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Modelling sailing time and cost for inland waterway transport

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Transport time and cost are decisive factors for shippers when they choose a mode for their transport. For inland waterway transport in particular, these aspects are more uncertain and less easy to generalize than for road and rail. This is due to the highly variable waterway conditions on free-flowing rivers and due to the large variety of inland ships. Today´s transport models, however, do not take these factors into account. This paper shows that dynamic fairway conditions, the ship's amount of propulsion power, and the captain's behaviour have a substantial impact on the attainable speed and fuel consumption of inland ships. This in turn has a significant impact on attainable sailing schedules and transportation cost, as we demonstrate through a case study for ships sailing on the Rhine-Danube corridor. We, therefore, conclude that there is a clear potential to improve the representation of inland waterway transport in freight models by modelling the effects of actual ship characteristics and waterway conditions at the micro-level.

Keywords: *inland waterway transport, transport modelling, waterway modelling.*

1. Introduction

Transportation time and cost are decisive factors for shippers when they choose a mode for their transport. For inland waterway transport (IWT) in particular, these aspects are more uncertain and less easy to generalize than for road and rail. This is due to the highly variable waterway conditions on free-flowing rivers and due to the large variety of inland ships. In a free-flowing river, water depth and current velocity vary strongly along its course due to differences in shape and slope of the riverbed. Furthermore, changes in rainfall and/or snowmelt will change the water depth and current velocity at given locations over time. For a given ship, this in turn leads to large differences in attainable speeds and fuel consumption at those speeds. The technical specifications and amount of installed power of the propulsion systems of inland ships are also very diverse, even for ships whose cargo carrying capacities are very similar. Two ships with a similar cargo carrying capacity can respond very differently to changes in waterway conditions. This makes it difficult to accurately model the transportation time and cost for IWT and, therefore, to improve the quality of today's freight transport models. This leads to inaccurate

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assessments of the performance of waterborne transport and prevents the models from properly supporting synchromodal transport decisions. In such decisions, one aims at making optimal use of a combination of transport modes based on real time information regarding the available transport capacity (Tavasszy et al., 2010).

IWT is already considered a difficult subject to deal with in strategic freight transport models, which do not yet take any variances in water levels into account. The common way to model IWT flows is to define a few reference ships with a certain capacity (generally measured in tons) for which fixed generalised cost levels per tonkilometre are assumed (see e.g. NEA, 2001, 2004, 2015; Grosso, 2011). The size of the applied reference ships is commonly defined according to the dimensions of the applicable waterway classification (e.g. the West European CEMT classification). Examples of models that deal with IWT by taking about 3 to 5 distinct ship types into account are the SMILE, NODUS, TRANS-TOOLS, and Zhang models (Van Dorsser, 2015; Jourquin and Beute, 1996; Jonkeren et al., 2011; Burgess et al., 2008; Zhang, 2013). Some basic models, such as the BASGOED model, do not even attempt to model different ship types, but instead apply a single time and distance-based cost factor in combination with a fixed time value per NSTR-level 1 type of good and a fixed OD specific access/egress cost factor (De Jong et al., 2010, 2011).

This common approach of distinguishing between a few different ship types results in deficient, or at least suboptimal, transport projections. First of all, the rough distinction into just 3 to 5 different ship types does not reflect todays variety in the dimensions and cost structures of inland ships (Roelse, 2002; RWS, 2011). In addition, this simplified approach does not take into account the fact that the capacity of an inland ship is a function of: the water depth, that affects the loading tonnage; the air clearance, that affect the loading volume for lighter cargoes such as containers; and the stability of the ship against capsizing, that constrains both loading volume and tonnage (Van Dorsser, 2016). Nor does it take into account the fact that the speed and fuel consumption of an inland ship are defined by the joint characteristics of the ship and the waterway (Hengst, 1995; Przedwojski et al., 1995). These shortcomings contribute to the fact that the fit of IWT in today's freight transport models is generally much less than the fit for other modes of transport (see e.g. Limbourg and Jourquin, 2009). The worse representation of IWT in freight transport models is also addressed by Burgess et al. (2008, p.135), who indicates in the final report of the TRANS-TOOLS model that: *"Also flows in inland waterways seem to have a wrong representation"*.

We believe that there is still significant room to improve the modelling of IWT flows by adopting a different approach, based on a GIS (Geographical Information System)-based description of the waterways. In such a GIS-based modelling approach, the available waterway dimensions are defined as a function of the existing infrastructure dimensions and the encountered water levels, while the characteristics of the ships are a function of their main dimensions and actual loading draught. Suggestions in this direction have already been made by Burgess et al. (2008), De Ceuster (2010), Schweighofer and Szalma (2014) and Van Dorsser (2015). The implication of the water levels for the modelling of freight transport volumes has recently gained interest in the light of adaptation to climate change (Jonkeren et al., 2009; Turpijn and Weekhout, 2011; Riquelme Solar, 2012), where the main focus has been on extreme events. This interest has, however not yet led to improvement of the representation of the waterway characteristics when modelling normal circumstances.

Improving freight transport models to the point that they can actively contribute to the optimal use of inland ships in a synchromodal transport chain requires an even more advanced modelling approach, that predicts speed and cost levels of an individual ship on the basis of its main dimensions, draught, and power installed – and the encountered waterway conditions during the trip (i.e. predicted water levels, current velocities, and speed limits). Ideally the ships in such an advanced model are defined parametrically (as discussed by Hekkenberg, 2013), which implies that the cost structure is defined as a function of the main dimensions, installed

power, and actual loading draught of the ship – and not restricted to the use of standard size ships, as is for instance the case in the cost model of Beelen (2011).

Because the fuel consumption of inland ships is directly related to the constrained dimensions of the inland waterways, it is likely to be important to take the interaction with the waterway system into account in the development of more advanced transport models. To this end, the only known example of a freight transport model that is able to calculate the effect of changing waterway dimensions on the fuel consumption of inland ships, is the Dutch BIVAS model. This model is however not intended to optimise of the speed of individual ships, but rather to estimate the effect of infrastructural changes on the overall performance of the system (Bolt, 2003).

We, therefore, conclude that the sailing time and cost levels for IWT are still oversimplified in today's transport models, because fixed values for the sailing speed and fuel consumption of a given ship type are assumed. This simplification implies that the depth of the waterway is constant, there is no current, the technical specifications of the actual ship are very similar to those of the reference ship and the draughts of the ships are always the same. Because the actual conditions deviate from these simplified conditions, this can lead to substantial errors, as we will demonstrate.

In this paper, we explore the impact of a dynamic fairway with changing water depth and current velocity on the travel time, fuel consumption and transportation cost for two similar sized inland ships on the Rhine-Danube corridor, between Duisburg in Germany and Budapest in Hungary. Section 2 starts with a description of the case study. Section 3 discusses the physics underlying the effect of the encountered waterway conditions on the speed and fuel consumption of inland ships. Section 4 presents the applied modelling approach for the case study. Section 5 addresses the case study results in terms of speed and fuel consumption for the two considered ships, three different sailing regimes, and ten different waterway conditions. An analysis of the impact of the case study results on the transportation cost of the inland ships follows in Section 6. Based on our case study, the opportunities to improve freight transport models are discussed in Section 7. Conclusions about the improved estimation of sailing time and cost of inland ships in strategic and operational inland waterway transport models are finally drawn in Section 8.

2. Case study description

This section provides a description of the case study. Section 2.1 presents a general overview, while section 2.2 discusses the characteristics of the ships that are studied. Sections 2.3, 2.4 and 2.5 consecutively discuss the way the waterway conditions, sailing strategies of the captain and the passage of locks are modelled.

2.1 General case description

The case study that is explored in this paper is the transport of trade cars from factories in Hungary to the consumer market in Germany, covering a distance of almost 1600 km. Trade cars are loaded onto so-called Roll-on – Roll-off (Ro-Ro) ships at Budapest and unloaded at Duisburg. The concerned waterway route is indicated in Figure 1. It covers a large part of the TEN-T Rhine-Danube corridor and includes waterway sections with strongly varying conditions which significantly influence a ship's performance, thereby making it a suitable route for this case study. The diversity of the encountered waterway sections creates much broader understanding of the subject matter than shorter, more common, trips on e.g. the lower Rhine can create.

