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A PROBABILISTIC MODEL OF VESSEL TRAFFIC AT THE INTERSECTION OF A FERRY CROSSING WITH A FAIRWAY

ABSTRACT

The article presents a model of vessel traffic at the intersection based on an idea of a ship domain at the intersection. To determine the domain of a fairway unit some kinds of errors and accuracy were used: accuracy of distance, accuracy of ship's length and error of her speed. To determine the ferry domain a deviation of the time of the ferry reaching a centre of intersection was applied. Danger zones for the ferry crossing have been determined. In area of a danger zone a collision sub-zone and a sub-zone of excessive approach have been distinguished. For description of the stream of entries of fairway units the Poisson stream with variable intensity was applied. The probability of avoiding collision during the ferries' crossing the intersection has been determined.

Keywords:
vessel traffic, ferry, fairway.

INTRODUCTION

The crossing of a ferry through an intersection with a fairway is a manoeuvre that risks collision with a unit sailing crosswise. With small traffic intensity this risk is small, and a trained and perceptive navigator is the only and sufficient guarantee of the vessels' passing each other safely at the intersection. With higher traffic intensity, the risk of collision is considerably larger (Galor 2003, Gucma 2001, Paulauskas 2005). An additional factor increasing the risk of collision is the condition of contemporary man (Massaiu 2005). Therefore, it becomes necessary to equip the navigators or operators of traffic control systems with tools aiding the safe performance of the crossing manoeuvre. Such tools, aiding the navigator in estimating the navigational risk of the ferry's crossing the intersection, are the ship's domain at the intersection and the danger zone.

INTERSECTION GEOMETRY

In the considered mathematical model of vessel traffic at the intersection of a ferry crossing with a fairway, the fairway units move in two directions along axes O_1 and O_2, and the ferries ply between harbours P_1 and P_2, crossing axes O_1 and O_2 under the angle α at points A_{ij} (fig. 1).

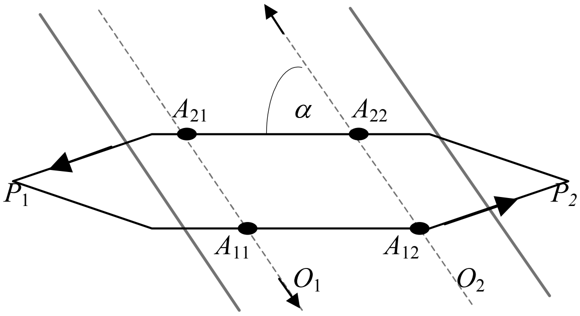

Fig. 1. Diagram of ferry crossing

Fairway units have priority, and ferry traffic is organised in such a way that if the intersection is not occupied by fairway units at the anticipated time of the ferry reaching the intersection, the ferries put off from opposite harbours and carry out the voyage according to plan until they reach the terminal harbour. If, on the other hand, the intersection is occupied at the anticipated time of the ferry reaching the intersection, the ferries wait for the crossing to start at their starting harbours. It was also assumed that both the ferries and the fairway units sail at constant speed in the neighbourhood of the intersection.

In the above considerations many markings with double indexes have been applied. The first index concerns the ferry leaving harbour P_i, and the other the vessel proceeding along axis O_j, so, for example, A_{12} denotes the crossing point of the route of the ferry leaving harbour P_1 with axis O_2. Time sections of the particular crossing stages have been marked in a similar way:

t_{11} – passage time from P_1 to A_{11},
t_{12} – passage time from P_1 to A_{12},
t_{21} – passage time from P_2 to A_{21},
t_{22} – passage time from P_2 to A_{22}.

VESSEL'S DOMAIN AT INTERSECTION

The domain of a vessel at the intersection is the area of the vessel's probable location at the intersection determined on the basis of information from a given traffic control system at the moment of estimating the safety of the vessels' passing each other at the intersection (Ciletti 1978, Kasyk 1998, Kasyk 1999, Kasyk 2001, Piszczek 1990). Conceived in this way, this area can become a suitable tool for the ferry navigator (or traffic control system operator), who estimates the chances of the ferry's safe passing ahead or astern of unit *S* approaching the intersection.

