A CAPACITY STUDY FOR VESSEL TRAFFIC USING AUTOMATIC IDENTIFICATION SYSTEM DATA

Matthias Deceuninck, Kurt De Cock, Stijn De Vuyst
Department of Industrial Systems Engineering and Product Design
Ghent University
Technologiepark 903, 9052 Zwijnaarde,
Belgium
email: matthias.deceuninck@ugent.be

Marc Vantorre, Katrien Eloot
Maritime Technology Division
Ghent University
Technologiepark 904, 9052 Zwijnaarde
Belgium

KEYWORDS

Simulation, Maritime traffic, Capacity study

ABSTRACT

In this study, we created a simulation model to assess the overall impact of implementing a one-way traffic policy due to construction works. The inputs of the simulation model are found by performing statistical analysis on data from the Automatic Identification System (AIS). The aim of this study is twofold: (a) map the vessel traffic during the reference period and (b) analyse the congestion for the new traffic conditions. We use a non-homogeneous Poisson process with piecewise linear intensity to model the arrival process. For scenarios with varying arrival intensities, we compare the vessels' waiting times as well as the maximum queue lengths. The latter is important for upstream traffic since there are space constraints.

INTRODUCTION

In an effort to improve the accessibility of city and port, the Flemish Government launched the Master Plan 2020 to unscramble the traffic knot in the Antwerp region (The Oosterweel Link, 2018). One of the projects involves the construction of canals tunnels passing under the Albert Canal, one of Belgium's most important and busy waterways. Due to these construction works, two-way traffic will no longer be possible in a section of the canal. In this respect, the motivation behind this study is to investigate the impact of implementing a one-way traffic policy. To forecast the vessel traffic in the canal, AIS data was collected. Since 2012 most vessels are required to carry an AIS transceiver on board which broadcasts information such as position, speed and direction through dedicated VHF frequencies. This information formed the inputs of our simulation model.

Simulation methods have been widely applied for the modelling of vessel traffic on waterways because they enable studies of more complex systems. In the literature, extensive simulation models have been developed to investigate the effects of numerous factors on performances measures such as capacity and waiting times. Golkar et al. (1998) used simulation to evaluate the capacity of the Panama Canal under dif-

ferent operating conditions. In Thiers and Janssens (1998), a detailed maritime traffic simulation model was developed for the port of Antwerp including navigation rules, tides and lock operations. Merrick et al. (2003) used simulation to perform a traffic density analysis in the San Francisco Bay area. The model tried to assess the overall impact of an expansion in ferry services which was a proposal of the California legislature. The Istanbul Channel has also received a lot of attention (e.g. Köse et al. 2003, Almaz et al. 2006, Özbaş and Or 2007). For example, Köse et al. (2003) developed a simulation model to test the effect of arrival intensity on the waiting times.

This paper is divided into five sections. In the next section, we discuss the data analysis. The third section describes the simulation model used in this paper. Various scenarios are investigated in the fourth section. Finally, conclusions are drawn in the last section.

METHODOLOGY

In this study, we employed the AIS data collected in the Albert Canal during the month of August 2016. The dataset contains the AIS data of all vessels passing one of the six intersections depicted in Figure 1. For each passage, the following statistics were registered:name, width in meter (Ship Beam), length in meter (Ship Length), speed, position and UTC (Coordinated Universal Time). After data cleaning, 17312 entries from 897 unique vessels were kept for analysis. The dimensions and traffic types of the vessels are shown in Figure 2. The average length of a vessel is equal to 82.08m. During the reference period, 61% of the vessels were cargo ships (AIS ship type numbers 70-79), 18% tankers (80-89) and only 1% passenger ships (60-69).

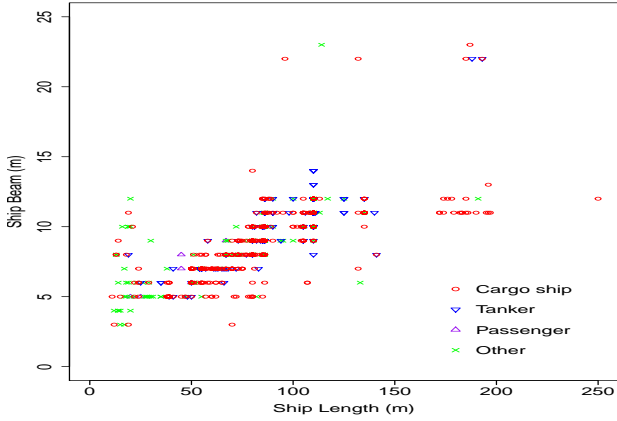Figure 1: View of intersections where AIS data is collected.