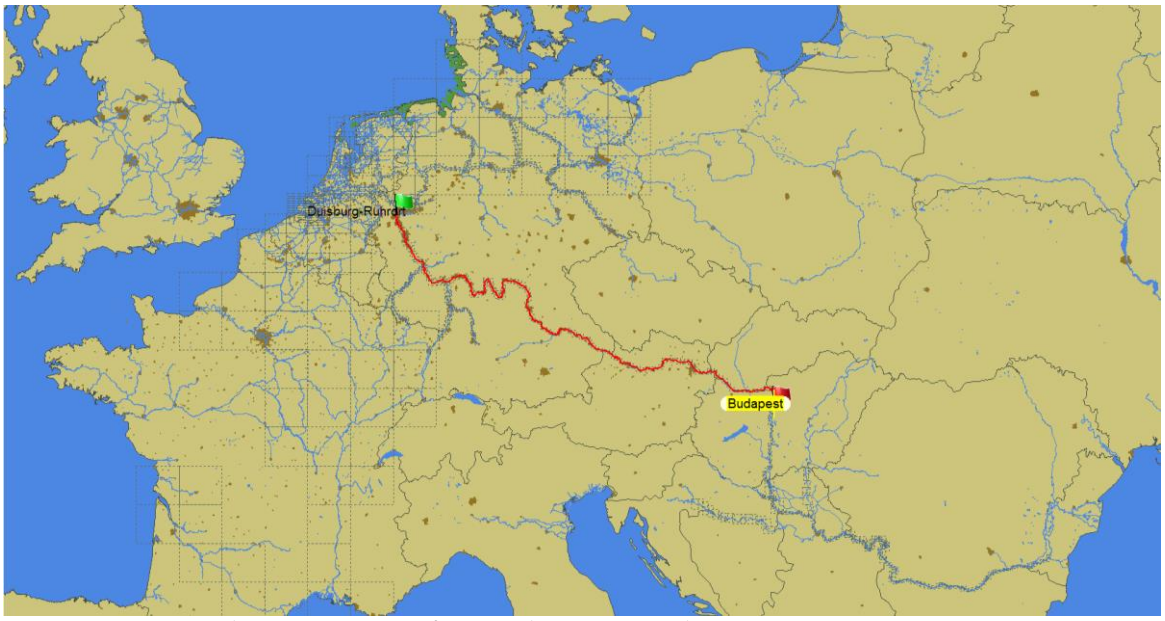

Figure 1. Concerned waterway route from Budapest to Duisburg
Source: PC-Navigo route planner

A similar Ro-Ro freight case has also been discussed in several previous studies (Stein et al., 2014, Blaauw et al., 2006), but these studies did not address the impact of the dynamic fairway properties, the installed engine power, and the applied sailing regime (e.g. slow steaming to reduce fuel consumption or fast sailing to meet a schedule), on the speed, fuel consumption and cost of inland ships.

To explore the effect of dynamic fairway conditions, installed engine power and applied sailing regime on the speed, fuel consumption and cost of inland ships, we estimated the effect of the encountered waterway conditions (i.e. water levels and current velocities) for two existing Ro-Ro ships with almost identical dimensions and an almost identical cargo capacity, but very different amounts of installed engine power. The two ships under consideration are mathematical models of *Kelheim* (ship 1) and *Heilbronn* (ship 2), that currently transport trade cars along the upper Danube. We analysed the speed, fuel consumption, and transportation cost for these two ships as a function of the encountered waterway conditions, the available engine power and the captain's behaviour.

2.2 Ship characteristics

The characteristics of the two inland ships in this case study are defined by their main dimensions (i.e. length, beam, and draught), their carrying capacity, and the available power of the ships' propulsion systems. Both ships have very similar length: 105 m for *Heilbronn* and 110 m for *Kelheim*. They both have a beam of 9.5 m and a capacity of 260 cars. Since trade cars are light and voluminous, the ships always operate at a draught of only 1.65 m, which implies that they can carry their full load even during periods of low water. This simplifies our case as it allows the analysis to exclude the impact of extremely low water levels on the utilization of the ships, and consequently on the cost per unit of cargo transported. Although the impact of utilization is, in itself, an interesting topic, it would unnecessarily complicate the discussion of sailing times and fuel consumption in this article.

Of course the dimensions of a ship also influence the investigated variables as different ship dimensions will influence attainable speed, fuel consumption and cost on a specific waterway section. The reason not to vary ship dimensions is, however, to provide focus to the study. Despite their similarities, the ships differ considerable with respect to the amount of engine power installed. *Heilbronn* has a 588 kW main engine, while *Kelheim* has a more than twice as

powerful main engine of 1320 kW (Donau-schifffahrt, 2015). Comparing them to modern similar-sized ships in Figure 2, we conclude that Heilbronn is at the lower end of the engine power range, while Kelheim is closer to the upper end of the range. The cluster of ships with powers upwards of 1900 kW are most likely twin-screwed ships that are intended to push a dumb barge and are therefore not directly comparable to the other ships.

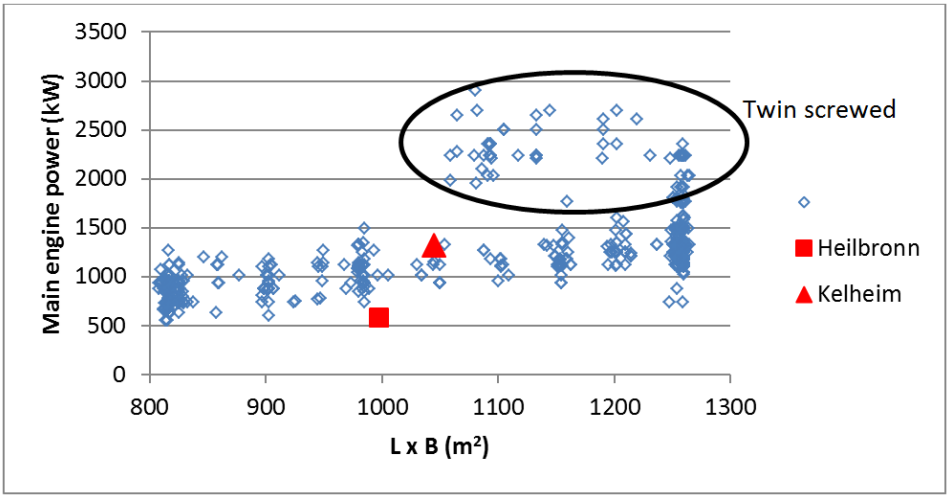

Figure 2. Power vs. dimensions of inland ships
Note: L x B is a measure for the size of the ship, defined as the product of its length and beam.
Source: Own figure, based on ship data from www.debinnenvaart.nl

2.3 Waterway conditions

Ships sailing between Duisburg and Budapest pass parts of the rivers Rhine and Danube as well as the entire river Main and the Rhine-Main-Danube (RMD) canal. Especially on the Rhine and Danube, water depth and current velocity change strongly along the course of the rivers and over time. Since exact data for every point along the fairway is not available, the waterway data along the route is schematized in this case study. For the Rhine and Main, water depth data at average water depth, highest navigable water level (HNWL, not exceeded more than 1% of days per year) and lowest navigable water level (LNWL, exceeded at least 94% of days per year) is obtained from the so-called 'pegel' water depth gauges at Dusseldorf, Bonn, Koblenz, Kaub, Frankfurt Osthafen, and Schweinfurt Neuer Hafen, as published on http://www.ELWIS.de (accessed: July 2015). On the Rhine, the length of the river sections to which the pegel data is applied is obtained from the waterway profile at LNWL as published by the Central Commission for Navigation on the Rhine (2015). The river Main is divided in two sections that meet at Lengfurt. Average current velocities on Rhine, Main, and RMD canal are obtained from voyage planner PC-Navigo, while highest and lowest values for the current velocities on the Rhine and Main were estimated at 175% and 75% of the average velocity, based on data for a part of the Rhine from Frings et al. (2014). On the RMD canal the current velocity and water depth are assumed to be constant. This leads to waterway data for the Rhine, Main and RMD canal as shown in Table 1. Waterway conditions on the Danube have been obtained from data underlying the work of Schweighofer and Szalma (2014), for which we lack permission to publish the numbers in tabular form.

Table 1. Data of waterway sections in the case study

	River-km	Section length	Water depth			Flow velocity		
			LNWL	HNWL	Avg.	LNWL	HNWL	Avg.
Section	[km]	[km]	[m]	[m]	[m]	[km/h]	[km/h]	[km/h]
Rhine	774-783	9	2.8	8.83	4.37	-3	-7	-4
	763-774	11	2.8	8.83	4.37	-3	-7	-4
	688-763	75	2.5	8.83	4.37	-3	-7	-4
	592-688	96	2.5	8.79	4.2	-3.75	-8.75	-5
	586-592	6	2.1	7.61	3.66	-3.75	-8.75	-5
	557-586	29	2.1	7.61	3.66	-4.5	-10.5	-6
	520-557	37	1.9	6.7	3.36	-5.25	-12.25	-7
	508-520	12	1.9	6.7	3.36	-3	-7	-4
	497-508	11	2.1	5.95	3.43	-3	-7	-4
Main	Rhine to Lengfurt	174.7	2.68	4.96	3.29	-0.75	-1.75	-1
	Lengfurt to RMD	209.3	2.62	5.11	2.92	-0.75	-1.75	-1
RMD Canal	0-36	36	4.25	4.25	4.25	-2	-2	-2
	36-140	104	4.25	4.25	4.25	0	0	0
	140-174	34	4.25	4.25	4.25	2	2	2
	174-204	30	4.25	4.25	4.25	4	4	4
Danube		724.6	No permission granted to publish tabular data.					
Total length of waterway route		1589.5						

2.4 Sailing strategies

As part of the case study, the sailing behaviour of the captain needs to be modelled, because it may, among others, change due to economic considerations like e.g. changes in fuel price or changes in freight prices (Jonkeren et al., 2012). The captain can either sail slowly to save fuel, or speed up to meet a tight schedule or transport more cargo in a given amount of time at the expense of a higher fuel consumption.

