IMPROVING THE ESTIMATION OF SHIP TRAVEL TIMES ON INLAND WATERWAYS

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ABSTRACT

We present an advanced method for estimating ship travel times on an inland waterway based on recorded ship trajectories. In contrast to previously published methods based on average travel times, we extend our modelling approach with respect to properties of the ship (length, width and forward) and environmental conditions (rain, illumination and wind). Input variables and modelling approaches have been varied for the different periods of a ship travelling on an inland waterway. While environmental conditions influence the travel time of a ship for driving into a lock, there is no effect visible during driving out. Travel times on sections between locks have been estimated based on previously observed speeds of the same ship. A previously presented method has been extended by a non-linear modelling approach, leading to superior results as shown by evaluations compared to the state of the art methods.

INTRODUCTION

Water transportation provides tremendous carrying capacity while consuming far less energy compared to other modes of transport such as truck, rail or air leading to substantial cost savings. The German federal waterways and shipping administration compared transportation distances given the same energy input. While on roads one ton of freight can be transported about 100km, this distance increases to 300km for railroad transports and 370km for maritime transports (1). The Texas Transportation Institute compared truck fright, railroads and inland towing regarding fuel efficiency and came to almost the same results (5).

A common opinion is that waterborne transportation is slow, but it often turns out that it is more reliable and even faster: While in Austria trucks are only allowed to be driven for 45% of a week (due to driving limitations during night times and on weekends), the Danube river is on average available for 98.2% of the year (2) with no further limitations arising. Moreover, selected goods are not time critical and the advantage of higher efficiency and less costs weights heavier then longer shipping times. For several goods the total shipping time is irrelevant as long as they are delivered on time.

However, for logistic processes relying on a fixed delivery time (e.g. just-in-time logistics), reliable estimations of travel speed (and therefore times of arrival) are crucial. In addition, knowing the time of arrival of (cargo) vessels at ports helps to pre-plan the deployment of human resources during loading and unloading operations and to pre-schedule subsequent transportation service (e.g. trucks). This is not only necessary in order to improve the complete supply chain, but also to keep quay times as low as possible, since in most ports landing stages are limited (and quay times are expensive).

While for high maritime navigation mainly weather and other ships influence travel times, this is different for most inland navigation scenarios, as there are bottle necks like bridges and locks along the river causing (in peak hours) congestion. Reliable predictions of travel times are more likely not available for such situations. Therefore, more advanced methods (than the currently applied first-come, first-serve-strategy) for scheduling vessels in bottle neck areas are promising for improving reliability of estimations on time of arrival. For example, time slots could be assigned to each vessel indicating in which period the ship could pass the lock. Although the overall speed of ships is not increased by this locking strategy, dangerous situations arising due to space limitations can be reduced and leading to an overall improvement of the (inland) waterway. Obviously, for finding an optimal schedule based on the assignment of time slots, it is necessary to reliably estimate for each vessel at which time it will/could arrive at the locks.

While there are several systems available for estimating and predicting travel times for roads (e.g. 3), only a limited number of studies is focusing on travel time estimation of vessels. In (4) we recently presented a method for estimating ship travel time on inland waterways between locks. The future travel speed is estimated based on previously observed speeds from the same ship. It turned out that there is a good correlation of speed between different locations. In this paper we present substantial improvements to our previous work which are:

- Predicting the time required for passing a lock.
- Predicting travel times between locks solely based on ship properties.
- Applying a non-linear relationship for modelling correlation of travel speed between different locations.

Accurately estimating the required time for passing the lock is necessary for predicting the time of arrival at locations beyond the subsequent lock. While in (4) only average locking times have been used, in this study the impact of environmental conditions and properties of the ship are investigated. For ships entering national borders or starting from a harbor, no previously observed travel times are available. Moreover, ships are loaded or unloaded at harbors and therefor travel speed is likely to change after their stop. Therefore it is an advantage to estimate arrival times in advance or immediately after (new) ship properties are available, instead of waiting until the ship has travelled a section and current travel speed is available. Although there is a good correlation of ship speeds between different locations, non-linarites have been observed and incorporated into the estimation model in order to improve the prediction.

