Journal of
Marine Science and Engineering

MDPI

Article

Dimensioning of Fairway Bends—Kinematic Method of Numerical Simulation

Stanisław Gucma [1], Marcin Przywarty [1,*], Jan Dzwonkowski [2] and Mateusz Bilewski [1]

[1] Faculty of Navigation, Maritime University of Szczecin, 70-500 Szczecin, Poland; s.gucma@am.szczecin.pl (S.G.); m.bilewski@am.szczecin.pl (M.B.)
[2] Szczecin—Pilot Station, 71-727 Szczecin, Poland; jdzwonkowski@szczecinpilot.pl
* Correspondence: m.przywarty@am.szczecin.pl; Tel.: +48-604-143-747

Received: 10 January 2020; Accepted: 12 February 2020; Published: 20 February 2020

check for updates

Abstract: The article presents a new kinematic method of numerical simulation intended for establishing dimensions of safe manoeuvring areas of bends in various types of fairways for vessels of specific parameters. The method consists of multiple numerical simulations of a ship's passage (ship's centre of gravity) through a bend, representing the entire physically possible movement of the ship, and an analysis of simulation results. The developed method was verified on the bends of the Świnoujście–Szczecin fairway, by comparing the results to the exact simulation method of a ship's movements. The relatively high accuracy and low costs of the method allow it to be used in a concept design of built or modern waterway systems.

Keywords: manoeuvring safety; safe manoeuvring area; dimensioning of fairway bends

1. Introduction

Although international seaborne trade lost momentum in 2018, with volumes only increasing at 2.7%, after a surge of 4.1% in 2017, in 2018 world seaborne trade volumes rose to a new all-time high of 11 billion tons [1]. The increase in seaborne trade causes an increase in the number and size of ships. In January 2019, the world fleet reached a carrying capacity of 1.98 billion dwt, 52 million dwt more than the previous year. [1]. The growing parameters of ships entail the necessity of port infrastructure development. One of the major problems in marine traffic engineering is to determine safe parameters of fairways, i.e., safe depth and width at the bottom in straight sections and bends (turns) of the fairway. Dimensioning of fairway bends for known angles of turn and arc radiuses comes down to the determination of their safe manoeuvring areas. A safe manoeuvring area of the bend must meet the basic condition of navigational safety [2]:

$$\left.\begin{array}{r} \boldsymbol{d}_{ik(1-\alpha)} \subset \boldsymbol{D}_i(t) \\ \bigwedge\limits_{p(x,y)\in D_i(t)} h_{x,y}(t) \geq T_k + \Delta_{ik(1-\alpha)} \end{array}\right\} \tag{1}$$

$\boldsymbol{d}_{ik(1\text{-}\alpha)}$ – safe manoeuvring area in i-th bend for k-th ship performing a simulated manoeuvre specified at the level of confidence 1-α;
$\boldsymbol{D}_i(t)$ – available navigable area of i-th bend (the condition of safe depth at instant t is satisfied);
$h_{xy}(t)$ – water depth at point (x, y) at instant t;
T_k – maximum draft of k-th ship;
$\Delta_{ik(1\text{-}\alpha)}$ – underkeel clearance in i-th bend determined for k-th ship at the level of confidence 1-α.

There are a number of empirical and simulation methods for determining safe manoeuvring areas (safe widths) in fairways. Empirical methods of the dimensioning of safe manoeuvring areas within straight fairway sections are relatively accurate and do not require simulation methods [3].

These include the method developed by Permanent International Association of Navigation Congresses (PIANC) [4], the Spanish method [5] and the Polish deterministic-probabilistic method developed by the Marine Traffic Engineering Centre (MTEC/CIRM) [6]. Their accuracy varies within 5% of the fairway width. On the other hand, empirical methods used for the dimensioning of safe manoeuvring areas of fairway bends are less accurate, and their accuracy calculated on the basis of its comparison to the results of simulation experiments and real traffic analysis, depending on ship type and bend parameters, may reach 60% of fairway width [6].

Simulation methods for the dimensioning of safe manoeuvring areas of fairway used in marine traffic engineering can be divided as follows:

1. real-time simulation of ship movement controlled by a human operator using non-autonomous simulation models;
2. fast-time simulation of ship movement with a mathematical model of the navigator using autonomous simulation models;
3. kinematic numerical simulation method determining a safe manoeuvring area based on multiple computer simulations of ship passage representing a wide set of physically possible ship movements in the bend.

Real-time ship movement simulation methods in which the simulation experiment is conducted on full mission bridge simulators (FMBS) following specific research procedures [1] enable the determination of bend widths with high accuracy. However, these methods are relatively cost-intensive due to the need to perform a lot of simulated passages executed by qualified fairway pilots in real time in order to have a reliable sample size [3].

Methods of fast-time ship movement simulation allow accurate determination of safe fairway width, but they have not been widely used due to a complex human decision algorithm, limiting the application of the method for complex manoeuvring [2].

The kinematic numerical simulation method for the determination of safe manoeuvring areas in a bend presented in this article is more accurate than empirical methods, much faster and less expensive than the method of real-time simulation. It allows the development of software that does not require specialist handling and can be used by waterway designers and marine administration personnel. Compared to the fast-time simulations they are easier to develop and use because of the lack of a problem related to complex human decision algorithm. The proposed method is easier and faster to build and use than methods using fast-time simulations. The quality of the results obtained with the use of fast-time simulations methods is influenced by the quality of the ship (steering) model, but also the model of the human decision-making process (errors), which makes obtaining reliable results in navigable complex waters difficult. According to [4], fast-time simulations are considered appropriate for representing the behavior of a pilot on relatively straight channels or fairways without complex bends or series of bends.