How fast or slow a captain should sail to achieve the right balance between speed and fuel consumption is strongly influenced by the actual water depth. A lower water depth leads to a much larger amount of power that is required to reach a given speed and, thereby, to a strong increase in fuel consumption, as will be discussed in the next section. Water depth even determines the maximum speed that a conventional cargo ship can reach. This speed, the so-called critical speed is defined in Equation 1:

$$V_{lim_h} = \sqrt{g \cdot h} \quad (1)$$

with:

V_{lim_h} : maximum speed in m/s;
g : gravitational constant of 9.81 m/s^2;
h : water depth at section in m.

Especially when the ship's speed approaches the limit speed, a large increase in power is required to realise a small increase in speed. As a result, captains will usually not sail faster than approximately 70% of this speed. Hengst (1995, p. 89) mentions a value of 68%. Furthermore, captains will normally limit the output of their engine(s) to approximately 85% of the maximum power output (i.e. 85% of the engine's Maximum Continuous Rating or MCR) in order to prevent excessive wear and tear. They can however, choose to increase power output of the engine and

sail faster if they need to keep a strict schedule or make up for lost time. On a number of waterways there are also legal speed limits. For the route under investigation, only the Rhine-Main-Danube canal has a formal speed limit of 11 km/h. There is also a speed limit of 12 km/h over a short stretch in the Canal of Gabcikovo, indicated by notice marks only. It is not laid down in any regulation.

The default behaviour of a captain is generally to sail 'sensibly', but for modelling purposes a more precise specification is required. We define 'sensible' as the mode where the captain:

- adheres to the legal speed limit, if applicable;
- does not exceed 70% of the critical speed and;
- limits the amount of power to 85% of MCR.

To evaluate the extent to which the captain can keep a schedule under adverse conditions, we also assess a 'fast' mode, where the captain will sail as fast as possible without breaking the legal speed limit or exceeding 100% of the maximum continuous rating of the main engine. As an intermediate mode, we assess the case where the captain sails at speeds up to 80% of critical speed without breaking speed limits or exceeding 85% of the engine's MCR. This implies that the captain is willing to accept a higher fuel consumption to keep his schedule, but is not willing to put excessive strain on the engine. Table 2 summarizes the abovementioned sailing strategies.

Table 2. Summary of sailing regimes

Sailing regime	Main Characteristics
'Sensible sailing mode'	adheres to the legal speed limit, if applicable; does not exceed 70% of the critical speed and; limits the amount of power to 85% of MCR.
'Intermediate sailing mode'	adheres to the legal speed limit, if applicable; does not exceed 80% of the critical speed and; limits the amount of power to 85% of MCR.
'Fast sailing mode'	adheres to the legal speed limit, if applicable; maximum attainable speed at 100% MCR.

2.5 Time required for the passage of locks

The final factor that affects the total sailing time in the case study is the time required for passage of locks. On this particular route, from Budapest to Duisburg, the ship will have to pass through 66 locks which adds time to the voyage. We have included this in the calculations as a delay of 0.75 hours per lock, based on Via Donau's estimates for the locks west of Vienna (Via Donau, 2007, p. D10). To verify this assumption, we analysed the actual lockage time of several ships throughout August 2015. Though the ships did not sail over the entire route from Budapest to Duisburg in the logged period, this analysis did confirm lockage times to be consistently between 0.5 and 1 hour. For this explorative case study we consider 0.75 hours as a good average, but the analysis can be improved by including statistical data for passage times of comparable ships at each individual lock along the route.

3. Ship-waterway interaction

The interaction between a ship and a waterway plays a major role in the speed that a ship can attain as well as in the amount of fuel that it needs to sail at a given speed. In section 3.1 the maximum attainable speed is discussed and in section 3.2 the approach to estimate the relation between speed and fuel consumption is described.

3.1 Maximum attainable ship speed

The maximum speed of an conventional inland cargo ship (i.e. a non-planing displacement ship) is theoretically limited by the following three aspects: (1) the length of the ship; (2) the water depth; and (3) the ratio between the cross-section area of the ship at the midship section and the cross-section area of the waterway. The reason that the maximum speed of a displacement ship is limited by its length is that it is unable to overtake the crest of the wave that the ship generates itself. For this reason the maximum speed of a displacement ship is bound by the speed of a wave with a length that is more or less similar to that of the ship. Linear wave theory learns that the corresponding hull speed can be expressed by Equation 2 (Przedwojski et al., 1995):

$$V_{lim_l} = \sqrt{\frac{g \cdot L_s}{2 \cdot \pi}} \tag{2}$$

with:

V_{lim_l} : maximum hull speed at unrestricted water depth in m/s;
g : gravitational constant of 9.81 m/s2;
L_s : length of ship in m.

The effect of water depth on the maximum speed of ships has already been discussed in Equation 1. From Equation 1 and 2 one can expect shallow water effects to be encountered when the water depth becomes less than approximately $1/6^{th}$ (i.e. $1/(2\pi)$) of the ship's length. In practice, however, the combination of these two effects is even more restrictive, as it follows from wave theory (Przedwojski et al., 1995) that the combined limiting hull speed is as indicated in Equation 3.

$$V_{\lim_l,h} = \sqrt{\frac{g \cdot L_s}{2 \cdot \pi} \cdot \tanh\left(\frac{2\pi h}{L_s}\right)} \tag{3}$$

with:

$V_{lim_l,h}$: maximum hull speed at restricted water depth in m/s;
g : gravitational constant of 9.81 m/s^2;
L_s : length of ship in m;
h : water depth at section in m.

From the '$tanh(2 \cdot \pi \cdot h/L_s)$' term in Equation 3 it follows that the maximum hull speed is reduced by about 0.4% when $h < L_s/2$ and by about 3.0% when $h < L_s/3$. Shallow water effects can therefore already play a role at water depths smaller than 1/2 to 1/3 of the length of the ship. As a consequence, the speed of inland ships, that often sail at water depths that are much smaller than the ship's length (e.g. only 1/20 of the length), is severely constrained by shallow water effects.

Finally the width of the waterway section also has a limiting effect on the hull speed. According to Schijf (1949), who developed a method based on preservation of energy to compute the maximum possible sailing speed at a given waterway section with a constrained depth and width, the limit speed is derived as a function of the ratio between the midship cross-section and the cross-section of the waterway. In his formula, the limit speed is obtained iteratively by solving Equation 4.

$$1 - \frac{A_S}{A_C} + \frac{1}{2}\left(\frac{V_{lim}}{\sqrt{g \cdot \bar{h}}}\right)^2 - \frac{3}{2}\left(\frac{V_{lim}}{\sqrt{g \cdot \bar{h}}}\right)^{2/3} = 0 \tag{4}$$

with:

V_{lim} : maximum ship speed at constrained waterway section in m/s;
g : gravitational constant of 9.81 m/s^2;
A_s : cross-section area of ship at midship in m^2;
A_c : cross-section area of waterway in m^2;

$\bar{h}$: average water depth of undisturbed cross-section in m.

Equation 4 shows that, when the waterway is not only constrained by shallow water, but also by limited width, the limit speed will be even lower than in case of shallow water only. In fact, in the ultimate case where A_s/A_c approaches 1 (i.e. the ship's midsection becomes just as large as the waterway crosssection) the limit speed goes to zero. This implies that at smaller waterway sections, both the depth and width of the waterway have a limiting effect on the maximum attainable ship speed. Comparable results have also been obtained by Bouwmeester (1977) who derived a similar theory based on preservation of momentum instead of energy.

3.2 Ship resistance, power demand and fuel consumption

The fact that displacement ships are unable to sail faster than a given speed, which is constrained by the characteristics of both the ship and the waterway section in which it sails, implies that ship's resistance increases towards a vertical asymptote at the applicable limit speed. The dimensions of the waterway, therefore, affect the resistance and fuel consumption of inland ships. It is common practice to first estimate the ship's speed-power relation in unconstrained water and then correct it for the constraints in waterway depth and width that are present.

Although relatively few empirical prediction methods for the speed-power relation of inland ships at unconstrained water conditions have been published, sufficiently accurate predictions for our purpose can be obtained on the basis of the resistance prediction method of Holtrop et al. (1990). To derive the required power and fuel consumption one needs to take into account the fuel efficiency of the engine, the losses in the drive line, and the efficiency of the ship's propeller. Estimates for the propeller efficiency are based on the Wageningen-B series (Oosterveld and Van Oossanen, 1975).

