Project acronym:	NOVIMAR
Project full title:	Novel Iwt and Maritime Transport Concepts
Grant agreement No.	723009
Coordinator:	Netherlands Maritime Technology Foundation

Deliverable 3.5 Demonstrator results

Duration:	48 months
Project Start:	01/06/2017
Project End:	31/05/2021

Deliverable data

Deliverable No	D3.5		
Deliverable Title	Demonstrator results		
Work Package no: title	WP3: Smart Navigation		
Task(s)	T3.5 – Demonstration		
Dissemination level	Public	**Deliverable type**	Report
Lead beneficiary	DST		
Responsible author	Dick ten Hove (MARIN)		
Co-authors	Benjamin Friedhoff, Felix Roettig (DST) Axel Lachmeyer, Alexander Lutz (ARG)		
Date of delivery	31-03-2020		
Approved	**Name (partner)**		**Date [DD-MM-YYYY]**
Peer reviewer 1	Maarten Flikkema		13-07-2020
Peer reviewer 2	Thomas Guesnet		13-07-2020
QA manager	Michael Goldan		07-09-2020

Document history

Version	Date	Description
1	06-07-2020	First merged draft
2	07-07-2020	Draft submitted to reviewers
3	15-07-2020	Final draft submitted to QA manager
4	29-07-2020	Final version
5	07-06-2021	Final Version – Dissemination level changed to Public

The research leading to these results has received funding from the European Union Horizon 2020 Program under grant agreement n° 723009.

CONTENTS

List of symbols and abbreviations

AIS	Automatic Identification System
CCNR	Central Commission for the Navigation of the Rhine
DST	Development Centre for Ship Technology and Transport Systems
ECDIS	Electronic Chart Display and Information System
FMB	Full mission bridge simulator
FV	Follower vessel
HAZID	Hazard identification study
HMI	Human-Machine Interface
IWT	Inland waterway transport
LV	Lead vessel
MMSI	Maritime Mobile Service Identity
NMEA	National Maritime Electronics Association
NOVIMAR	NOVel Iwt and MARitime transport concepts
ROT	Rate of Turn
SHS	Ship handling simulator
SSS	Short sea shipping
TCP	Transmission Control Protocol
VT	Vessel train
WP	Work package
VTS	Vessel Traffic Services

1 EXECUTIVE SUMMARY

1.1 Problem definition

The NOVIMAR project researches the vessel train (VT), a waterborne platooning concept featuring a manned leader vessel and a number of follower vessels which are virtually connected and follow at feasible distance by means of automatic control. The vessel train concept is a totally new approach for inland waterway and short sea transport. The development plan of the train concept includes various tests and demonstrations with different methods and tools, used with an increased level of technology readiness. This deliverable describes the work carried out in Task 3.5 and the results of the demonstrations in the simulator (MARIN) and with scaled models in the towing tank (DST). For both demonstrations the command and control modules developed in Task 3.2 and 3.3 where prepared, configured and analysed (ARG and IN).

1.2 Technical approach and work plan

Before the vessel train concept is deployed in a full-scale environment with actual ships and surrounding traffic iterative development and improvement is required. Besides desk studies the performance of the systems needs to be assessed in controlled environments. Here direct numerical simulations, full mission bridge or fast-time simulations with simplified mathematical models and scaled model tests can be used.

In NOVIMAR direct numerical simulations were used for detailed analyses in Task 3.4 and applied to identify the coefficients for the manoeuvring model of two typical motor barges. Afterwards, these manoeuvring models were implemented in MARIN's ship handling simulator and used for the simulator campaign as reported in this deliverable. Originally, it was intended that investigations would be carried out in WP5 using the DST simulator. The studies documented here in the context of WP3, however, were planned with the MARIN simulator. Since the implementation of the command and control modules were both complex and elaborate and the partners IN and ARG only had a task in WP3 and not in WP5 it was decided to join forces of WP3 and WP5 in two simulator sessions on the MARIN simulator (May and October 2019). With improvements of the control system according to the learnings from the simulator, extensive model scale tests were performed (February 2020). One of the two motor barges used for the direct numerical simulations in Task 3.4 was used in scale 1 by 16 as following vessel.

The following activities were performed:

- Preparation of a demonstration plan with requirements, schedule and risk analysis.
- Configuration of the software and hardware modules from Task 3.2 for the various scenarios defined in in the demonstration plan.
- Execution of the simulator demonstrations according to the plan.
- Free sailing model test in a controlled environment, using equipment and procedures developed in Task 3.2 and 3.3.

1.3 Results

The vessel train, composed of one lead vessel and two follower vessels and with hardware-in-the-loop was demonstrated with real-time simulations on the river Waal. The simulator allowed to provoke challenging situations which were used to derive valuable input for further development steps.

The skippers used the command and control system to navigate the vessel train. The skippers successfully coupled and decoupled the system when all the vessels had approximately the same speed and reached the setpoint of 150 metres distance. The automatic mode and assisted mode of the control system worked as designed. The skippers used the predefined track in the automatic mode successfully and were able to move the track to starboard or port through the TrackPilotVT interface. In assisted mode, the follower vessel followed the past track of the lead vessel on the straight stretches and in the bends with minimal offset on the river. Changing between the automatic mode and assisted mode could lead to unexpected behaviour in case of a large offset to the new track when switching. This can be handled by the TrackPilotVT by adjusting the tuning of the lateral control to the skipper’s need.

When going upstream, the vessel train followed the track with a minimal offset. When going downstream it was experienced that:

- The control system was more sensitive for speed changes and sometimes lead to loss of control of the follower vessels. This was fixed during the simulator tests by increasing minimum throttle setting as the rate-of-turn-controller of the simulator was not able to cope with small thrust (as opposed to commercial solutions).
- When the lead vessel reduces speed in downstream manoeuvres, the follower vessels sometimes overshoots the distance setpoint. As the system tries to recover the sailing distance, the rate of turn of the propeller is slowed down to a minimum to reduce speed, which in return leads to lower rudder force and loss of control. The settings of the TrackPilotVT were fine-tuned during the simulations to avoid overshoots.
- Coupling procedure is sensitive for speed changes when going downstream.

Settings for current speed are important for a correct working control system, especially for downstream sailing. Settings were adapted during the simulations.

The participating skippers stressed that the concept of automatically following a past track or predefined track set out by a lead vessel is very promising, although they agreed that the control system and the vessel train concept require further improvement (see section 6.1) before they are ready for full market uptake. Based on their experience they were of the opinion that:

- In complex traffic situations with traffic going upstream and downstream on a bendy waterway the navigational control should be returned to from the lead vessel to follower vessels in order to avoid collisions with other traffic.
- The reaction of the controller was different from what a skipper would expect, making it difficult for the skippers to predict the rate of turn and vessel motions . Further tuning of the control system and a short-term prediction of the path of the follower vessels (as it is a default

functionality on most ECDIS systems for single vessels) on the navigation system of the leader vessel is recommended.