The ferry navigator located at harbour P_1, estimates the position of unit *S*, that is, its distance *d* from point A_{1j}. He does it, of course, with definite accuracy m_d. He also estimates its speed v_S, with error m_V and the unit's length L_S with accuracy m_L. In connection with this, in the anticipated time of the ferry *F* reaching the intersection (point A_{11} or A_{12}), assuming that both ship move at constant speeds v_F and v_S respectively, unit *S* will be occupying the area called domain at the intersection.

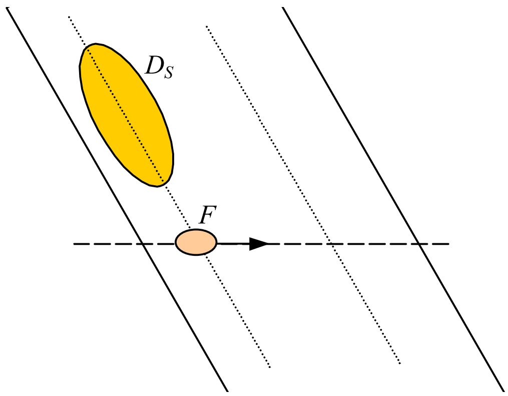

Fig. 2. Domain of vessel *S*

The domain of vessel *S* has the shape of an ellipse with semi-axes a_S and b_S (Coldwell 1983, Fuji 1977, Kasyk 1998, Kasyk 2001), where a_S denotes the semi--axis in the direction of fairway axis, and b_S denotes the semi-axis across fairway axis. Semi-axis b_S is equal to half the width of the traffic lane of vessel *S*, which can be determined by one of the methods applied at the Marine Traffic Institute (Gucma, the Panama Canal etc.; Gucma & Jagniszczak 1997, Ferry crossing 1997). On the other hand, the value of semi-axis a_S is expressed by the following formula:

$$a_S = \frac{1}{2} L_S + m_L + m_d + \overline{t_{11}} \cdot m_V \qquad (1)$$

where: m_V – error of unit's speed;

$\overline{t_{11}}$ – average passage time from P_1 to A_{11};

m_d – estimating accuracy of unit's distance from the intersection;

m_L – estimating accuracy of unit's length;

L_S – length of a ship S.

Errors of estimating particular vessel movement parameters can considerably vary from each other depending on the harbour they are made at and the movement direction of fairway units they concern. It was decided to apply double number indexes for designations of particular errors and domain dimensions. Hence, the above formula for the domain of a ship proceeding in direction of axis O_1 determined from harbour P_1 will be as follows:

$$a_{S11} = \frac{1}{2} L_S + m_{L11} + m_{d11} + \overline{t_{11}} \cdot m_{V11} \qquad (2)$$

The length of the longitudinal semi-axis a_{Sij} of the domain of fairway unit moving along axis O_j determined from harbour P_i is equal to:

$$a_{Sij} = \frac{1}{2} L_S + m_{Lij} + m_{dij} + \overline{t_{ij}} \cdot m_{Vij} \qquad (3)$$

where: m_{Vij} – error of unit's speed, determined from harbour P_i;

$\overline{t_{ij}}$ – average passage time from P_i to A_{ij};

m_{dij} – estimating accuracy of unit's distance from the point A_{ij} determined from harbour P_i;

m_{Lij} – estimating accuracy of unit's length, determined from harbour P_i.

Transverse semi-axis b_S can vary for particular directions of vessel movement, which is why it has been marked with the symbol b_{Sij}. Of course, in some cases there will be no difference between errors of various movement directions, and then the difference in notation does not translate into size difference. This will be particularly visible in the case of the estimation being performed by the traffic control system operator.

Within the designated domain the vessel may be located at any point with fixed probability $(1-\alpha)$. The position, speed, size and traffic lane width of vessel S were determined at this reliability level. It is most frequently the same for all movement directions of fairway units and ferries.

