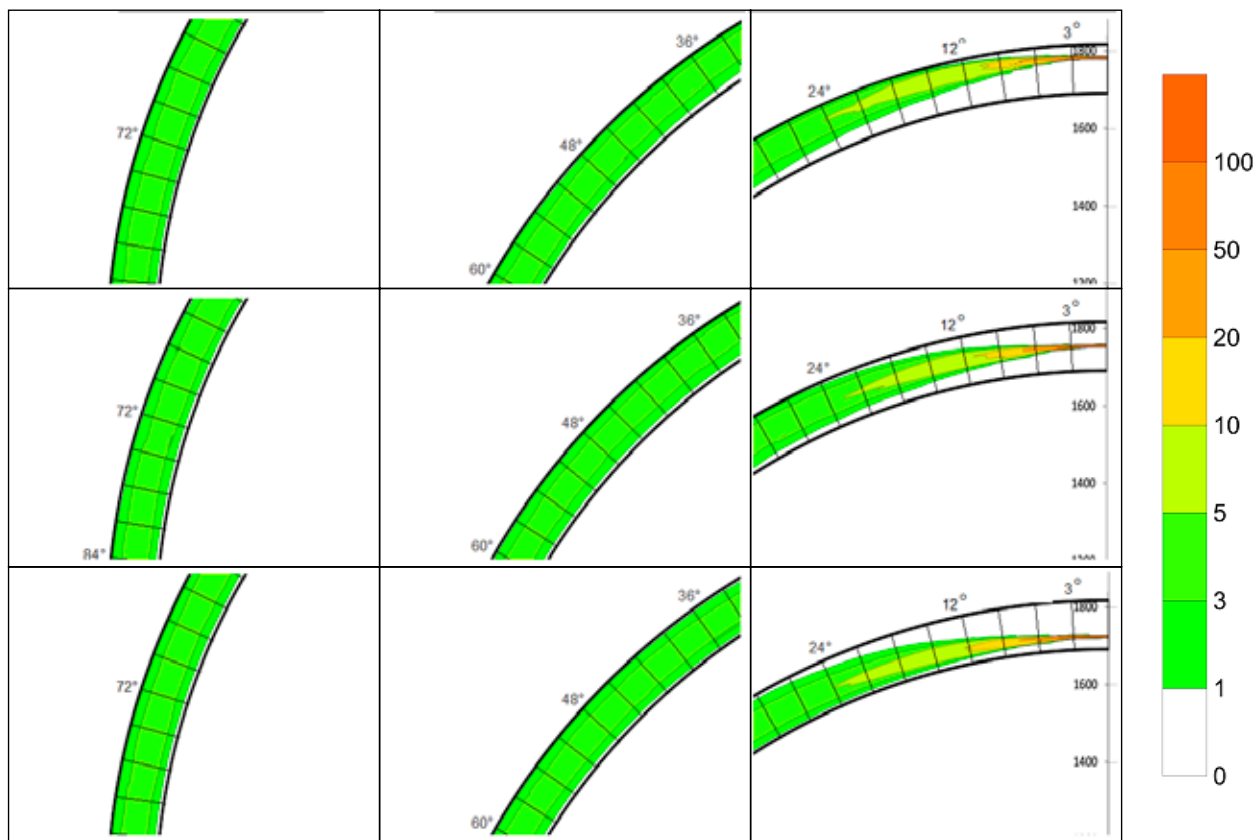


Figure 5. Density distribution of the main stream in each sector for end positions in the centre of the waterway and shifted 30 m in both directions

