Simulation Study to Assess the Maximum Dimensions of Inland Ships on the River Seine in Paris

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Abstract. Traversing the river Seine in Paris is challenging for inland navigation vessels due to the density and diversity of local traffic and the variety of manoeuvres to be encountered in a confined environment. The waterway authority, Voies Navigables de France (VNF), commissioned a study to assess the relevance of the current regulations when present and future vessels of varying types and dimensions cross Paris. This paper describes the use of fast time and real time simulations to assess the maximum dimensions of ships crossing the Seine in Paris. In a first phase, fast time simulations were executed with a track controller, which allowed to identify bottlenecks on the full length (12 km) of the river Seine in Paris. Based on those results, critical scenarios were selected to be tested on a full mission bridge simulator by skippers familiar with the crossing of Paris. Inspired by PIANC INCOM WG 141 Detailed Design and Safety and Ease Approaches, the main challenges related to the simulation setup and the assessment methodology are presented and discussed in this paper. The simulations have shown that the main bottlenecks are related to the succession of passages under narrow bridges with non-aligned openings. The maximum water levels for which safe passage is possible, were determined for each ship type and compared with the existing regulations. Finally, recommendations were formulated, which were then discussed with VNF, end users and stakeholders.

Keywords: Transport of containers · River · Bridges · Manoeuvring simulator

1 Introduction

The river Seine is a major axis of the French inland waterway transport network with a high traffic density. Traversing the city of Paris is challenging for inland navigation vessels due to the variety of manoeuvres involved. In the area of the two isles, the main artery of the waterway is passing in between the two isles (south of the Ile Saint-Louis and north of the Ile de la Cité), so that larger ships have to deal with sharp bends in

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between the two islands. On top of that, there is a high number of historically important bridges, where traffic has to pass underneath narrow arches, while taking into account delicate current conditions on a bending trajectory (see Fig. 1).

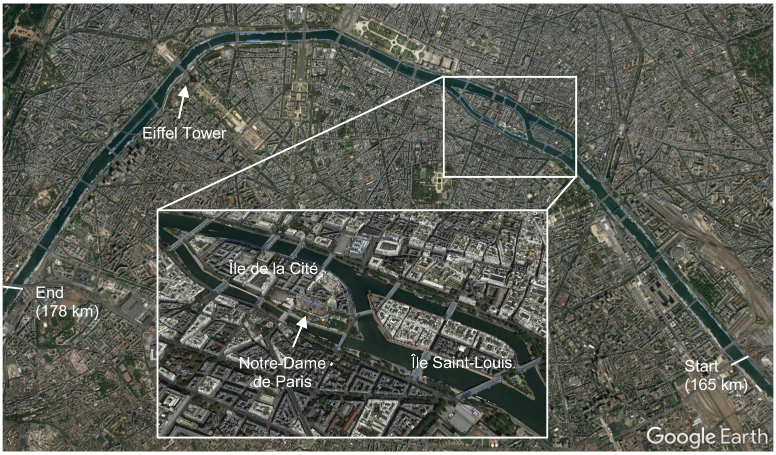


Fig. 1. Study area (12 km): river seine crossing the city of Paris, France.

Some decades ago, regulations concerning the maximum ship dimensions depending on the water level of the river were put in place to ensure the safety of navigation. However, with increasing capacity demand and with new types of ships, the question arose whether the regulations are still up to date and whether the safety is sufficient to increase the traffic and ensure the competitiveness of inland waterways transportation.

Specific nautical studies executed in the past on short stretches of the Seine river have been consulted. Some recommendations about the navigation of 135 m × 11.4 m ships between the two islands are given by CETMEF (2010) based on full-scale tests. Recommendations for 105 to 125 m long and 11.4 m wide ships in the same area are given by DNT (2016) based on navigation simulations. Navigation simulations executed by CETMEF (2013) provided information about the navigation conditions around Alexandre III bridge. Moreover, DST (2013) gave some recommendations about turning manoeuvres of 135 m long passenger ships downstream of Grenelle island, in the southwest of Paris. However, a comprehensive study assessing the maximum length of ships able to cross Paris under different hydraulic conditions had never been conducted. To this end, the waterway authority (VNF) commissioned a study to assess the navigation in Paris under different hydraulic conditions for the largest ships that are expected to cross Paris. VNF therefore requested to concentrate on the influence of length and ship type for 11.4 m wide ships.