The first point can be overcome if The VT is operated in a foresighted and reserved manner. Corresponding procedures need to be included in the training for VT skippers. Only in extreme situations with erratic behaviour of other traffic members the control needs to returned. The risk can be further minimized by implementing the vessel train into the regulatory framework, e.g. in the context of encountering with the blue sign or crossing the fairway.

With some improvements of the control system following from simulator results, extensive model scale tests were performed. During these tests the complexity was increased in a step-wise manner (see section 5.3) to improve the longitudinal (speed/distance) and lateral control. After testing and tuning parameters with the follower alone, the vessel train was navigated through the test stretch many times varying the vessel and current speeds, the set distance between the vessels, the manoeuvring of the leader and the flow regimes at the barriers. Especially, for boundary conditions changing in time and space the control performance was improved significantly. In upstream navigation it was possible to keep the vessel train in a steady state at a speed over ground of zero.

The scale model experiments showed that the vessel train control system is able to steer the ship safely in all upstream conditions except extreme cross flow conditions: The tested vessel train configuration was unable to pass a test stretch with local cross flow of approximately 50 % of the mean flow velocity. Heading and lateral offset could not be controlled within acceptable limits. However, this situation goes beyond realistic scenarios for e.g. the waterways of the Rhine-Alpine corridor and was tested to challenge the control system only.

When sailing downstream the vessel train control system in the tested setup is not able to handle normal and emergency stops because there is no rudder force to steer the ship if the throttle is reversed. This is similar to manual control, where the boatmaster can act according to the surrounding traffic situation by means of the bow thruster, temporary engine reversal or performing an evasive manoeuvre. To be able to deal with this problem it is required to include a bow thruster in the control strategy. A concept for the implementation was developed and will be further investigated in Task 3.6.

1.4 Conclusions and recommendation

The scale model experiments showed that the vessel train control system is able to steer the ship in all upstream conditions except extreme current conditions. In the case of emergency and normal stops improvements to the rate of turn controller and the lateral control by including the bow thruster into the control strategy could be used to further improve controller performance. Both acceleration and deceleration could be improved by using a common speed setpoint for all ships and a centralized emergency stop signal with the leader vessel also using speed control. This way speed changes of the leader vessel caused by varying current conditions would be reduced and thus distances between all vessels would vary less.

The simulator experiments showed that it is technically feasible to sail with the VT. However, the lead vessel operator tasks become more complex, despite the automated navigational tasks, on busy, bendy inland waterways. This can be partly overcome if in heavy traffic overtaking is not allowed for a coupled vessel train and the vessel train stays as far as possible on its own side of the fairway. For safe and easy navigation it is recommended to include the VT into the regulatory framework. These topics are further elaborated within WP5.

2 INTRODUCTION

2.1 Task 3.5 Demonstration

The following extract from the proposal describes the work performed in the preparation of this deliverable.

The main objective of this task is to demonstrate the vessel train concept for the scenarios outlined in the DoA and D3.1. Envisaged activities are:

- Sub-task T3.5.1: Prepare a demonstration plan with requirements, schedule and risk analysis.
- Sub-task T3.5.2: Configure the software and hardware modules from T3.2 for the various scenarios defined in task T3.1.
- Sub-task T3.5.3: Carry out the simulator demonstrations according to the plan from T3.5.1.
- Sub-task T3.5.4: Using free sailing models one of the scenarios is demonstrated on model scale in a controlled environment, using equipment and procedures developed in Task 3.2 and 3.3.
- Sub-task T3.5.5: Prepare the task deliverable.

Role of the Partners:

- DST (leader) plans and coordinates the demonstrations and carries out the model scale demonstration.
- MARIN carries out the simulator demonstrations.
- ARG provides the configurable vessel control algorithms from T3.2, tune these to the scenario requirements and acts as vessel operator during all demonstrators.
- IN provides software modules and ECDIS system from T3.2/T3.3 for validation and use in demonstrations.

Input/output relations:

- Task T3.5 receives input from tasks T1.3, T3.1, T3.2, T3.3, T3.4.
- Task T3.5 provides output to tasks T1.5, T3.6, T5.2, T5.3.

2.2 Analysis

The development plan of the vessel train concept includes various tests and demonstrations. At different technology readiness levels (TRL) different tools are used with corresponding levels of complexity and their capability (see Figure 1). The following methods are therefore used to examine the VT concept as completely as possible:

- Manoeuvring Simulations
    - Direct numerical simulations in T3.4
    - Fast-time ship handling simulations (Fast-time SHS)
    - Full mission bridge ship handling simulations (SHS)
- Towing tank model tests
- Full scale demonstrations in T3.6

Every method has its own advantages and restrictions to show and improve the overall performance of the vessel train.

Tests and demonstrations are executed on the partially integrated system applied to various scenarios depending on the status of the developments during the NOVIMAR timeline. Not each scenario requires each component, but the component will be part of the integrated system. Each component is demonstrated and the final full-scale demonstrations will require all components developed in WP3.

Demonstrations are possible at various levels of complexity and selected scenarios. Fast-time manoeuvring simulations can include the manoeuvring simulation models developed in T3.4.4 and the Command and Control software from T3.2.3. In fast-time simulations the VT-control is on an accelerated time basis by an autopilot without the man-in-the loop. Simulations by full bridge or control room mockup include the man-in-the-loop, using the control system and navigation aid from T3.2. To test the situation awareness functions (T3.2.4) complete traffic scenarios are simulated. These are used to guide the discussion in WP5 T5.2 on the human tasks on-board the vessel(s) and T5.3 on safety.

2.3 Approach

Figure 1 shows the sequence of the step-by-step examination of the VT concept on the basis of the methods mentioned. This figure is originally generated at an earlier stage of the project for D3.1. The sequence is slightly modified in some points during the course of the project (see also section 4: plan execution). The simulator campaign of T5.2 is performed on DST’s simulator SANDRA with the vessel train manually controlled as planned for hazard identification and development of operational procedures. Fast-time simulations are replaced by real-time simulations due to the limited scaling factor in time of approximately four and the disproportionate extra effort for the implementation. The campaign of T5.3, however, is moved to the MARIN simulator to join forces in a campaign together with T3.5 reported herein. The results of the model tests and direct numerical simulations performed in T3.4 are used in the hydrodynamic modelling for the full mission bridge simulations. The model scale demonstrations of T3.5 are conducted when the hardware becomes available after use on the MARIN simulator.