The hardest part in the estimation of the ship resistance and fuel consumption is to correct for constrained waterway dimensions, for which generally applicable and sufficiently validated correction methods are still lacking, and for which a detailed description of the real waterway conditions is required. To start with, the method of Schijf (1949), that can be used to derive the return current and power demand at any speed level for a relatively tight canal section, does not take the exact shape of the waterway into account, but instead uses the factor A_s/A_c (see Equation 4). This method is imprecise as various shapes of the river bed with a similar A_s/A_c will not necessarily result in a similar return current. The model is also not valid for describing the shallow draught behaviour of ship on a wide waterway section, such as in a lake, though approximations can be made by assuming a virtual width of roughly up to 10 times the ships beam. In addition, the true width and cross-section shape of the waterway is also not always sufficiently known either, so that further assumptions have to be made. This complicates the use of Schijf- or Bouwmeester-like methods to achieve water depth-adjusted resistance and fuel consumption estimates.

A simplified version of the Schijf method has nevertheless been implemented in the Dutch BIVAS model. To deal with issue that the A_s/A_c fraction approaches zero in areas without any width constraint, BIVAS uses an alternative formula for which the origin cannot be traced, to calculate the return current under these conditions. A specific warning is also made that the model is not intended to calculate the resistance and fuel consumption of an individual ship, but is meant to estimate the average effect on the fleet (Bolt, 2003). The BIVAS model is, therefore, not optimal to estimate the specific fuel consumption of the ships in our case study.

The rather unsatisfactory way of dealing with different waterway cross-sections in the Schijf model and the present unavailability of detailed data to describe the waterway cross-section as a function of the water level, has encouraged the use of simpler shallow water corrections by

Karpov[4] as documented by Van Terwisga (1989). This Karpov method, that is for instance used in the dissertations of Van Hassel (2011), Beelen (2011), Hekkenberg (2013) and Van Dorsser (2015), can, at least in theory, result in an underestimation of the shallow water effects, because waterway width constraints are not properly taken into account. However, since the route under investigation consists of relatively wide waterways, the impact of this simplification will be limited. We therefore consider it sensible to apply the Karpov correction in our case study, although additional research on shallow and constrained water correction methods is recommended to improve future modelling.

The encountered current velocity is included by adding it to or subtracting it from the calculated speed of the ship. The limited effect of the hydraulic gradient of the river (i.e. the ship sailing up- and downhill) has not been taken into account. As an example, for *ship 2,* the Heilbronn approximation, this approach leads to the speed-power-water depth relations as shown in Figure 3. For *ship 1* a very similar relation is valid, but due to its more powerful engine, it will be able to reach higher speeds at the same water depth.

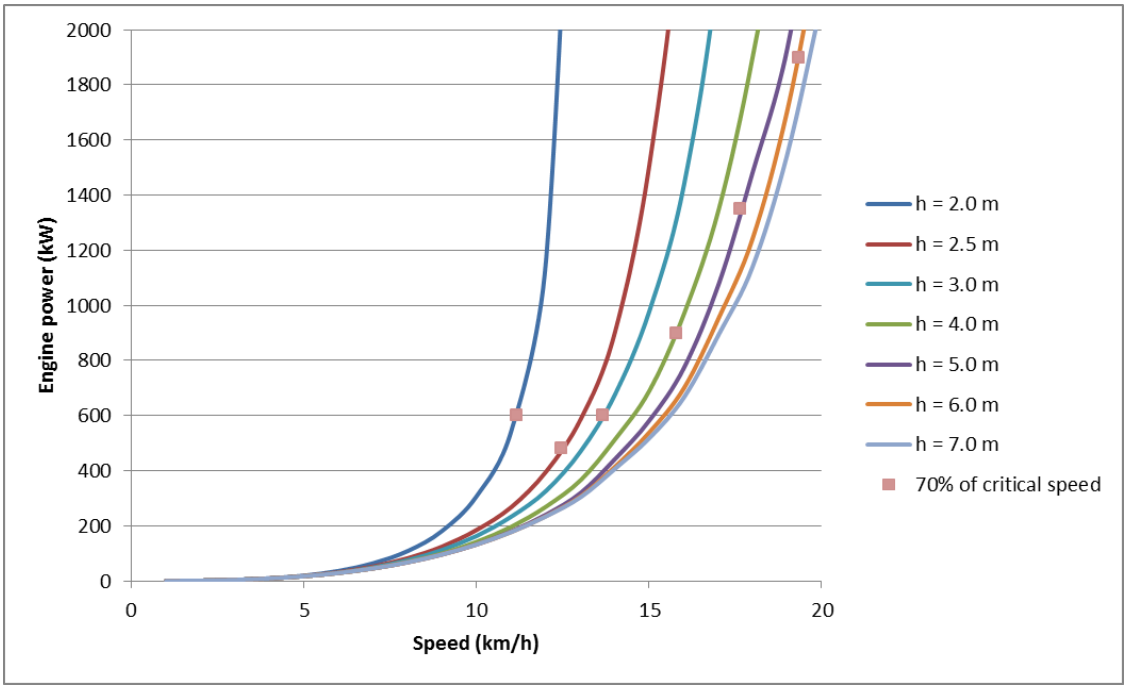

Figure 3. Calculated Speed-power curves of Heilbronn
Note: 'h' in the legend stands for undisturbed water depth

On top of the speed-power data from Figure 3, approximately 5 kW of power needs to be added to arrive at the total power consumption of the ship to account for the power use of the ship's electrical systems. We have further assumed a specific fuel consumption of 210 g/kWh to derive fuel consumption from calculated power levels. Based on the technical properties of the ships and their interaction with the waterway system, the maximum speed, required power and fuel consumption were calculated for each ship at any water depth and current velocity. The actual speed and fuel consumption during the trip further depend on the speed strategy the captain uses when sailing the ship as presented in table 2.

[4] The original paper by Karpov, (Karpov, A.B., "Calculation of Ship resistance in restricted waters", TRUDY GIIT. IV, Vol. 2., 1946) is written in Russian and is no longer publicly available.

4. Waterway modelling approach

In order to explore the speed, fuel consumption, and eventually the cost for transporting trade cars with the two ships under consideration, the encountered waterway conditions (i.e. depth and current velocity) have been schematised for the case study. For the entire route, the high, average and low water depths, and current velocities are shown in Figures 4 and 5. In each of the cases it is assumed that either high or low water levels are encountered throughout the entire route. This is a simplification as the relative water levels do not have to be the same over the entire stretch, but we consider this a sensible assumption to explore the need to model the ship speed and fuel consumption in conjunction with the waterway system.