STATE OF THE ART

Estimating and predicting travel times is an important issue for intelligent transportation systems. A broad variety of technologies is used for gathering different kinds of traffic data. Upon this, numerous approaches have been developed aiming at estimating or predicting travel times. This is the case for road traffic but not inland waterway transportation. All major ships on inland waterways are tracked due to a directive of the European Union (7) and therefore sufficient traffic data would be available. Despite that the literature regarding travel speed estimation for ships is rather limited compared to road traffic. A reason for this may be that inland waterway transportation has rather different characteristics: Travel times of road vehicles are determined by considering the relationship between demand (traffic volumes) and supply (road capacity). Methods for predicting motorway travel times are considering the expected traffic demand for estimating future travel times (see for example (3)). On waterways supply exceeds demand by far hence these methods are not applicable. On the other hand road vehicles are equally constrained by the traffic situation and therefore experience almost same travel times. Beside external factors (weather, illumination, streaming) also individual properties of the ship (engine power or forward draft) have an influence on travel times. Thus a more reasonable approach would be to estimate ship travel times on an individual basis.

Despite the individual character of ship travel times, many researchers are trying to estimate average ship travel times for a limited number of ship classes. E.g. the European Conference of Ministers of Transport indicated in (8) a cruising speed of inland navigation vessels in the range of ten to twelve km/h independent of the type of ship. A travel time estimator for the Danube (6) is provided by the “via donau”, an enterprise responsible for maintenance and development of the Danube in Austria as inland waterway. From the information system an expected travel time between different harbors along the Danube can be requested. The state of charge as well as human factors are not considered, and therefore true travel times will most likely deviate from the estimated average.

A method for calculating emissions of ships on inland waterways is presented in a report of Klein et al (9). They applied average vessel speeds based on data of 28 different ships on various inland waterways. A distinction has been made only between fully loaded and totally unloaded ships. Almaz and Altiok (10) investigated probability distributions of travel times specific to vessel types for different origin-destination pairs on the Delaware River in the US. Neither the loading of the ship nor environmental conditions have been considered for establishing travel time distributions. Ulusçu et al (11) assumed in their study that ships move at maximum allowed speed of 10 knots (18.52 km/h) in the strait of Istanbul. Xiao et al investigated in (13) the speed distribution of ships traveling on a Chinese waterway. They identified different distributions for three types of ship sizes and direction of movement. The distributions haven been used by Xiao et al in another study for calibrating a nautical traffic simulator with a multi-agent system for investigating safety issues (14). Goerlandt et al also define three types of ships (tanker, passenger and cargo ships) and analyzed travel speed distributions (15). Especially for passenger and cargo ships a very broad distribution is visible, indicating, that a more detailed distinction of ships has to be performed. The time required for passing one or several lock is always contained implicitly in travel times between origin and destination. In contrast to the study at hand, these travel times have not been analyzed separately.

Sun at al (12) investigated which factors are increasing the energy efficiency of ships on inland waterways. Assuming a constant engine power, his results may be used conversely to investigate variability of travel speed. Factors were current flow velocity, waves, water resistance, wind resistance and friction resistance caused by the surface roughness of the ship’s hull. A main factor for decreased travel speed (or increased power consumption) is water resistance which also depends on the square footage of the front. Further the effective square footage of the front depends on the forward draft, varying with the filling level. Shu et al stated in their study from 2013 that only a limited number of factors are considered in existing maritime traffic models. In particular, the influences of external factors (wind, visibility and current), vessel encounters and human factors on vessel behavior have not been investigated (16). Shu et al investigated the influence of direction of the current and encounters on travel speed.

Finally an approach for obtaining arrival times of ships would be to ask the captain. A limited communication range and language barriers make this approach rather unfeasible. Moreover it is hard for the captain to estimate his arrival, especially if she/he is not traveling the waterway frequently.

In contrast to previous research activities our approach is to consider individual ship properties instead of average values. The approach has not been restricted to a limited number of ship classes, but we considered ship dimensions as continuous input variables. Since water resistance has been identified as a main factor for higher energy consumption, the forward draft was used as additional input for the model. Because travel speeds are strongly correlated between different locations on the waterway (4), previously observed speeds are used for predicting future travel times. Finally travel times are also investigated in dependence of environmental factors i.e. weather situation and illumination conditions.

The outline of the paper is as follows: In the subsequent section the ship data base used for our modeling approach is presented. In the sequel, first the preprocessing is explained and secondly, the models for predicting travel times between locks and for passing a lock is described. After this the approach is evaluated for longer trips and compared to an existing method. A summary and recommendation for future research activities is given in a conclusions section.