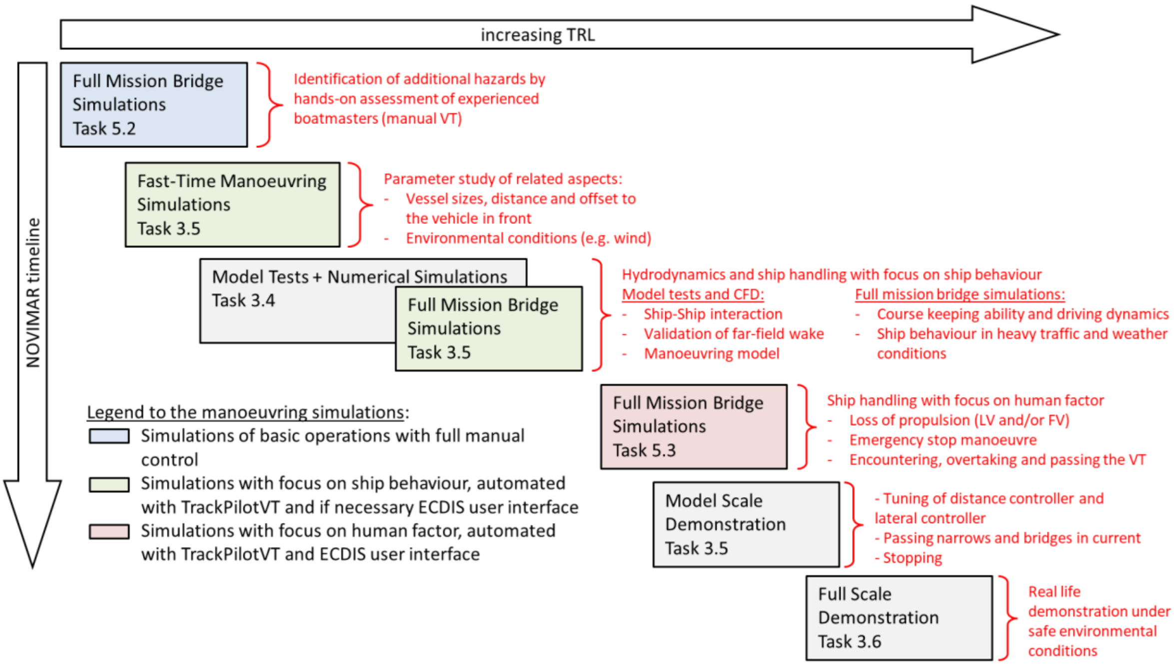


Figure 1: Description and procedure of the research methods in WP3 and 5

According to the adjusted schedule of the project, the demonstrations on simulators are performed in 2019 followed by the model scale demonstrations in 2020 and the full-scale demonstrations will be performed by the end of 2020.

The first full mission bridge simulations with manually steered vessels can be carried out without any prerequisites and are used for hazard identification and development of operational procedures and executed and reported as part of T5.2. For the other simulations and model tests, the TrackPilotVT system must be available for each vessel. This system is controlled by the ECDIS system (RADARpilotVT). Initially, the TrackPilotVT can also be controlled from outside, but a complete ECDIS system should also be available on all vessels involved for advanced simulations and the large-scale demonstration. Given the limited number of available devices the simulator demonstrations can be performed on up to three different vessels, one lead vessel and two follower vessels. The model-scale and full-scale demonstrations can be performed on two vessels, one lead vessel and one follower vessel.

For each of the planned demonstrations scenarios, for example a sequence of situations and boundary conditions, have been elaborated (see section 4: plan execution). They are assigned to different TRLs of the vessel train control system and should be applied in the proposed order to develop and test the system with increasing complexity and avoid redundant tests.

A long list of situations was derived from the hazard identification study early within WP5. These situations were discussed with WP3 perspective (see annex D). Many of these situations share the same requirements and reactions of the control system. Therefore, the long list was reduced to a few basic situations and discussed regarding the best suited time and tool for the demonstration. The results are summarized in Table 1 below.

Table 1: Conditions and situations selected for different demonstrations

Case: Navigation under normal conditions	SHS Non-automated	Model tests	SHS focus on ship behaviour	SHS focus on human factor	Full scale demonstration
Vessels with differing size, speed and manoeuvring capabilities	X		X		
VT (two or more vessels): Straight course, bend, narrow passage, bridge passage	X	X	X		X
Coupling and decoupling of FV to the LV	X		X		X
Encountering traffic			X	X	
Passing vessels			X	X	
Stopping		X	X	X	X
Case: HAZID (Emergency and handling of risk)					
Stopping of the VT as emergency		X	X	X	
Loss of propulsion of LV				X	
Loss of propulsion of FV				X	

3 PLAN

3.1 Objectives

The T3.5 task objective is to demonstrate the vessel train concept for the scenarios outlined in task 3.1 and summarized in paragraph 2.3 (see also D3.1).

3.2 Planned activities (demonstration plan)

3.2.1 Configuration of the control systems and navigation aid

The navigation control system consisting of the TrackPilotVT developed by Argonics and the RADARpilotVT developed by Innovative Navigation is configured and adapted for use in the simulations and the model tests.

3.2.2 Simulation of basic ship operations focussing on ship behaviour

Ship handling simulators rely with their mathematical manoeuvring models on the hydrodynamic research and are able to identify the human factor during the operation of a ship. While these simulators usually run in real-time corresponding to the full scale, they can also be used in a fast-time mode without manual control. During the simulations the vessel trains behaviour will be investigated under different conditions. Therefore, a suitable operational area is selected or developed containing a set of challenges for the VT. It consists of the basic operational tasks like coupling, decoupling and sailing lined up behind the leader in both directions, upstream and downstream. Furthermore, the operational area consists of different hydrodynamic ambitious cases, like shallow banks, current gradients and cross current conditions typical for European rivers.

Simulations have the capability to perform initial tests with a vessel train without any risk of accidents and financial losses. The environmental conditions like weather, daytime or the operational area can be easily adapted. However, simulations are based on a hydrodynamic model of the ship, the waterway and their interaction. Although models are limited in their capability of reproducing all hydrodynamic effects on the vessel train, most important parts of hydrodynamic effects are covered by existing ship-ship interaction models and ship-environment interaction models, like for example bank suction effects, already implemented in the simulator.

Despite the high effort involved in modelling the terrain, currents and ships, not all physical quantities and their interaction can be exactly mapped in the simulator, because of limitations in computation time and modelling possibilities. For example, the fluid flow around the ships and the interaction with the river currents cannot be computed in real-time. Engine dynamics, ship manoeuvring, ship-ship interaction, and ship-bank interaction are based on more or less complex mathematical models (see also NOVIMAR deliverable D3.4). Nevertheless, the use of simulators is a meaningful instrument recognised by international experts to support decision making. The advantage is that, unlike real sailing, the relevant parameters in the simulator can be systematically varied, recorded and investigated under laboratory conditions. SHS thus provides a valuable basis for the preparation of recommendations. In addition, the simulator can be used to analyse extreme driving situations that would have been avoided in large-scale tests due to a higher risk.

