MODELING AND SIMULATING TRAFFIC FLOW ON INLAND WATERWAYS

by

Nicolas Fischer[1], Martin Treiber[2] and Bernhard Söhngen[3]

ABSTRACT

This contribution presents a microscopic model of inland waterway traffic flow which is applied to simulate a simple scenario of a river waterway with a bottleneck. The model is composed of (i) a physics-based submodel describing the vessel dynamics in free-flow situations, (ii) a widely used car-following model for vessels following each other, and (iii) decision submodels regarding encounters and overtaking maneuvers. Depending on the situation, the "ship-following" model overrides the physics-based component, and the decision models override both. The decision models have been formulated with a novel approach comparing the required with the available navigational space in the actual driving situation. Human-factor effects have been taken into account by a statistical approach of determining additional navigational space. A method to link these additional widths to ease scores thereby allowing to rank the maneuver difficulty has been depicted.

The developed model has been applied to a simple generic situation: two different types of vessels traverse a river section with a bottleneck in the middle in upstream and downstream directions. It turned out, that the bottleneck capacity highly depends on the traffic composition and the flow of the vessels going downstream.

1. INTRODUCTION

1.1 Motivational Background

The German Federal Waterways Engineering and Research Institute (BAW) has been instructed by the Rhine Authorities of the Federal Waterways and Shipping Administration to review the existing fairway widths of the Rhine river below Iffezheim dam up to the border of the Netherlands and to propose appropriate revised widths if necessary. One of the motives to perform new investigations is the fact that fairway widths on the German Rhine river are more or less historically determined, e.g. to support rafts on the upper Rhine river, and not adapted to a steadily changing fleet with generally very much larger, but also better steerable vessels than in former years, where the fairway widths were established. The latter are furthermore nearly constant over long reaches, e.g. the Upper Rhine River up to Mainz with about 90 m, the Middle Rhine River with about 120 m and downstream Koblenz 150 m, without any adaptations (with few exceptions) e.g. concerning vessel dimensions, curvature of the river or cross currents. This means that neither the possible traffic situation, e.g. only one-way or two-way with encounters or overtaking maneuvers of all the permitted vessels, is the same from reach to reach, nor can the ships sail with the same safety and ease of navigation standard (in short s&e). This situation shall be improved in the future e.g. by adapting the local fairway widths to the demands of modern vessels and existing and future traffic situations.

---

[1] Dresden University of Technology, Institute for Transport & Economics, Germany, Nicolas.Fischer@tu-dresden.de

[2] Dresden University of Technology, Institute for Transport & Economics, Germany, Martin.Treiber@vwi.tu-dresden.de

[3] German Federal Waterways Engineering and Research Institute (BAW), Bernhard.Soehngen@baw.de

This may probably lead to wider fairways at existing width-bottlenecks compared to the situation today. However, operational economics, safety and ease of navigation demands and those from ecological and politico-economic aspects, have to be balanced appropriately in fairway design.

In this context, the possible navigational constraints in case of fairway widths that are not sufficient for the largest permitted vessels and strived traffic situations have to be evaluated. These are the reduction of possible vessel speeds or even more important, the waiting times in front of width bottlenecks. This is the task of the investigations by the BAW, reported herein, which are elaborated by the Institute of Traffic Econometrics and Statistics of the University Dresden, Germany. They are part of a 3 step investigation:

- First, the existing navigational conditions with special respect to critical situations and traffic statistics at some typical bottlenecks of the Rhine River were examined by video observation and AIS-data exploration (BAW, together with Institute of Ship Design and Transport Systems, University Duisburg-Essen, Germany).
- Second, the necessary navigational space of selected vessel types at different loading conditions and water stages were observed by GPS survey and analyzed by BAW, especially concerning extra widths in curves, in case of cross currents and "human factor". They were extrapolated, together with navigational simulation methods, to determine the necessary fairway widths from the technical point of view for selected design cases. This approach is based on previous investigations in context with the improvement of the navigation conditions in the well-known Middle Rhine reach between Mainz and St. Goar, especially to increase fairway depths. This may be achieved with less effort at depth bottlenecks in case of a smaller fairway. The German research project named KLIWAS, "Climate Change and Navigation", which was e.g. looking for mitigation measures against negative effects of the Global Warming (Wassermann et al. 2010, Söhngen & Paprocki, 2013) lead to several semi-empirical formulae for calculating the different contributions to the widths demands of vessels in rivers. These will be described more detailed in Sec. 2.1
- The third step of the investigations is the development of a traffic simulation model to account for the mentioned navigational constraints at width bottlenecks. The application of simplified and therefore fast calculation methods for traffic simulations is necessary to perform a large number of simulation runs, e.g. to check possible navigational conflicts and to solve them numerically in analogy to real ship pilots, but also to perform calculations for a huge number of situations over a long period of time to generate traffic statistics and by this to overcome random effects of the simulations.

1.2 Traffic Simulation

Similar to the situation in vehicular road traffic, bottlenecks on narrow, highly frequented inland waterways have a large impact on the traffic operations of vessels. Bottlenecks on inland waterways not only include static bottlenecks, such as locks or narrow passages, but also dynamic bottlenecks generated by factors like the vessel size and speed, curves, or the fairway profile. These are described by dynamically computing the space required for each vessel using the methods introduced e.g. by Söhngen & Paprocki (2013) and illustrated by VBW (2013). By comparing the required to the given space, bottlenecks can be identified, depending on the current state of the involved vessels. Furthermore, approximate equations of motion for individual vessels on a free flowing river derived from a physics-based model are proposed e.g. in Wassermann et al. (2010).

Current simulations of inland waterway traffic focus on static bottlenecks, particularly on locks and their operational properties such as service times. Dai, M. & Schonfeld, P. (1993) present a microscopic model with a focus on delays due to variations in lock service times. Travel times between locks are estimated by assuming constant speed. In effect, their model is an application of queue theory.

A microscopic model with focus on sea-going vessels approaching and leaving the port of Antwerp in Belgium through a number of locks is presented by Thiers, G.F. & Janssens G.K. (1998). It includes vessel interactions like crossings, overtaking maneuvers and general sailing principles.

To our knowledge, neither models nor simulation tools for physically realistic traffic flow dynamics of vessels on a free-flowing river have been published yet. Such a model should not only describe the physics-based motion of individual vessels in the presence of static and dynamic bottlenecks. It must also include interactions with other vessels such as encounters, overtaking maneuvers, or anticipative decelerations so as to avoid critical encounters at or near bottlenecks. In addition to the physical forces, such interactions will produce "social forces" augmenting or overriding the physical equations of motion.

While we are not aware of existing dynamic interaction models for inland waterway traffic flow, such models exist for pedestrian traffic ("social force model" of Helbing, D. (2001)), and vehicular traffic. In the latter, the longitudinal dynamics are described by car-following models, and the transversal dynamics by lane-changing models (see, e.g., Treiber, M. & Kesting A. (2013)). Examples of car-following models suitable for a generalization to waterway traffic include the Intelligent-Driver Model (IDM) by Treiber, M. et al. (2000) or a derivative thereof, the "Improved IDM" (IIDM) by Treiber, M. & Kesting A. (2013).

In this paper, we propose a dynamic microscopic model for inland waterway traffic flow by synthesizing the physics-based equations of motion and the models for dynamic bottlenecks by Söhngen et al. (2014) with an IIDM-based "ship-following model" and newly developed decision models for encounters and overtaking.

We simulate multi-modal two-way waterway traffic flow near a bottleneck and show how this model can be used to identify bottlenecks, estimate capacities, assess required fairway widths and depths and give recommendations for maximum vessel sizes.

In Sec. 2, we introduce the model. In Sec. 3, we describe the simulation of the two-way bottleneck scenario and investigate the influence of different vessel types and relative traffic demands on the dynamic bottleneck capacity. In the concluding Sec. 4, we discuss the results and give hints for further research.

2. MODEL DESCRIPTION

We use a one-dimensional microscopic approach to simulate the traffic flow on inland waterways. This means that every vessel is simulated as an individual object with attributes such as vessel type, dimensions, maximum power or loading and dynamical variables such as direction, acceleration, velocity and position. The equations of motion of each vessel include physical laws and restrictions specified in the physics submodel described in Sec. 2.1. The equations also include interactions with other vessels in form of a behavioral submodel for the steersman with the intention to realize a fast and efficient passage while avoiding critical situations.

We define different traffic situations containing free and bounded traffic, overtaking and encounters. Some of these can occur simultaneously, but each is described by certain parts of the traffic model. Free traffic describes the situation in which a vessel is not restricted by the behavior of other vessels. If a vessel has to slow down because of a leading vessel, the bounded traffic state occurs. Encounters occur when a vessel going in the opposite direction is within a defined range ("information radius"). These situations occur without an active decision by the steersman. Overtaking maneuvers are the result of an active decision by the steersman. The decision to overtake a leading vessel is formulated in terms of an incentive and a safety criterion.