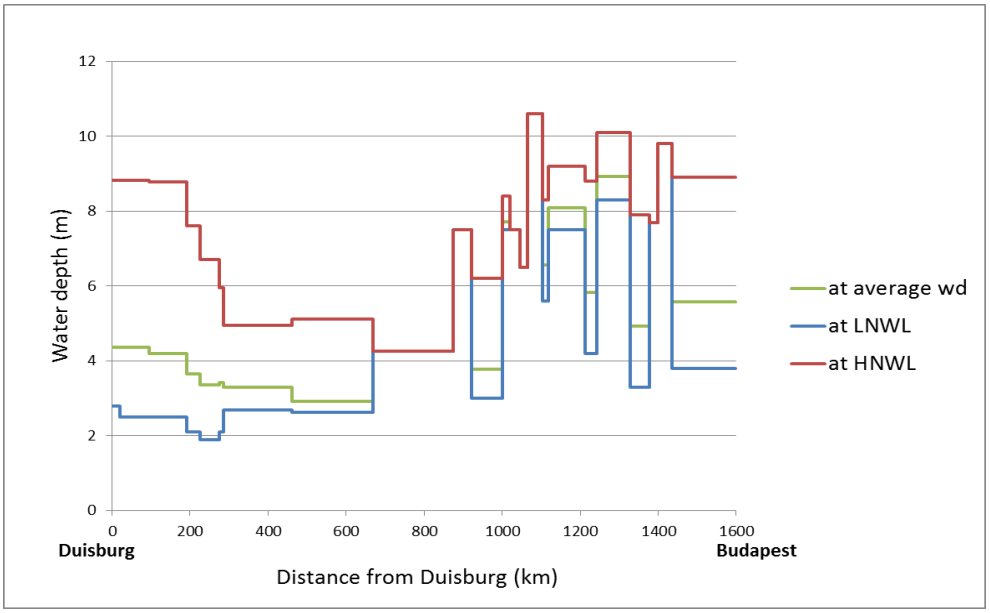

Figure 4. Water depth distribution along the route

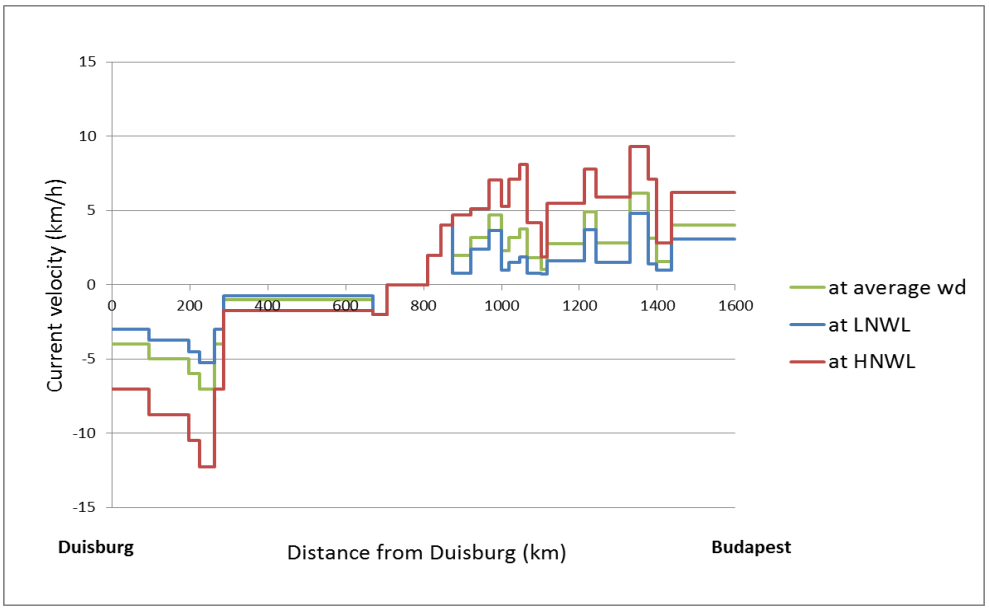

Figure 5. Current velocity distribution along the route, sailing from Duisburg to Budapest

For the assessment of this case study, the obtained water depth and current velocity distributions of each section are both discretized to ten values with equal probability of occurrence. E.g. the highest water depth on a given stretch is represented by the value that is exceeded 5% of the

time, the second highest value is represented by the value that is exceeded 15% of the time, etc. To estimate the frequency of occurrence for given water depths and current velocities, it is further assumed that both variables can be represented by skew normal distributions, implying that water depths are close to the average water depth much more frequently than close to the extreme water depths. This general assumption is supported by data from Beuthe et al. (2012), which presents the water depth distribution at pegel Kaub during 4 years.

5. Case study results

From the case study, conclusions can be drawn regarding the influence of water depth, associated current velocities, engine power and sailing strategy on fuel consumption and sailing times. Section 5.1 presents the sailing times and fuel consumption for both ships in 'sensible sailing' mode, while section 5.2 reviews the impact of different sailing modes. The calculated sailing times are validated in section 5.3.

5.1 Sailing times and fuel consumption

The calculated voyage times of both ships at different water depths during 'sensible sailing' mode are presented in Figure 6. From the figure, it is clear that both ships respond to changes in water levels in a different way. Due to its higher installed power, ship 1 sails faster than ship 2, but is also able to benefit more from increasing water depth because it has enough power to reach 70% of the limit speed if the water depth increases. The limited amount of installed power in ship 2 prevents it from reaching 70% of the limit speed at larger water depths. At the highest water levels, it does not have enough power to counteract the higher current velocities associated with these water levels, leading to an increase in sailing time.

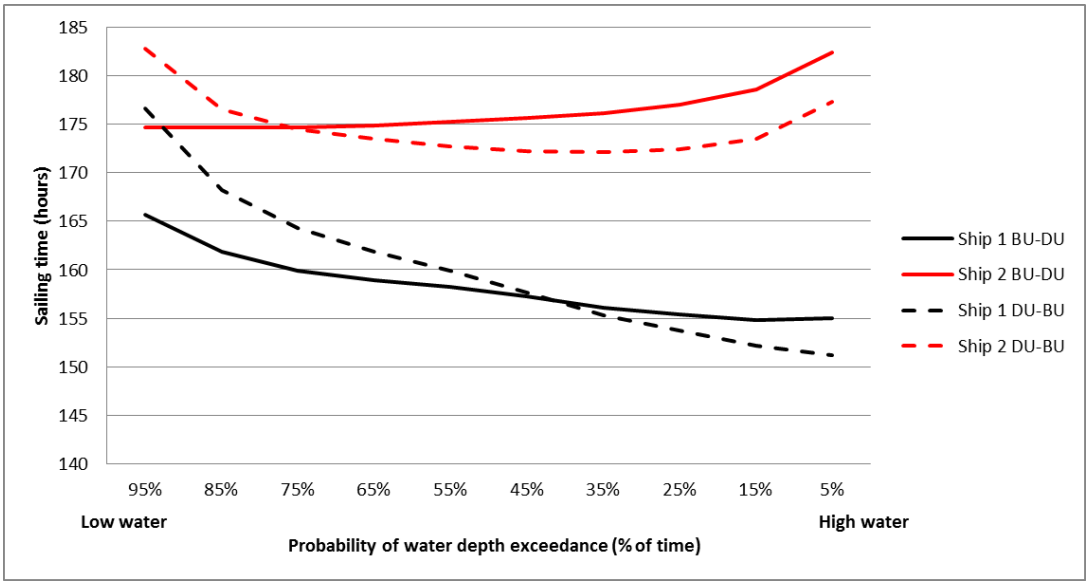

Figure 6. One-way sailing times - sensible sailing

That the speed of ship 2 is limited by a lack of power is also apparent from Figure 7, which shows fuel consumption as a function of sailing time. The line indicating the fuel consumption of ship 2 is proportional to the line indicating the sailing time. This implies that the engine's power output is roughly constant. In contrast, for ship 1 increasing water levels lead to lower sailing times and a higher fuel consumption.

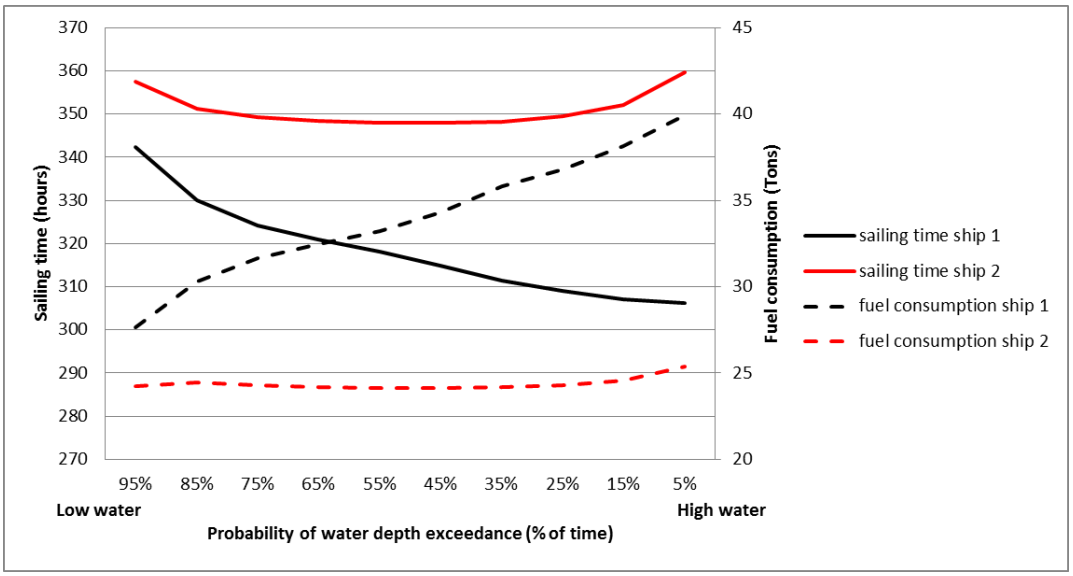

Figure 7. Roundtrip sailing time and fuel consumption - 'sensible sailing'

From Figure 7, the large impact of different water levels and installed power becomes apparent. Fuel consumption of ship 1 can be over 50% higher than that of ship 2, while voyage times of ship 1 can be can be approximately 55 hours less than that of ship 2 if water levels are high.

The sailing times reported in Figures 6 and 7 include the time spent at locks. Given the previously discussed assumption that each ship spends 2 x 66 x 0.75 = 99 hours in locks, this implies that the nett sailing time, i.e. sailing time excluding the locks, of ship 2 is approximately 5% more than that of ship 1 at low water levels and increases to 20% more at high water levels.

5.2 The impact of sailing strategies on sailing times and fuel consumption

In the previous section, we analysed the fuel consumption and sailing time of both ships when the captain sails sensibly. The captain can, however, influence his travel times and fuel consumption by the way he sails the ship, as was explained in Section 2. For high-powered ship 1, the impact of sailing strategy is much larger than for low-powered ship 2. This is shown in Figures 8 and 9, in which the indicated sailing time includes the passage time of the locks.