The operation of a VT is investigated by full mission bridge simulations at MARIN. Physical modelling of the VT vessels in the simulator is based on the model tests and numerical computations of T3.4. The main objectives are the development of solutions for the operation of a VT in waterway traffic, the de-/coupling, and other selected manoeuvres (see 4.2.2) or hazard cases like loss of connection, rudder failure or engine failure. The vessel train operator tests the interaction with the vessel train equipment and the vessel train itself. Additionally, the operator has to develop a strategy for the vessel trains interaction with traffic sailing on predefined tracks. During these tests the requirements for a basic and safe operation of vessel trains is determined as input for WP5.

3.2.3 Model Scale Demonstration

The outcome of the demonstration in the SHS is approved by model tests at DST by selected manoeuvres and sailing conditions. Especially complex hydrodynamic challenges like the influence of the current, stopping manoeuvres and the minimum operating speed are investigated. The distinctions between upstream and downstream sailing are evaluated by introducing a current to the model basin. The influence of the varying current is tested by adding a barrier in the basin to produce a strong current gradient and increased flow velocity (see 4.2.3). This is done to challenge and tune the distance controller and the lateral controller. In accordance to the basic simulations a standard R-Manoeuvre will be performed. Scaled tests in a model basin include the complex physics but are in comparison to full scale demonstrations limited by the capabilities of the testing facility. Because of the limited navigational area in the model basin a VT can consist of a leader and only one follower. The operation of traffic vessels is excluded as well as coupling and decoupling operations.

3.3 Resources and involved partners

Role of the Partners:

- DST (leader) plans and coordinates the demonstrations and carries out the model scale demonstration.
- MARIN carries out the simulator demonstrations.
- ARG provides the configurable vessel control system from T3.2, tune these to the scenario requirements and acts as vessel operator during all demonstrators.
- IN provides software modules and ECDIS system from T3.2/T3.3 for validation and use in demonstrations.

3.4 Timeline

According to the time schedule of the NOVIMAR project, the demonstrations as part of T3.5 (see also Figure 1) consists of full mission bridge simulator demonstrations at MARIN in May 2019 and October 2019 and demonstrations with free sailing models on a model scale in a controlled environment at DST in February 2020.

4 PLAN EXECUTION

4.1 Introduction

This chapter contains the plan execution by describing the activities carried out per sub-task together with the changes of the plan. Demonstration of the VT concept is done in three stages: simulations, model scale, and full scale. Task 3.5 covered the simulations and model scale demonstrations. Demonstrations as part of T3.5 consisted of full mission bridge simulator demonstrations at MARIN in two sessions, one in May 2019 and one in October 2019, and demonstrations with free sailing models on a model scale in a controlled environment at DST in February 2020.

4.2 Performed activities

4.2.1 Configuration of the control systems and navigation aid (T3.5.2)

This paragraph describes the setup of the RADARpilotVT from Innovative Navigation GmbH and the TrackPilotVT from Argonics GmbH within the test scenarios for the full mission bridge simulations conducted in May 2019 and October 2019 at the Marin Simulator in Wageningen. As developments of WP3.2 were still going on, this report does not describe a final state but reflects the work-in-progress state of the needed setup for the simulations.

Argonics: TrackPilotVT

Figure 2: TrackPilotVT installed on the lead vessel bridge

TrackPilotVT Interfaces

Up to three devices of the TrackPilotVT are used in the scenarios. Two in the follower vessel and one in the leader vessel. In all vessels, the setup is identical. The following information is provided by the simulator to the TrackPilotVT:

- GPS measurement
- Heading information
- Rate of turn measurement
- AIS data

Switching between manual steering and TrackPilotVT control was possible from the bridge console, however this state was not reflected into the TrackPilotVT. After switching the TrackPilotVT had to be switched off/on through the TrackPilotVT interface.

The TrackPilotVT controls the vessel by:

- NMEA-based control of the engine/throttle (only on the follower vessels)
- NMEA-based control of the rate of turn controller/rudder of the vessel

In the final set-up the TrackPilotVT provided the rate-of-turn setpoint for the rate-of-turn controller installed on the vessel/simulator.

Data exchange between the TrackPilotVT and the RADARpilotVT:

- Control data exchange
- Route exchange
- Fairway boundary exchange

TrackPilotVT Connection drawings

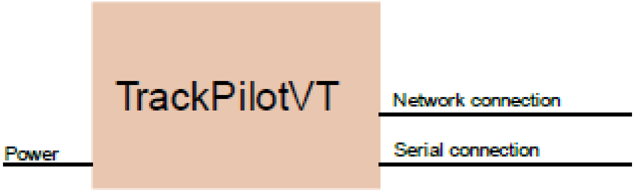


Figure 3: TrackPilotVT connections

Innovative Navigation: RADARpilotVT

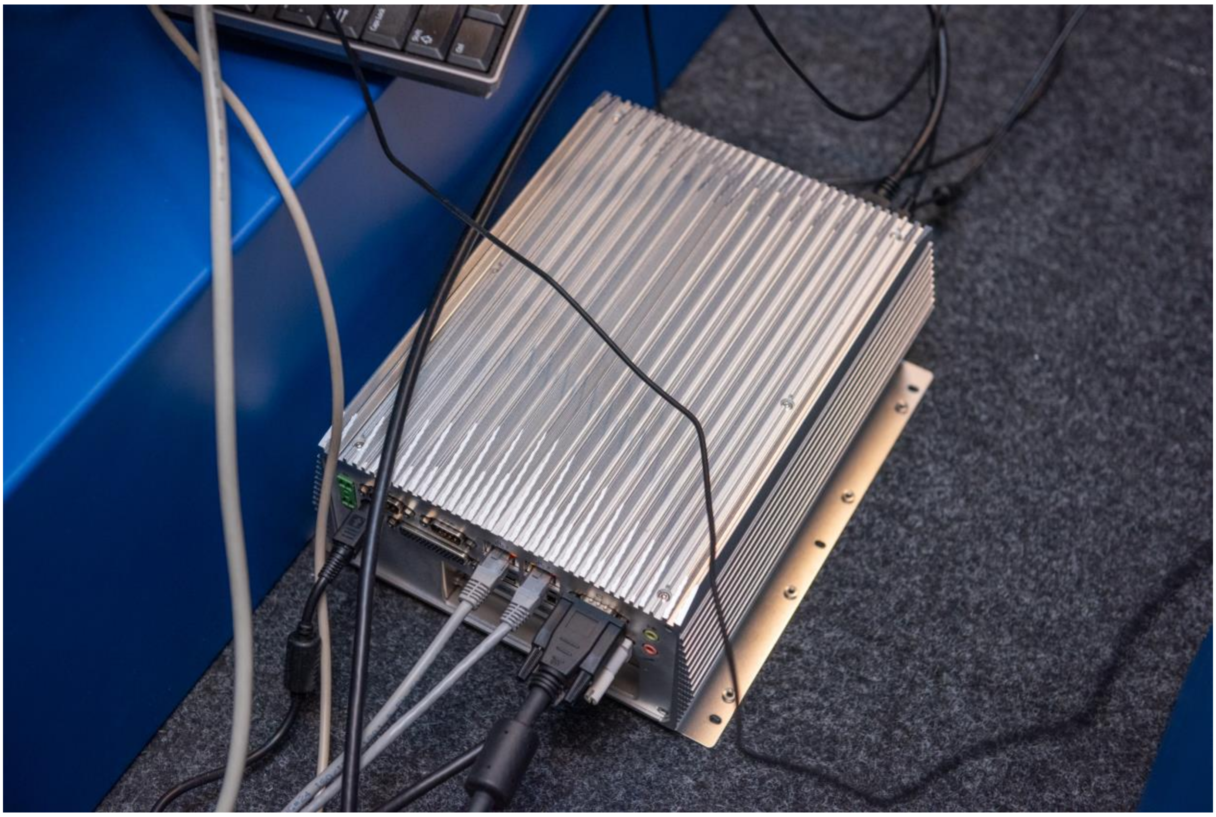


Figure 4: RADARpilotVT installed on the lead vessel bridge

RADARpilotVT Interfaces

Three devices of the RADARpilotVT are used in the scenarios. One in each follower vessel and the other in the leader vessel. In all vessels, the setup is identical. The following information is provided by the simulator to the RADARpilotVT:

- GPS measurement
- Heading information
- AIS data
- Time synchronization

The RADARpilotVT controls the TrackPilotVT by:

- Switching on and off during coupling and decoupling phase
- Setting the reference MMSIs for the leader and follower vessels
- Providing access from the simulator bridge to the Argonics HMI of the leader and follower vessels. From the leader vessel access was possible to all TrackPilotVT systems also on the

follower vessels. From the follower vessels access was possible to the local TrackPilotVT system only.

Data exchange between the TrackPilotVT and the RADARpilotVT:

- NMEA-based control data exchange
- NMEA-based Route exchange
- NMEA-based Fairway exchange

Data exchange between the RADARpilotVT of the leader vessel and the follower vessels:

- AIS application specific data
- NMEA based alarming and keep-alive
- NMEA based target exchange for situation awareness
- NMEA based control commands

RADARpilotVT Connection drawings

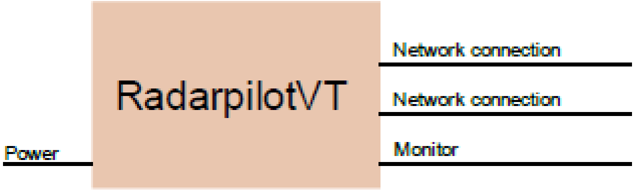


Figure 5: RADARpilotVT connections

RADARpilotVT Operating System

The RADARpilotVT is based on CentOS 7 Linux. The system is kept up-to date in the commercial RADARpilot720° version. The network is protected with a firewall that allows only what is necessary for communication. In the setup in the simulator it is NMEA communication and time synchronization. A more detailed description is available in D3.2.

Vessel Train interconnection

In the setup in the simulator, (cyber-)security issues were not addressed and the focus was not on the inter-ship connection, but on the functional design of controlling the VT in the simulator. Therefore, the systems were directly connected to the simulator’s Local Area Network (LAN).

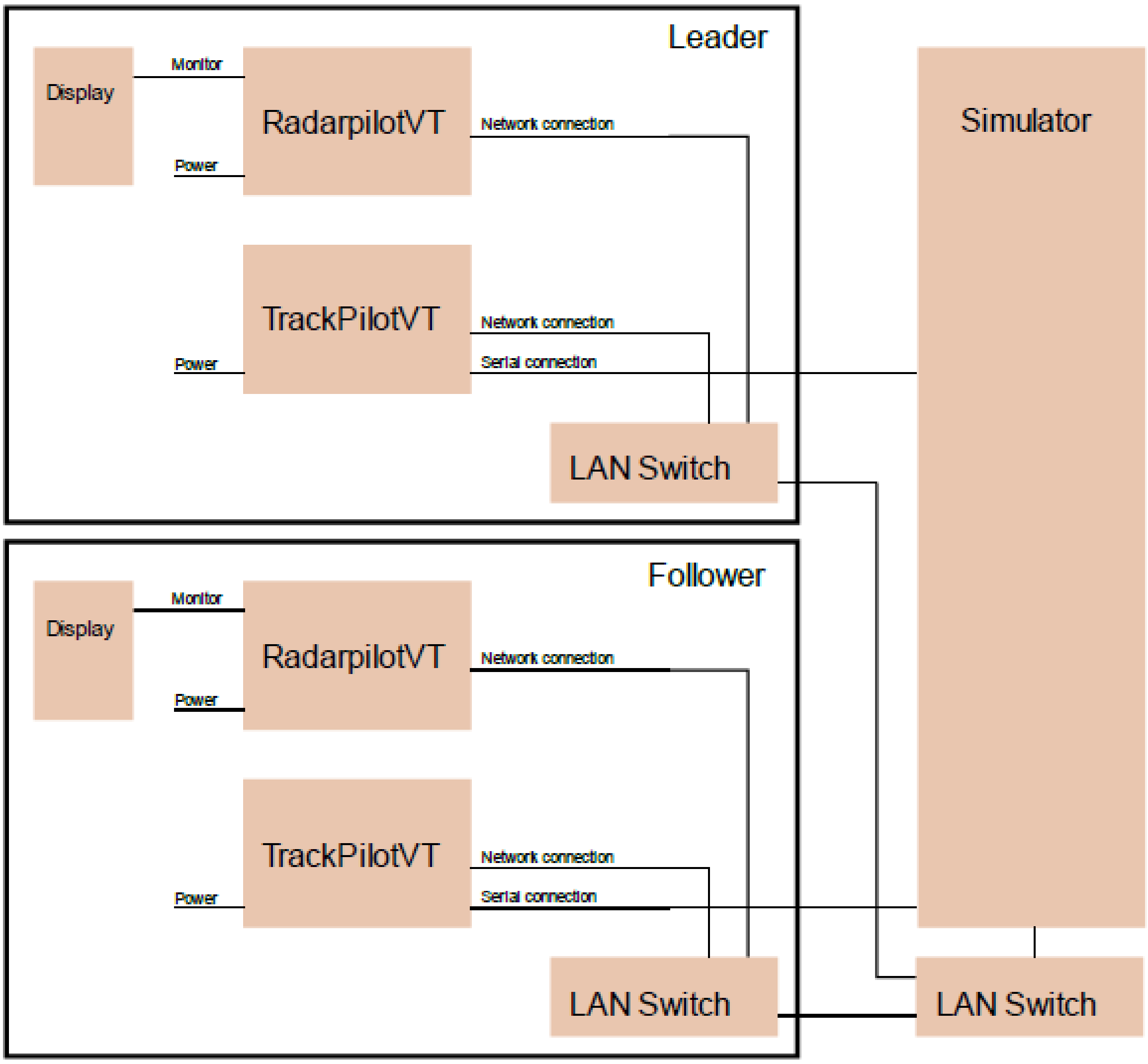


Figure 6: VT interconnections

4.2.2 Simulation of VT operations (T3.5.3)

Simulator set-up

As part of the NOVIMAR project in total three full mission bridge (SHS) simulations were performed within WP 3 and 5, one at DST and two at MARIN. Table 2 depicts a short overview of the three simulations.