The behavioral model itself has several components: A longitudinal acceleration model which is similar to car-following models for vehicular road traffic, and decision models to determine whether encounters with vessels in the opposite directions are safe or whether an overtaking maneuver is desired and safe. The decision submodels interact with the longitudinal model by overriding the accelerations during encountering or overtaking maneuvers. All safety components of the behavioral submodel are based on dynamic areas for each vessel required for safe operations. These are specified in terms of longitudinal safety gaps and minimum lateral gaps depending on the dynamical state of the vessel (speed, direction) and on the river geometry and flow profile. The latter are described in Sec. 2.1. For each combination of vessels and combination of vessel speeds the needed and available space can be computed. By discretizing the speeds and the positions on the river, the bottlenecks can be computed in advance.

Instead of simulating the fully two-dimensional motion, we apply an effective 1D model by simulating the longitudinal motion only and by assuming that, laterally, the vessel follows a given course axis. All the lateral dynamics and restrictions (e.g., while overtaking or encountering another vessel) are contained in the decision submodel.

The "human-factor effects" are accounted for,

(1) by using a restricted "information radius", this means, the reach, where the steersman gets or searches for information about the other vessels that could affect its own movement,

(2) by varying pilots skills, personal fitness or mentality that will influence his decision, if he tries to avoid conflicts, e.g. to wait in front of a bottleneck or to accept a situation with a lower s&e score, and

(3) by taking the empirical probability distribution of "human-related extra widths into account.

The latter is part of the semi empirical equations shown in the next section. Possible navigational conflicts, will not be solved during the simulation in every case – even if it is numerically possible, because this would be an artificially guided traffic and not a real traffic situation. Unsolved conflicts depend especially on the chosen information radius. The latter may be linked to the chosen pilot type and randomly varied. After the simulation, the unsolved conflicts have to be assessed according to the necessary measures to avoid an accident, e.g. by driving highly attentional – this would reduce the human-related extra width –, or by using a bow thruster (if available or applicable).

Considering this, we rank the difficulty of the necessary/possible maneuver and by this the real s&e-standard in every critical situation. This allows the user of the traffic simulations to assess the necessity of fairway enlargements, together with the probability of occurrence of critical situations. The assignment of a special situation to s&e-standards may be made according to the report of PIANC INCOM WG 141 (Deplaix & Söhngen, 2013, Söhngen 2013). A first draft of a possible assignment is shown in Sec. 2.1.3.

2.1 The Physics Model

As mentioned before, it is not feasible to use detailed nautical simulation methods as those from ship handling simulators in traffic simulations, especially concerning the used navigational space. One of the reasons as indicated above is the high computing time of these simulation techniques. But even if the computing times were much lower, it seems at the present state of modeling almost impossible to steer a vessel realistically in a two-dimensional domain by a numerical autopilot, while taking the actual boundaries of the navigational water, the driving dynamics and the traffic situation with all the other vessels into account. Hence, simplifications are necessary at present stage of computing equipment and knowledge as follows:

1. Usage of cross-sections, generally in 100 m distances, to define the available navigational space, the water depths and longitudinal and crosswise flow velocities and their crosswise distribution – as in case of application of a one-dimensional flow model. On this basis, the possible draughts, ship speeds and the necessary navigational space can be calculated.
2. Taking averaged ship courses and corresponding radii of curvature, coming generally from field data for all relevant vessel types (generally classes Va, Vb and VI), loading conditions (empty or loaded) and driving directions (upstream, downstream).

3. Usage of semi-empirical formulae, derived from field data and driving dynamics theory, concerning all the deterministic influence parameters regarding (a) longitudinal and (b) sideways movement of the vessel, as
    (a) ship resistance and necessary engine power, depending on ship speed relative to water, critical ship speed, driving direction, together with flow velocity, bed roughness and longitudinal water level slope, to calculate ship speed according to chosen engine power (Wassermann et al. 2010),
    (b) ship's overall dimensions, extra width in curves of a drifting vessel with and without using a bow thruster and its powering, extra widths to counteract cross currents or cross winds, extra widths necessary to perform maneuvers as encounters or overtakings or to sail close to bank slopes or groins.
4. Usage of simplified formulae to estimate extra widths due to instabilities of ship course, skills or inattention of the steersman ("human factor"), coming from field or model data, which are generally statistically distributed (Söhngen & Rettemeier 2013).

In the following, two important contributions to the needed sideways navigational space, besides the breadth of the vessel, will be considered in more detail, the extra widths in curves without using a bow thruster (Sec. 2.1.1) and extra widths sailing in the vicinity of groins (Sec. 2.1.2). Also an approach will be outlined how to account for effects of "human factor" (Sec. 2.1.3).

2.1.1 Extra width in curves without using a bow thruster

If there are no active forces available to compensate the centrifugal forces and the secondary currents in flowing rivers directly, the ship has to take up a drift angle against the sideways drift. In a steady state situation, the centrifugal forces will be compensated properly by the crosswise forces onto the drifting underwater body. Because the drift forces are generally inconstant alongside the vessel, the corresponding moments have to be compensated as well by adequate rudder forces. In effect, depending on vessel speed over ground, which scales the centrifugal force, the vessel speed v_{sw} relative to water, which scales the possible crosswise drift force, together with the draught T and water depth D, determines the necessary drift angle β and therefore the extra width in curves Δb_{K}, which is related from geometrical considerations, shown in Fig. 1, to the relative position of the pivot point of the vessels c_{F}.

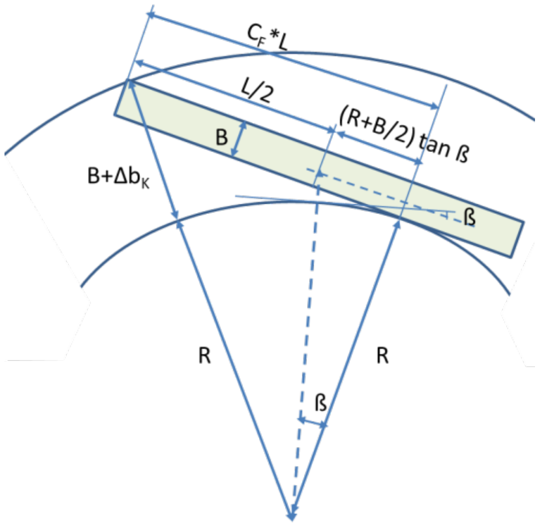


Figure 1: Definition sketch of the extra width Δb_{K} in steady curved drive.

This leads to the following approximation equation, valid if the ships length L is small compared to the curvature radius R (more exactly one can use the Pythagorean theorem). The equation shows the strong influence of c_{F} and L on the extra width in curves:

$$\Delta b_{\mathrm{K}} \approx \frac{1}{2} {c_{\mathrm{F}}}^2 \frac{L^2}{R} \tag{1}$$

The parameter c_{F} is defined as the position of the pivot point, measured from stern to bow, where the vessel axis is placed tangential to the curve circle, divided by the ships length L. It strongly depends on T/D with smaller c_{F} in case of high T/D, because the water is forced to "squeeze" below the vessel in case of small under keel clearances, leading to large crosswise forces while drifting. On the other hand, empty vessels with small T/D increase the c_{F}- value and so, the extra widths in curves. Together with high flow velocities v_{Flow} in case of a downhill drive, because the latter increases the centrifugal forces at the same vessel speed relative to water, this leads to higher necessary drift angles to counteract these increased forces. The result is a strong influence of $v_{\mathrm{Flow}}/v_{\mathrm{sw}}$ on c_{F} as demonstrated in Fig. 2 for a class Va vessel.

Figure 2 bases on the theory of force balances, whereby not only centrifugal, drifting and rudder forces are considered, but also the influence of a crosswise water level slope. The latter supports the vessel to stay on course in a steady state curve drive, but it may occur that the steersman takes up the drift angle just before entering the bend. In this case, the crosswise water level slope does not yet exist and the corresponding supporting forces are not relevant. This effect is indirectly involved in Fig. 2, because the parameters of the theory, including the crosswise slope and the force coefficients on the underwater body, were calibrated by using several measurements in German canals and rivers. Hence, the shown c_{F}-values may be somewhat higher (rage of uncertainty approximately $\pm$ 0.1) in case of vessels, starting to take the drift angle just before the curve and lower in case of a real steady state situation.

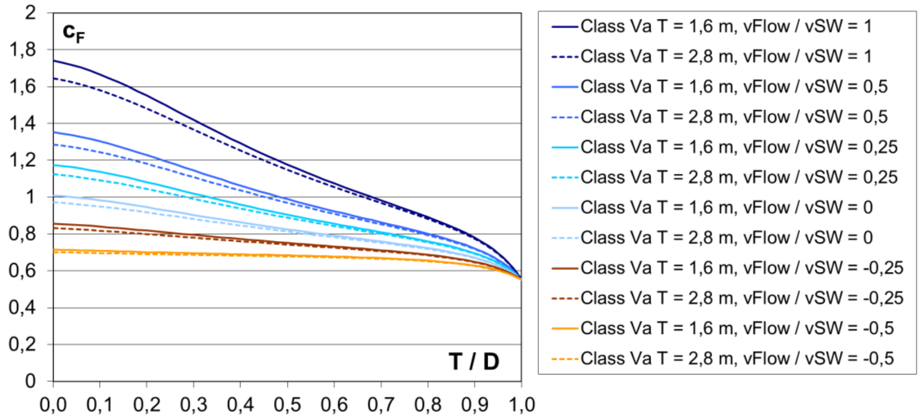


Figure 2: Influence of draught to water depth ratio T/D and flow velocity v_{Flow} sign - upstream and + down-stream),in relation to ship speed relative to water v_{sw} on c_{F} (without bow thruster use, no secondary currents), calculated for a class Va vessel ($L = 110\mathrm{m}$, $B = 11.45\mathrm{m}$).