The kinematic numerical simulation method is used for the determination of the manoeuvring component of safe areas in fairway bends [7]. The method uses a movement model that conceptually consists in multiple simulations of a ship's centre of gravity passages along the bend divided longitudinally into sectors and transversely into segments. The model represents a wide set of physically possible ship movements in the bend. Paths of ship's centre of gravity consist of, numerically calculated in each sector, circle arcs or sections that are further regarded as separate manoeuvring events (Figure 1). Sets of manoeuvring events generated in this way are subject to further analysis for the safety of manoeuvring [8].

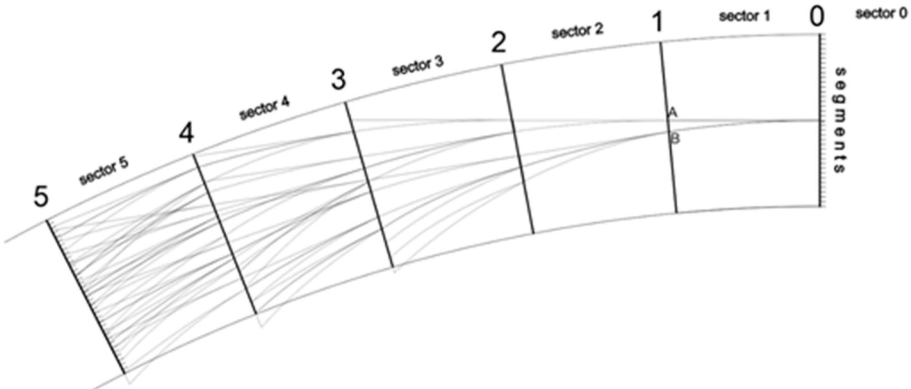

Figure 1. Paths of ship's centre of gravity in the kinematic model of movement.

The method has the following assumptions [7]:

- movement model on which the method is based refers to the centre of gravity, which means that the swept path of the ship is different from the path followed by its centre of gravity by an additional margins depending on the drift and parameters of the ship (e.g. breadth and length);
- tests are of a retrospective nature and start from the position in which the ship's centre of gravity completes negotiating a bend;
- for sets of events to describe the entire physically possible movement and the movement model to be similar to reality, the arcs along which the ship's centre of gravity moves have to result from the maximum rudder settings used in sea practice;
- the sector size is chosen so that it is equal to the ship track during the changes made in settings of the steering gear. The time is established as 10 seconds, which meets the classification society requirements referring to the rudder change from 'midships' to the maximum rudder angle in a fairway bend of 20°, recommended by international organisations [9,10];

The procedure for calculating the possible paths of the center of gravity of a ship is as follows:

- For the sector 0 (end of the maneuver) it is assumed that the ship has a heading corresponding to the straight section of the fairway adjacent to the bend and the rate of turn (ROT) is 0 °/min.
- Because the ROT is 0 °/min in section 0, it is possible that the rudder angle is 0° or 10° in section 1. Hence, the positions of 2 points in section 1 can be determined (points A for rudder angle 0° and B for rudder angle 10° in the Figure 1).
- For each of these 2 points, possible paths in section 2 are determined. The number of possible points is 5, i.e. 2 for point A (rudder angle 0° and 10°) and 3 for point B (rudder angle 0°, 10° and 20°).
- The calculations are repeated until the last section of the bend. It is also checked whether the paths are in the assumed preliminary boundaries of the bend.

The results of movement model calculations are sets of arcs and sections (manoeuvring events) in each sector, subject to analysis resulting from the assumptions of the developed method.

Input data for the movement model are: geometric parameters of the fairway bend and adjacent straight sections, their boundaries and longitudinal and angular speeds for rudder deflection angles of 10° and 20°, depending on ship size. The longitudinal speed of a ship negotiating a bend depends on its parameters (angle of turn, arc radius) and ship parameters. It usually ranges from 6 to 10 knots.

The angular speed (ROT) in the bend depends on:

- parameters of the bend (angle of turn, arc radius),
- rudder deflection angle (10° or 20°),
- ship size and manoeuvring characteristics,

- initial ship speed,
- external conditions (wind, current, waves).

It was assumed that the angular speed of a ship in the bend depends on length of the ship and the block coefficient of the hull. Additionally, the impact of the initial longitudinal speed and rudder angle were taken into account. Due to the variability of external conditions (wind, waves, current, shallow water) the authors decided not to take them into account in the determination of the ship's ROT in the bend at this stage of development. The ship's ROT can be calculated using the following relationship [7]:

$$ROT = ROT_{NOM} + \Delta ROT_{SOG} + \Delta ROT_{\alpha} \tag{2}$$

where

ROT – ship's ROT in the fairway bend [deg/min];
ROT_{NOM} – nominal ROT determined from manoeuvring data [deg/min];
ΔROT_{SOG} – change in the ROT due to other than nominal initial longitudinal speed of the ship [deg/min];
ΔROT_{α} – change in the ROT due to the change in rudder angle [deg/min].

The impact of the selected factors on the ship's ROT in the bend was determined on the basis of the review of the publications [11–13] and gathered manoeuvring data from ships of various types and sizes. First, a relationship was derived between the length of the ship and the ROT read out from available manoeuvring data for a 90 degree turn (Figure 2). An analysis was made for ships of various sizes, different loading conditions and for longitudinal speeds corresponding to full speed ahead, at maximum rudder angle (35°–45°). The ships were divided into two groups based on the block coefficient criterion: large (Cb ≥ 0.75) and small (Cb < 0.75). The nominal ROT values for ships of various sizes and block coefficients were determined through an analysis of the gathered data (Table 1).