Design guidelines based on three different approaches were recently published by PIANC (2019) with the vision of optimization of inland waterways dimensions based on local constraints, present and future fleet. A first step in the design or upgrade of an existing waterway is to use national guidelines. If no national guidelines are applicable, the PIANC guidelines provide recommendations for the dimensions of fairways (Concept Design) depending on the so-called Safety & Ease level which is aimed by the waterway authority.

This first approach has some limitations, e.g., it is not applicable in rivers with high flow velocities. Existing examples can then be used as a reference if the situation is comparable to the one studied (Practice Approach). When the situation is too different and large uncertainties remain or if environmental, local constraints limit the dimensions of the waterway, a third approach (Detailed Design) is recommended.

Under bridges, PIANC recommends guaranteeing a minimum height on the total width of the fairway with additional safety distance for collision risk. However, most of the waterways in France were designed before any regulations about air draft had been put in place (Deplaix and Daly 2019) and the fleet has significantly changed over the last decades. Therefore, the minimum height under arched bridges would only be guaranteed over a very narrow width if applied in Paris. Moreover, no guidelines are given for rivers with significant flow velocities.

A ship manoeuvring simulator is a useful tool to reproduce the passage under bridges in specific hydro-meteorological conditions. Söhngen and Butterer (2015), for example, simulated the passage of a 135 m long motor vessel within the width delimited by two piles of a flat bridge. Real time simulations are also used extensively to evaluate the accessibility in bends, as for example is the case for the Nord-Pas-de-Calais network in France (Adams et al. 2019) and the Upper-Seascheldt in Belgium (Eloot 2015).

This paper describes the use of simulations to assess the operational limits based on ship length on the river Seine inside the city of Paris and is illustrated by a selection of the main scenarios of navigation with motor ships in bends and under non-aligned narrow and low arched bridges. Section 2 describes the simulation setup. Section 3 presents the methodology applied to assess the safety of the manoeuvres and the main findings. The challenges and limitations of the methodology are discussed in Section 4. In Section 5, conclusions are given.

2 Simulations Setup

2.1 Manoeuvring Simulators

Several hundreds of scenarios with different ship types (fret and passengers) were simulated in Paris on three full mission manoeuvring simulators at Flanders Hydraulics Research. The simulators are dedicated for research studies and training. The main simulator is composed of a bridge with 360° aerial view of the surroundings projected on a cylindrical screen as shown on Fig. 2. A second simulator was used to simulate the navigation of large passenger ships and coupled to the first one to simulate ship meetings in bends. A third simulator was used to simulate the navigation of a small hydrofoil craft. The bridge of all simulators is equipped with:

- ECDIS and radar;
- Controllable camera views;

- Controllable bridge height;
- Propulsion and steering controls adapted to each ship type.

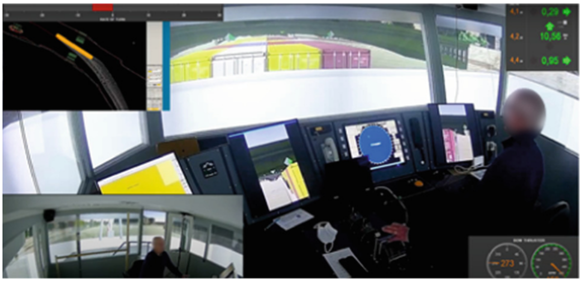


Fig. 2. Main full mission bridge simulator with 360° view at FH.

2.2 Waterway Environment

A total length of 12 km of the river Seine crossing Paris was modelled in 3D for this study. The 3D environment is divided into two independently designed parts:

- 3D external view: this is the visible part of the environment above the waterline (see Fig. 3). This part is projected on screens and allows the skipper to orient himself. The visual aspect of the external environment created is of medium resolution except for bridges which are accurately reproduced (± 10 cm) from original plans.

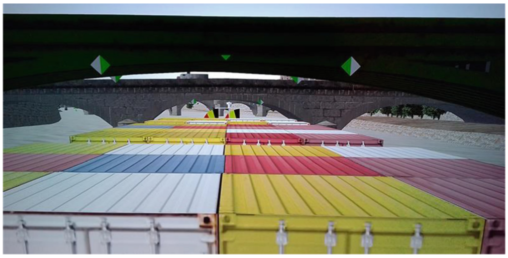


Fig. 3. 3D external view of the non-aligned bridges.