The semi-empirical equations behind Fig. 2 are shown below. They use the approach of UFC (2005) concerning the drift forces (terms with $c_{\mathrm{D,max}}$ and $c_{\mathrm{D,0}}$, parameters c^*, β, β_c) and the slender body theory to account for the so called instable moment (terms with $c_{\mathrm{m,hy}}$ and parameter c_{i}), taking empirical equations to approximate the influence of T/D on the hydrodynamic masses of the vessel (term f_1). Concerning the influence of the crosswise water level slope, the theory says that the corresponding supporting force in case of a quasi-steady situation is the same as the amount of the centrifugal force of a vessel, drifting with the flow ($v_{\mathrm{sw}} = 0$), i.e. sailing downstream with the surrounding flow velocity (used with sign + in case of downhill drive and sign - upstream), because the water of the flow field will be supported by the sideways slope in the same manner. This theory leads to a coefficient of $f_{\mathrm{v},2} = 0$ in the equation for $f^{(1)}$, together with $c_{\mathrm{c}} = 1$. If there is no sideways slope, theory gives $f_{\mathrm{v},2} = 1$ and $c_{\mathrm{c}} = 1$, but the field data lead to $f_{\mathrm{v},2} = 0.3$ and $c_{\mathrm{c}} = 1.5$. Hence, the observed supporting slope-effect is in average smaller than expected, i.e. the c_{F}-values derived from measurements are bigger than those from the theory.

$$c_{\mathrm{F}} = \frac{1}{2} + c_{\mathrm{i}}\frac{B}{L} + \frac{\frac{2}{c_{\mathrm{D,max}}}\frac{B}{L}\frac{\gamma}{\gamma_{\mathrm{L}}}\,c_{\mathrm{c}}\,f^{(1)} + \frac{1}{6}}{\frac{c_{\mathrm{m,hy}}}{c_{\mathrm{D,max}}}\frac{B}{L}\frac{\gamma}{\gamma_{\mathrm{L}}}\,4\,k' + 1} + \Delta c_{\mathrm{FS}} \tag{2}$$

$$c_{\mathrm{m,hy}} = f_4(f_3 f_2 + f_1),\ f_1 = \frac{T/_D}{1-T/_D},\ f_2 = 1 + 0{,}35\ln\left(\frac{B}{T}+1\right),\ f_3 = \frac{\pi}{2}\frac{T^2}{TB+0{,}2T^2},\ f_4 = \frac{TB+0{,}2T^2}{TB} \tag{3}$$

$$k' = 1 - 3.4^{-0{,}22\left(\frac{L}{B}-1\right)},\ f^{(1)} = \left(1 + 2\frac{v_{\mathrm{Flow}}}{v_{\mathrm{sw}}}\right) + f_{\mathrm{v},2}\left(\frac{v_{\mathrm{Flow}}}{v_{\mathrm{sw}}}\right)^2 \tag{4}$$

$$c_{\mathrm{D,max}} = c_{\mathrm{D},0} + \left(c^* - c_{\mathrm{D},0}\right)\left(\frac{T}{D}\right)^{\beta},\ c_{\mathrm{D},0} = 0{,}22\left(\frac{L}{\gamma B}\right)^{\beta_c}. \tag{5}$$

Coefficients: $\beta_c = 0.5$, $\beta = 2.0$, $\gamma = 0.85$, $\gamma_L = 0.9$, $f_{\mathrm{v},2} = 0.3$, $c^* = 3.2$, $c_c = 1.5$, $c_{\mathrm{i}} = 0.5$

These formulae are based on some simplifications concerning the vessels hull form and rudders. Because of this, a correcting parameter Δc_{FS} was introduced. Comparison with field data shows that it varies around ± 0.1. In average for class Va and Vb vessels no corrections are necessary for vessels without passive or active bow rudders used.

For completion, it should be mentioned that Fig. 2 and the equations are valid without the influence of secondary currents in rivers. The latter forces the steersman to take an additional sideways drift angle for compensation. Assuming that the corresponding sideways movement of the vessel is the same as the cross current velocity of the secondary motion, averaged over the draught of the vessel, this leads to the following equation to increase c_{F} by the influence of secondary flow velocities, assuming a linear distribution of the secondary flow velocity over depth and its magnitude from appropriate hydraulic model experiments in river bends (Yee-Chung 1990):

$$\Delta \mathrm{c_F} \approx \mathrm{c_S}\frac{D}{L}\left(1 - \frac{T}{D}\right)\frac{|v_{\mathrm{Flow}}|}{v_{\mathrm{sw}}},\ \mathrm{c_S} \approx 5.9 \tag{6}$$

Comparisons between calculated and observed c_{F} show further that the use of bow thrusters may help to reduce the c_{F} and so the extra widths significantly, but only in case of moderate vessel speeds and strong thrusters. The theory to account for these effects is complicated and does not lead to an appropriate formula to be implemented into the traffic simulation model. But the research on this subject is yet not finished. Nevertheless, measurements show that the c_{F} may be reduced at least by about Δc_{F} 0.1 up to 0.2 in case of proper bow thruster. This simple rule of thumb will be used as a first attempt for the traffic simulations.

2.1.2 Extra width at groins

The free flowing Rhine River is trained mostly by groins. If they are designed properly, especially if the relation of groin spacing s_{G} to groin length l_{G} is between about 1 and 2, the flow will be guided alongside the groin heads and turbulence fluctuations are moderate. Nevertheless, especially at the beginning and the end of groin fields and also at some historically designed groin fields with higher relations $s_{\mathrm{G}}/l_{\mathrm{G}}$, unsteadily occurring and separating eddies especially at groin heads can lead, together with the time-averaged flow field alongside groins, to significant cross flow velocities as illustrated in Fig. 3 (left picture). These may be accepted and not counteracted by maneuvers from the steersman, especially at a downhill drive, because there is no time to act against them. This leads to a sideways displacement to the intended ship course and so, to corresponding additional widths. Sailing upstream the impact time of the cross currents is much longer and it makes sense to take a drift angle against the direction of the cross currents. But this drift angle also increases the necessary navigational space.

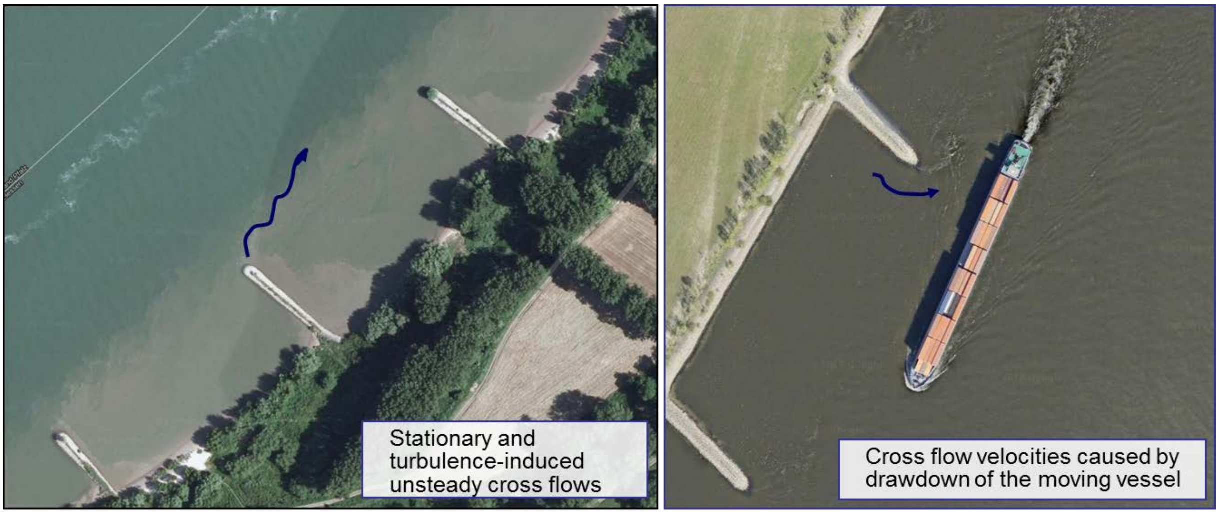


Figure 3: Illustration of turbulence- (left picture) and ship-induced flows (right picture) in the vicinity of groins.

From analysis of model tests with different groin properties (lengths l_G, spacing s_G, water depth, groin height above ground), BAW performed statistical analyses of turbulent lengths scales and corresponding unsteady cross currents in the vicinity of groins, depending mostly on the s_G/l_G ratio and the distance of the vessel's course to the groin heads (Söhngen et al., 2014). Using averaged values of these cross current velocities, one can use formulae for the additional widths in cross current fields, coming from ship handling simulation runs (Söhngen et al., 2012). For a given s_G/l_G ratio and for water stages below the groin heads, the corresponding extra widths are mostly scaled by the flow velocity (the larger the bigger) and ship speed (the larger the smaller) with higher values for a slow uphill drive and smaller ones for a fast downhill drive, especially because of the different impact times.