Table 2: Overview of the NOVIMAR simulator sessions

SHS location	Simulation set-up	Goals
1. DST	5 ships all sailing manually by skippers in a convoy on inland waters, with use of ship handling simulators	• Determine feasible distances between the LV and 4 FVs • First estimations on workload, required warning and alerting, time needed to react on failures
2. MARIN	1 LV and 1 FV simulations with skippers and integrated VT control system, sailing on inland waters (River Waal)	• Demonstration of the technical control system • Gain understanding of the usage of the control system from a human factor perspective
3. MARIN	1 LV and 2 FV's simulations with (12) skippers and an updated VT control system, sailing on inland waters (River Waal)	• Analyse impact on workload • Analyse information requirements • Analyse operational procedures • Analyse human failures • Analyse trained needs

First simulations at DST

The first simulations were performed at DST in the early stage of development, with 5 skippers, without the VT control system. The main focus was on determining feasible distances between the vessels of the VT in different scenarios. In addition, the simulations provided a general first impression of sailing with a convoy, taking into account subjects on distances between vessels, workload of the VT operators, communication requirements, warning and alerting, time need to react on failures or malfunctions. These simulations were executed and reported as part of T5.2.

Second simulations at MARIN

The intention of the second set of simulations was that they would be executed in a fast-time mode (see also Figure 1), but during installation and configuration of the TrackPilotVT it was estimated that the programming effort for fast-time implementation would have exceeded the time saved by speeding up the simulations. Therefore, it was decided to execute also the first set of simulation in real-time mode instead of fast-time (see also section 4.3). The second simulation was performed in conjunction with the T5.2. The demonstration allowed T5.2 to see the human-machine interaction for the first time and gain an understanding of the allocation of tasks between the operator and automation and how the system enabled and support the operator to meet the operational goals. The simulations were performed in May 2019.

Third simulations at MARIN

According to the original plans full mission bridge simulations for T3.5 were foreseen at MARIN while for T5.3 simulations were planned with the simulator at DST. Since the implementation of the command and control modules were both complex and elaborate and both IN and ARG had no task in WP5 it was decided to join forces of WP3 and WP5 on MARIN's simulator in a combined simulator session. The third set of simulations were performed with 12 inland skippers and the VT control system installed at MARIN, in collaboration with DST, from October 21 to October 25, 2019.

The simulator set-up at MARIN was slightly different for the first set of simulations in May 2019 and the second set of simulations in October 2019. The first simulation used two vessels with hardware bridges, the leader vessel and one follower vessel (see Figure 1 and Figure 7). Other vessels (see the description of the scenarios below) in the simulation were controlled by an autopilot to follow a given path. From the controller room the scenarios could be adapted to the testing needs. For the set-up of the simulator two Compact Manoeuvring Simulators of MARIN (see Annex 2) were linked in a simulation network. The VT operator controlled the lead vessel from bridge 1 (see Figure 7). The bridge layout is u-shaped as on an operating inland vessel, with the addition of the VT control system's TrackPilotVT and RADARpilotVT. Six 4K TV screens showed a visual field of 360°. Bridge 2 for the follower vessel had a similar set up to bridge 1, but without the TrackPilotVT HMI installed. The follower vessel bridge was only used for coupling and decoupling of the follower vessel to the VT. No manning was available for the follower vessel during the first simulator session, except for the coupling and decoupling procedure. The follower vessel was controlled by the TrackPilotVT installed on the follower vessel.

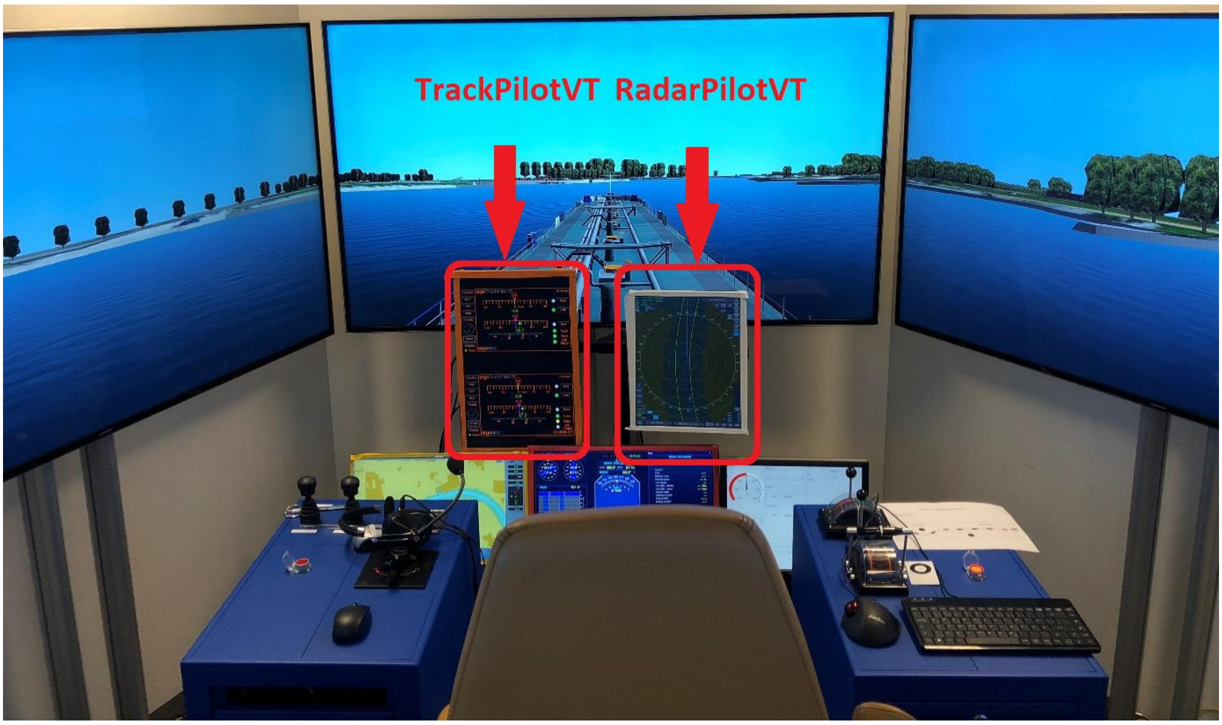


Figure 7: Bridge 1, where the participants operated the VT, with the prototype control system consisting of the TrackPilotVT and RADARpilotVT

The simulations of the first set of simulations at MARIN focussed on:

- coupling/decoupling
- track following sailing straight stretches and bends

- changing from assisted mode to guided mode,
- changing the sailing distance between the leader vessel and follower vessel
- reducing sailing speed, both upstream and downstream
- handling of regular encounters with other traffic

Results were used for development of operational procedures and further development of the TrackPilotVT and RADARpilotVT.