DATA BASE

According to a directive published by the European Union, each ship has to be equipped with a transponder. This has to be compatible with inland AIS (automatic identification system) and providing the current position of a ship via satellite-based radiolocation. In Austria, this directive was implemented by introducing DoRIS (Donau river information service)operated by “via donau”. Static information (length, width or forward draft) has to be provided by the skipper when registering to the system. Dynamic data (position or speed over ground) are transmitted automatically at a frequency of 0.1 Hz. Data of all equipped ships on the Austrian part of the Danube (~350km) between July and December 2013 have been used for this study. Further the locations of the nine hydropower plants and four harbors on the Austrian part of the Danube are known. The waterway has been segregated into sections delimited by locks. Additionally an area of 3km before and after each hydropower plant has been assigned to the lock area. This was necessary for investigating travel speeds of ships approaching to and departing from a lock.

In Figure 1 the Austrian part of the Danube is visualized and all defined sections are enumerated. The lock area is indicated by red dots. Section length varies between 12km (section 9) and 54km (section 4).

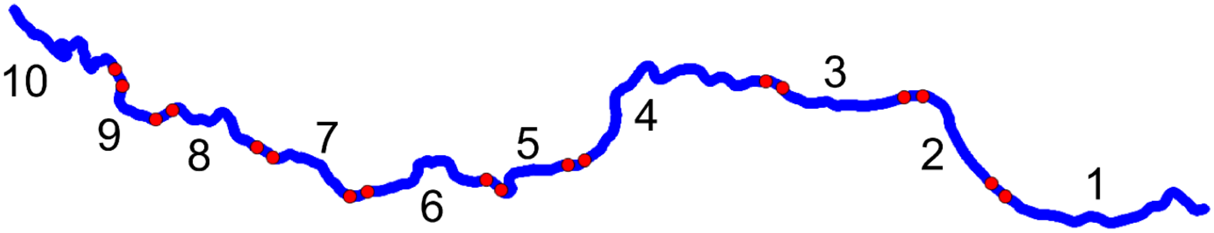

Figure 1: Location of lock areas and predefined sections on the Austrian part of the Danube

A weather station is located at each hydropower plant gathering constantly the amount and type of precipitation, wind speed and direction, air temperature and so on. These data are recorded permanently and have been prepared for the same period ship data are available. The illumination condition is defined as position of the sun which can be easily calculated based on location, date and time.

METHOD

In this section the methodology for estimating ship travel times is presented. After describing the preprocessing of the data, models for estimating the time to pass a lock is introduced. Subsequently models for estimating travel times on sections (between locks) are discussed.

Preprocessing

In order to investigate travel times and develop models for sections and locks, the trajectories of ships have to be segregated. By doing so travel times for driving between locks, for moving in and out of the locks and waiting times inside lock chambers are obtained. An exemplified fragmentation of a ship’s trajectory is visualized in Figure 2. A ship is considered to drive out up to three kilometers after the lock. Conversely driving in is assumed to begin three kilometers ahead the lock chamber. I.e. a section is defined as the waterway between two locks, except three kilometers after and before each of the delimiting locks. The limits for the region assigned to driving in and out of a lock have been defined based on recorded accelerations and decelerations.

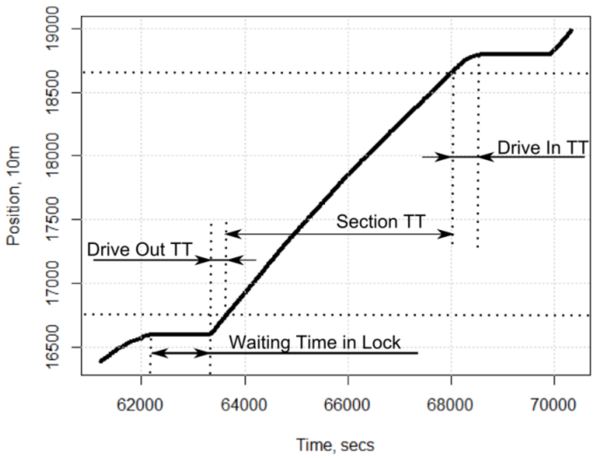

Figure 2: Example for a segregated ship trajectory

Although an inland waterway is considered as congestion free, it is visible from trajectories that ships are occasionally stopping. There are several reasons for stopovers like unloading, a break or refilling. Since the objective is to assess ship travel times without considering operational activities, these stopping data have been discarded from the data base. Records on sections where no movement has been observed (stops) have been filtered.