On the opposite, the ship induced water level drawdown imposes an outflow from the groin fields towards the vessel as illustrated in Fig. 3 on the right side. This ship-induced cross current leads to corresponding larger additional widths in case of high ship speeds relative to water, because of the higher water level drawdown. This is demonstrated in Fig. 4 for typical boundary conditions in the Rhine.

The corresponding formulae are too complicated to be presented herein and to be used during the traffic simulations, because they have to be applied for each traffic situation. This means: for every vessel, every cross-section and every possible scenario it has to be checked before performing the next time step. Therefore all the possible extra widths, depending on vessel type, loading condition, vessel speed and distances to the groins (for simplification and lying on the safe side this distance may be chosen according to a vessel sailing on the edge of the fairway) for all cross-sections (and water stages) are calculated and stored once for discrete values of the dynamic parameters.

The example in Fig. 4 shows that the extra width at groins may be bigger than the ship breadth in case of high flow velocities and ship speeds. These values are typical for some reaches on the Rhine river.

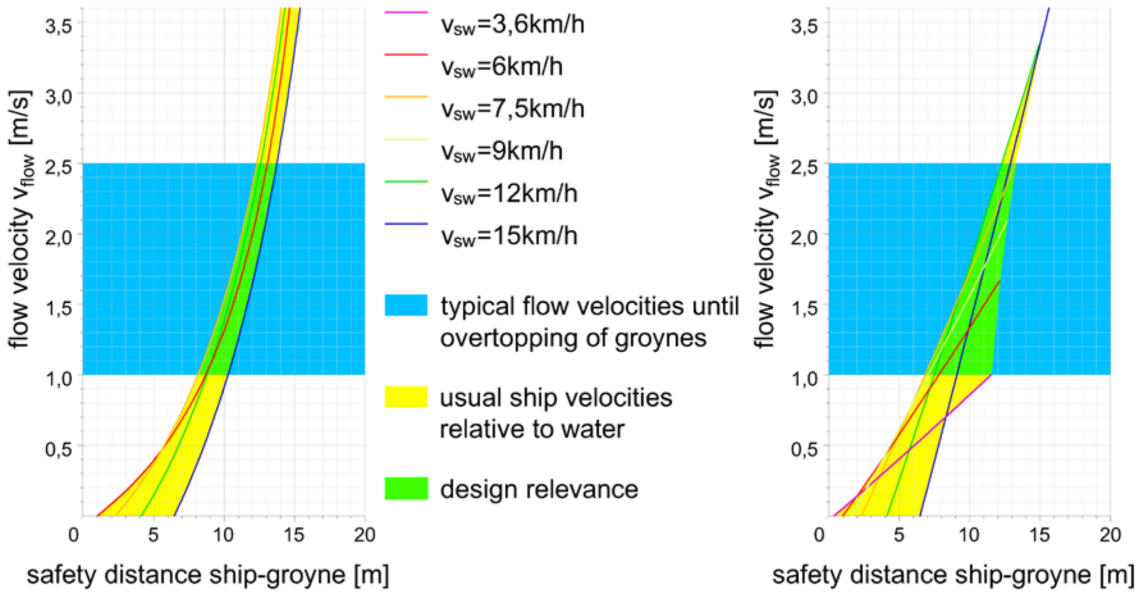


Figure 4: Extra widths for a fully loaded class Va vessel ($T = 2.8$m) sailing downstream (left) and uphill (right) with different vessel speeds relative to water v_{sw}, calculated for typical boundary conditions of the Middle Rhine River ($s_G = 200$m, $l_G = 100$m, $v_{Flow} = 0 - 2.5\,\mathrm{m/s}$) at mean water stage (groins are just overtopped, but not significantly, $D = 4$m).

2.1.3 A first attempt to account for human-factor effects

The extra width Δb_i plays an important role in waterway design and so in traffic simulations. It describes the more or less restricted orientation in the navigation channel (especially of container carrying or empty vessels), the delayed reaction on necessary course corrections caused by the inherent driving instability of a sailing vessel, or generally the attention and skills of the steersman ("human-factor effects"). Modeling problems concerned to these effects are related to the statistical distribution of the extra widths Δb_i.

Considering at first a one-way traffic situation, measurements show that the parameters of these statistical distributions, especially the dependence of mean and standard deviation, depend on the curvature of the river (smaller values in straight reaches), the ship type (higher values for container vessels or tankers), the sailing direction (downstream higher than upstream), or the vessel speed (larger at higher speeds). However, an adequate formula to account for these effects has not been derived yet. One reason is that the scatter of the data is very large.

Figure 5 demonstrates this. It shows the probability distribution of Δb_i, derived from field data. The data were mostly collected from modern large motor vessels and push-tow units, sailing on the rivers Rhine and Neckar. Figure 5 contains all the measurements without differentiation according to the boundary conditions. The method used to derive these data is a spectrum analysis of transversal and angular accelerations during the drive of many observed modern vessels. The analysis method allows for splitting off the lowest frequencies, induced by centrifugal accelerations in curves, from those that can be allocated to be the possibly delayed reaction of the steersmen, e.g. the reaction on instabilities of the ship drive, on river turbulence or generally on human-factor effects (Söhngen & Rettemeier 2013, Söhngen & Paprocki 2013). Integration over time and combination of results from lateral and angular accelerations delivers the distribution of the corresponding extra widths.

The derived extra widths Δb_i are between zero and about 10 m with an average at about 3 m and a mode value of about 2 m. This means that a good pilot is able to limit the extra widths by adequate maneuvers. A "typical high value", characterized by the 75th percentile of 4 m, corresponds well with the values in the German Canal Guidelines (BMVBS 2011) concerning encounters. A "typical peak value", corresponding to the 97th percentile which is often used for statistical tests, is about 7 m. This, again, corresponds well with the German Guidelines for the design of one-way traffic canals. The latter value accounts for the uneventful drive in a long one-way canal reach leading to a reduced level of attention. Consequently the extra width in such a situation has to be chosen higher than in case of encounters which are short maneuvering situations where it can be expected that the steersman will be highly attentive. However, such a high level of attention cannot be maintained over a long time.

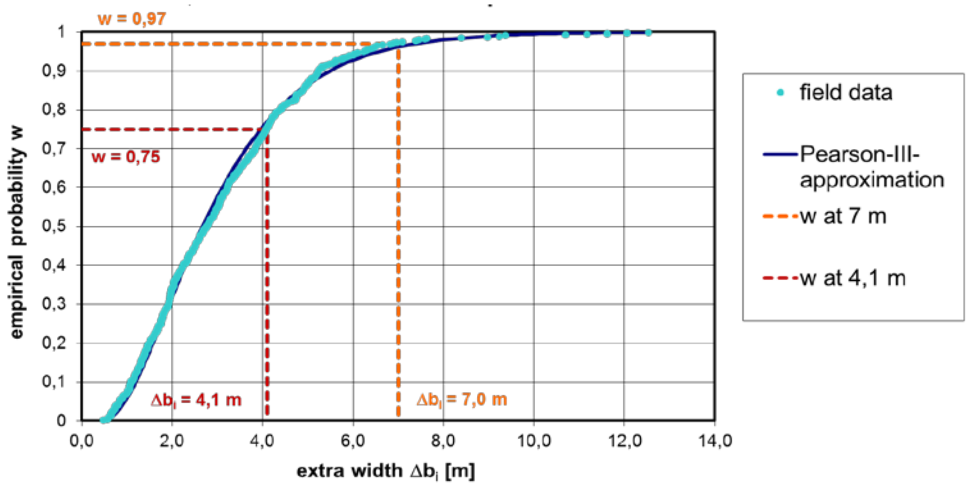


Figure 5: Probability distribution of extra widths needed caused by instabilities and human-factor effects, derived from observed ship drives on the rivers Rhine and Neckar.

ease score	designation	allocated additional widths Δb_i	superposition method for Δb_i in case of more than one vessel in a cross-section	corresponding assumptions for safety distances and usage of bow rudders
A	nearly unrestricted drive	ca. 7 m	linearly (assuming no consideration of other users of the navigation channel)	maneuver without any cooperation of the concerned steersmen, no usage of additional rudders necessary
B	moderate to strongly restricted drive	ca. 4 m	statistically as standard deviations (assuming that the probability of two high Δb_i is seldom)	there is the necessity to meet or overtake with cooperation, but generally there is no need to use additional rudders
C	strongly restricted drive on short distances	ca. 2 m	statistically as standard deviations	there is the necessity to meet or overtake with cooperation and to use e.g. a bow thruster if available and efficient

Table 1: Ease scores according to PIANC INCOM WG 141 and possible allocation of extra widths from instabilities and its superposition in case of more than one vessel in a cross-section (preliminary numbers according to Figure 5) to be used to interpret manoeuvres in traffic simulations (together with assumptions concerning safety distances and bow rudder use).