Figure 8: Controller room

The second set of full mission bridge simulations used three Compact Manoeuvring Simulators linked in the simulator network, the leader vessel and two follower vessels all three equipped with updated versions of the TrackPilotVT and RADARpilotVT.

LV bridge

The leader vessel was equipped with two screens showing VT specific functionality. On the right-hand side, the RADARpilotVT with the ECDIS chart, tracks and VT specific information is shown. On the left-hand side, the Argonics HMIs of the leader and follower vessel are shown with on top the overall information of all vessels and below the separate controller screens of each individual vessel.

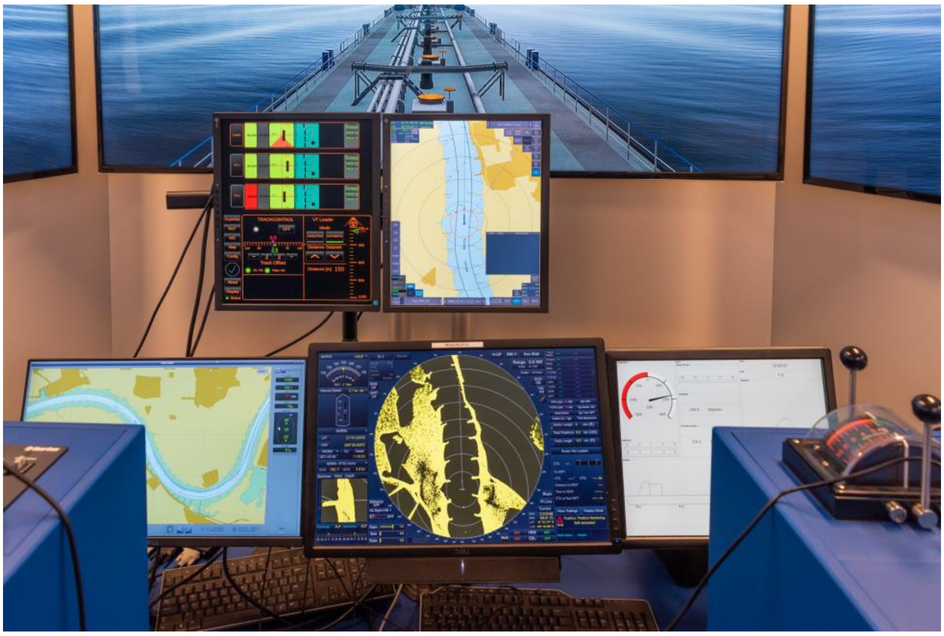


Figure 9: Leader vessel bridge equipment

Figure 10: Leader vessel outside view

FV bridges

On the follower vessels, only one screen showed on top the RADARpilotVT and below the TrackPilotVT control screen. This reduced setup was sufficient for the simulations.

Figure 11: Bridge mock-up of follower vessel 1

Figure 12: Bridge mock-up of follower vessel 2

Scenarios

VT Concept that was tested

- 1 lead vessel with operator on the bridge (inland vessel, 110 m)
- 1 or 2 follower vessels with operator standby on the bridge (inland vessels, 110 m)
- Vessels differ in maximum speed and manoeuvrability; the hydrodynamic modelling of the vessels was based on the results of T3.4

- Start distance between vessels: 300 – 150 m (see also the detailed description of the scenarios below)
- Starting status in simulations: uncoupled
- In manual steering mode no rate-of-turn controller available, but only manual steering with rudder possible
- The lead vessel had always manual control of speed (telegraph setting), the follower vessel speed was controlled by the TrackPilotVT

Responsibility

Once the follower vessels were coupled, the FV operator does not have a navigation task, the LV operator is responsible for the connected follower vessels.

The following operations are taken into account. These operations will be tested in different operational conditions, for example upstream and downstream.

Table 3: Tested operations

Normal operations	**Emergency operations**
Joining & leaving vessels of the train: connecting with the VT	Safely solve the loss of control: Rudder/engine failure on one of the vessels
Navigating narrow and bendy waterways	Deal safely with failure control system: Connection error or failure, loss of AIS data
Passing bridges	
Avoiding encountered/crossing traffic	

Navigation area

Figure 13 shows the Boven-Rijn and Waal starting from km 866 on the East side up to km 888 on the West side. From East to West is downstream. The river is characterized by:

- the junction at the Pannerdensche Kop where the Boven-Rijn splits up in the Waal and the Pannerdensch Kanaal;
- the bended section of the Waal;
- the bridge passages near Nijmegen;
- the junction with the Maas Waal Kanaal.

Vessels are allowed to use the blue flag (meeting starboard – starboard). Especially the smaller vessels use this to avoid high currents in the bends Nijmegen (passing the bridge) and Erlecom. Together with the high traffic density of 25 vessels per hour passing at peak hours this results in a complex traffic pattern.

The river Waal was selected as navigation area in the simulations because it contained:

- Straight stretches and bends
- Junctions
- Narrow passages
- Deep outside bends, shallow inner bends
- Shallow spots in crossings between bends

A mediate condition was modelled with an average current velocity of 1 m/s on the centerline of the fairway.

Figure 13: Area of interest in the simulations (River Waal)

Operational scenarios

In total 8 scenarios were created. In each scenario, the vessel train has the same velocity of 15 km/h relative to the water at the start of the simulation. At the start of the first set of simulations the distances between the vessels of the VT were about 300 metres, but based on the experience of the first simulations this was slowly reduced to a final value of 150 m. The scenarios were created to study the capability of the control system and the support of the control and navigation system to the VT operator to handle common traffic situations.

Scenario A; Familiarisation

Lead vessel and the follower vessels navigating different sections of the area, without further traffic. This scenario is used for familiarisation with the vessels, equipment and procedures for coupling and decoupling.