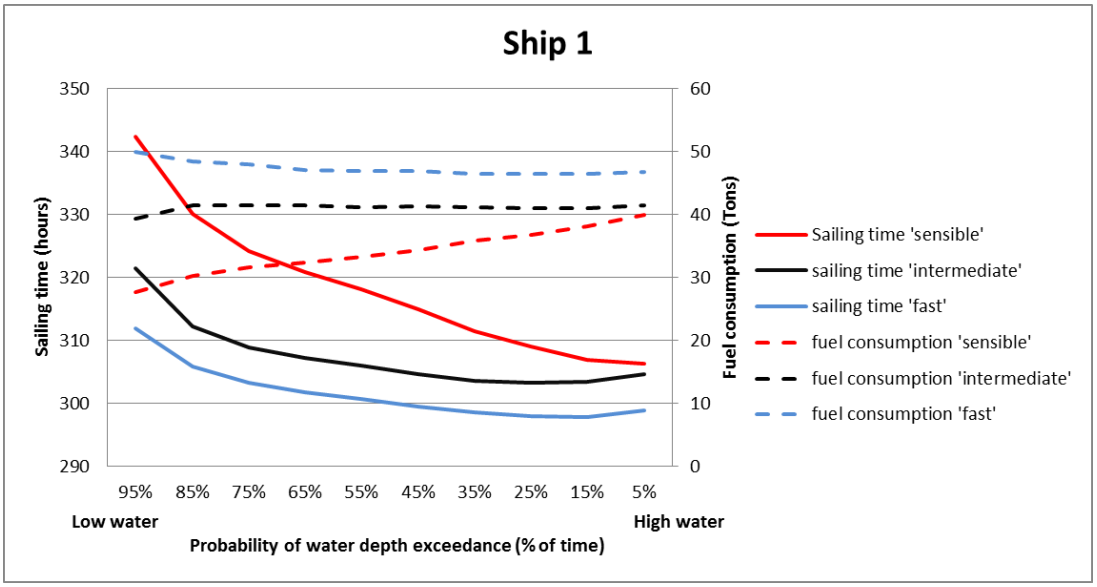

Figure 8. Impact of sailing strategies on fuel consumption and sailing times - ship 1

Ship 1's captain can almost completely counteract any negative effects of low water on the sailing schedule by increasing power, at the cost of nearly doubling fuel consumption and putting a high strain on his engine. (In 'fast' sailing mode the engine power output is set to its maximum).

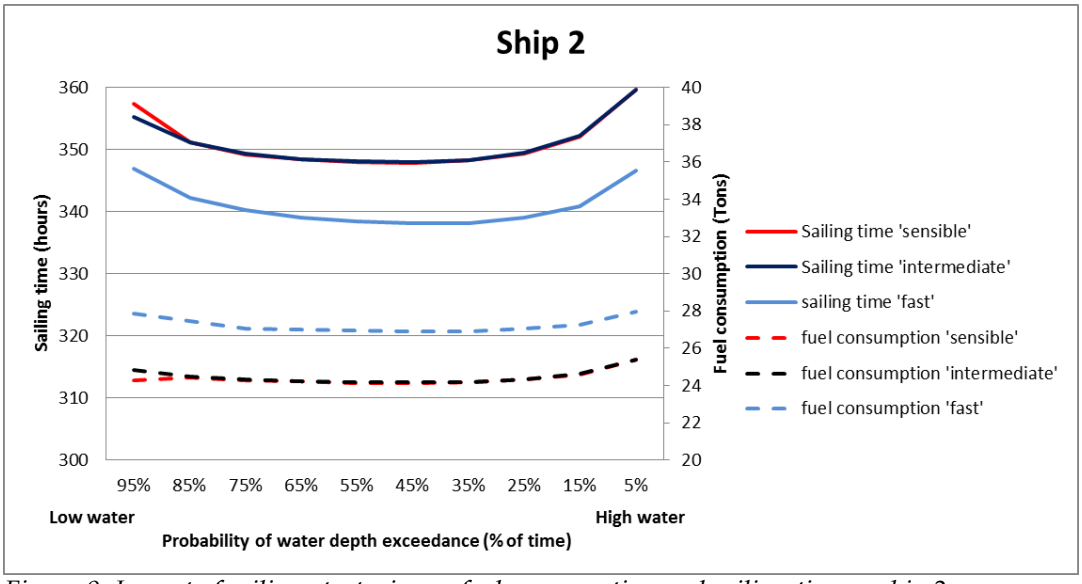

Figure 9. Impact of sailing strategies on fuel consumption and sailing times - ship 2

For ship 2, sailing strategy has a much smaller impact on sailing time and fuel consumption. Since the ship cannot reach 70% of critical speed with 85% of the engine's power unless water levels are extremely low, the effects of switching from sensible to intermediate sailing will not change fuel consumption or traveling times. Only increasing the maximum engine output, i.e. using the 'fast' sailing strategy, will influence travel times and fuel consumption. Figure 9 shows that a roundtrip time of just under 350 hours is achievable at all times at the cost of approximately 2.5 tons more fuel and an increased loading of the engine at extreme water levels.

5.3 Validation of sailing times

In order to validate the results, the calculated values for ship 2 were compared with available reference data from other sources. Since trade cars are much more voluminous than bulk goods, the total cargo weight will always be low, as a result of which the draught and resistance of both ships are lower than that of other cargo ships with similar length and beam. Therefore, one can argue that the estimated speed of low-powered ship 2 is more or less comparable with 'average' ships and can therefore be used to provide basic validation. High-powered ship 1 will be considerably faster and is therefore less suitable for comparison.

To validate the voyage times of ship 2, the calculated values are compared to the ones presented in Via Donau (2007, p. D9) for ships of 1350 and 2000 T deadweight. Table 3 shows that the reference data are in the same range as the calculated sailing time. The minor deviations can be explained by differences in ship specifications and limits in the accuracy of the powering model; simplifications in the applied waterway characteristics, which exclude short shallow stretches; the exclusion of waiting times at national borders; as well as the effects of different draughts and the effect of not including the hydraulic gradient.

Table 3. Comparison of results for ship 2 with sailing time reported by other sources

From	To	Calculated min	Calculated max	Via Donau 1350 T	Via Donau 2000 T
Budapest	Duisburg	174.6 h	182.6 h	195 h	178 h
Duisburg	Budapest	172.1 h	182.7 h	179 h	172 h
Budapest	Regensburg	70.7 h	87.4 h	93 h	77 h
Regensburg	Budapest	45.7 h	54.3 h	59 h	59 h

6. Cost analysis

To determine how the calculated differences in sailing time and fuel consumption affect the transportation cost, the two need to be combined in a single analysis. In section 6.1, the cost of a roundtrip is analysed, while in section 6.2 a more detailed analysis of the cost per waterway section is performed.

6.1 Roundtrip cost analysis

The dimensions of the case study ships comply with the new M7 class of RWS (2011) for which a cost estimate is provided by NEA (2015). This estimate indicates that the fixed cost for a continuously 24/7 operated container ship at the Rhine is in the order of 671500 euro per year. When dividing this cost by 8400 operational hours, as suggested by Hekkenberg (2013) and Van Dorsser (2015), one finds a fixed cost of 80 euro per hour. Assuming another 10 euro per hour to cover the cost of the car decks, one can expect the fixed cost for providing the ship and its crew to be in the order of 90 euro per hour, or 2160 euro per day. When comparing these numbers to those reported by Van Dorsser (2015, p.307), and taking into account the cost increase over the past 5 years, this number seems to be realistic.

At present, the price level at inland shipping fuel stations is about 0.36 euro per litre (based on an actual quote of a fuel station on 31st of October 2016), Taking into account a density of about 0.85 kg per litre gasoil, the cost is about 425 euro per metric ton. However, the fuel price is recovering from a very low value in 2015 and price levels may go up in the near future. We therefore included two scenarios, reflecting a fuel price of respectively 400 and 600 euro per metric ton.

The overall cost of a roundtrip is obtained by multiplying the total sailing time by the cost per hour and multiplying the fuel consumption by the fuel price. The upper and lower cost limits for all combinations of sailing strategy and fuel price scenario are shown for both ships in Figure 10.