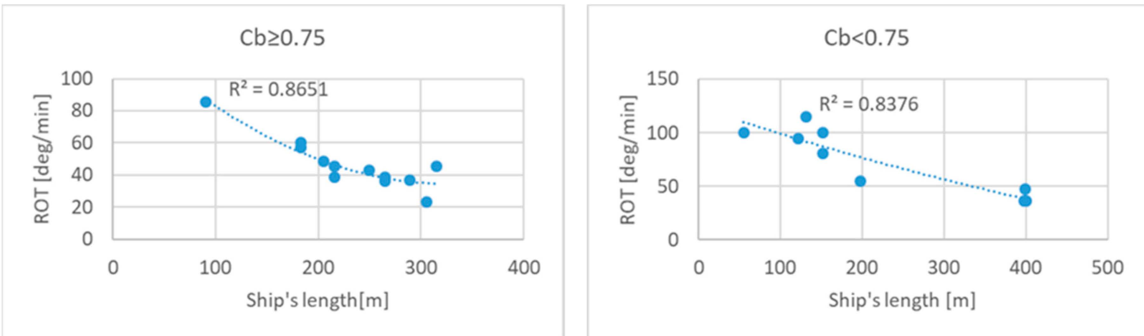

Figure 2. Rates of turn (ROT) of ships of various lengths and block coefficients of the hull [7].

Table 1. Nominal ROT in fairway bends.

Ship's Length [m]	ROT_{NOM} [deg/min]	
	Cb ≥ 0.75	Cb < 0.75
60	101.362	108.722
80	91.626	103.846
100	82.610	99.050
120	74.314	94.334
140	66.738	89.698
160	59.882	85.142
180	53.746	80.666
200	48.330	76.270
220	43.634	71.954
240	39.658	67.718
260	36.402	63.562
280	33.866	59.486
300	32.050	55.490

A change in the ROT that results from other than the nominal initial longitudinal speed of the ship was calculated from gathered manoeuvring data and from a literature review [14]. It was found that no significant differences exist between ships with large and small block coefficients, so the analysis was combined for both ship groups (Figure 3).

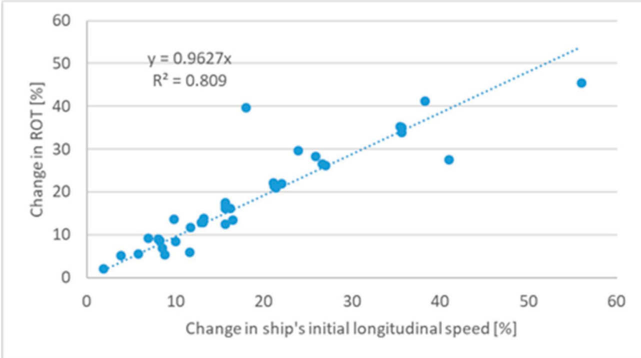

Figure 3. The change in ROT that results from the longitudinal speed change [7].

Based on an analysis of the results, it was assumed that the percentage change of ROT is equal to the percentage change of initial longitudinal speed. Therefore, it can be calculated by using the following relationship:

$$\Delta ROT_{SOG} = \left[\frac{SOG - SOG_{NOM}}{SOG_{NOM}}\right] ROT_{NOM} \quad (3)$$

where

- ΔROT_{SOG} – change in the ROT due to other than nominal initial longitudinal speed of the ship [deg/min];
- SOG – initial longitudinal speed of the ship [kts];
- SOG_{NOM} – initial longitudinal speed adopted for the determination of ROT_{NOM} [kts];
- ROT_{NOM} – nominal ROT [deg/min].

An additional decrease in the ROT due to the rudder angle being less than the maximum can be calculated as:

$$\Delta ROT_{\alpha} = -k(ROT_{NOM} + \Delta ROT_{SOG}) \ \ [\mathrm{deg/min}] \quad (4)$$

The values of the coefficient k determined from literature review [11,13] are presented in Table 2.

Table 2. Nominal ROT in fairway bends.

Rudder Deflection Angle [deg]	k
>=35	0
30	0.09
25	0.24
20	0.29
15	0.39
10	0.50
5	0.57

2. The Kinematic Numerical Simulation Method of Dimensioning Safe Manoeuvring Areas in Fairway Bends

The safe manoeuvring area of a bend in the kinematic numerical simulation method is located between the certain boundaries. The boundaries of fairway bends in the method concerned are defined by the positions for each sector, in which the ratio of hazardous manoeuvring events to successful manoeuvring events, i.e., those having their continuation from beginning to end of the bend, is 5%. This value corresponds to a ratio of 95% of safe manoeuvring events to successful manoeuvring events.

It was assumed that hazardous manoeuvring events are those in which the ship, to reach the end of the bend, must proceed in the examined sector at the limit rate of turn. At the external boundary, this is the maximum ROT (rudder angle 20°) while at the internal boundary it corresponds to rectilinear movement with rudder angle 0°. The ship moving between the boundaries thus defined can in at least 95% of cases use any ROT in the range from 0° (straight movement) to that corresponding to the assumed maximum rudder angle (20°).