The objective of preprocessing was to obtain individual travel times for single sections and locks. Further the fragmentation was necessary for following reasons:

- Factors influencing travel times during driving in and out of a lock differ from those influencing travel times on sections. Therefore the applied models will diverge for locks and sections.
- Waiting time inside the lock chamber is independent of ship's properties or activities and has to be handled separately.

Travel Time Estimation for Passing a Lock

For modelling the travel time required for passing a lock, properties of the ship and environmental conditions are considered. Properties of the ship are length, beam and forward draft (in meters), while environmental conditions are daylight (defined as binary variable), amount of precipitation (mm/h) and wind speed (m/s). All investigations are separately performed for locks and sections. The time required for passing a lock is further subdivided into a time for driving in and out and a waiting time inside the lock chamber. The ID of the lock or section as well as direction of movement (upstream or downstream) is an additional input variable for the model.

Waiting time inside a lock chamber is assumed to be independent from ship properties and environmental conditions. Required time for lifting and lowering a ship between water levels rather depends on capabilities of the lock itself. In the left plot of Figure 3 the distribution of waiting times in a lock chamber is visualized. An analysis of variance (ANOVA) indicated that neither ship properties nor environmental conditions have any significant influence on the waiting time. Only for different locks a significant difference in the expected waiting time has been observed. In the right plot of Figure 3 the differences of waiting times in dependence of lock ID is visualized. Based on these results an average waiting time for each lock is estimated and applied for predicting ship travel times running over one or more locks.

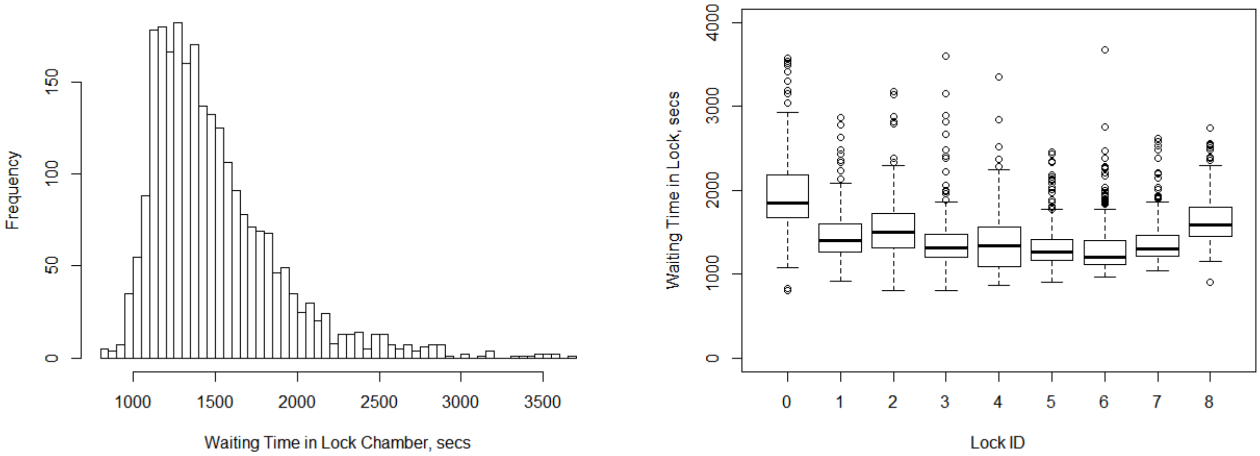

Figure 3: Distribution of waiting times inside lock chamber (left) and in dependence of lock ID (right)

It is assumed that the time required for driving into a lock depends on various factors. Speed and acceleration are influenced by properties of the ship. Adverse conditions (rain, wind or weak illumination) may affect the driving behavior and therefore increase travel time. An ANOVA has been carried out with the travel time as output variable. H0 assumes no difference in travel time for different values of a factor and H1 states that there are significant differences. The ANOVA has been applied on travel times for both driving in and out. Significances of investigated input factors are listed in Table 1. The p-value describes the probability of being wrong, when assuming a factor to have an influence on the output variable. Very low p-values indicate a high probability, that the according factor has any influence. For a 5% significant level all investigated factors except wind speed have an influence on the drive in travel time. Adapted from results of the ANOVA a linear model was estimated using only significant factors.

Table 1: Result of ANVOA: p-values for factors influencing drive in travel time.