FERRY DOMAIN

As the time of the ferry reaching point A_{11} is a random variable t_{11}, it will deviate from the mean value $\overline{t_{11}}$ by a certain time period $t_{\beta 11}$, with the reliability level $(1-\beta)$. Hence:

$$P\left(\overline{t_{11}} - t_{\beta 11} < t_{11} < \overline{t_{11}} + t_{\beta 11}\right) = 1 - \beta \tag{4}$$

This signifies that on reliability level $(1-\beta)$ in the anticipated time of reaching point A_{11} the ferry may be located in distance $t_{\beta 11} \cdot v_F$ in front of a point A_{11} or in the same distance behind this point. So, the ellipsis with semi-axes a_{F11} and b_{F11} is also the domain of the ferry at the intersection (fig. 3), where

$$a_{F11} = \frac{1}{2} L_F + t_{\beta 11} \cdot v_F \tag{5}$$

On the other hand, semi-axis b_{F11} is equal to half the traffic lane width of the ferry in a particular part of the crossing.

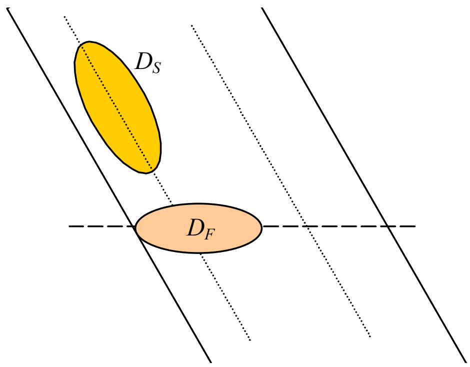

Fig. 3. Ferry domain

The ferry will be able to cross the fairway safely if, while crossing the intersection, its domain is located in the prescribed distance either in front of or behind the fairway unit domain.

The above considerations concern the case where the decision to cross the intersection is made by the ferry's master. They can, however, be generalised to the situation with an established traffic control system (like the VTS) where the decision is made by the system's operator. In such a case, when determining the vessel's domain the errors will have different values, and some of them will be completely inessential.

DANGER ZONES

By determining domains D_F and D_S the ferry's navigator or the traffic control system operator can estimate (with the assumptions mentioned) whether the vessels will pass each other safely at the intersection. On the basis of extreme situations, when the ferry passes in front of (or behind) the fairway unit in the smallest permissible distance, two danger zones were determined on the O_1 axis. They are marked by the symbols Z_{11} and Z_{21} in figure 6. The presence of the fairway unit in Z_{11} zone signifies a probable dangerous situation for this unit (excessive approach or collision) with a ferry leaving harbour P_2. By performing analogous considerations of extreme situations for fairway units proceeding along axis O_2, two danger zones were determined for the ferry crossing on axis O_2. These zones are marked by symbols Z_{12} and Z_{22} in figure 6.

In accordance with the assumption that the vessels move in intersection neighbourhood with constant speeds v_S, the distance p_{11} from the intersection was determined. In this distance the fairway unit would have to be located at the moment of the ferry leaving harbour P_1, in order for the ferry to traverse axis O_1 in the prescribed distance p_{per} before its domain. Analysing the situation presented in fig. 3, the following formula was obtained

$$p_{11} = b_{F11} \cdot \sin\alpha + p_{per} + \left(\overline{t_{11}} + t_{\beta 11}\right) \cdot m_{v11} + m_{d11} + m_{L11} + \left(\overline{t_{11}} + t_{\beta 11}\right) \cdot v_S \tag{6}$$

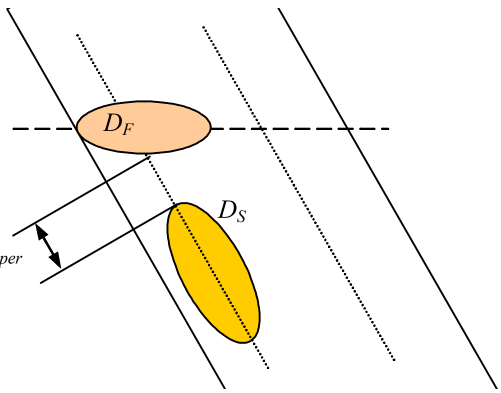

Fig. 4. The ferry passes behind the fairway unit

Similarly, analysing the situation presented in fig. 4, where the ferry traverses axis O_1 in permissible distance s_{per} astern the vessel, the extreme distance s_{11} was obtained as follows

$$s_{11} = \left(\overline{t_{11}} - t_{\beta 11}\right) \cdot v_S - b_{F11} \cdot \sin\alpha - s_{per} - m_{d11} - m_{L11} - \left(\overline{t_{11}} - t_{\beta 11}\right) \cdot m_{v11} \tag{7}$$