Numerical tests are conducted for the ship's centre of gravity, whose location was adopted as the centre of its breadth and length overall. The fairway boundaries are then calculated by the addition of half of a ship breadth and the values corresponding to the ship's drift due to the assumed maximum ROT of the ship. The boundaries between which the ship may move in a bend are preliminarily calculated by empirical methods.

In this way, the dimensioning of the safe manoeuvring area of a bend by the kinematic method of numerical simulation is conducted according to the following algorithm (Figure 4):

1. Determination of the conditions for safe operation of ships on the fairway including the designed bend. These conditions are expressed as a set of conditions for safe operation of a 'maximum ship' i.e. a ship having the largest dimensions on the fairway:

$$\boldsymbol{W} = [C_b, L_c, B, T,\ V_i, \boldsymbol{H}_i] \tag{5}$$

where

C_b – block coefficient that characterizes the type of the 'maximum ship' [-]
L_c – length overall of the 'maximum ship' [m];
B – breadth of the 'maximum ship' [m];
T – draft of the 'maximum ship' [m];
V_i – speed of the 'maximum ship' in i-th section of the fairway [kts];
$\boldsymbol{H}_i$ – set of allowable hydrometeorological conditions for the passage of the 'maximum ship' along i-th section of the fairway.

$$\boldsymbol{H}_i = \left[\Delta h, V_w,\ V_{pi}\right] \tag{6}$$

where

Δh – allowable drop of water level on the fairway for the 'maximum ship' [m];
V_w – allowable speed of the 'maximum ship' entering the fairway [kts];
V_{pi} – allowable current speed for the 'maximum ship' in i-th section of the fairway [kts].

2. The determination of the bend parameters, including its beginning and end, by specifying four points (Z_1, W_1, Z_2, W_2) corresponding to the boundaries of straight sections adjacent to the bend (Figure 6). Besides, the width of these straight sections is determined by the CIRM method at the confidence level (1-α) = 0.95 or it results from infrastructure restrictions in the area.
3. Preliminary determination of bend boundaries (safe depth contours) by the CIRM's probabilistic-deterministic method. The width of safe manoeuvring area in the bend for one-way traffic at the confidence level (1-α) = 0.95 is calculated from this relation [6]:

$$d_{z(1-\propto)} = d_{mz} + 2d_{n(1-\propto)} \tag{7}$$

where

$d_{z(1\text{-}\alpha)}$ – safe width of the manoeuvring area of the bend at the confidence level (1-α) [m];
$d_{n(1\text{-}\alpha)}$ – navigational component of the width of the safe manoeuvring area of the bend at the confidence level (1-α) [m];
d_{mz} – manoeuvring component of the safe manoeuvring area width of the bend [m];

The manoeuvring component of safe manoeuvring area width is, respectively [8,15]:

$$d_{mz} = d_m + \Delta d \tag{8}$$

where

d_m – manoeuvring component of safe manoeuvring area width in a straight section of the fairway [m];
Δd – widening of the vessel's swept path in a bend [m].

4. Determination of the safe manoeuvring area of the ship's centre of gravity for a bend at the level of confidence (1-α) = 0.95 through numerical research and an analysis of the results for four cases, i.e., for both directions of passing through the bend and for two positions of the end of the turn determined by the boundaries of the manoeuvring areas of adjacent straight sections of the fairway determined at the confidence level (1-α) = 0.95 (Figure 6). The safe manoeuvring area of a ship's centre of gravity in the bend is determined by adding four components of the manoeuvring areas of the ship's centre of gravity calculated at the confidence level (1-α) = 0.95 (Figure 5) [7]:

$$\boldsymbol{d}_{ms(1-\alpha)} = \boldsymbol{d}_{pz(1-\alpha)} \bigcup \boldsymbol{d}_{pw(1-\alpha)} \bigcup \boldsymbol{d}_{lz(1-\alpha)} \bigcup \boldsymbol{d}_{lw(1-\alpha)} \tag{9}$$

where

$\boldsymbol{d}_{pz\,(1\text{-}\alpha)}$ – manoeuvring area of the gravity centre of a ship turning right, completing the manoeuvre at a point of external boundary (Z1) of the adjacent manoeuvring area of a straight fairway section, (1-α) = 0.95;
$\boldsymbol{d}_{pw\,(1\text{-}\alpha)}$ – manoeuvring area of the gravity centre of a ship turning right, completing the manoeuvre at a point of internal boundary (W1) of the adjacent manoeuvring area of a straight fairway section, (1-α) = 0.95;
$\boldsymbol{d}_{lz\,(1\text{-}\alpha)}$ – manoeuvring area of the gravity centre of a ship turning left, completing the manoeuvre at a point of external boundary (Z2) of the adjacent manoeuvring area of a straight fairway section, (1-α) = 0.95;
$\boldsymbol{d}_{lw\,(1\text{-}\alpha)}$ – manoeuvring area of the gravity centre of a ship turning left, completing the manoeuvre at a point of internal boundary (W2) of the adjacent manoeuvring area of a straight fairway section, (1-α) = 0.95;

The internal boundary in each sector is the position determined by 5% of successful manoeuvring events, in which the centre of gravity must move straight ahead to reach the end of the bend at a position that is on the boundary of the next fairway section. Similarly, the external boundary is determined by 5% of successful manoeuvring events, in which the centre of gravity must move at maximum ROT to reach the end of the bend in a place corresponding to the boundary width of the next fairway section.