Name	**Data type**	**Drive in**	**Drive out**
Length	Continuous	**2.2 e-10**	**< 2e-16**
Beam	Continuous	**1.4 e-10**	**6.4 e-10**
Forward draft	Continuous	**0.0093**	**6.4 e-8**
Upstream/Downstream	Binary	**< 2e-16**	**< 2e-16**
Lock ID	Nominal	**1.2 e-5**	**0.00028**
Day/Night	Binary	**1.8 e-6**	0.5099
Precipitation	Continuous	**0.0407**	0.978
Wind speed	Continuous	0.31	0.951

The time required for leaving the lock area has been investigated in the same manner. Again an ANOVA has been performed in order to identify influencing factors (compare Table 1). In contrast to travel times for driving in, environmental factors have no influence at all. Beside ship properties, only the location and direction of movement has a significant influence. Again a linear model is estimated considering only significant factors.

For estimating the time a ship needs to pass a lock, segregated travel times (drive in time, waiting and drive out time) are summarized. As described in Formula 1 the waiting time inside the lock t_L is only based on location (ID) and direction of movement (*dir*). Drive out travel time t_{DO} is additionally based on length (l_i), width (b_i) and forward draft (d_i) of ship *i*. The model for estimating travel time for driving in t_{DI} also utilizes information about illumination (il_{ID}), precipitation (pr_{ID}) and speed of wind (ws_{ID}) for a given lock ID.

$$t_{ID,dir,i} = t_{DI}(l_i, b_i, d_i, ID, dir, il_{ID}, pr_{ID}, ws_{ID}) + t_L(ID, dir) + t_{DO}(l_i, b_i, d_i, ID, dir) \quad (1)$$

For evaluating the modeling of driving in and out as well as the composition of travel times, estimated values have been compared to observed ones. The model parameters have been estimated for ship data of August 2013. Evaluation has been performed on another set ship data (July 2013). For each ship passing a lock the estimation error was calculated as the absolute difference between true and estimated travel time. Performance of the model has been compared to average travel times as proposed in (4). In that study an average travel time for each lock was used as predictor. The comparison of the error distribution is visualized in Figure 4. A slight improvement of the applied linear model compared to the average travel time is visible.

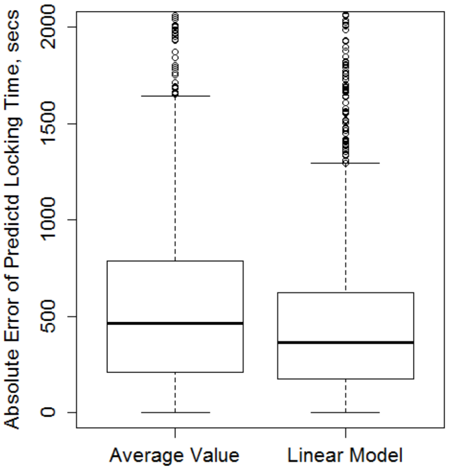

Figure 4: Boxplot of abs. prediction error for reference method and linear model

Travel Time Estimation for Sections

For modelling travel times on sections, environmental conditions have not been considered. The reason for this is that weather data have only been measured at locks. For section areas only interpolations would be available. Based on the experience of lock operators and authorities for inland waterways, we assumed that environmental conditions only have an influence in the vicinity of locks. In order to compare sections of different length travel speed was modeled instead of travel time (travel time divided by section length). As indicated by an ANOVA, travel speed is influenced significantly by ship properties (length, beam and with), location (section ID) and direction of movement (upstream/downstream).

A linear model has been estimated including significant factors determined by the ANOVA. After fitting the regression parameters on a set of training data (3871 trips), an evaluation has been performed on a set of test data (2558 trips). In the left plot of Figure 5 observed speeds are plotted against predicted ones. A separation into two areas is visible, where each region corresponds to one moving direction. Inside one area the reproduction of true travel times is not satisfying. Thus an alternative method better suitable for non-linear data has been applied. We used a support vector regression which is based on the concept of support vector machines (SVM). A SVM is used for binary classification. The basic idea is to find a hyperplane which separates the input space perfectly into two classes. Since example data is often not linearly separable, SVM's introduce the notion of a "kernel induced feature space". This casts the data into a higher dimensional space where the data is separable. SVM's have also been extended to solve regression tasks, where the system is trained to output a numerical value, rather than a binary classification (17). In this study a radial basis kernel has been used and spread parameter of the kernel was the inverse of number of input dimensions. Moreover the same input factors as applied for the linear model have been selected.