If we take these numbers of Δb_{i} as a first attempt to account for human-factor effects, whereby they have to be adjusted to the mentioned influences as curvature or driving direction, they may be linked to some ease scores, as they will be defined in the future guidelines of PIANC INCOM WG 141 (Deplaix & Söhngen 2013), together with the method of their superposition in case of encounters or overtaking situations. The approach is based on the results of comparing the calculated necessary widths of straight canals compared to those defined in the German and Dutch guidelines for one- and two-way traffic and low and high traffic density. This is done in Table 1, which can be used in the following manner in the traffic simulations:

- Because the steersman tries generally to sail as easily as possible, in practice the used extra widths for an undisturbed drive can be assumed to be those for the highest ease score A in Table 1. All the maneuvers that occur during a traffic simulation run, where the available navigational breadth is larger than the necessary space, calculated by using peak values of Δb_{i}, the corresponding ease-score can be assigned to be “A”, which is the aimed score for the Rhine River. The decision, whether a maneuver will be accepted from normal skilled and minded pilots or not may also be based on the necessary navigational space calculated by peak values of Δb_{i} compared to the available widths of the navigable water.
- If a situation occurs during traffic simulation, e.g. because the chosen information radius of the considered vessel is low, where the necessary navigation space calculated for score “A” is too high compared to the available space, but may be sufficient in case of using Δb_{i} from ease score “B” (high, but not peak-values of Δb_{i}), then the maneuvering situation may be ranked to be score “B”. The situation needs more attention for performing the maneuvers, but it is still feasible without using e.g. a bow thruster.
- If the necessary navigable space has to be reduced by using the smallest Δb_{i} in Table 1 to avoid touching the sideways boundaries of the navigable water, the ease score of a special traffic situation may be named “C”, which is the lowest score. The drive is possible but needs high driving skills and attention and – if available and effective – the use of a bow rudder. In even narrower situations it may be assumed that an accident could happen.

The approach outlined above will be used as a first attempt to account for human-factor effects in the traffic simulation model, whereby the mentioned numbers of Δb_{i} shall be modified according to the progress of the BAW research. Also a consideration of randomly varied Δb_{i} is planned.

2.2 Behavioral Acceleration Model

The longitudinal behavioral component of the waterway traffic micromodel is derived from an established car-following model for vehicular road traffic. Car-following models describe the response of the driver in terms of the desired acceleration as a function of the (bumper-to-bumper) gap s to the leading vehicle, the driver's speed v, and the speed v_{l} of the leader. Because of its easily interpretable parameters and smooth acceleration profiles, we chose the Intelligent-Driver Model (IDM) by Treiber, M. et al. (2010) as the basis model. It is specified by the acceleration equation

$$\frac{dv(s,v,v_l)}{dt} = a_{\mathrm{free}}(v) - a\cdot\left(\frac{s^*(v,\Delta v)}{s}\right)^2. \qquad (7)$$

The free acceleration function

$$a_{\mathrm{free}}(v) = a\cdot\left[1-\left(\frac{v}{v_0}\right)^4\right] \qquad (6)$$

models an acceleration which has its maximum at speed zero and decreases smoothly to zero when approaching the desired speed v_0. However, this situation will be handled by the physics submodel of Sec. 2.1 in most cases. More interesting, for our purposes, is the interaction component

$$a_{\mathrm{int}}(s,v,v_{\mathrm{l}}) = -a\cdot\left(\frac{s^*(v,\Delta v)}{s}\right)^2 =: -a\cdot z(s,v,v_{\mathrm{l}})^2, \qquad (7)$$

modeling the intention of a driver or steersman to follow the leading vehicle in bound traffic at a dynamical gap

$$s^*(v, \Delta v) = s_0 + \max\left[0, vT + \frac{v - v_l}{2\sqrt{ab}}\right], \tag{8}$$

which is composed of the minimum gap s_0 for standing vehicles, a timegap T, and a dynamical contribution enabling the smooth approach to slower or standing vehicles with a comfortable deceleration b.

It turns out that a slight modification of the IDM, the Improved IDM (IIDM) as described by Treiber, M. & Kesting, A. (2013), is suited better for the purposes of waterway traffic. One reason is that the decision model as introduced below can result in speeds larger than the desired speed. The IIDM distinguishes between the cases $z < 1$ (the actual gap is larger than the desired gap), and $z \geq 1$. Its acceleration function reads

$$\left.\frac{dv}{dt}\right|_{v \leq v_0} = \begin{cases} a(1 - z^2) & z \geq 1 \\ a_{\text{free}}\left(1 - z^{2a/a_{\text{free}}}\right) & \text{otherwise} \end{cases} \tag{9}$$

for $v \leq v_0$, if the vehicle is faster than the desired speed, the acceleration function is given by

$$\left.\frac{dv}{dt}\right|_{v > v_0} = \begin{cases} a_{\text{free}} + a(1 - z^2) & z \geq 1 \\ a_{\text{free}} & \text{otherwise} \end{cases} \tag{10}$$

with the extended free-acceleration function

$$a_{\text{free}}(v) = \begin{cases} a\left[1 - \left(\frac{v}{v_0}\right)^4\right] & \text{if } v \leq v_0 \\ -b\left[1 - \left(\frac{v_0}{v}\right)^{4a/b}\right] & \text{if } v > v_0. \end{cases} \tag{11}$$

This model has the same set of IDM parameters, the desired speed v_0, the time gap T, the minimum gap s_0, the maximum acceleration a, and the comfortable deceleration b.

By adjusting the parameters, different driving styles can be modeled. Typical parameters for vessels on inland waterways are given in Sec. 3.1.

2.3 Combination of the Physics-Based and Behavioral Models

We use a combination of the Improved Intelligent Driver Model as described in Sec. 2.2 and the physics model described in Sec. 2.1 to combine physics and behavioral components. The physical accelerations $a^{\text{phys}}_{\text{max/min}}$ with maximum and minimal engine power limit the acceleration a_{IIDM} given by the IIDM:

$$a_{\text{Vessel}} = \max\left(a^{\text{phys}}_{\text{min}}, \min\left(a^{\text{phys}}_{\text{max}}, a_{\text{IIDM}}\right)\right). \tag{12}$$

The physics model can be influenced by varying the engine power, the IIDM by varying the desired velocity.

In free traffic, the dynamics are described by the physics model. The steersman adjusts the desired engine power and the acceleration is given by the physics model. As a consequence the speed is limited to the physically maximum possible speed. In the IIDM the desired velocity is set to infinity, thus the acceleration given by the IIDM does not vanish with increasing velocity. However, it is limited by the physics model if the physically maximum possible speed is reached. If the vessel approaches a leading vessel, the IIDM takes over and reduces the acceleration to keep the safety distance from the leading vessel. By using this combination of the physics model and the IIDM the free and bounded traffic are completely modeled. During encounters and overtaking maneuvers, the steersman actively reduces the desired velocity, to solve conflicts. To initiate an overtaking maneuver, the acceleration is computed regarding the next vessel instead of the current leading vessel. These two traffic situations are described in more detail in the next sections.

2.4 Decision Components

2.4.1 Encounters

We assume that the vessel going upstream has to handle encounters by adjusting its speed. If it cannot handle the encounter, the vessel going downstream is requested to reduce its speed to the minimal possible speed. This situation only occurs, if the vessel going upstream is already in a bottleneck and cannot exit it, before the vessel going downstream arrives. The bottlenecks are computed by comparing the required to the given space as described in Sec. 2.1. They depend on the speed of both vessels. To assess if a conflict can be solved, the bottlenecks are computed for discrete speed values of the vessels involved at every given cross section. We assume a constant speed of both, vessels going up- and downstream, to compute the area in which the encounter takes place. Since we do not model the lateral dynamics, a constant time is assumed for the "lane-change", thus the needed space grows with the speed. The cross section must accommodate both vessels during their lane-changes as well. A visualization of the spatiotemporal occupancy region is given in Fig. 6. The vessel going upstream adjusts its speed to the maximum possible speed which solves the conflict. If the vessel going upstream has already passed the point of the initial lane-change, it is only allowed to reduce or keep its current speed. The steersman sets this speed as desired speed for the IIDM, the acceleration is now computed in terms of this desired speed. This decision is reviewed and corrected every time step.