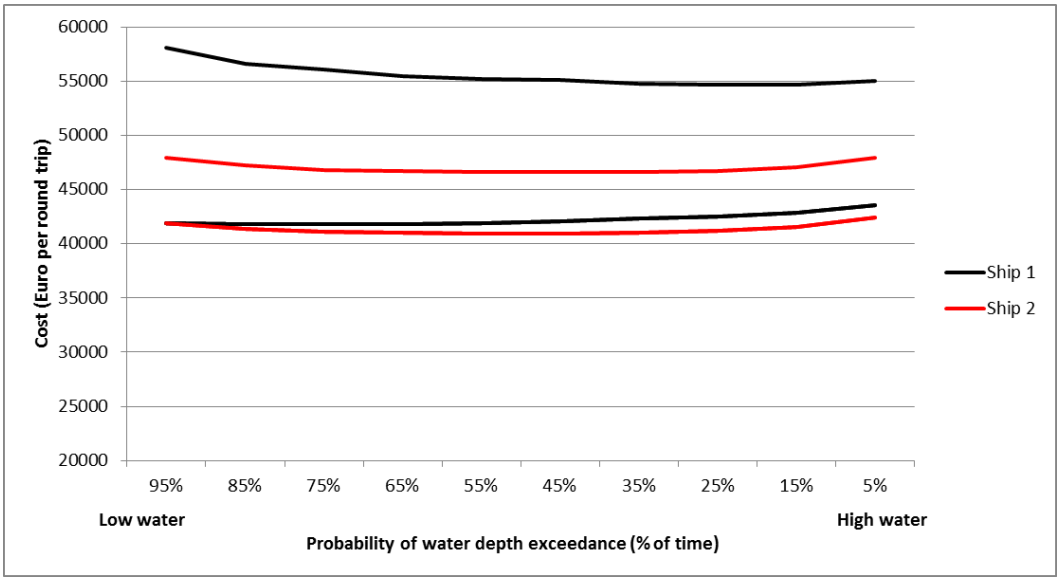

Figure 10. Bandwidth of cost per roundtrip
Note: this figure is based on fuel prices ranging between 400 and 600 euro per metric ton.

The figure shows that for high-powered ship 1, the highest cost estimates are approximately 1.25 to 1.4 times as high as the lowest estimates, while the difference is only about 14% for low-powered Ship 2. The figure suggests that the estimates are much more stable than might be suspected on the basis of the previous detailed analysis. To further underline this point, Figure 11 shows the cost for all sailing strategies at a fixed fuel price of 600 euro per ton.

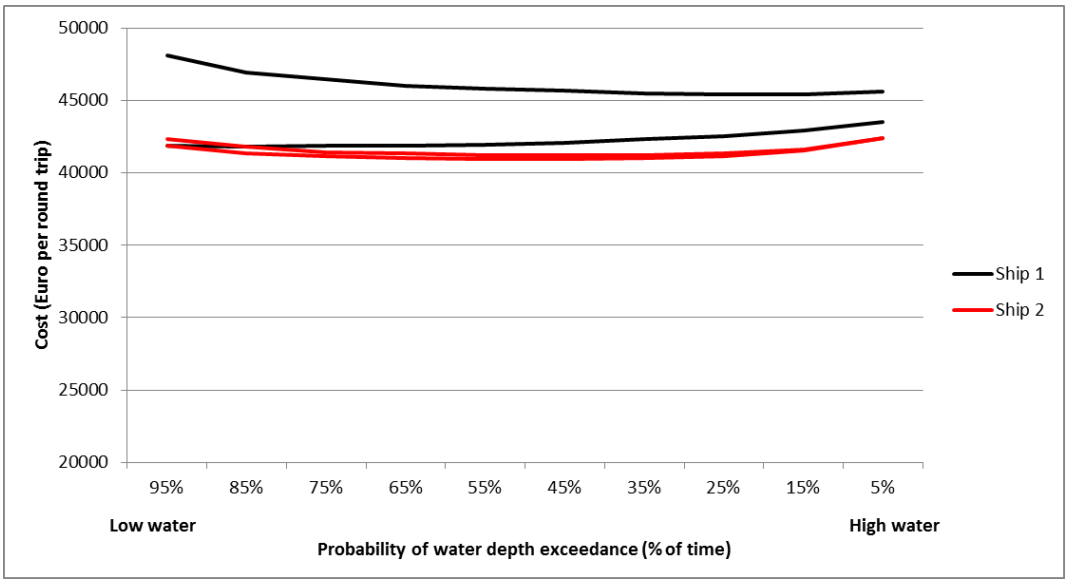

Figure 11. Bandwidth of cost per roundtrip at a fuel price of 600 Euro/ton
Note: this figure does not take variance in fuel prices into account.

From the figure, it becomes clear that the majority of the cost bandwidth in Figure 10 is due to the difference in fuel price, since the bandwidth becomes much smaller when the fuel price is assumed fixed, in particular for ship 2.

For high-powered ship 1, the sailing strategy has an effect of about 5% to 15% in overall cost levels depending on the encountered water levels. The relatively stable cost levels for the roundtrip can be explained by the fact that time and fuel cost partially cancel each other out: using more fuel to sail faster reduces time cost. Time cost makes up 60-80% of all cost and the waiting times at locks, which we do not change, are a substantial part of that. Moreover, the effect of the sailing regime on the speed of the ships is limited due to the nature of the speed-power curve. So unless one sails extremely slow or has the ability to use a very large amount of power, the impact of the sailing strategy on the overall voyage cost is indeed limited.

The outcome of this case study suggests that, when time is not an evaluation criterion, it may be reasonable to ignore the effect of waterway conditions and sailing regime in strategic freight models, as is presently the case. However, the validity of this conclusion largely depends on the summing of results from a large number of very different waterway sections. A very different image emerges if we analyse the performance at the individual waterway sections.

6.2 Cost analysis per waterway section

If we assess the transportation cost for ship 1 at the 'sensible sailing' regime with a fuel price of 600 euro per metric ton on individual sections of the waterway, excluding locks, and distinguish between the eastbound (Du-Bu) and westbound (Bu-Du) leg of the roundtrip, a more nuanced image is obtained.

Figure 12 shows the bandwidth of transportation cost for ship 1 due to different water levels and associated current velocities along the route in both directions. It shows that the cost is between 8 and 32 euro per kilometre on the individual stretches , depending on sailing direction and water level. The figure is strongly influenced by the impact of different current velocities. Especially when sailing upstream against a strong current, transportation cost can be more than three times as high as when sailing downstream. The generally applied assumption that waterway conditions, installed engine power, and sailing regime have only limited impact on IWT cost is, therefore, not valid for individual waterway sections that are subject to currents.

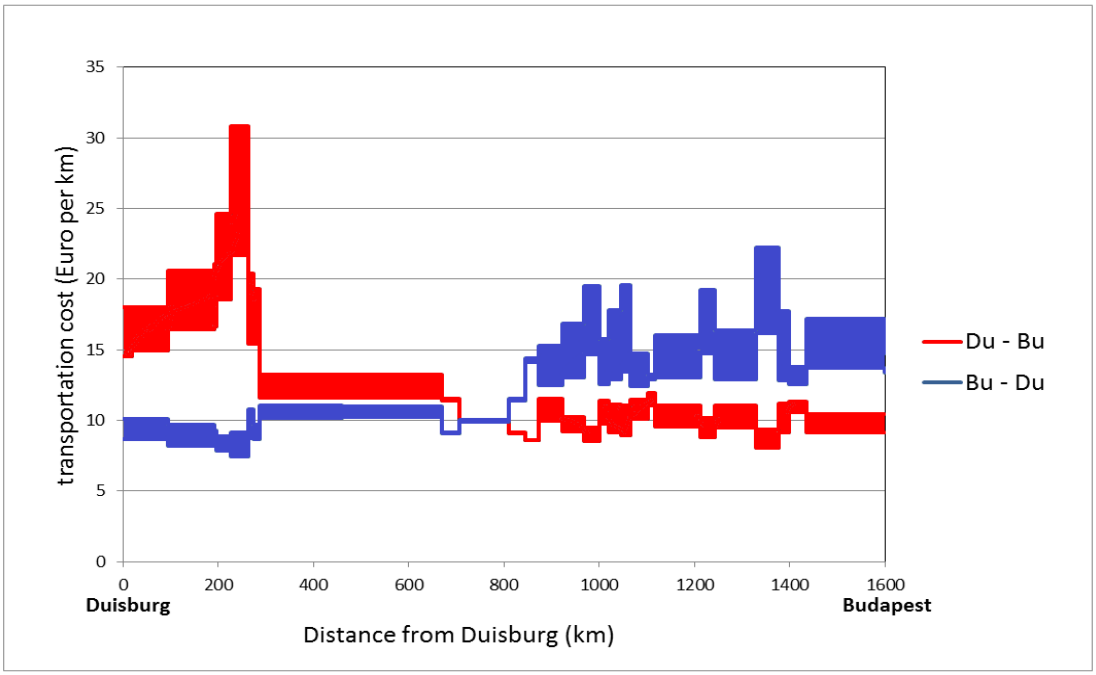

Figure 12. Bandwidth of cost per fairway section for ship 1 - 'sensible sailing'

To further assess the effect of sailing regime and engine power on the transportation cost at a given waterway section, Figure 13 zooms in on the waterway near Kaub (i.e. the section where upstream transportation cost reaches 32 euro per kilometre due to high current velocity) and on the 'Main' (i.e. the long section where upstream and downstream costs are close together due to moderate current velocities). The figure shows the costs of both ships. From left to right, the columns per ship represent sensible, intermediate and fast sailing. The lower and upper bound of each column represent the minimum and maximum costs over the entire range of water levels. The costs at average water level are indicated by the red line.