- Bathymetry: this is the part under the waterline. It was reproduced from the bathymetric data and influences the hydrodynamic behaviour of the ship.

2.3 Hydraulics Conditions

The current was implemented with TELEMAC, which is a software package developed by IMDC that resolves the 2D shallow water equations to model the water flow (Breugem 2020). The mesh has a resolution of 10 m with a refinement of 5 m close to the banks and 2 m around the bridge piles. To obtain approaching current velocities at the depth corresponding to the draft of the ships, a correction factor based on a logarithmic distribution of the velocities was applied. Hydraulic conditions from low water (0.82 m measured at the reference station Austerlitz) to the maximum water level for which navigation is currently allowed (4.30 m measured at Austerlitz) were modelled with an increment of 0.10 m. The significant variation of the water level along the study area (i.e. longitudinal profile) was also implemented. The modelled flow fields were later tested and validated on the manoeuvring simulator by experienced skippers.

2.4 Ship Models

The ship models listed in Table 1 were all implemented in the simulators used in the study. The manoeuvring behaviour of each ship model is determined by a mathematical model which computes:

- hydrodynamic forces, propulsion and steering forces, shallow water effects, restricted water effects;
- aerodynamic forces;
- interaction with encountering and overtaking target vessels.

Table 1. Ship models

Ship type	Transport	ECMT class	Length	Beam	Draft	Air draft
Push convoy	bulk	Vb	180	11.4	1.70 / 2.80	2.90 / 4.00
Push convoy	bulk		150	11.4	1.70 / 2.80	2.90 / 4.00
Motorship	2 layers cont. / bulk		135	11.4	1.70 / 2.80	2.90 / 4.00 / 3.65 / 4.75
Motorship	2 layers cont. / bulk		125	11.4	1.70 / 2.80	2.90 / 4.00 / 3.65 / 4.75
Motorship	2 layers cont. / bulk	Va	110	11.4	1.70 / 2.80	2.90 / 4.00 / 3.65 / 4.75
Motorship	passengers		125	11.4	2.10	6.00
Motorship	passengers		60	10	1.48	4.00
Motorship	passengers		5	2.5	1.62 / 0.9	1.62 / 2.28

The mathematical model of the container vessels and bulk carriers shown in Table 1, is based on tests performed with a 1:25 scale physical model of a ECMT class Va vessel (110 m x 11.4 m), which was validated by full scale measurements (Verwilligen et al. 2015). Mathematical models for longer vessels (135 m x 11.4 m) were also derived and used for various nautical studies on the simulators at Flanders Hydraulics Research. For this study, models of lengths 105 m and 125 m were derived from the ECMT class Va model.

The models at a draft of 2.8 m were derived by interpolating the available drafts in the database. Models with a draft of 1.7 m (corresponding to a moderately loaded vessel) were deduced by extrapolation.

The models of the 60 m x 10 m and 125 m x 11.4 m passenger ships were derived from a 110 m x 17 m ship model equipped with rotating pods (Z-Drive thrusters) in the simulator database (Delefortrie et al. 2014).

Various ECMT class Vb/VIb/VIa pushed convoy combinations have been tested in the towing tank for shallow water for several drafts and water depths (see Fig. 4). The Vb model, available for two loading conditions, was used to develop two new models for 150 m and 180 m pushed convoys (Delefortrie et al. 2020). The models at a draft of 2.8 m were interpolated from the two available loading conditions and the models at a draft of 1.7 m were developed by CFD calculations (Van Hoydonck et al. 2020).

Fig. 4. Towing tank tests: ECMT class Vb.

The 5 m long passenger hydrofoil craft was derived from a simplified model of Riva boat type scaled to the desired dimensions and tuned based on full scale trials (only flying mode was modelled).

2.5 Track Controller for Fast Time Simulations

Flanders Hydraulics (FH) and Ghent University use five different fast time simulation techniques to systematically study ship manoeuvres in shallow and confined waters (Lataire et al. 2018). For this study, “Fast-time Track Controller” simulations (referred to as “fast time simulations” in this paper) were used taking full use of the mathematical model. The controls of the ship (rudder and propeller) are changed in time by a Prescience Model based Track Controller called PMTC by Chen et al. (2021) to follow a predefined path at a predefined speed. The input of this type of simulation is the desired trajectory and the margin for deviations that are allowed over the trajectory (Eloot et al. 2009).