Figure 2: (Corrected) Dimensions and ship type of the vessels observed during the reference period.
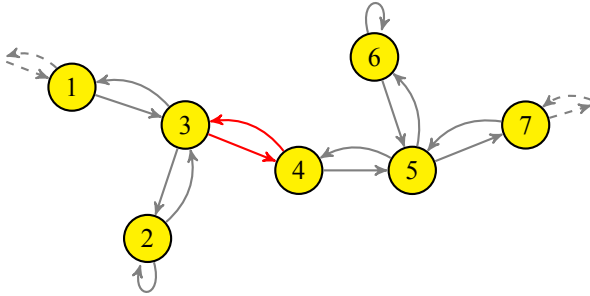

Figure 3: Graphic representation of possible movements.

A directed graph can be used to represent the traffic in the waterway. This is shown in Figure 3 where the arcs represent all the possible movements of the vessels and the nodes subdivide the waterway into sections of homogeneous capacity. Vessels enter or leave the system at a boundary node (nodes 1 and 7) or at one of the docks (nodes 2 and 6). We want to stress that the nodes do not fully correspond with the intersections in Figure 1. The arc between nodes 3 and 4 corresponds with the narrowed waterway where one-way traffic will be implemented. In the remainder of this paper, we will denote this section of the channel as the construction zone. The length of the construction zone is approximately equal to 880m. Furthermore, we will refer to vessels moving in the direction 1→7 (7→1) as upstream (downstream) traffic.

For the analysis, we are mainly interested in the traffic through the construction zone as this will be the section with congested traffic. Figure 4 depicts the vessel traffic for the first week of August 2016. The black lines denote the length of the vessel that is passing the section at that moment in time, with the positive and negative axis respectively corresponding to upstream and downstream traffic. To get an idea of the traffic intensity over the course of a week, we also plot the KDE (kernel density estimation) for the upstream/downstream (red, solid) and total (blue, dashed) traf-

Path	mean ships/h	peak(.5h)	peak(1h)	peak(2h)
$1 \rightarrow 4$	1.95	7.92	5.95	4.63
$2 \rightarrow 4$	0.02	0.72	0.61	0.35
$6 \rightarrow 3$	0.08	1.40	0.82	0.50
$7 \rightarrow 3$	1.86	5.78	4.97	3.93
$3 \leftrightarrow 4$	3.91	14.04	11.01	9.25

Path	mean shm/h	peak(.5h)	peak(1h)	peak(2h)
$1 \rightarrow 4$	176.88	717.11	538.16	418.86
$2 \rightarrow 4$	0.94	42.11	35.79	20.23
$6 \rightarrow 3$	5.78	101.66	59.53	36.77
$7 \rightarrow 3$	155.77	595.22	440.36	355.43
$3 \leftrightarrow 4$	339.37	1069.66	903.06	758.57

Table 1: Vessel traffic through the construction zone during the reference period.

fic. For n ships with arrival times t_i (in hour) and length l_i (meter), $i = 1, \ldots, n$, with mean $\bar{l}$, the instantaneous arrival rate, expressed in ship meters per hour (shm/h), at time t is estimated as

$$\hat{\gamma}_h(t) = \frac{1}{nh} \sum_{i=1}^{n} \frac{l_i}{\bar{l}} K\left(\frac{t - t_i}{h}\right), \qquad (1)$$

with the so-called kernel $K(t)$ being a 'cosine' window. A crucial parameter is the bandwidth h (in hours) since this parameter determines the smoothness of the resulting estimate. Intuitively one wants to choose h as small as the data allows. A small h results in low bias but increases the variance of the estimates. In Figure 4, we set h equal to 1 hour and find for the first week a mean of 311 shm/h with a maximum of 716shm/h. We can clearly observe some daily seasonality with multiple peaks. Furthermore, it can be seen that there is significantly less traffic on Sundays.