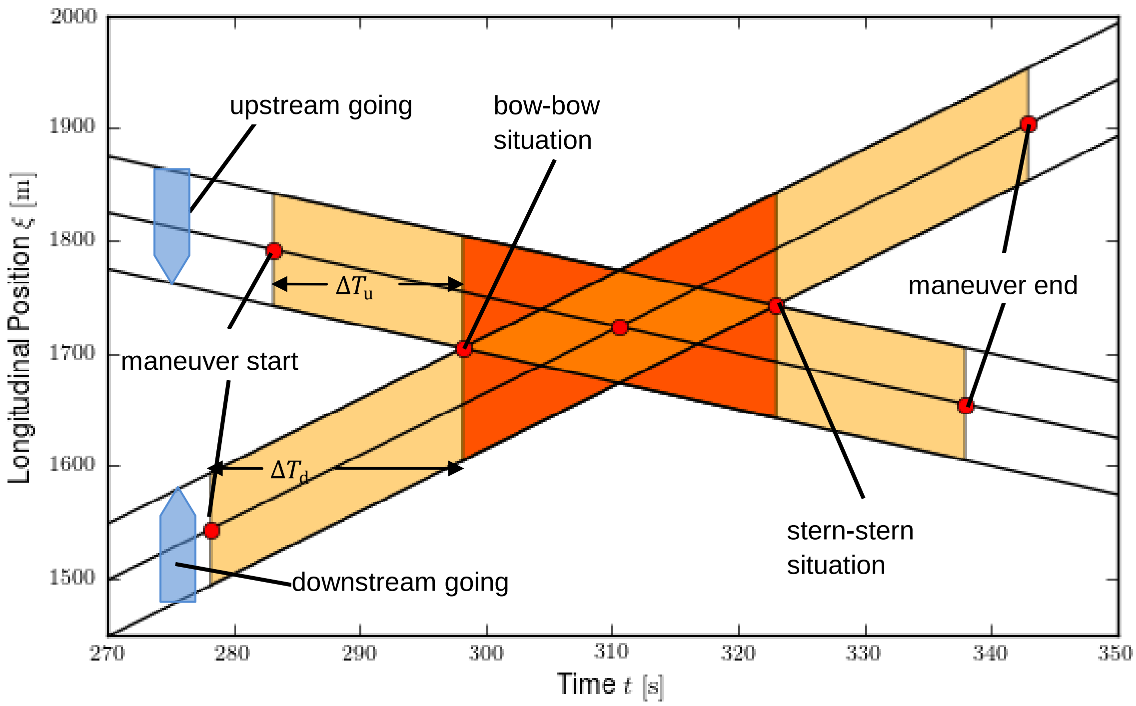
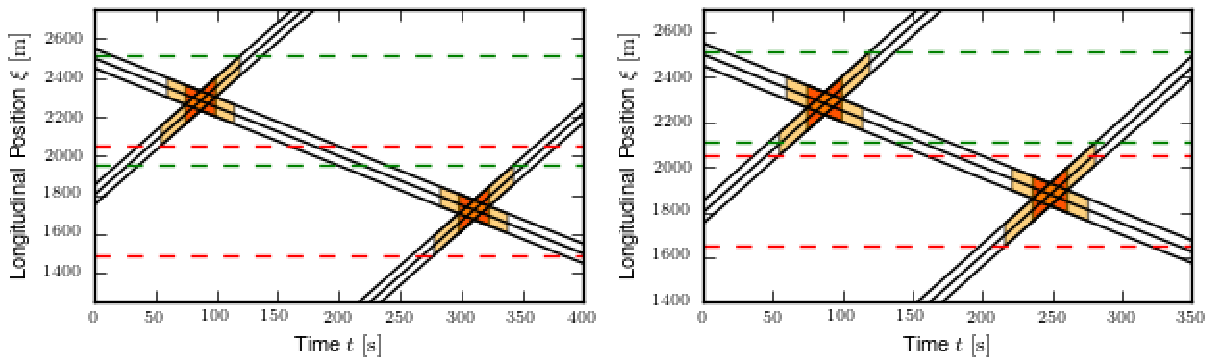


Figure 6: Spatiotemporal occupancy regions to visualize the encountering strategy. Important maneuver points are labeled. The maneuver starts at the time $\Delta T_{u/d}$ before the bow-bow situation and ends the same time span after the stern-stern situation.

If there is more than one vessel going downstream, the vessel going upstream must handle all encounters at once, if the encounter ranges overlap spatially, as shown in Fig. 7. The vessels going downstream are combined to one virtual vessel, the vessel going upstream has to adjust its speed.



(a) Seperate encounters (b) Virtual vessel encounter

Figure 7: Spatiotemporal occupancy regions to visualize the encountering strategy regarding two (or more) vessels going downstream. Green dashed lines denote higher and red dashed lines the lower boundary of the encounter range. In case (a) the ranges of two encounters do not overlap, the encounters are prepared separately, while the ranges overlap in case (b), the vessels build a virtual vessel and have to treated at simultaneously.

The vessel going upstream adjusts its desired speed during the maneuver preparation only. As soon as the maneuver is prepared, it is executed with the current desired speed. The success of the maneuver is monitored. The vessel going upstream is allowed to prepare the next encounter with another forthcoming vessel. The preparation of an encounter maneuver is finished once the vessels lie bow to bow. At this point the vessel going downstream is removed from the virtual vessel, following vessels going downstream remain therein. The speed is limited by the physical boundaries and, when it is following another vessel, by speed of and distance to this vessel. If the vessel had to decelerate to its minimal possible speed, it only accelerates after the maneuver is finished.

2.4.2 Overtaking Maneuvers

If a vessel follows a leading vessel the steersman can decide to overtake it. In order to do so, two criterions have to be fulfilled: The incentive criterion and the safety criterion.

The incentive criterion is formulated in terms of the acceleration. Instead of the current leading vessel, the acceleration regarding the next vessel is computed and compared to the current possible acceleration. If it is larger, the incentive to overtake is given. However the safety criterion has to be considered, before the overtaking maneuver can take place.

The safety criterion is similar to the computation of bottlenecks during the encounter maneuver. The range needed for the overtaking maneuver is computed assuming constant speed of all participants. Again, lane-changes are assumed to take constant time. A vessel going upstream does not have to react on an overtaking vessel it encounters. It is the responsibility of the overtaker, to assure that the required space is given. If this is not the case, the overtaking maneuver is aborted and the vessel going upstream has to handle the encounter.

3. SIMULATIONS

In this section we use the described model to simulate the traffic in a simple scenario of bidirectional traffic traversing a single bottleneck of a river waterway.

3.1 Simulation Setup

Two different types of vessels, large (type 1) and small (type 2), traverse a river channel with a bottleneck in the middle. The vessel parameters are given in Table 2.

	Vessel type 1	Vessel type 2
Length	110 m	85 m
Width	11.45 m	9.5 m
Mass	3174 t	1817 t
Average draught	2.8 m	2.5 m
Maximum draught	2.8 m	2.5 m
Desired engine power (up)	1100 kW	900 kW
Desired engine power (down)	330 kW	270 kW
Maneuver time	20 s	20 s

Table 2: Vessel parameters.

The parameters chosen for the IIDM are the same for both vessel types and given in Table 3. The parameters a and b are chosen such that they represent typical accelerations of the physics model. We consider a river segment with an average depth of 4.5 m within the fairway and an average flow velocity of 2 m/s with a 500 m long bottleneck from riverkilometer 8 to 8.5. The bottleneck is characterized by a locally reduced cross section profile associated with a raised water flow velocity of 2.1 m/s. Two large vessels (type 1) cannot traverse it simultaneously but any other combination of two vessels can. The vessel sources and sinks are located at kilometer 3 and 13. Only the vessels going upstream have to handle the encounters and adjust the speed, e.g. are affected by the bottleneck. Overtaking maneuvers are not taken into account.

Time gap T	$90\ \mathrm{s}$
Minimum gap s_0	$100.0\ \mathrm{m}$
Desired speed v_0	$\infty \frac{\mathrm{m}}{\mathrm{s}}$
Maximum acceleration a	$0.05\,\frac{\mathrm{m}}{\mathrm{s}^2}$
Comfortable deceleration b	$0.02\,\frac{\mathrm{m}}{\mathrm{s}^2}$

Table 3: Typical IIDM parameters for vessels on inland waterways.

We perform a series of simulations with varying traffic demand and fleet composition in the upstream and downstream directions. We define the bottleneck capacity as the maximum vessel flow (number of vessels per time unit passing a certain cross section in front of the bottleneck) that the bottleneck can sustain without congestion and investigate how the capacity depends on the influencing factors mentioned above. To detect a traffic congestion of the vessels going upstream the criterion is that at least 5 of these vessels are slower than $0.4v_{\mathrm{desired}}^{\mathrm{free}}$, with $v_{\mathrm{desired}}^{\mathrm{free}}$ the physically maximum possible speed with the desired engine power at the current position. The traffic demand is varied from 0 vessels/h to 15 vessels/h for the vessels going downstream, while the demand for the vessels going upstream is varied from 0 vessels/h to 20 vessels/h. However, a vessel is only added to the traffic on the river if there is enough space, so the real traffic flow can be less than the traffic demand. To compute the real flow as a function of the local density, flow-density data are aggregated by counting and averaging the number of vessels and their speed in the ranges from river-kilometer 9 to 10 and 10 to 11 over time frames of 30 minutes.

In addition to the flow-density data, we compute theoretical "fundamental diagrams" which, by definition, give the steady-state flow if identical vessels as a function of the density (Treiber M. & Kesting, A. (2013)). Generally, flow-density data and fundamental diagrams consist of two regions, the free traffic characterized by low densities and increasing flow with density, and the bounded traffic characterized by decreasing flow with increasing density. The slope of the free branch is given by the desired free speed, which is the physically maximum possible speed with the desired engine power. The fundamental diagram is computed at a position outside the bottleneck for both vessel types and both directions.

3.2 Simulation Results

A typical example of vessel trajectories is given in Fig. 8. The flow of the vessels going downstream is so large that some vessels going upstream are not able to pass the bottleneck immediately and have to slow down or stop in front of it.