In the developed application for the calculation of the safe manoeuvring area of the centre of gravity, the user enters geometric parameters of the area determined by the CIRM method, determines the number of intervals and sectors, the required course and place of leaving the bend, and the allowable rates of turn of the ship's centre of gravity. Next, the limits of allowable bend radiuses and rates of turn can be optionally introduced, separately for each of the sectors. The bend is symbolically depicted on the right-hand side of the application so that the parameters can be verified. The calculations are made according to the algorithm starting from the departure from the bend. The algorithm indicates potential positions and courses that the ship may have assumed in the previous sector and saves those tracks in the memory (list). Because the number of tracks is growing rapidly, which would make calculations impossible (both RAM memory and computing time are limited), the algorithm checks if the assumed limit of tracks has not been exceeded. In the tests, presented below in this article, the number of tracks was limited to 100,000. If the limit is exceeded, then for each of the tracks a number [0,1] is drawn at random and compared to the quotient of the number of obtained tracks and the defined limit. If the drawn number is larger, then this track is rejected. This will allow the number of tracks examined not to exceed significantly the specified limit. If the limit is not exceeded, the algorithm immediately passes to the next sector and repeats the calculations until the beginning of the bend is reached. Once the tracks are created, each is examined for the number of potential antecedents, and the results are saved in a text file. The program also enables drawing a set of tracks in a graphical file.

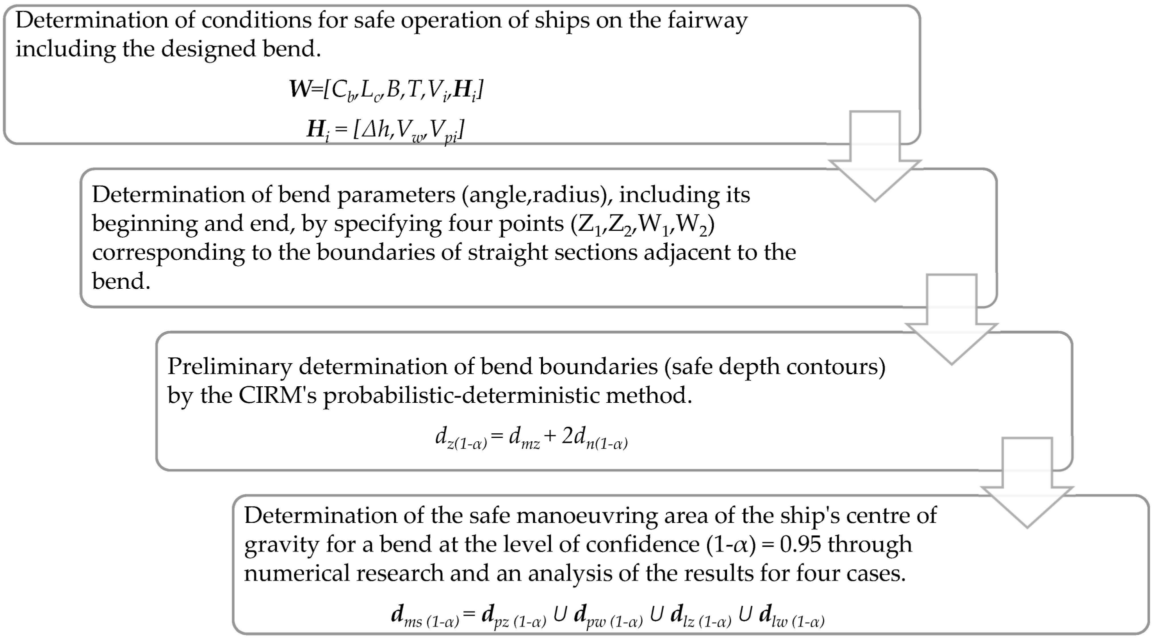

Figure 4. Algorithm of the dimensioning of the safe manoeuvring area of a bend by the kinematic method of numerical simulation.

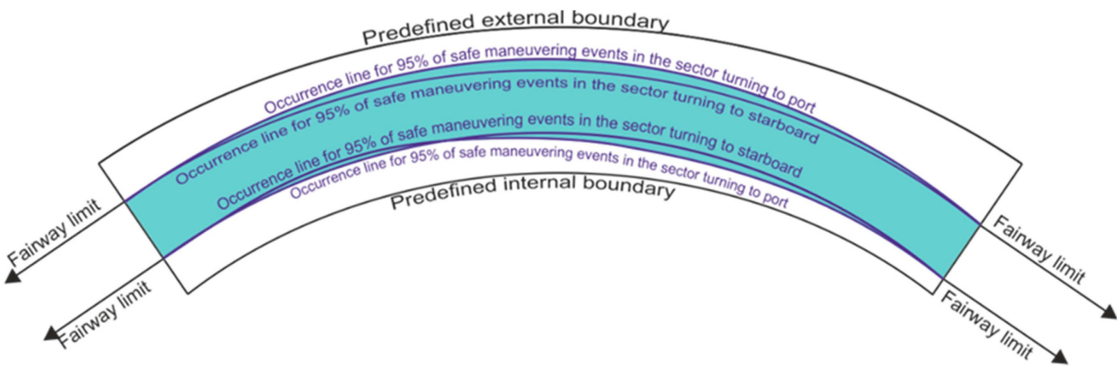

Figure 5. An example outcome of tests conducted by the kinematic method of numerical simulation. Recommended shape of the bend is presented in blue.