The part of the fairway on axis O_1 contained between extreme distances s_{11} and p_{11} from point A_{11}, was marked with the symbol Z_{11} and defined as danger zone for the ferry crossing.

By determining in a similar way the other extreme distances s_{ij} and p_{ij}, we also obtain the limits of danger zones Z_{ij} as distances from points A_{ij}. They are given by the following formulae

$$p_{ij} = b_{Fij} \cdot \sin\alpha + p_{per} + \left(\overline{t_{ij}} + t_{\beta ij}\right) \cdot m_{vij} + m_{dij} + m_{Lij} + \left(\overline{t_{ij}} + t_{\beta ij}\right) \cdot v_S \tag{8}$$

$$s_{ij} = \left(\overline{t_{ij}} - t_{\beta ij}\right) \cdot v_S - b_{Fij} \cdot \sin\alpha - s_{per} - m_{dij} - m_{Lij} - \left(\overline{t_{ij}} - t_{\beta ij}\right) \cdot m_{vij} \tag{9}$$

In order to uniform the reference point for extreme distances on the same axis a simplified intersection diagram was introduced (see fig. 5).

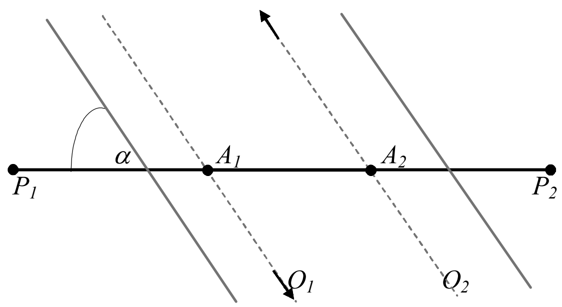

Fig. 5. Simplified diagram of ferry crossing

Points A_1 and A_2 are marked on this diagram as the centres of line segments $\overline{A_{11}A_{12}}$ and $\overline{A_{21}A_{22}}$. In such depiction the zone limits counted from points A_1 and A_2 will increase or decrease by half the length of line segment $\overline{A_{11}A_{12}}$. In this way, four danger zones for the ferry crossing presented in figure 6, were obtained.

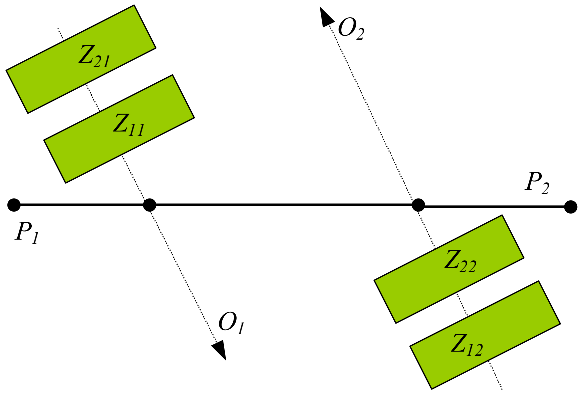

Fig. 6. Danger zones for the ferry crossing

Each fairway unit approaching the crossing line will have danger zones assigned to it, one for ferries leaving harbour P_1, another for ferries leaving harbour P_2. If the unit is located in one of these zones, then the start of the ferry crossing is delayed. Starting it at this moment would cause the domains of passing vessels to contact each other, which might bring about a dangerous situation at the intersection.

In some cases, the danger zones Z_{11} and Z_{21} are so close to each other or directly overlap (Kasyk 1998) that for the sake of simplicity they can be joined into one zone Z_1. A similar procedure can be applied to zones on axis O_2. In this way, two danger zones Z_1 and Z_2 are obtained, contained between extreme distances s_{ii} and p_{ki} (see fig. 7).

