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An Influence of the Order to Maintain Minimum Distance Between Successive Vessels on the Vessel Traffic Intensity in the Narrow Fairways

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ABSTRACT: All vessel traffic regulations disturb the randomness of the vessel traffic stream. In this paper the disturbing factor is the order to maintain minimum distance between successive vessels. The intensity of the disturbed vessel traffic has been determined. To achieve this goal the convolution method has been used. Next the connection between traffic stream parameters and this disturbed intensity has been analysed.

1 INTRODUCTION

1.1 *Narrow fairways*

The vessel traffic on narrow fairways is subject to different restrictions: speed limit, overtaking ban, passing ban and others. When ships must go one by one they must maintain minimum distance between each other. This distance is specific for each basin, for example on the Świnoujście – Szczecin fairway, the minimum distance between successive vessels is equal to 2 cable.

1.2 *Vessel traffic intensity*

The intensity of vessel traffic is measured by a number of vessels passing in a time unit (Jagniszczak & Uchacz 2002, Gucma 2003). When ships report individually and independently of one another, the intensity can be describing by Poisson distribution (Ciletti 1978, Fujii 1977, Montgomery & Runger 1994). In the case when vessel traffic is disturbed, the density can be determined by using the convolution method. In earlier works (Kasyk 2006) author presented solutions of different problems using particular parts of the convolution method. And this paper is the first application of full convolution method worked out by author (Kasyk 2008).

2 DETERMINATION OF INTENSITY

2.1 *Component random variables*

According with the convolutions method (Kasyk 2008, Nowak 2002) it's necessary to isolate particular random variables. The time difference between leavings the fairway section with the disturbance, by successive ships is equal to:

$$DT = X + \left(Y_B - Y_A\right) + \left(W_B - W_A\right) \tag{1}$$

where X denotes the waiting time for the reporting of the successive fairway unit in none disturbance traffic; Y denotes the time necessary to change of vessel traffic parameters; W is the time necessary to cover the fairway section on which the order to maintain minimum distance between successive vessels exist. The indexes A and B by names of random variables denotes realisations of particular variables for different successive units.

The variable X has an exponential distribution (Ciletti 1978, Fujii 1977, Gucma 2003, Kasyk 2004, Nelson 1995). In this paper the variable Y has a normal distribution (Kasyk 2006). When the ship is forced to sail after the more slowly unit, she must reduce her own speed. The longest time necessary to cover the fairway section on which the order to maintain minimum distance exist is equal to d/v_{av}, where d is the length of this section and v_{av} is the average velocity in this section. While the shortest time of covering this fairway section amounts d/v_{max}, where v_{max} is the highest velocity in this section. On narrow fairways, usually the average velocity doesn't differ much from the maximum velocity. Hence the variable W can be described by an uniform distribution on the interval from d/v_{max} to d/v_{av}.

2.2 *Probability distribution of vessel traffic intensity*

Using all operations of the convolution method (Kasyk 2008), p.d.f. of variable 1/T has been determined. This variable, as the inverse of the time between leavings the fairway section by successive ships, denotes the number of ships leaving the special section in the time unit. This is a continuous variable and its probability density function f(x) is given by the form presented below. In this form the function erf(z) appears. It is the integral of the Gaussian distribution, given by:

$$\mathrm{erf}(z) = \int_0^z \mathrm{e}^{-t^2}\, dt \tag{2}$$

The function erfc(z) is given by: $\mathrm{erfc}(z) = 1 - \mathrm{erf}(z)$.