5. The determination of the safe manoeuvring area of the bend for the 'maximum ship' at the confidence level (1-α) = 0.95 using the following relationship:

$$d_{m(1-\alpha)}(j) = d_{ms(1-\alpha)}(j) + \Delta d_z + \Delta d_w \tag{10}$$

where

$d_{ms(1-\alpha)}(j)$	–	width of the manoeuvring area of ship's centre of gravity at j-th sector of the bend at the level of confidence (1-α) [m];
Δd_z	–	additional margin of the manoeuvring component of the bend width allowing for ship's parameters (Lc, B) and its drift angle on the external part of the bend [m];
Δd_w	–	additional margin of the manoeuvring component of the bend width allowing for the ship's parameters and its drift angle on the internal part of the bend [m].

An additional correction of the manoeuvring component is determined using the drift angle method.

$$\Delta d_z = +\frac{L_c}{2} \cdot sin\alpha \frac{B}{2} \cdot cos\alpha \tag{11}$$

$$\Delta dw_= \frac{B}{2} \tag{12}$$

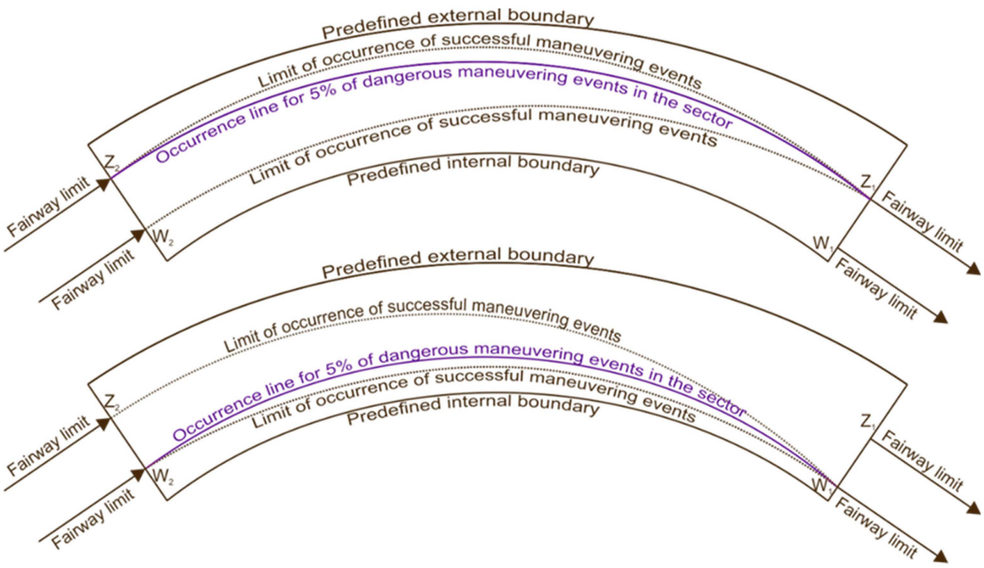

Figure 6. An example distribution of manoeuvring events for one direction of ship movement resulting from numerical tests.

3. Verification of the Kinematic Numerical Simulation Method of the Dimensioning of Safe Manoeuvring Areas in Fairway Bends

The method was verified in two bends of the fairway linking the ports of Świnoujście and Szczecin:

- Mańków bend (41.1 ÷ 42.3 km of the fairway)
  - turning angle $\Delta\psi$ = 26°
  - radius of arc R_z = 2200 m
- Ińskie bend (51.7 ÷ 53.0 km)
  - turning angle $\Delta\psi$ = 42°
  - radius of arc R_z = 1860 m

The tested 'maximum ship' was a bulk carrier with the following parameters:

w	=	47,000 t	–	displacement, loaded ship;
L_c	=	195 m	–	length overall;
L_{pp}	=	185 m	–	length between perpendiculars;
B	=	29 m	–	breadth;
T	=	11 m	–	draft;
A_L	=	1200 m^2	–	lateral windage area;

The bulk carrier was adopted as a 'maximum ship' to use the Świnoujście–Szczecin fairway after its upgrade, for which simulation tests were carried out [16,17]. The results of the tests served for the verification of the kinematic method of the determination of safe bend widths.

Taking into account ship and area parameters as well as sea practice, a longitudinal speed of eight knots was assumed.

Safe manoeuvring areas of the tested bulk carrier in the Mańków and Ińskie bends were determined by two methods (Figures 7 and 8):

- kinematic method of numerical simulation (described above);
- method of ship movement simulation, where the experiment was conducted on a full-mission bridge simulator Polaris from Kongsberg [16]. This simulator meets the Class A standards of marine simulator certification, which means hardware compliance with the requirements of the International Convention on Standards of Training, Certification and Watchkeeping (STCW). The simulator is used for trainings in accordance with the requirements of the STCW convention and recommendations of NI (Nautical Institute) and IMCA (International Marine Contractors Association). The number of simulation maneuvers in the test series was assumed to be equal to 12 for one wind direction. The tests were conducted for the two least favorable wind directions. Since no significant differences in the results were found, safe maneuvering areas were determined jointly for both directions of wind (with the number of trials being equal to 24). Approximately 10 pilots and experienced captains participated in the study. Each of them made several passages.

Safe manoeuvring areas determined by the CIRM method are also presented in the Figures 7 and 8 as green lines, as they were used in the kinematic method of numerical simulation.

The sizes of safe manoeuvring areas of the examined bulk carrier (L_C = 195 m, B = 29.0 m, T = 11.0 m) for the Mańków andIńskie bends calculated by three methods are shown in Table 3.

Table 3. The areas of safe manoeuvring areas of the Mańków andIńskie bends.