In the right plot of Figure 5 the result of the trained SVM applied on test data is presented. Basically the reproduction of true travel speeds is smoother and better prediction results are visible. The supremacy of SVM is also observable from absolute error boxplots visualized in Figure 7.

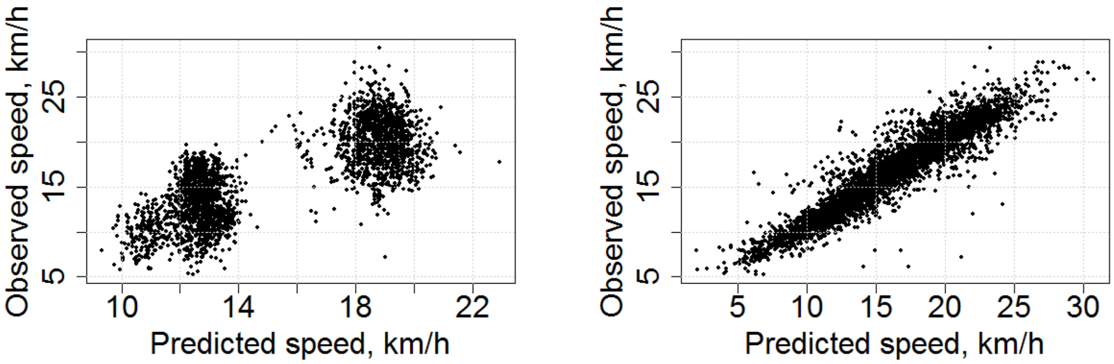

Figure 5: Visualization of prediction quality for linear model (left), support vector machine (right).

As encouraged in our previous paper (4) the travel time prediction for a single ship can be improved by considering previously observed travel speeds. A correlation of travel speed is observable for different section as visible in Figure 6. In (4) we assumed that the deviation between individual travel speed and average value is sustaining over several sections. I.e. each ship has a constant deviation from an average section speed. This conforms to a linear relation of speed between different sections. In this study we advanced our approach by applying a non-linear relationship. A second order polynomial has been fitted to speed values (least squares fit). The optimization problem is defined as follows

$$\mathbf{min}_{\alpha\in\mathbb{R}}\left[\boldsymbol{v_i}-(\boldsymbol{\alpha_1}+\boldsymbol{\alpha_2}\cdot\boldsymbol{v_j}+\boldsymbol{\alpha_3}\cdot\boldsymbol{v_j^2})\right]^{\mathbf{2}} \qquad (2)$$

where α_i are the parameters of the polynomial, v_i is the travel speed on the current section and v_j is the speed on a subsequent section. The function has been fitted to speed observations of all pairs of sections. The results of three combinations are exemplified in Figure 6.

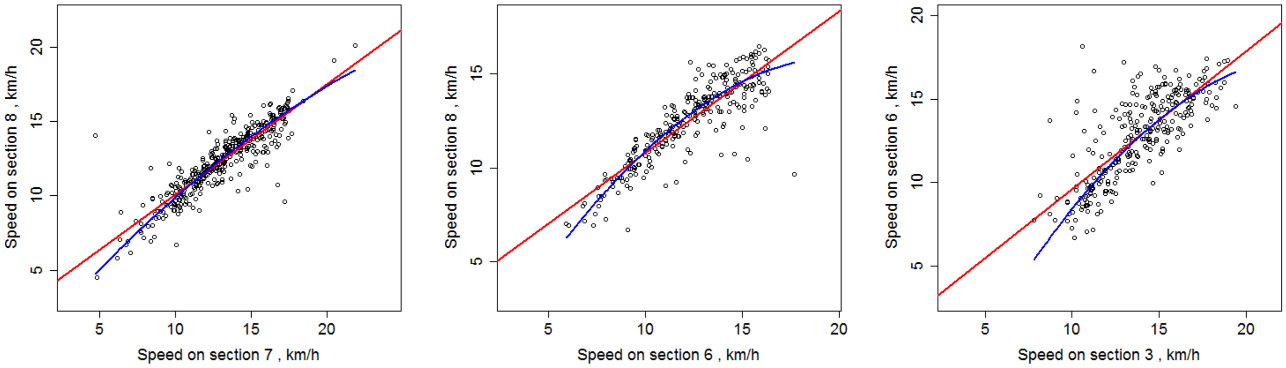

Figure 6: Travel Speed on different sections, fitted polynomial (blue) and linear model (red)