Finally, Table 1 gives an overview of the vessel traffic through the construction zone coming from all possible directions. In the last row, we can see that the total traffic through the construction zone has a mean of 339.37 shm/h with the highest arrival intensity being 533.83 ship meters in 30 minutes ($h = 0.5$h).

SIMULATION MODEL

The simulation software package FlexSim 2016 is used for the implementation of the simulation model of the maritime traffic. Simulation allows us to analyse and compare the results of different scenarios. In this section, we describe the arrival process, traffic control measures and other features of the model.

Arrival process

The following input data are generated for each vessel entering the system from a boundary node: arrival time, dimensions, speed and path. Instead of using the real data directly, we generate artificial scenarios where all input factors are randomly generated based on the probability distributions obtained from the data. This allows us to investigate scenarios
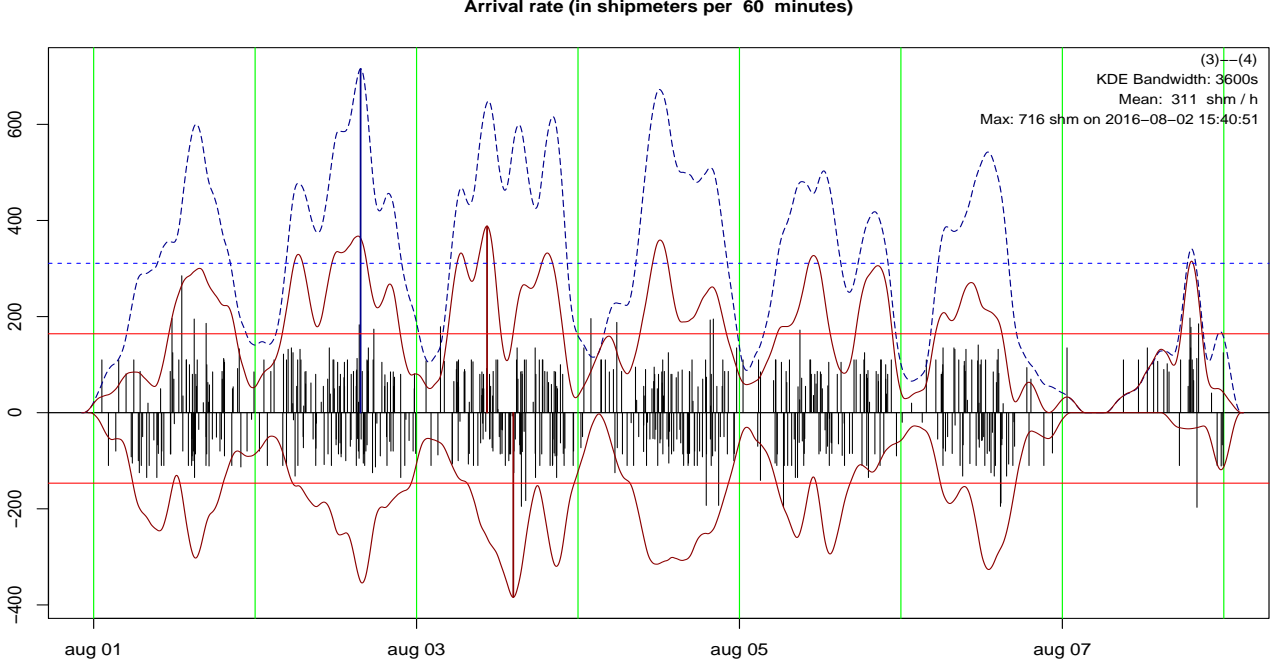
Arrival rate (in shipmeters per 60 minutes)

Figure 4: Upstream (positive vertical axis) and downstream (negative vertical axis) vessel traffic through the construction zone combined with their kernel density estimates ($h = 1$ hour). The red (solid) lines correspond with the upstream and downstream traffic while the blue (dashed) lines give the mean and KDE of the total traffic.

in which the traffic has similar characteristics as in Figure 4 but with a different intensity: $\lambda = \alpha\lambda^{\mathrm{ref}}$ with the multiplier α varying from 1 to 1.5. This may be necessary since follow-up studies found that the traffic was considerably higher during the subsequent months (+11%).