Method of Calculations	**Mańków Bend** • **Turning Angle: 26°** • **Radius: 2200 m**	**Ińskie Bend** • **Turning Angle: 42°** • **Radius: 1860 m**
simulation method of ship movement	81,956 m^2	107,163 m^2
kinematic method of numerical simulation	114,764 m^2	148,790 m^2
probabilistic-deterministic CIRM method	148,004 m^2	188,007 m^2

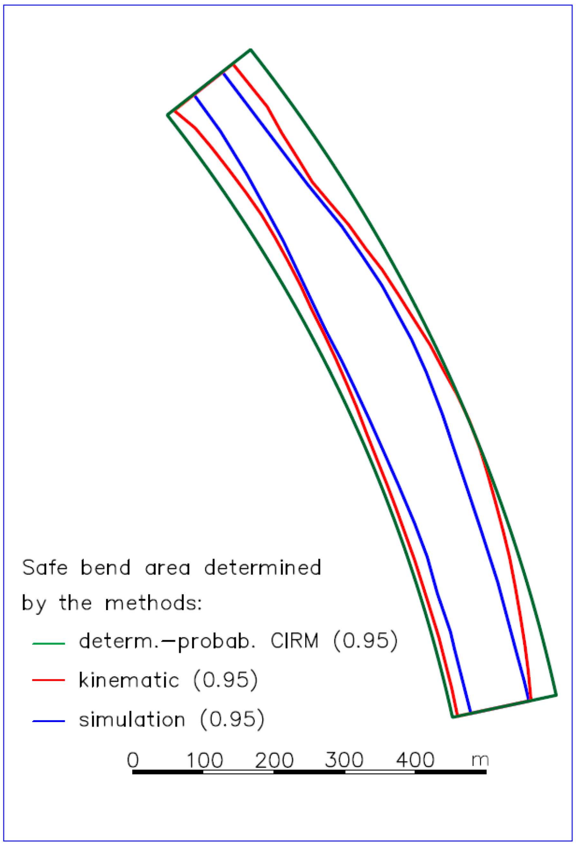

Figure 7. Safe manoeuvring areas of the Mańków bend.

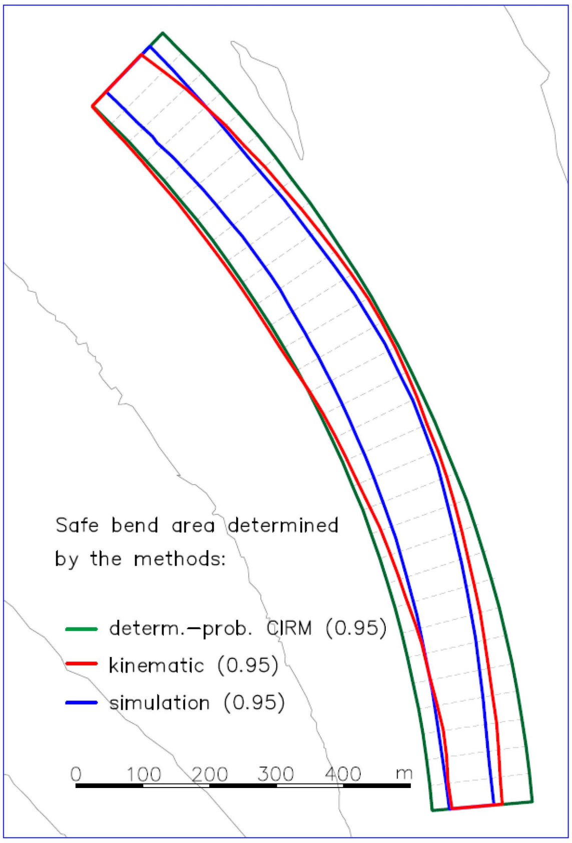

Figure 8. Safe manoeuvring areas of the Ińskie bend.

The following conclusions can be drawn from the results:

1. Safe widths of the bend determined by a simulation experiment conducted on a Kongsberg-made full-mission bridge simulator at the Maritime University of Szczecin, with a participation of highly qualified pilots, who executed a reliable number of bend passages, can be regarded as model ones due to their high accuracy.
2. The kinematic method, like the simulation method, estimates the safe bend width as a function of the turning angle. The CIRM method determines a safe width of the bend as a constant quantity (like the other empirical methods).
3. The kinematic method overestimates the area of safe manoeuvring areas by approximately 40%, regardless of turning angles and bend radiuses.
4. The CIRM method, one of the most accurate empirical methods, overestimates the area of safe manoeuvring areas by 60% for the turning angle of 26° and by 80% for the turning angle of 42°.

4. Summary

The newly developed kinematic method of numerical simulation serves for the determination of safe manoeuvring areas of fairway bends. This method uses a model of ship movement in a bend and consists of multiple numerical simulations of the movement of a ship's centre of gravity through the bend. The simulations represent the whole physically possible ship movement during the manoeuvre.

The developed kinematic method of numerical simulation was used for the determination of safe manoeuvring areas of the Mańków bend (turning angle 26°) and the Ińskie bend (turning angle 42°) in the Świnoujście–Szczecin fairway, where the examined ship was a bulk carrier (L_C = 195 m, B = 29.0 m, T = 11.0 m). The results were compared to the results of ship movement simulation method and the probabilistic-deterministic CIRM method (empirical).