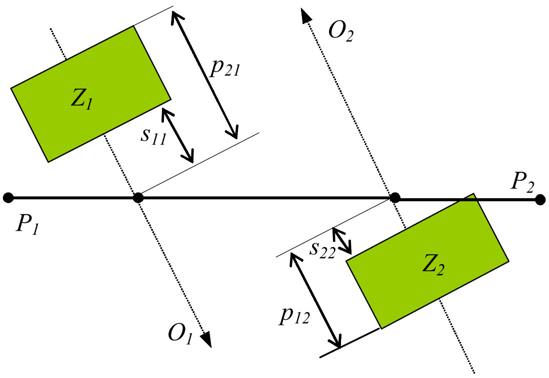

Fig. 7. Simplified danger zones for the ferry crossing

The span of danger zone Z_1 is equal to the sum of $p_{21} + \left|\overline{A_{11}A_{21}}\right| - s_{11}$. The span $\left|Z_1\right|$ was obtained as follows

$$\left|Z_1\right| = b_{F21} \cdot \sin\alpha + p_{per} + \left(\overline{t_{21}} + t_{\beta 21}\right) \cdot m_{v21} + m_{d21} + m_{L21} + \left(\overline{t_{21}} + t_{\beta 21}\right) \cdot v_S + \\ + \left|\overline{A_{11}A_{21}}\right| - \left(\overline{t_{11}} - t_{\beta 11}\right) \cdot v_S + b_{F11} \cdot \sin\alpha + s_{per} + m_{d11} + m_{L11} + \left(\overline{t_{11}} - t_{\beta 11}\right) \cdot m_{v11} \tag{10}$$

The span of danger zone Z_2 is equal to the sum of $p_{12} + \left|\overline{A_{11}A_{21}}\right| - s_{22}$, that is

$$\left|Z_2\right| = b_{F12} \cdot \sin\alpha + p_{per} + \left(\overline{t_{12}} + t_{\beta 12}\right) \cdot m_{v12} + m_{d12} + m_{L12} + \left(\overline{t_{12}} + t_{\beta 12}\right) \cdot v_S + \\ + \left|\overline{A_{11}A_{21}}\right| - \left(\overline{t_{22}} - t_{\beta 22}\right) \cdot v_S + b_{F22} \cdot \sin\alpha + s_{per} + m_{d22} + m_{L22} + \left(\overline{t_{22}} - t_{\beta 22}\right) \cdot m_{v22} \tag{11}$$

The above calculations are true in so far as the ferry is actually located in its domain in the anticipated time of its reaching the intersection, and the fairway unit in its own domain. These events take place with probabilities $(1-\beta)$ and $(1-\alpha)$. Hence, the reliability level *CL* of the designated danger zones is equal to

$$CL = (1-\alpha) \cdot (1-\beta) \tag{12}$$

If the extreme situations are considered without taking account of permissible distances $p_{per} + s_{per}$, then the designated danger zones will concern probable collision situations between the ferry and the fairway unit. This is why in each of the designated zones there can be distinguished a collision sub-zone, which constitutes the central part of the danger zone, and the sub-zone of excessive approach (fig. 8).

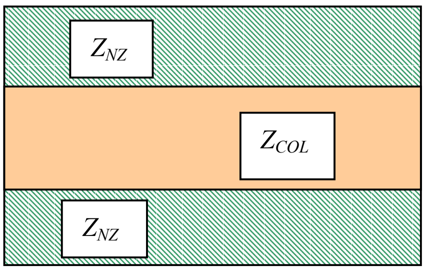

Fig. 8. Sub-zones of the danger zone

When estimating the risk of crossing the intersection the above sub-zones may affect the ferry master's decision whether to enter the traffic and what the menacing consequences may be (smaller in the case of excessive approach sub-zone and larger in the case of collision sub-zone). The span of zone Z_{COL} is smaller than the span of zone Z_j by the sum (p_{per} + s_{per}).