An important question that arises is the modelling of the non-stationary arrivals. As discussed earlier, a time-dependent arrival process is observed from the data with both daily and weekly seasonalities. Let $A_k(t)$ denote the arrival process at node k. We assume that $A_k(t)$ follows a non-homogeneous Poisson process with a piecewise-linear intensity function: $A_k(t) \sim \mathcal{P}(\lambda_k(t))$. That is, the interarrival times are independent and exponentially distributed with intensity $\lambda_k(t)$. A piece-wise linear function is chosen to simplify the model as such complex time series are prone to over-fitting for a small dataset.

Our approach consists of partitioning each weekday into 1-hour intervals, calculate for each hour the average intensity and then interpolate between the obtained values. Let $\lambda_{k,j}^{\mathrm{ref}}$ denote the average traffic intensity during the jth interval at node k, then for $j = 1, 2, \ldots 24$, we have

$$\lambda_{k,j}^{\mathrm{ref}} \frac{1}{D_{\mathrm{ref}}} \sum_{i=1}^{n} \sum_{d=1}^{D_{\mathrm{ref}}} \mathbb{1}_{\{j-1 \leqslant t_i \,(\mathrm{mod}\,24) < j\}}, \qquad (2)$$

with D_{ref} the number of days in the reference period (excluding weekends) and $\mathbb{1}_{\{\cdot\}}$ the indicator function which evaluates to 1 if its argument is true and to 0 if this is not the case. We exclude weekends from the dataset because there is generally less traffic and we are interested in the performance
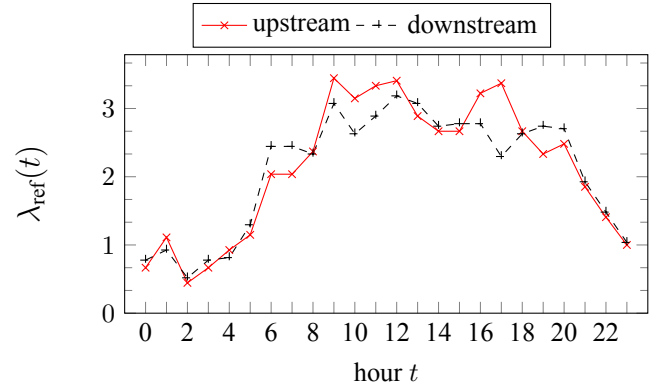

Figure 5: Intensity function $\lambda_{\mathrm{ref}}(t)$ estimate for upstream and downstream vessel traffic (excluding weekends).

measures during congestion. Using linear interpolation, the instantaneous intensity function $\lambda_k^{\mathrm{ref}}(t)$ is then equal to

$$\lambda_k^{\mathrm{ref}}(t) = \lambda_{\mathrm{ref},j^*} + (t - j^*)(\lambda_{k,j^*+1}^{\mathrm{ref}} - \lambda_{k,j^*}^{\mathrm{ref}}) \quad t \geq 0, \;\; (3)$$

with j^* rounded down to the nearest hour: $j^* = \lfloor t \,(\mathrm{mod}\,24) \rfloor$. The resulting intensity function for upstream and downstream traffic are given in Figure 5. Most traffic is between 6am and 8 pm.

Traffic control measures

Traffic through the construction zone is reduced to one lane. Temporary traffic lights are installed at nodes 3 and 4 which
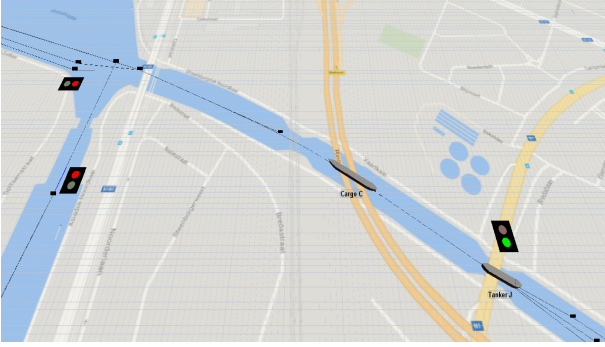
Figure 6: A snapshot of the simulation model.