The analysis of the results indicates that:

1. The kinematic method of numerical simulation, like the ship movement simulation method, determines the width of the safe manoeuvring area of ships on the bend as a function of the turning angle. The CIRM method, like the other empirical methods, determines the width of the safe manoeuvring area of the bend as a constant quantity.
2. The kinematic method of numerical simulation overestimates the manoeuvring area of the bend by approximately 40% (regardless of the turning angle) compared to the results obtained with real-time simulations, regarded as the reference method (the most accurate). This is related to the fact that the movement simulation involves the human factor. Officers navigating ships in restricted areas, especially with the use of leading lines, keep the ship exactly on the centerline of a traffic lane, which reduces its dimensions.
3. The probabilistic-deterministic CIRM method overestimates the safe manoeuvring area of the bend compared to the ship movement simulation method by approximately 60% for the turning angle of 26° and by 80% for the turning angle of 42° (this is one of the most accurate empirical methods).
4. The costs of the kinematic method of numerical simulation are significantly lower than the costs of ship movement simulation and comparable to the costs of empirical methods.
5. The computer program created allows the results to be obtained within a limited period of time. Single calculations using a computer equipped with the 8th-generation i7 processor and 12 GB RAM took less than an hour.

The verification of the kinematic method of numerical simulation indicated that:

- the method overestimates the area of safe manoeuvring areas of the bend by approximately 40% compared to the ship movement simulation method, regardless of the turning angle. At the same time the kinematic method maintains the dependence of the safe manoeuvring area width on the current angle of turn.
- the kinematic method of numerical simulation is much more accurate than the empirical methods in use.

Taking into account the low costs of the kinematic method of numerical simulation compared to the ship movement simulation method and its relatively high accuracy, we can recommend the method for concept design of various waterway systems, including approach channels, inner fairways and port entrances. The recommendation of the method for concept design [4] is confirmed by the results of verification tests. The kinematic method increases the area of the safe turn manoeuvring area by about 40% compared to simulation methods that take into account the shallow water effect and the bank effect and which are used at the detailed stage of turning design [2,3].

Further work on the development of the presented method will concern taking into account external conditions (e.g. currents or shallow water effect). The main limitation of the method is that it can be used only for individual bends of approximately regular shape. This problem can be solved in further stages of work on the method.

Author Contributions: Conceptualization, S.G. and J.D.; methodology, S.G, M.P. and J.D.; software, M.B.; validation, M.P. and J.D.; writing—original draft preparation, S.G.; writing—review and editing, M.P. and M.B.; visualization, M.P and J.D.; supervision, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research outcome has been achieved under the research project No. 1/S/CIRM/16 financed from a subsidy of the Ministry of Science and Higher Education for statutory activities of Maritime University of Szczecin.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNCTAD. *Handbook of Statistics*; United Nations Publications: New York, NY, USA, 2019.
2. Gucma, S. Sea Waterways. In *Design and Operation in Terms of Traffic Engineering*; Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej: Gdańsk, Poland, 2015. (In Polish)

3. Gucma, S.; Gucma, L.; Zalewski, P. *Simulation Research Methods in Maritime Traffic Engineering*; The Maritime University of Szczecin Press: Szczecin, Poland, 2008.
4. PIANC. *Harbour Approach Channels—Design Guidelines, Report n° 121*; PIANC: Brussels, Belgium, 2014.
5. Puertos Del Estado. *ROM 3.1-99, Design of the Maritime Configuration of Ports, Approach Channels and Harbour Basins*; Spanish National Ports & Harbours Authority: Madrid, Spain, 2007.
6. Gucma, S. *Maritime Traffic Engineering—Guidelines for the Design of Maritime Waterways and Ports and the Conditions for Their Safe Operation*; Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej: Gdańsk, Poland, 2017. (In Polish)
7. Gucma, S.; Dzwonkowski, J.; Przywarty, M. Kinematic method of determining safe fairway bend widths. *IJMNSST*, in press.
8. Dzwonkowski, J. A Kinematic Method for Determining Safe Bend Parameters on Fairways. Ph.D. Thesis, Maritime University of Szczecin, Szczecin, Poland, 2018. (In Polish)
9. PIANC. *Workshop on Design Guidelines for Inland Waterways. Smart Rivers*; PIANC: Brussels, Belgium, 2014.
10. PRS. *Rules for the Classification and Construction of Sea-Going Ships Part III Hull Equipment*; PRS: Gdańsk, Poland, 2013. (In Polish)
11. Nowicki, A. *Knowledge about Sea Vessels Manoeuvring*; Trademar: Gdynia, Poland, 1999. (In Polish)
12. Eloot, K.; Delefortrie, G.; Mostaert, F. *Manoeuvring Characteristics: Sub Report 7—Comparison of the Manoeuvring Characteristics of the COSCO 20,000 TEU and Other Ultra Large Container Ships*; Flanders Hydraulics Research: Antwerp, Belgium, 2018.
13. Fossen, T. *Handbook of Marine Craft Hydrodynamics and Motion Control*; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2011.
14. Przywarty, M.; Gucma, L.; Perkovic, M. Influence of speed reduction on navigational safety of container ships. *SJMUS* **2013**, *108*, 125.
15. Canadian Coast Guard. *Canadian Waterways National Manoeuvring Guidelines—Channel Design Parameters*; Department of Fisheries and Oceans: Ottawa, ON, Canada, 1999.
16. MUS. *Navigational Analysis of the Modernization of the Świnoujście—Szczecin Fairway (Dredging to 12.5 m)*; Europrojekt Gdańsk, S.A., Ed.; Maritime University of Szczecin: Szczecin, Poland, 2015.
17. Gucma, S. Optimization of parameters of the system of dredged sea waterways to a given depth on the example of the reconstruction of the Świnoujście—Szczecin fairway. *AoT* **2016**, *40*, 29–38. [CrossRef]