The travel time prediction on a section is performed by applying the fitted polynomials to speed observations of previous sections. I.e. for given speed v_i on section i the speed v_j on a subsequent (but not necessarily neighbored) section j can be estimated. If several observations from previous sections are available, the results of different polynomials are combined by a weighted mean. The weight is defined as the inverse of the error obtained during the fitting step (Formula 2). In Figure 7 the prediction error in terms of relative deviation from an observed travel time is visualized for all discussed methods: Assuming an average value applicable for all ships or applying a linear prediction model (with ship properties as input values) yield worst results. The SVM performs much better although no updated speed observations are considered but only static attributes of the ship. The reference method as presented in (4) and our approach are considering previously observed speeds and therefore perform best. Moreover the new approach outperforms slightly the reference method.

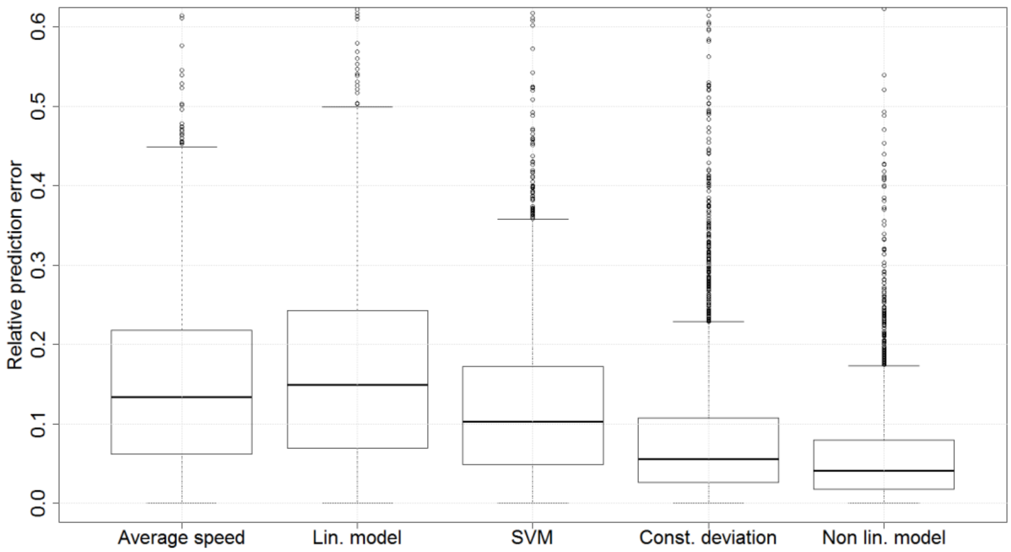

Figure 7: Comparison of different prediction methods for section travel times

APPLICATION

In the previous section travel times have been estimated solely for single sections or locks. In this section all developed methods are applied for predicting travel times of ships travelling several sections and locks. From the test data set trajectories of all ships travelling at least on two sections have been selected. At the end of each section the arrival time at the end the subsequent section is predicted. E.g. if a ship arrived at the end of section one, then the travel time until the end of each subsequent section is estimated based on the observed speed of section one. After the ship moved further to the end of section two the travel time for reaching the end of the subsequent section is predicted. Each time the prediction is compared to the true travel time and a relative error calculated. Results are visualized in Figure 8 where following two methods have been compared:

- Average speed of current section minus deviation from average speed in previous section plus average time for passing the locks. This approach represents the method as presented in (4).

- Apply fitted polynomial for travel speed prediction plus linear models for estimating travel time for driving in and out plus average locking time, i.e. the approach developed in this study.

A clear improvement of our approach for predicting travel times is visible for trips up to three sections. For longer trips a lower average prediction error is observable, but due to higher variances statistically significance of results is not given.