Figure 7: Delay times for base case scenario.

Figure 8: Average delay times during weekdays for base case scenario.

are manually operated to maximize the throughput. The operators always try to empty the waiting queues completely in one go to avoid that vessels need to perform multiple departure and stopping manoeuvres (once for each green-red cycle). Vessels that arrive at a non-empty queue or red light enter the queue at the tail and leave the queue according to a FIFO policy. It is assumed that the spacing between vessels in the queue is equal to 2m and increases to at least 30m for moving vessels. It is further assumed that vessels are moving with a uniform speed along a certain arc and that speed changes are immediate. In order to avoid nuisance waves, a speed limit of 5 kph is set in the entire working zone. Finally, a lower speed is also assumed for vessels coming from one of the docks to take into account the time that is needed to perform turning manoeuvres. A snapshot of the simulation model is given in Figure 6.

Performance measures

To assess the overall impact of the new traffic conditions, the following performance measures are considered relevant:

- The vessels' delays D at the traffic lights.

- The length L (in ship meters) of each queue.

RESULTS AND ANALYSES

In this section, we analyse the system for different scenarios. We first look at what happens when the arrivals exactly correspond with the reference period (approx. 2800 vessels). Figure 7 depicts the delay times for the first week of this base case scenario. The maximum delay for this time period are respectively equal to 25 and 71 minutes for upstream and downstream traffic. Most vessels do not experience any waiting and the average delays are respectively equal to 3.0 and 4.2 minutes. Obviously, the vessels' delays depend on the arrival time. Figure 8 shows for each moment of the day the delay that a vessel may expect. It can be seen that the average delays during daytime are approximately 4 and 7 minutes for respectively upstream and downstream traffic, while less than 2 minutes during night time.
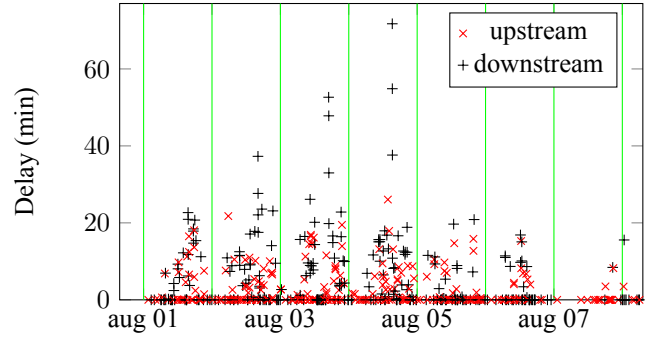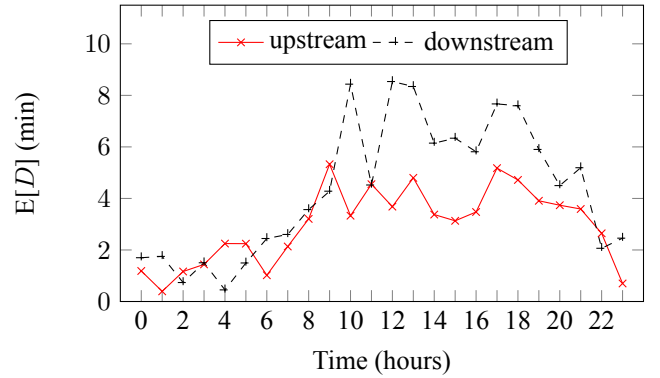
Next, we generate data using a non-homogeneous Poisson process with time-varying rate $\alpha \lambda_k^{\text{ref}}(t)$ as given by Equation (3). For each scenario, a simulation time of 124 weekdays is used to estimate the performance measures of which 4 weekdays are used as warm-up period. Figure 9 depicts the distribution of the queue length for upstream traffic. It can be seen that 90% of the time the queue is shorter than 100m (log Prob[$L > 100$]= -1). The maximum queue lengths that we encountered during the 4-month simulations were less than 800m for $\alpha \leq 1.2$. Given these results, we thus do not expect any problems regarding the space constraint (queue space ≈800m) for upstream traffic in the harbour when the arrival intensity increases less than 20% compared to our reference set. For higher arrival intensities, the operator may need to give priority to upstream traffic to avoid a crowded queue during peak hours.