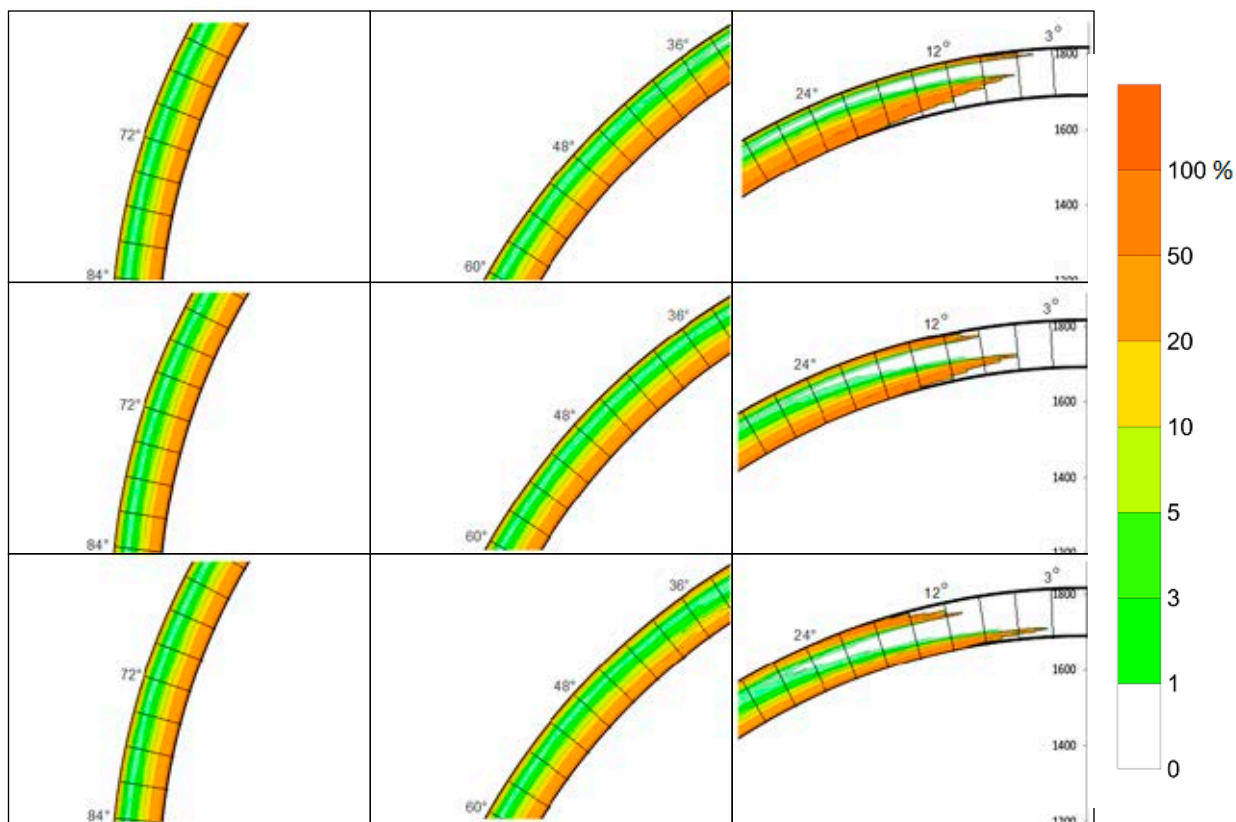


Figure 6. Percentage share of the main stream in the entire stream across each sector for end positions in the centre of the waterway and shifted 30 m in both directions

to an end position +30 m is still dominant and is located close to the outer waterway boundary.

Figure 5 presents the results achieved for the main stream, meaning the stream in which the navigator can freely choose the angular speed. From these results, it can be concluded that:

1. From sector 90° to 18° main flow covers half of the waterway width, as was the case for the entire stream.
2. In the ca. 4 m distance from the inner boundary of waterway, the percentage share of flow is close to 0%.
3. Dominating flow boundaries are shifted from 15 to 20 m in the direction of the outer boundary of the waterway, but the maximum and median flows are in the axis of waterway.
4. Visible differences between the results for each end position start from ca. sector 36° . For the end position 0 and +30 m, the dominant flow is close to the outer boundary of the waterway and both flows are similar to sector 27° where they split.

Figure 6 presents the area where the navigator can freely change the angular speed (white in colour) and the percentage share of the situations with restrictions concerning angular speed. Assuming a maximum share of situations with restrictions of 10%, the centre of gravity of the vessel should be positioned in sector 30° at a distance of about one third of the waterway's width from the outer boundary. The width of such a defined flow (less than 10% with restrictions) is about half of the waterway width. For end positions of 0 (centreline of the waterway) and -30 m, the circulation radius should be changed; for the end position +30 m the radius can be maintained. This shows that proper construction of waterways helps the navigator achieve the

assumed end position and maintain a stable radius of circulation.

Conclusions

The presented method of analysing traffic flow on a waterway bend is in its preliminary phase of development. Confirmation, based on the simulation experiments, and further theoretical studies, based on mathematical modelling (Gutenbaum, 2003) is required. The presented results confirm that the developed method can be used to develop a comprehensive simulation model of vessel traffic.

The approach presented in this paper, after verification and validation, will allow for the preliminary determination of parameters of waterway bends with the consideration of local conditions such as currents, winds, shallow waters etc. and for the analysis of vessel traffic flows on a waterway bend.

References

1. AARSÆTHER, K.G. & MOAN, T. (2007) Combined Maneuvering Analysis, AIS and Full-Mission Simulation. *International Journal on Marine Navigation and Safety of Sea Transportation*. Faculty of Navigation, Gdynia Maritime University. Gdynia.
2. Analiza (2014) *Analiza nawigacyjna modernizacji Toru Wodnego Świnoujście-Szczecin (pogłębienie do 12.5 m)*. Praca naukowo-badawcza pod kierunkiem S. Gućmy, Szczecin (in Polish).
3. GUCMA S. et al. (2015) *Morskie drogi wodne. Projektowanie i eksploatacja w ujęciu inżynierii ruchu*. Gdańsk: Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej (in Polish).
4. GUTENBAUM, J. (2003) *Modelowanie matematyczne systemów*. Warszawa: Polska Akademia Nauk.
5. PIANC (2014) Harbour Approach Channels. Design Guidelines. Report No. 1212.