$$\begin{aligned}
f(x) = {} & \frac{1}{2r^2x^2}\Bigg(4r + \frac{4\sigma}{\sqrt{\pi}}\exp\left(\frac{-(xr-1)^2}{4x^2\sigma^2}\right) + \frac{4\sigma}{\sqrt{\pi}}\cdot \\
& \cdot\exp\left(\frac{-(xr+1)^2}{4x^2\sigma^2}\right) - \frac{8\sigma\sqrt{\ }}{\sqrt{\pi}}\exp\left(\frac{-1}{4x^2\sigma^2}\right) - \frac{4}{x}\mathrm{erf}\left(\frac{\sqrt{1}}{2\sigma x}\right) + \\
& +2\left(\frac{1}{x} - r\right)\mathrm{erf}\left(\frac{rx-1}{2\sigma x}\right)\sqrt{2}\left(\frac{1}{x} + r\right)\mathrm{erfc}\left(\frac{rx+1}{2\sigma x}\right) + \\
& +\frac{1}{\lambda}\exp\left(\lambda^2\sigma^2 - \lambda r - \frac{\lambda}{x}\right)\cdot\Bigg(\exp(2\lambda r)\,\mathrm{erfc}\left(\frac{rx + 2\lambda\sigma^2 - 1}{2\sigma x}\right) + \\
& +\mathrm{erfc}\left(\frac{2\lambda\sigma^2 - rx - 1}{2\sigma x}\right) + \exp\left(\frac{2\lambda}{x}\right)\mathrm{erfc}\left(\frac{2\lambda\sigma^2 - rx + 1}{2\sigma x}\right) + \\
& +\exp\left(\frac{2\lambda}{x} + 2\lambda r\right)\mathrm{erfc}\left(\frac{2\lambda\sigma^2 + rx + 1}{2\sigma x}\right) - 2\exp(\lambda r)\cdot \\
& \cdot\mathrm{erfc}\left(\lambda\sigma - \frac{1}{2\sigma x}\right) - 2\exp\left(\lambda r + \frac{2\lambda}{x}\right)\mathrm{erfc}\left(\lambda\sigma + \frac{1}{2\sigma x}\right)\Bigg)\Bigg)
\end{aligned} \tag{3}$$

Integrating the function f(x) in corresponding limits we obtain the probability mass function of the variable I (the vessel traffic intensity after leaving the fairway section with the order to maintain minimum distance):

$$P(I = n) = \int_{n-0,5}^{n+0,5} f(x)\,dx \tag{4}$$

3 ANALYSIS OF DEPENDENCE DENSITY FUNCTION ON TRAFFIC PARAMETERS

3.1 *Traffic parameters*

Function f(x) depends on three parameters: λ, σ and the difference r = (*b* – *a*). 1/λ is the mean of the variable X. σ is the standard deviation of the variable Y and the interval [*a* , *b*] is the range of the variable W. Figure 1 presents the dependence of f(x) on the parameter λ, with established σ and r.

All parameters have been examined in ranges corresponding with real conditions. Hence r is located between 0.1 hour and 2 hours, σ stays within the range from 0.01 hour to 1 hour and λ is from the interval [0.1/h, 10/h].

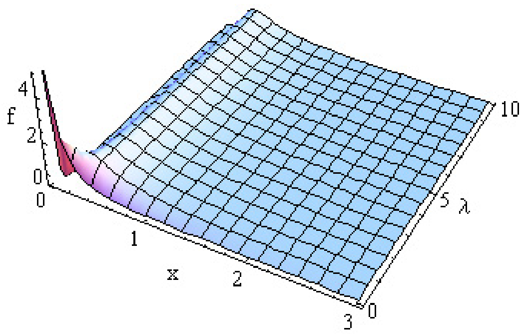

Figure 1. Dependence of function f(x) on parameter λ.

Fig. 2 presents the dependence of the function f(x) on the parameter σ, with established λ and r.

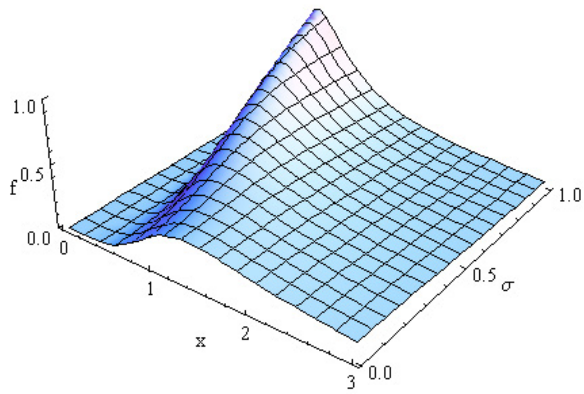

Figure 2. Dependence of function f(x) on parameter σ.