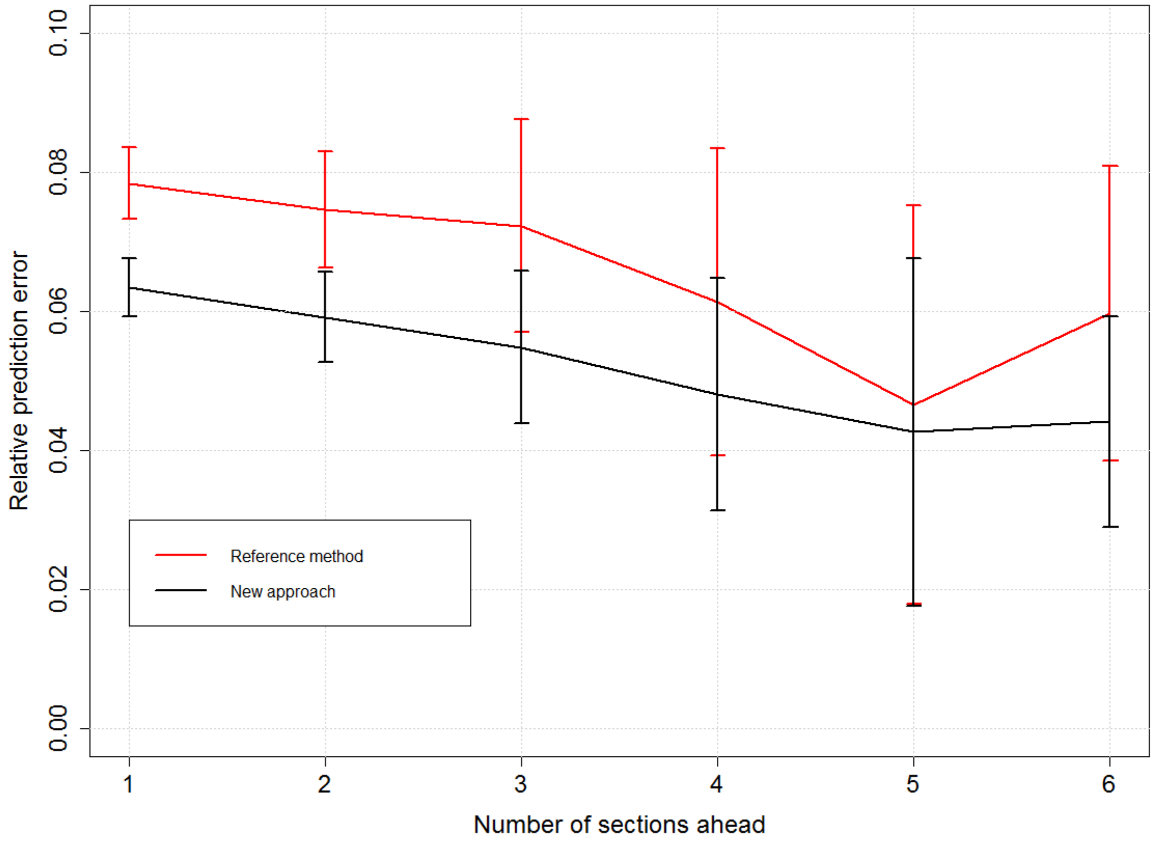

Figure 8: Evaluation of trips traveling several sections

CONCLUSION

We discussed in this study various methods for predicting the time of arrival for ships on inland waterways. All methods are based on AIS data for inland waterways recorded on the Austrian part of the river Danube. A distinction was made between travel time for passing a lock and on sections between locks. The base method as described in current literature relies on average values for a small number of ship classes. In a first step the travel time prediction for sections has been replaced by a linear model and a SVM (in order to model non-linear relationship) with ship dimensions as input variables. While the linear model showed no improvement compared to the base line, the SVM outperformed both. The SVM can be applied for travel time prediction in case no mobility data of ships are available but only static (length and width) or semi-static (forward draft) attributes.

Considering previously observed travel speeds of single ships could improve the prediction substantially. This approach has been presented previously (4) and was extended in this study. By assigning a non-linear relationship between observed and future travel speeds an improvement could be achieved compared to our previous approachWhile in (4) an average time for passing a lock has been assumed, we investigated the time required for driving into and out of the lock in dependence of ship dimensions and environmental conditions. Especially for driving in environmental conditions like rain or illumination have an impact on travel times.

The travel time of voyages over several sections is predicted separately for locks and sections and summarized afterwards. An evaluation indicated that the more detailed modelling of travel times for sections and locks could reduce the overall prediction error.

Predicted travel times can be used by lock operators for assigning time slots for locking in order to optimize the throughput of locks. Also harbor operators can use predicted travel times for pre-planning the deployment of human resources and pre-scheduling subsequent transportation service. For ship operators predicted travel time is useful information in case he/she is not familiar with the waterway. It can be forwarded to the addressee of the freight and supports the planning operating times of the ship.

Stops of ships have been excluded from tracking data since operational stops are not part of the modelling task. By gaining a more detailed insight into ship operations, time delays caused by stopovers may be considered for estimating travel times. Additionally the influence of encounters and environmental conditions on the section is not represented in our models and remains a task for future research activities.

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