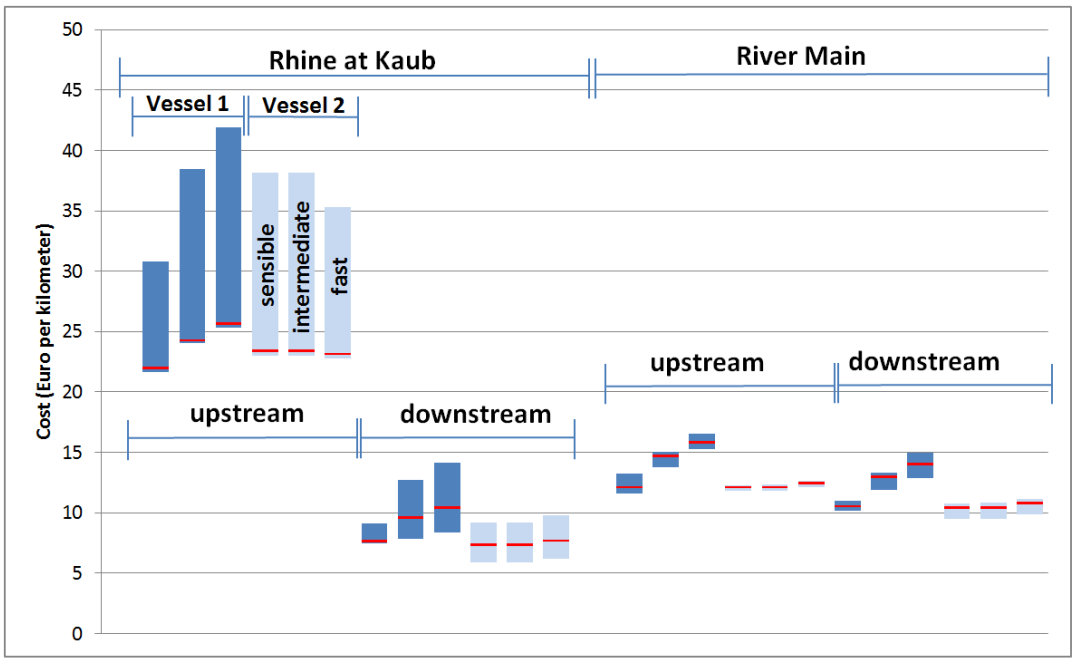

Figure 13. Cost analysis for selected waterway sections

It is important to note that the lower and upper limits of cost in Figure 13 do not necessarily coincide with low and high water levels. E.g. for upstream sailing at Kaub, the highest costs occur at both very high and at very low water levels. At high water levels, current velocities are high and therefore ship speed is low while at very low water levels shallow water effects slow the ship down. The lowest costs at Kaub occur for intermediate water depths, when both shallow water effects and current velocities are limited.

This leads to the important observation that if one defines the cost on the basis of mean water levels for locations with strong currents and/or periods with low water depth, one may substantially underestimate the average cost levels over the year.

Differences in engine power and sailing regime are also important. For low powered ship 2 the cost of sailing upstream 'sensibly' at high current velocities is 24% larger than for high powered ship 1. The cost per kilometre of ship 2 can be reduced by about 7% by switching to fast sailing mode, while for ship 1 a shift from sensible to fast sailing would result in a 36% increase. When sailing downstream at Kaub, the cost can also vary substantially, between 5.9 and 14.1 euro per km (i.e. more than a factor 2) depending on the encountered water level, installed engine power, and sailing regime. About half of this variation can be explained by the sailing regime.

At sections with moderate current flows, such as on the river Main, the variance in cost per kilometre is smaller, but still substantial. It varies between about 11.6 to 16.6 euro per kilometre upstream and between 9.5 to 14.9 euro per kilometre downstream. Most of the variance is caused by the sailing regime of high powered ship 1, for which the 'fast' sailing cost is up to 31% higher than sensible sailing upstream and 35% higher downstream.

7. Opportunities to improve freight models

Strategic freight transport models do not seem to have a sound representation of inland waterway transport. In order to improve the explanatory power of these models it is suggested to develop a new generation of micro-level models in which IWT is no longer modelled by a few distinct waterway classes with fixed dimensions and standard ships, but by a GIS based framework, that builds on the structure already in place in existing nautical route planners (i.e. taking into account the specific properties of each individual waterway section and infrastructure object along the route). The opportunities to improve the representation of IWT in freight transport models by means of a micro-level approach are twofold. Most obvious are the effects of the improved fairway description on the capacity estimates of the ships (e.g. tonnage loaded at certain water levels or stacking height of containers in relation to the actual height of bridges along the route). Less obvious is the effect of the encountered waterway conditions on the ship's speed, fuel consumption, and overall transportation cost per kilometre.

This article addresses the latter aspect regarding the possibility to improve the representation of IWT in freight transport models by incorporating a physical description of the ship and fairway at the micro-level. Literature is clear about the substantial impact of ship dimensions (i.e. length, beam, and draught) on fuel consumption, but the effects of waterway properties, installed engine power and applied sailing regime have not received much attention yet. We discussed a specific case for two almost identically sized ships with a very different engine power installed. For these ships we analysed the speed, fuel consumption and overall transportation cost levels in case of a predefined 'sensible', 'intermediate' and 'fast' sailing regime. We found a clear potential to improve cost estimates for ship operations on individual routes by taking the variation in ship and waterway characteristics into account and assuming, as we would recommend, a sensible sailing regime as default mode.

Surprisingly, we found a relatively small variation in overall cost levels per roundtrip of only about 5% to 15% after fixing the fuel price in our case study. This implies that benefits from incorporating micro-level cost estimates in more aggregated strategic freight models could be

smaller than expected. One can however not draw such conclusions without looking into the details. A partial explanation for the relatively small variation in cost levels is the fact that the encountered current velocities cancel each other out for the upstream and downstream trip especially if the ship's draught is identical in both directions, as we assumed for this case study. If one zooms in at the individual waterway sections one finds a much larger variances in cost. The variation in overall cost per roundtrip is also expected to be larger for high-draught ships that are more substantially affected by shallow water conditions and variations in loading condition. As such, we regard the 5% to 15% variance in overall cost levels on the route from Budapest to Duisburg as an indication that variances can be relatively small on longer river sections. However, the Kaub section indicates that they can also be very substantial. At this location the cost for a roundtrip vary from about 30 euro to 56 euro per kilometre stretch (almost a factor 2) depending on the water level, installed power, and applied sailing regime (see Figure 13). Furthermore, we find that cost levels differ significantly per waterway section. Based on the details for the individual waterway sections we foresee good opportunities to improve strategic freight models by estimating IWT cost at the micro-level and applying the aggregated results to the strategic model.

Benefits from improving estimates of sailing time and cost are expected to be even larger at the operational level. Incorporation of actual ship and waterway conditions has a substantial potential to improve operational shipping models that are used to economise the use of the ship based on real time information and forecasts of water levels and current velocities. The relevance of such models also follows from the fact that they are now being developed by MARIN in the framework of the COVADEM project (www.covadem.eu, accessed: March 2017). Another useful application would be to incorporate micro-level estimates of ship speed and fuel consumption in future operational models for synchromodal IWT operations, because synchromodal operations are not only sensitive to cost, but especially to time. In this case the improved estimate can either be used to sharpen estimated time of arrival (ETA) projections of the ships or to optimize the overall cost level of the fleet.

Given the expected benefits, we consider it logical to start further develop operational IWT models at the micro-level, and then, when these models are operational, to use them to replace the existing approach used in today's strategic freight models.

8. Conclusions

Despite their importance, estimates of sailing time and fuel consumption of ships are still accounted for in a fairly basic way in strategic freight transport models that assume a fixed speed and fuel consumption regardless of the encountered water depth and current velocities. In addition they also assume inland ships to have homogenous characteristics and disregard the effect of the installed engine power and applied sailing regime (i.e. slow steaming to save fuel or sailing fast to meet a tight schedule) on the ship's speed and fuel consumption. On the basis of the case study discussed in this paper we conclude that ship characteristics and dynamic fairway conditions have a substantial impact on the speed, fuel consumption and cost of IWT. Benefits of incorporating actual ship and fairway characteristics into model projections are expected to be the largest at the operational level, as operational models, by nature, look into the details of each waterway section. Operational applications for instance enable ship owners to economise their fuel consumption and can also be used to improve ETA estimates feeding into dynamic models for optimising synchromodal transport solutions. Operational models for fuel optimisation are currently under construction, which indicates that they may become available in the near future. Once available, these micro-level estimation models can be used to replace the existing approach in today's strategic freight models.

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