2.6 Skippers

The real time simulations in this study were executed by professional skippers who have ample experience with navigation in Paris. One skipper is particularly familiar with 110 to 180 m long bulk convoys with a beam of 11.4 m, another skipper is particularly familiar with container ships of 86 m × 9 m and a third skipper is particularly familiar with passenger ships sailing in Paris. Prior to the actual simulations, the skippers spent a day on the simulators, during which they could test the modelled environment and provide feedback on the realism of both the mathematical manoeuvring model and the hydraulic model. The skippers shared their experience before, during and after each simulation. The human factor is taken into account by repeating the scenarios with two different skippers at the water level identified as possible limit. The scenarios are also assigned to skippers based on their particular experience (push convoy, container ships, passenger ship…) so that the different nuances in sailing different ship types are taken into account.

3 Detailed Study

3.1 Methodology

3.1.1 Simulation Protocol

Due to a large number of different parameters involved in the study, the simulations were carried out in two phases. A first phase consisted of fast time simulations to investigate the influence of each parameter and to identify the most critical conditions and bottlenecks. A second phase of the study consisted of real time simulations which allowed a more detailed analysis of the critical scenarios identified in the first phase.

3.1.2 Debriefing and Skippers Feedback

After each real time simulation, the skippers are invited to the control room to give their opinion about the manoeuvres that were performed. The difficulty as well as the safety of the manoeuvre is rated on a scale from 1 to 6. At this point, the nautical expert can already judge the accessibility level based on what was observed and discussed in the control room. However, the final results depend on the comparative and objective analysis of all the parameters conducted after a detailed post-processing of the simulation runs (based on the safety criteria described in 3.1.3). Preliminary results are nevertheless useful to drive the protocol and select the testing conditions in an optimized way.

3.1.3 Safety Criteria

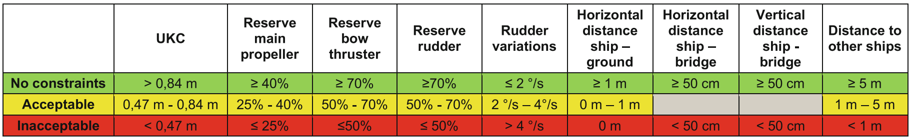
Different criteria are used to evaluate the difficulty and safety of the manoeuvres. At low water levels, the most critical parameter is the distance between the ship and the depth line corresponding to the draft of the vessel. At high water levels, the most critical parameters are the horizontal distance between the ship and the line corresponding to the air draft of the ship and the vertical distance between the ship and the bridge. Three other parameters are monitored as well: the reserve of the propeller, the reserve of the bow thruster and the reserve of the rudder. In general, the reserve of a control parameter n, written as R_n, is the reserve that is available in case a problem occurs and is defined by Eq. (1) in function of the mean value $\hat{n}$ and the maximum value n_{max} of the parameter n over the duration of a simulation.

$$R_n = 1 - \frac{\hat{n}}{n_{max}} \tag{1}$$

For the three criteria mentioned above, the control parameter n is equal to the number of revolutions of the main propeller, the number of revolutions of the bow thruster and the rudder angle respectively.

Another parameter that is used as a criterion to assess the safety margin of a manoeuvre is the number of rudder variations (in °/s) derived from the mean rate of turn. This parameter is a good indication of the level of stress that the pilot experiences during the manoeuvre. Three other parameters are also considered in the analysis: under keel clearance (UKC), the vertical distance between the ship and a bridge and the distance to other ships.

The manoeuvrability of the ship can then easily be evaluated based on the criteria using a colour code. Figure 5 shows the colour code used in this study and indicates for which values for each of the parameters a colour changes.



	UKC	Reserve main propeller	Reserve bow thruster	Reserve rudder	Rudder variations	Horizontal distance ship – ground	Horizontal distance ship – bridge	Vertical distance ship - bridge	Distance to other ships
No constraints	> 0,84 m	≥ 40%	≥ 70%	≥70%	≤ 2 °/s	≥ 1 m	≥ 50 cm	≥ 50 cm	≥ 5 m
Acceptable	0,47 m - 0,84 m	25% - 40%	50% - 70%	50% - 70%	2 °/s – 4°/s	0 m – 1 m			1 m – 5 m
Inacceptable	< 0,47 m	≤ 25%	≤50%	≤ 50%	> 4 °/s	0 m	< 50 cm	< 50 cm	< 1 m

Fig. 5. Safety criteria and colour codes used for the evaluation.