Finally, Figures 10 and 11 respectively present the delay time distributions for upstream and downstream traffic. It can be seen that approximately 10% of the vessels (log Prob[$D > t$]= -1) have a delay of more than 20 minutes and less than 1% a delay longer than 40 minutes. Long delays are more common for downstream traffic. This can be explained by the fact that a higher priority is given to upstream traffic because of space constraints.
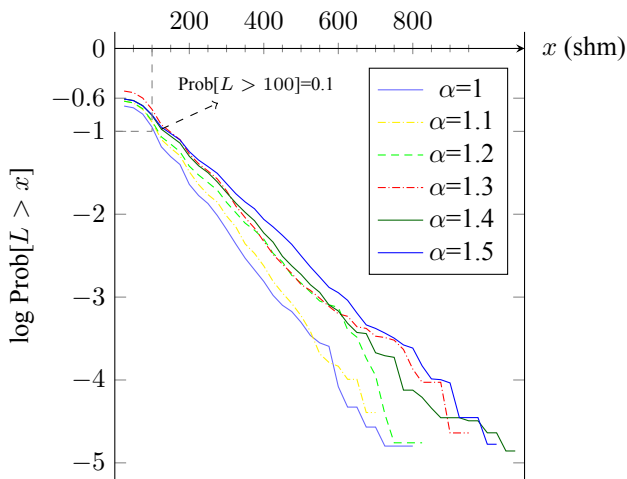
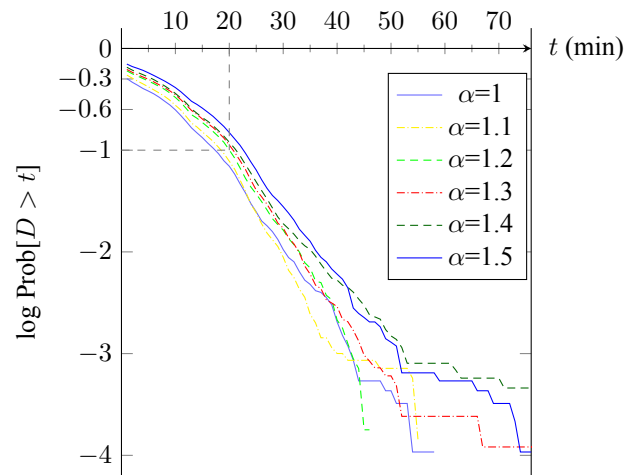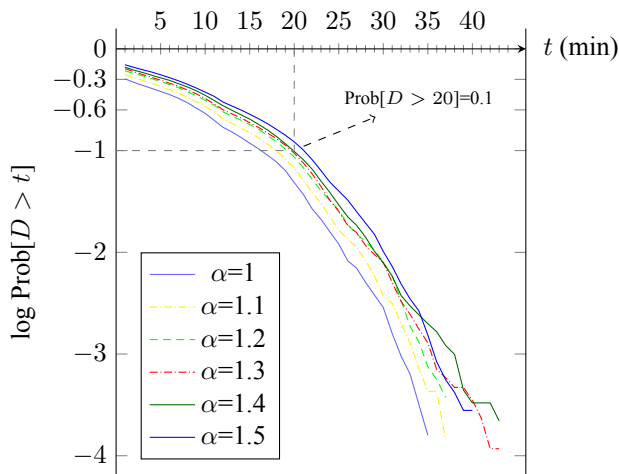Figure 9: Distribution of the queue length for upstream traffic as a function of the arrival intensity.

Figure 10: Distribution of the delays for upstream traffic as a function of the arrival intensity.

CONCLUSIONS

A stochastic simulation model was created to assess the overall impact of implementing a one-way policy in the Albert Canal. Due to construction works, only part of the canal will be available for vessel traffic. The inputs of the simulation model were found by performing statistical analysis on real Automatic Identification System (AIS) data. The main performance measures include the vessels' waiting times and the queue lengths. Several scenarios were investigated with varying arrival intensities.

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Figure 11: Distribution of the delays for downstream traffic as a function of the arrival intensity.

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