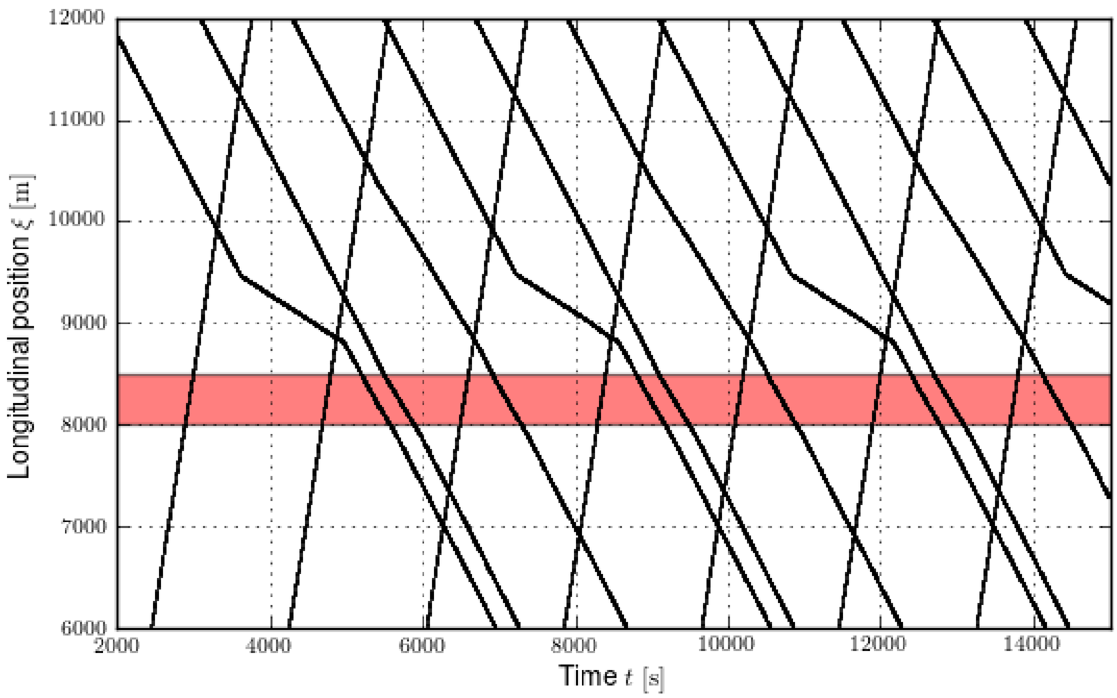


Figure 8: Typical trajectories of encountering vessels in presence of a bottleneck (red). Vessels going upstream have to decelerate to let forthcoming vessels pass.

The computed fundamental diagrams are given in Fig. 9 (a-d). We find the maximum flows indicated by the triangle tips and the desired speeds, given by the free branches slopes. The values are given in Table 4.

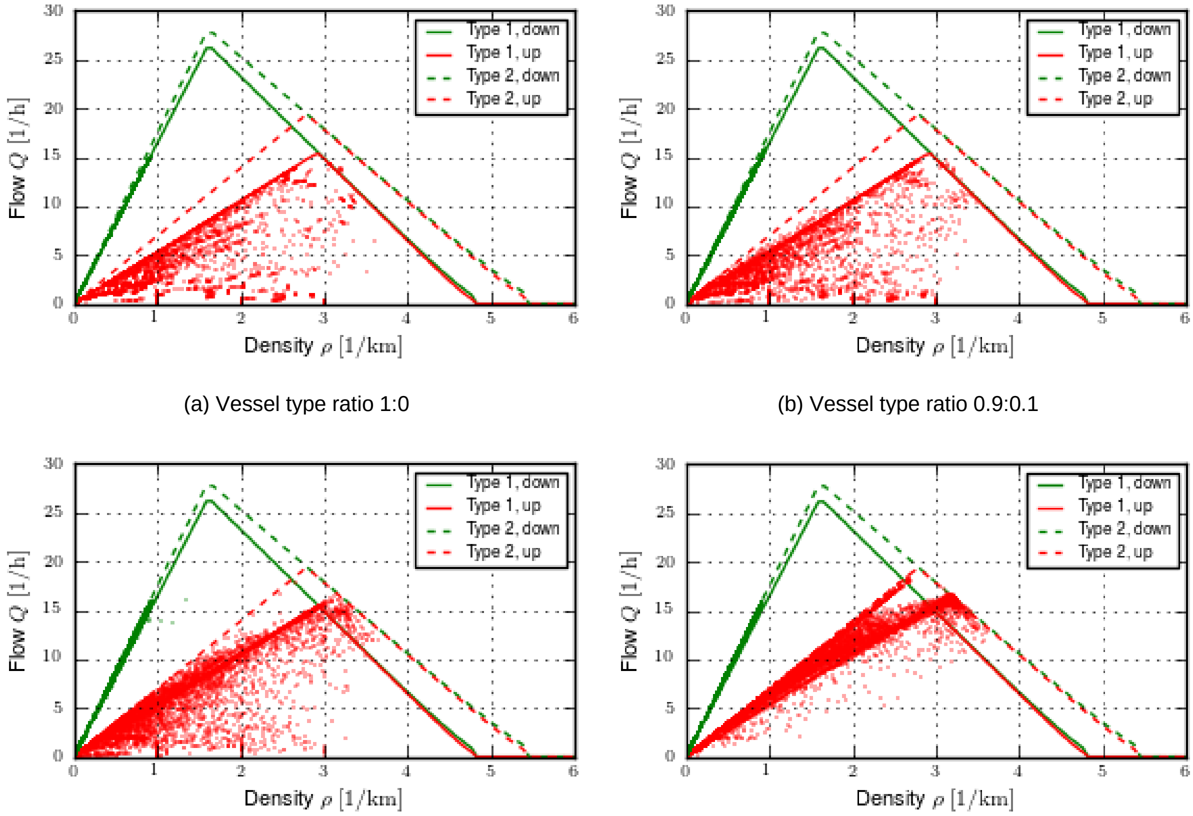
	Type 1 upstream	Type 1 downstream	Type 2 upstream	Type 2 downstream
$Q_{\max}\left[\frac{\text{vessels}}{\text{h}}\right]$	15.4	26.2	19.3	27.8
$v_{\text{desired}}\left[\frac{\text{m}}{\text{s}}\right]$	1.47	4.58	1.94	4.87

Table 4: Maximum flows and desired speeds for the different vessel types in both direction as depicted by the fundamental diagrams.

The maximum densities are equal for both, the upstream and downstream directions, but depend on the vessel type. We find $\rho_1^{\max} = 4.8$ vessels/km and $\rho_2^{\max} = 5.4$ vessels/km.

The flow-density data points for different traffic compositions are presented in the same figures as the fundamental diagrams. In case of the vessels going downstream, the points scatter around the free branches of the fundamental diagrams. If the traffic consists of both vessel types, both free branches and the area in between are occupied. The higher the flow of slower type 1, the more points lie on the free branch of the type 1 fundamental diagram, for high densities. Many of the flow-density data points lie within the triangle built by the two branches and the ρ-axis. Some data points are scattered close to the bounded branches. With an increasing percentage of type 2 vessels, flow-density data of free traffic effectively extend to higher densities until they reach the bounded branches of the type 2 vessels.

Although the maximum traffic demand for the vessels going upstream is 20 vessels/h, the actual flow is smaller, as seen in the flow-density data. If the traffic consists of type 1 vessels only, the maximum measured flow is 14.25 vessels/h. It increases slightly with the rate of type 2 vessels.