ENTRY PROCESS OF FAIRWAY UNITS

According to assumptions presented, ferry traffic is subordinated to vessel traffic on the fairway. Therefore, the traffic intensity of fairway units and the time between traversing the crossing line by successive fairway units essentially affects the ferry traffic on the crossing. Having danger zones defined and designated for the ferry crossing, we can determine the probabilistic links between the ferry traffic stream and the fairway unit traffic stream.

The stream of fairway unit entries is a Poisson stream (unless there are strong factors disturbing the randomness of entries) (Researches 1986, Ciletti 1978, Gajek 1996, Kasyk 2004, Montgomery 1994). A parameter of this stream is its intensity, i.e. the number of a vessel's entries in a time unit.

Empirical research shows that the intensity of entries is in fact different in various periods, both in diurnal and in weekly or annual depiction (Gucma 2003, Kasyk 2004). Therefore, the Poisson stream with variable intensity was applied for the description of the stream of entries of fairway units (Klimov 1979). If the period we are concerned with is divided into n separable intervals: $\langle x_0, x_1), \langle x_1, x_2), \langle x_2, x_3),...$ then the function $a(t) = a_n$ for $t \in \langle x_{n-1}, x_n)$ and for $n \ge 1$ determines the intensity of stream in particular intervals. Poisson stream with variable intensity (Klimov 1979) is fully characterised by the probabilities: $P_k(\Delta) = P\{\nu(\Delta) = k\}$, $k = 0,1,2,...$, where Δ denotes the time interval $\langle x, y)$, and $\nu(\Delta)$ is the number of entries in the interval Δ. These probabilities are calculated according to following formulae (Klimov 1979)

$$P_k(\Delta) = \frac{\left[\alpha(y) - \alpha(x)\right]^k}{k!} e^{-\left[\alpha(y)-\alpha(x)\right]} \tag{13}$$

where $\alpha(x) = \int_0^x a(\tau)\, d\tau$ for $x \ge 0$, is the leading function of the stream.

On the other hand, the ferry traffic stream is determined by the time schedule, which can be disturbed by the ferry unit traffic.

PROBABILITY OF AVOIDING COLLISION DURING THE FERRIES' CROSSING THE INTERSECTION

The ferry leaving harbour P_1 at time t_0 will safely perform the planned voyage, that is, will pass the intersection not creating a collision situation with any fairway unit and reach the harbour in time planned, only if and when there are no fairway units in the danger zones Z_j in time from t_0 to $t_0 + t_{\text{leav}}$. Time t_{leav} is the time from making the decision about unmooring to the ferry's actual leaving the berth.

Event NZ_j, consisting in the fact that there will be no fairway units in danger zone Z_j in time from t_0 to $t_0 + t_{\text{leav}}$, is tantamount to there being no fairway unit entries in time from $\left(t_0 - T_1\right)$ to $\left(t_0 + t_{\text{leav}}\right)$. T_1 is the mean time for the fairway units to cover danger zone Z_1, that is $T_1 = \frac{|Z_1|}{v_S}$. Hence, on the basis of dependence (13) the probability of event NZ_1 was obtained as follows

$$P\left(NZ_1\right) = P_0\left(\left\langle t_0 - T_1; t_0 + t_{leav}\right)\right) = e^{-\left[\alpha\left(t_0 + t_{leav}\right) - \alpha\left(t_0 - T_1\right)\right]} \tag{14}$$

The probability of event NZ_2 was determined in a similar way

$$P\left(NZ_2\right) = P_0\left(\left\langle t_0 - T_2; t_0 + t_{leav}\right)\right) = e^{-\left[\alpha\left(t_0 + t_{leav}\right) - \alpha\left(t_0 - T_2\right)\right]} \tag{15}$$

The probability of ferries leaving from opposite harbours being able to put off at time t_0 and safely pass the intersection without creating a dangerous situation with a fairway unit is the product of probabilities of events NZ_j and reliability levels on which zones Z_j were determined and is expressed by the following formula

$$P = \left(1-\alpha\right)^2 \cdot \left(1-\beta\right)^2 \cdot e^{-\left[2\alpha\left(t_0 + t_{leav}\right) - \alpha\left(t_0 - T_1\right) - \alpha\left(t_0 - T_2\right)\right]} \tag{16}$$