3.1.4 Nautical Expert Evaluation

Finally, an accessibility level is attributed and commented by the nautical expert based on the safety criteria defined in Sect. 3.1.3, the analysis of the trajectories as well as feedback from the skippers. A manoeuvre is considered as impossible when at least one of the safety criteria turns red.

3.2 Analysis

3.2.1 Fast Time Simulations

A first phase of fast time simulations was executed for every ship model at different water levels varying every 10 cm. The reference trajectory is based on the navigation axis found on the ECDIS chart and adapted based on skippers' experience provided during the validation day as well as from trajectories observed in previous studies which were executed for other purposes in this study area. The results were compared with previous studies executed in the city centre of Paris in order to validate the threshold of the different criteria. The results were also compared to actual regulations and skippers' feedback on reference cases for which the safety and ease level is well known. Tuning of the Track Controller parameters was then necessary to increase the realism of the manoeuvres as well as tuning of the threshold levels of the criteria.

The main bottlenecks were highlighted from fast time simulations and the waterway was divided into different critical sections. The passage under the Pont-Neuf was identified as the most critical section for the ships with a beam of 11.4 m at every water level due to a reduced beam. At the lowest water level, the base of the pile located underwater is a bottleneck for fully loaded vessels while the reduced width due to the arch of the bridge becomes the bottleneck at high water levels, especially for empty ships.

3.2.2 Real Time Simulations

Based on the results of the fast time simulations, a protocol was established with logical links to prioritize the scenarios to be tested with the skippers on the full mission bridge simulators. The number of scenarios could thus be estimated in advance but the final protocol had to be decided upon during the simulation day based on a rapid analysis by the skipper and the nautical expert immediately after each run.

Detailed post-processing was carried out after each simulation day and the results were grouped together in different data sheets, providing an overview per ship and per sailing direction Fig. 6 gives an example of what such a sheet looks like for a 135 m × 11.4 m container ship. It can be seen that the analysis indicates that navigation is impossible in the second section of the simulated trajectory (red color).

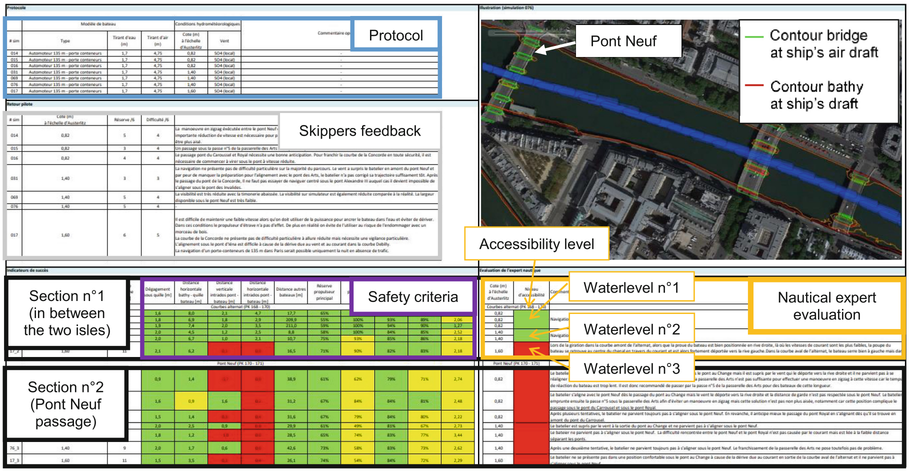


Fig. 6. Extract from a simulations sheet for a 135 m × 11.4 m container ship sailing downstream with a draft of 1.7 m. Analysis of the section n°1 and n°2 of the waterway.

3.2.3 Synthesis

The results of the fast time simulations and real time simulations were combined to recommend a level of accessibility for each of the sections of the 12 km long trajectory. The main bottleneck for 11.4 m wide ships was sailing under the Pont Neuf, where the ship must arrive perfectly aligned due to the restricted width. This is especially difficult to achieve when sailing downstream after passing the bends in between the two islands and the non-aligned bridges.