Figure 3 presents the dependence of the function f(x) on the parameter r, with established λ and σ.

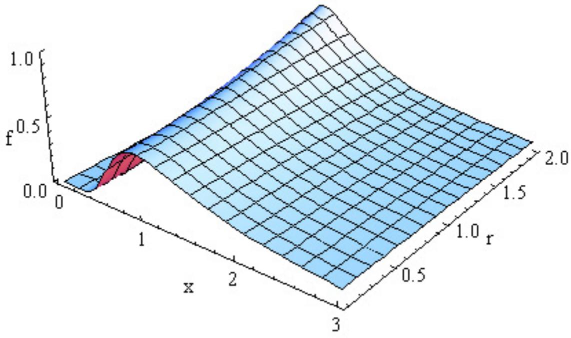

Figure 3. Dependence of function f(x) on parameter r.

Function f(x) changes little for different values σ and r (a bit more for σ). With the change of value of λ the function f(x) changes a lot. Especially when λ closes to 0, the curve f(x) has greater values and it has maximum for the argument closer 0.

3.2 *Comparison between disturbed intensity and random intensity*

The vessel traffic intensity on the exit of the fairway section with the order to maintain minimum distance is different than the vessel traffic intensity on the entrance to this section. The greatest differences appear in the case when the exponential distribution parameter has value greater than 1 (the higher value of λ the bigger differences between intensities) and values of parameters σ and r are high (Fig.4). The closer 0 λ, the less differences between intensities. And when σ and r close to 0, then density function curves of intensities almost coincide (Fig.5).

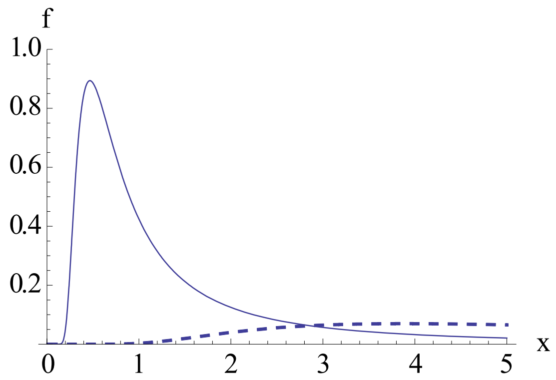

Figure 4. Difference between intensities for large λ

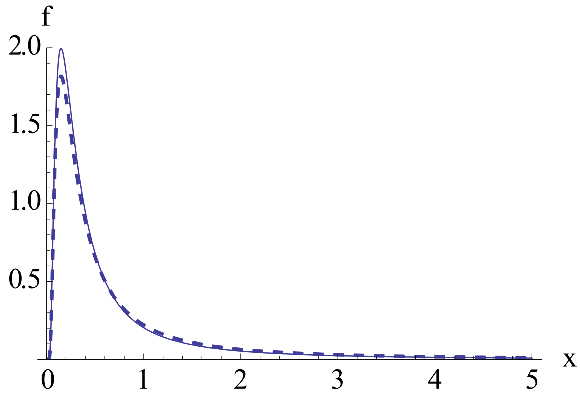

Figure 5. Difference between intensities for λ closing to 0

In above figures the probability density function of the vessel traffic intensity on the entrance to the fairway section on which the order to maintain minimum distance between successive vessels exist, is marked by dashed line.

3.3 *Extreme case*

In the case, when there are so many ships that they sail one by one with the minimum distance $d_{\min}$ between each other, then the intensity is equal to:

$$I = \frac{d_{\min}}{v_{av}} \cdot \frac{1}{3600s} \tag{5}$$

where d_{min} is expressed in metres; the average vessel speed v_{av} is expressed in metres per second.

4 CONCLUSIONS

Intensity of the disturbed vessel traffic, as a number of reports in a time unit, has been approximated by continuous random variable 1/T. Applying the convolution method the density function of variable 1/T has been determined.

If disturbances in fairway vessel traffic are big (values of parameters σ and r are high), then there are large differences between the vessel traffic intensity on the exit of the fairway section with the order to maintain minimum distance and the vessel traffic intensity on the entrance to this section.

For practical uses, the random variables separated in this model, should be verified with measurements or simulations.

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