In an analogous way, there can be determined the probability of two ferries leaving opposite harbours being able to put off at time t_0 and safely pass the intersection not creating a collision situation with a fairway unit. It is the same that the probability of avoiding a collision situation during the ferry's passing the intersection, without performing any anti-collision manoeuvres. This probability can be calculated as follows

$$P = \left(1-\alpha\right)^2 \cdot \left(1-\beta\right)^2 \cdot e^{-\left[2\alpha\left(t_0 + t_{leav}\right) - \alpha\left(t_0 - T_{COL1}\right) - \alpha\left(t_0 - T_{COL2}\right)\right]} \tag{17}$$

where T_{COLj} denotes the mean time in which the fairway units cover collision subzone Z_{COLj}.

PROBABILITY OF THE FERRY'S PUTTING OFF WITH DELAY t_X

Formula (16) can also be interpreted as the probability that the voyage planned for time t_0 commences and terminates without delay caused by the intersection being occupied by the fairway unit. If the ferry voyage is to begin at time t_0, and in the time from t_0 to $t_0 + t_x$ there is a fairway unit in one of danger zones Z_j, the crossing will be delayed by time not smaller than t_x. Probability $P(t_x Z_j)$ that in time from t_0 to $t_0 + t_x$ zone Z_j is occupied is complementary to 1 probability that in time from t_0 to $t_0 + t_x$ zone Z_j is free. Hence

$$P\left(t_x Z_j\right) = 1 - P_0\left(\left\langle t_0 - T_j ; t_0 + t_x \right)\right) = 1 - e^{-\left[\alpha\left(t_0 + t_x\right) - \alpha\left(t_0 - T_j\right)\right]} \tag{18}$$

The delay can also be affected by the occupancy of zone Z_1 or zone Z_2. Hence the probability of the ferries' planned voyage being delayed by time not smaller than t_x is equal to

$$P\left(t_{op} \geq t_x\right) = \left(1 - \alpha\right)^2 \cdot \left(1 - \beta\right)^2 \cdot P\left(t_x Z_1 \cup t_x Z_2\right) \tag{19}$$

And, after taking dependence (18) into account, the following formula is obtained

$$\begin{aligned} P\left(t_{op} \geq t_x\right) = \left(1 - \alpha\right)^2 \cdot \left(1 - \beta\right)^2 \cdot \Big[\left(1 - e^{-\left[\alpha\left(t_0 + t_x\right) - \alpha\left(t_0 - T_1\right)\right]}\right) + \\ + \left(1 - e^{-\left[\alpha\left(t_0 + t_x\right) - \alpha\left(t_0 - T_2\right)\right]}\right) - \left(1 - e^{-\left[\alpha\left(t_0 + t_x\right) - \alpha\left(t_0 - T_1\right)\right]}\right) \cdot \left(1 - e^{-\left[\alpha\left(t_0 + t_x\right) - \alpha\left(t_0 - T_2\right)\right]}\right)\Big] \end{aligned} \tag{20}$$

RECAPITULATION

Poisson's stochastic process has already been applied more than once for the modelling of vessel traffic on waterways (Researches 1986, Ciletti 1978, Gajek 1996, Kasyk 1999, Kasyk 2004). The application of Poisson's stream with variable intensity made it possible to take into consideration the vacillations in the number of vessel entries. Combining the properties of Poisson's process with danger zones defined by the author creates new possibilities of determining probabilistic connections between ferry streams and fairway unit streams. This also made it possible to determine a number of vessel traffic safety parameters at an intersection. Among these are:

– the probability of avoiding a dangerous situation during the ferry's crossing the intersection (without performing anti-collision manoeuvres);

- the probability of avoiding a collision situation during the ferry's crossing the intersection (without performing anti-collision manoeuvres);
- the probability of avoiding an excessive-approach situation during the ferry's crossing the intersection (without performing anti-collision manoeuvres), the probability of the ferry putting off with delay t_x.

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Received August 2006
Reviewed February 2007