During the simulations, the skippers preferred to sail fast in order to improve manoeuvrability and attempt to pass safely under the Pont Neuf. As this involved repeating the same passage on the simulator and a certain advance knowledge of the problems involved, the manoeuvre cannot be considered as acceptable unless some measures are taken.

Some scenarios were only feasible after repeating the simulations or by using a specific technique, such as speeding up. Those scenarios show that only a well-trained skipper familiar with the navigation in high water levels could manage to pass safely. The risk is that a change of regulations would open the navigation to new skippers with no experience of crossing Paris, who might not anticipate the bottlenecks. Therefore a certification system (where the waterway authority makes an exception for a ship exceeding the maximum dimensions allowed), training strategy (e.g. by using ship handling simulators) and other recommendations were formulated when the navigation could not immediately be validated based on simulation results.

When all conditions have been tested, a final accessibility level can be recommended for the full length of the trajectory for each design ship in order to visualize easily the operational limits (i.e. water levels) of the different ships, as shown in Fig. 7. This helps the waterway authority in the decision making for an adaptation of the current regulations, which are based on ship length. The results were then discussed with VNF and stakeholders.

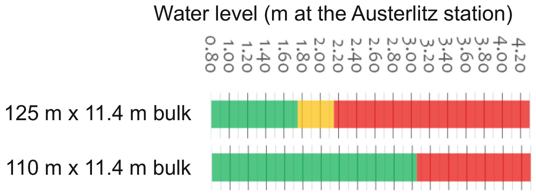


Fig. 7. Extract from the synthesis of simulation results showing. the operational limits (i.e. water levels) for two different bulk carriers (green = possible, orange = very difficult, red = impossible).

4 Challenges and Limitations of the Methodology

4.1 Safety Margins

At very high water levels, the headroom under bridges is so reduced that the skippers take advantage of the shape of the ship to pass underneath a bridge, for example by using the reduced air draft of the bulk carriers in front of the ship bridge. Figure 8 shows that the skipper brings the bow very close to the left side of the bridge (orange shape) and the aft of the ship close to the centre of the bridge (dark blue shape). However, in the analysis, a rectangular cuboid (bounding box) is considered around the ship (see Fig. 9) and some scenario can be rejected even though the skipper thought he had safely passed under the bridge based on what he saw during the simulations. Due to uncertainties on the actual shape of the superstructure of the ship crossing Paris, the analysis uses a conservative approach to make the conclusions applicable to any shape of superstructure.

Videos of the simulations as well as the 3D visualization software developed by Siradel, in which simulations can be replayed, can be used as a support for a more detailed discussion with the stakeholders about safety margins in order to take a final decision on the accessibility level.

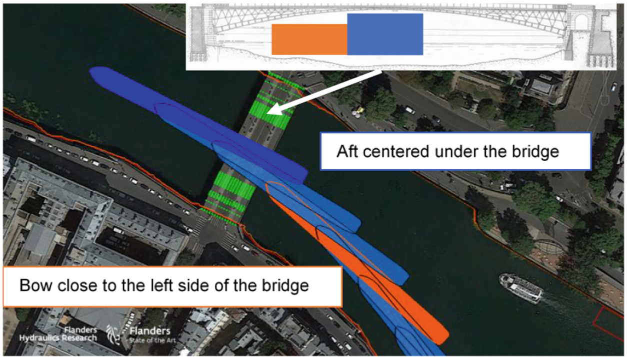


Fig. 8. 125 m ship passing the Pont d’Arcole in Paris.

Fig. 9. Bounding box used to compute safety distances.

4.2 Human Factor

Several scenarios were executed by different skippers who shared their experience and techniques to tackle the bottlenecks with the operator. For example, one skipper would slow down, quickly using reverse engine at the exit of the second bend in between the islands, while another one would accelerate and reach high speeds (as shown in Fig. 10). Other skippers, equipped with a 360° bow thruster, would use it to slow down the ship while maintaining high main engine power to get a high rudder efficiency. However, such feedback needs to be balanced with the fact that the scenarios tested on the simulators differ from what is experienced in real life since, in reality, most skippers are used to sail on a ship with a beam that is smaller than 11.4 m. The feedback of the skippers was taken into account to provide recommendations at the end of the study such as investigating scenarios which were not considered initially, for example with a smaller ship beam, or to look for solutions so that navigation could be allowed, for example by using a certificate system or by requiring training on simulators.