(a) Vessel type ratio 1:0

(b) Vessel type ratio 0.9:0.1

(c) Vessel type ratio 0.5:0.5

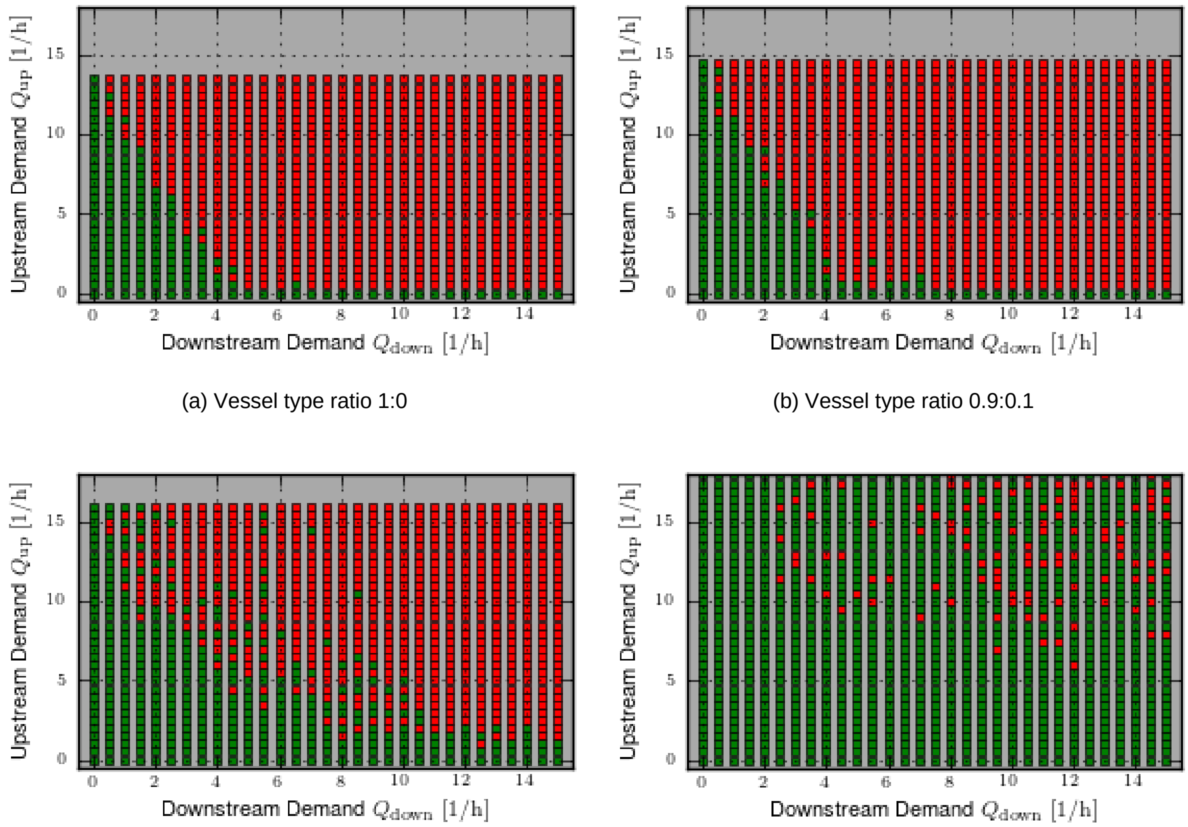
(d) Vessel type ratio 0.1:0.9

Figure 9: Flow density data (symbols) and theoretical fundamental diagrams (lines) for both vessel types in the upstream (red) and downstream (green) directions and for different traffic compositions A:B of the two vessel types 1 (A) and 2 (B). Notice that there is no congested traffic in the downstream direction, thus no congested downstream flow-density data.

In Fig. 10 (a-d) the traffic state for combinations of different traffic demand of vessels going up- and downstream is shown for different traffic compositions. Green dots correspond to free traffic, red dots to congested traffic. Only vessel flows that were observed in the flow-density data have been considered in the figures.

The bottleneck capacity as defined in the previous section highly depends on the flow of downstream going vessels, as can be seen in the given figures. The more type 2 vessels are contained in the traffic composition, the more scattered the boundary between congested and free traffic becomes. In case of

10% of type 1 vessels, or less, no bottleneck capacity can be defined from the figure, randomly scattered flow combinations above $Q_{\text{up}} = 6$ vessels/h and $Q_{\text{down}} = 2.5$ vessels/h result in a congestion.



(a) Vessel type ratio 1:0

(b) Vessel type ratio 0.9:0.1

(c) Vessel type ratio 0.5:0.5

(d) Vessel type ratio 0.1:0.9

Figure 10: Phase diagram for the free and congested traffic states as a function of the upstream and downstream demand (vessels per hour) and for different traffic compositions A:B of the two vessel types 1 (A) and 2 (B).

3.3 Discussion of the Results

The fundamental diagrams show the expected triangular shape. As anticipated, they differ for the different vessel types and directions. On the free branch the dynamics are determined by the physics model, while the IIDM prevails on the bounded branch. This explains the similar shape of the bounded branches for both driving directions of a vessel type. The free or physically possible speed, indicated by the slope of the free branch, is larger for vessels going downstream than for vessels going upstream. The maximum densities correspond to the expected maximum densities of $\rho^i_{\max} = 1/(s_0 + l_i)$ where l_i is the length of vessel type i.

The measured flow-density data of the vessels going downstream lie scattered around the free branch. This indicates, that these vessels are not affected by the bottleneck. Only vessels going upstream have to handle the encounters, bounded traffic states occur. The vessels going upstream can handle all encounters, the vessels going downstream do not have to decelerate, since all flow-density data points lie on the free branches. Thus no critical situations occur.

The type 2 vessels are slowed down by the type 1 vessels as can be seen by the flow-density data points in Fig. 9 (c) and (d). Although the number of type 2 vessels is large, the flow-density data points lie on the type 1 vessels free branch, indicating the slower speed. This effect will be reduced by allowing overtaking maneuvers.

Data points lying under the fundamental diagram represent mixed states of free and bounded traffic, arising from the aggregation of the data and by dynamical effects.

As main result, we observe that the bottleneck capacity depends strongly on the flow of vessels going downstream and the traffic composition. While in the absence of vessels going downstream the theoretical capacity is above 15 vessels/h, it declines to 10 vessels/h if the downstream flow is merely 1 vessels/h and the traffic consists of type 1 vessels only. A flow of $Q_{\mathrm{down}} \approx 5$ vessels/h is large enough to completely block the bottleneck for vessels going upstream. The more type 2 vessels are included in the traffic composition, the higher is the probability of a gap large enough for a vessel going upstream to pass the bottleneck. This results in a higher bottleneck capacity and the observed scattered boundary between free and congested traffic.

4. CONCLUSION

In our contribution, we demonstrated how a microscopic, fully dynamical simulation of traffic flow on inland waterways can be designed and implemented by combining models from different research fields. A new decision model to manage encounters and overtaking maneuvers has been introduced and human-factor effects have been considered. Since the model has been formulated in separate parts, it would be possible to plug in different physics models or required space computations and thereby adapt it to other vessels types.

By our microscopic approach of simulating each vessel individually, the model is capable of simulating heterogeneous traffic with different kinds of vessels and different characters of steersmen. It can be investigated how changes to the river infrastructure like fairway depths and widths, changes in water levels, different fleet compositions or even new types of vessels will influence the traffic flow.

By using a semi-empirical approach for the computation of additional widths, we are able to model different solutions of conflicts in traffic situations. It is even possible to take human-factor effects into account and rate the difficulty of a maneuver in terms of an ease-score.

Finally, we gave a simulative proof of concept of the model's workings and demonstrated what kind of data can be generated. As a last result, we found that the capacity of a bottleneck is very dynamic depending strongly on the fleet composition and the percentage of vessels going downstream.

To simulate the traffic on the Rhine or any other river, real data of encounter and overtaking trajectories are needed to validate the decision models and calibrate the model parameters. In addition, further research is needed to obtain statistical data of vessel types, traffic composition and arrival distributions.

References

BMVBS, (2011). Guidelines on standard cross sections of inland navigation channels, Federal Ministry of Transport, Building and Urban Development, Germany, 2011

Dai, M.D.M. & Schonfeld, P. (1991). Simulation of Waterway Transportation Reliability. Transportation Research Record 1313 (98)

Deplaix, J.-M., Söhngen, B. (2013). Workshop Design Guidelines for Inland Waterways - Safety and Ease Standards (PIANC-INCOM WG 141). Smart Rivers Conference 2013

Helbing, D. (2001). Traffic and related self-driven many-particle systems. Rev. Mod. Phys. 73 (1067)

Rettemeier K. (2013). Workshop Design Guidelines for Inland Waterways - Review of Existing Guidelines (PIANC-INCOM WG 141). Smart Rivers Conference 2013

Söhngen B., Maedel N., Hahne L., Verdugo I., Iribarren J. (2012). Additional navigational widths of inland vessels passing cross current fields. PIANC ON COURSE, January 2012

Söhngen B., Rettemeier K. (2013). Design Guidelines for Inland Waterways. (PIANC INCOM WG 141)

Söhngen, B., Rettemeier, K. (2013). Workshop Design Guidelines for Inland Waterways - Concept Design Method (PIANC-INCOM WG 141), Smart Rivers Conference 2013

Söhngen, B., Paprocki, M., KLIWAS-TP 4.4/2013, Schlussbericht, Mindestbreiten der Fahrrinnen für eine sichere und leichte Schifffahrt. BMVI, Koblenz 2013

Söhngen, B., Paprocki, M., Feierfeil T., Orlovius A., Leismann K. (2014).„Abladeoptimierung Mittelrhein, Schlussbericht zum Fahrrinnenbreitenbedarf“. BAW, to appear

Thiers, G. F. & Janssens, G. K. (1998). A Port Simulation Model as a Permanent Decision Instrument. SIMULATION 71 (117)

Treiber, M., Hennecke, A.& Helbing, D. (2000). Congested traffic states in empirical observations and microscopic simulations. Phys. Rev. E 62 (1805)

Treiber, M.& Kesting, A. (2013). Traffic Flow Dynamics. Data, Models and Simulation. Springer. ISBN 978-3-642-32459-8.

UFC (2005). Unified Facilities Criteria, Design: Mooring, UFC 4-159-03. US Army Corps of Engineers. 3 October 2005

VBW (2013). Fahrdynamik von Binnenschiffen, Fahrverhalten auf Binnenwasserstraßen. Fach-ausschuss Binnenwasserstraßen und Häfen (VBW/HTG) und Fachausschuss für Binnenschiffe (VBW/STG). Germany, 2013

Wassermann, S., Söhngen, B., Dettmann T., Heinzelmann C. (2010). Investigations to define minimum fairway widths for inland navigation channels. PIANC World Congress Liverpool, UK, 2010

Yee-Chung, Jin (1990). A study of flow in curved open channels. University of Alberta. Dep. Of Civil Engineering. 1990