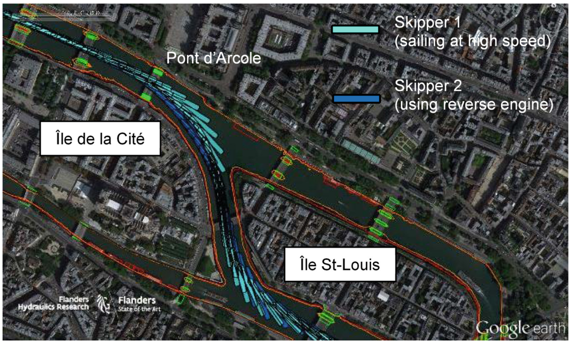


Fig. 10. Simulations with a 125 m long ship sailing in current.

4.3 Realism of the Simulation Tool

In this study, high level of detail for the modelling of the waterway was requested, especially around the bridges for which an accuracy of 10 cm was respected. This level of detail is important for the analysis of the simulation runs, but also for the immersive experience of the skipper and has an impact on the results of the simulations.

Moreover, distances can be more difficult to estimate on a simulator than in reality due to blind spots and the fact that the skipper only sees a virtual image centred on a fixed eye point. During the validation days, the simulators had to be adapted to avoid blind spots, therefore a 360° simulator was selected, and an extra feature allowed the skipper to move the view to the side of the ship to have a better visibility on the aft part of the ship (as shown in Fig. 11). In reality, the skipper is assisted by crew members who can move around the ship to evaluate distances.

Under low bridges, the skippers would usually lower the ship bridge by the maximum amount and steer the ship by passing their head through a hatch. This is not possible on the simulator; therefore the eye point has been placed 20 cm above the roof of the ship (see Fig. 2). This indicates that the level of realism clearly needs to be commented on in the simulation report, as discussed in Mansuy et al. (2021) and PIANC (2019).

Fig. 11. View moved to the side on Sim 360°.

The level of realism of the mathematical model also has an impact on the results. To tackle this, the feedback of the skippers is directly included in the datasheets where the real time simulations are synthesized (cf. Sect. 3.2). The datasheets were presented to VNF and stakeholders and after discussion balanced conclusions were drawn. One of the main conclusions was that it would most likely be possible to sail at higher water levels with ships having a beam smaller than 11.4 m. To validate this, additional simulations with ships with a beam smaller than 11.4 m were ordered by VNF. Moreover, it is recommended to have a real-life tests phase on the river Seine if the operational limits obtained from simulations need to be refined even further as the diversity of the fleet and the experience of the skippers is large.

5 Conclusions

A study was carried out to optimize the operational limits for which present and future vessels of varying types and dimensions cross Paris. Fast time and real time simulations were executed for different water levels of the river with experienced skippers at Flanders Hydraulics Research. The simulations showed that the main bottleneck is located at the narrow width under the Pont Neuf where 11.4 m wide ships have difficulties aligning in order to pass safely.

A critical water level up to which ships can safely sail could be successfully identified for the different ship models that were tested. Moreover, recommendations on the optimization of the operational limits by means of further measures were formulated (certification system, training on simulators, progressive tests in real conditions…).

The methodology applied, inspired by PIANC WG 141 recommendations, shows that in a detailed study, not only objective evaluation criteria should be considered but also the skippers' feedback and the recommendations from the waterway authority, from the end users and from the stakeholders who have experience with the conditions in reality. The nautical expert can then discuss both objective and subjective results to help the waterway authorities with the decision making.

Finally, in conditions which have never been experienced by the skippers or which are at the limits of feasibility, the manoeuvrability of ships is difficult to calibrate. However, the simulator should be considered as a tool which allows testing the response of a ship in unknown situations from which the different stakeholders can learn. Such use should be distinguished from the use of a simulator for training purposes during which a skipper is taught to be become familiar with a well-known situation.

Based on the results of the first study, it has been shown that regulations based on length only may be too restrictive for ships with smaller beams. Therefore, additional simulations have been ordered to assess the influence of ship's beam on the operational limits. New simulations have been executed with ships of reduced beam closer to the actual fleet characteristics.

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