Scenario B; Encountering traffic in bend Nijmegen

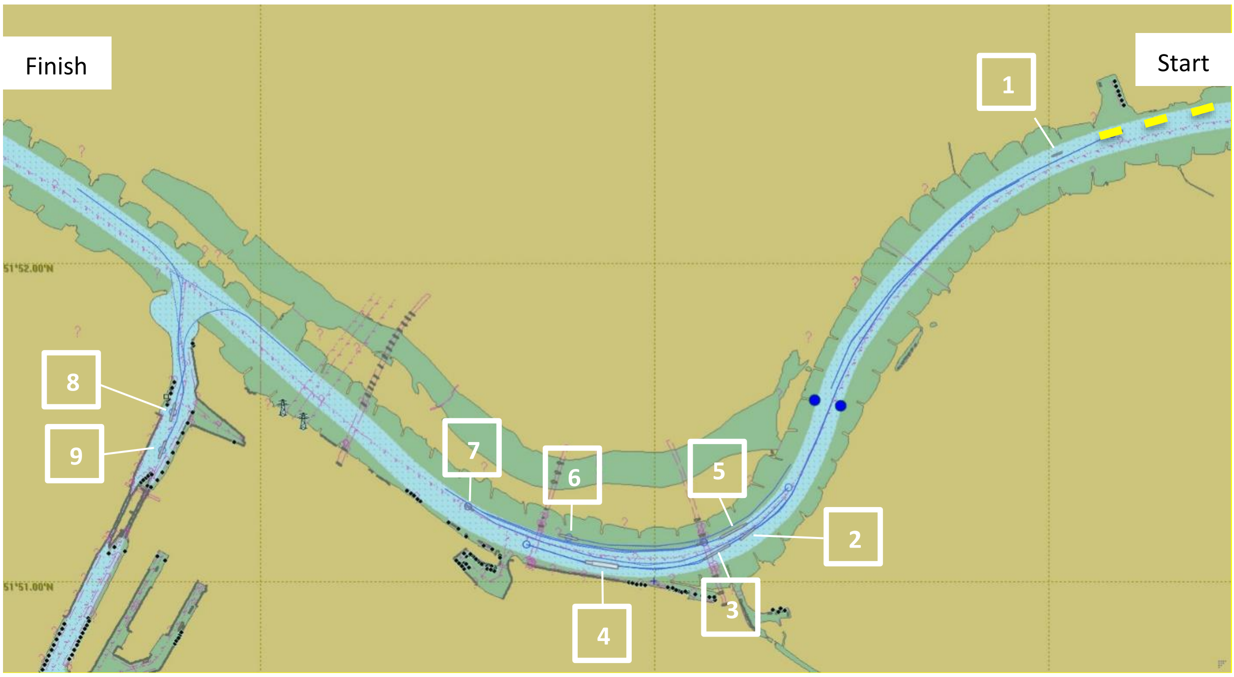


Figure 14: Scenario B

The vessel train starts in a long bend and is sailing downstream. Ahead of the lead vessel on 200 meters, a small vessel (1) is sailing downstream on starboard side with a lower speed, that the LV operators needs to react on: taking over or wait. After that, vessel 2 and 3 are going upstream and meet the vessel train, but they stay on their side of the river. Next, a larger pushtow (4) will take the turn while the vessel train should catch up vessel 5. The VT operator needs to decide to take-over vessel 5 or wait for vessel 4 to pass. Vessel 6 is going upstream on the left side of the river, creating less space for vessel 5 to move to starboard, when the VT is near to overtake 5 – unless the VT decides to wait. Vessel 7 is going downstream as well, and has a lower speed than the VT. The vessel is positioned to hinder the VT before reaching the canal from where vessel 8 and 9 are coming from. The VT needs to decide whether it is safe for overtaking vessel 7, while further down the river two vessels (8 and 9) are slowly sailing out of the canal towards the river; vessel 8 is crossing the river and sailing upstream, vessel 9 is crossing the river and goes downstream.

Scenario C; Downstream of Nijmegen

The VT starts in the long bend, uncoupled, with the same settings: 15 km/h and 150 m distances between the vessels. The VT sails upstream.

Figure 15: Scenario C

The VT starts with one vessel (1) ahead also sailing upstream, that needs to be dealt with, taking over or communicating to create a safe passage. Vessel 2 leaves the canal sailing downstream when the VT is getting closer. VT reduces speed and/or communicates for safe passage. Vessel 3 and 4 are traffic that is going downstream and stay on starboard side of the fairway.

Scenario D; Meeting traffic in a long bend

The VT starts downstream of the long-stretched bend sailing upstream.

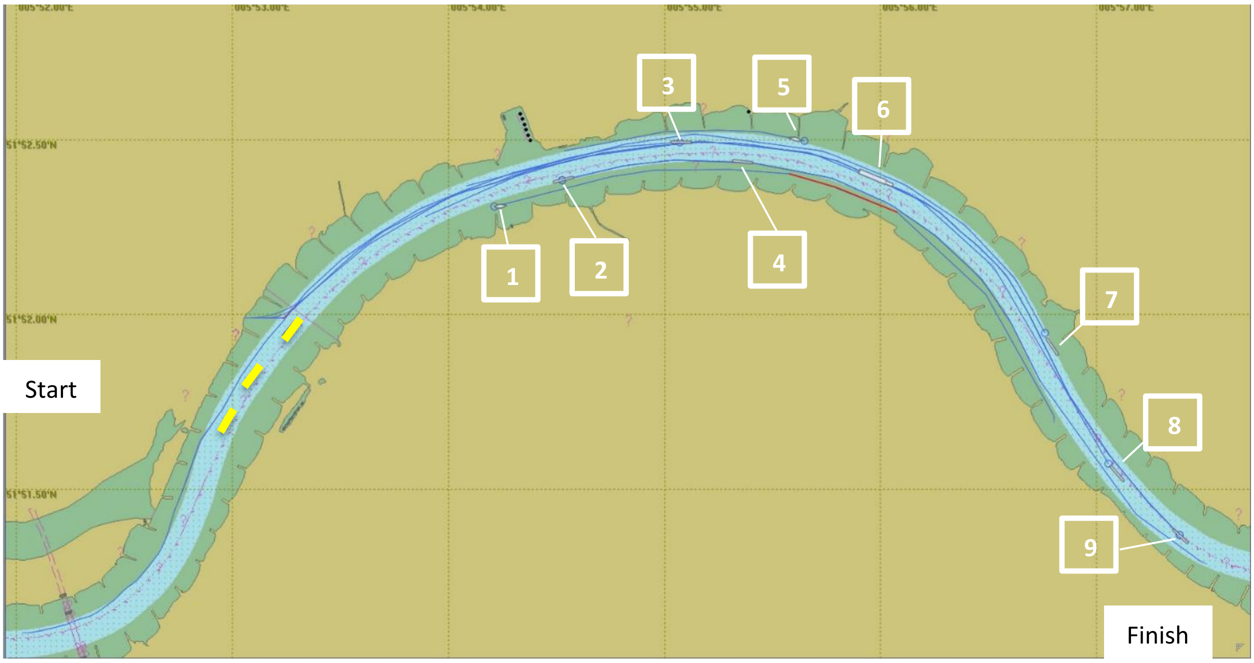


Figure 16: Scenario D

The main goal of this scenario is to pass the different clusters of vessels. Vessel 1, 2 and 4 sail slowly and their track and speed are designed to meet vessel 3, 5 and 6 all at (roughly) the same location. The VT needs to anticipate to this navigational scenario and predict how the VT can have a safe passage. After that, vessel 9 and 8 are taking over vessel 6, again at the location where the VT passes vessel 7. The VT needs to detect the overtaking manoeuvre and anticipate.

Scenario E; Meeting with other traffic in a narrow bend

The VT sails downstream.

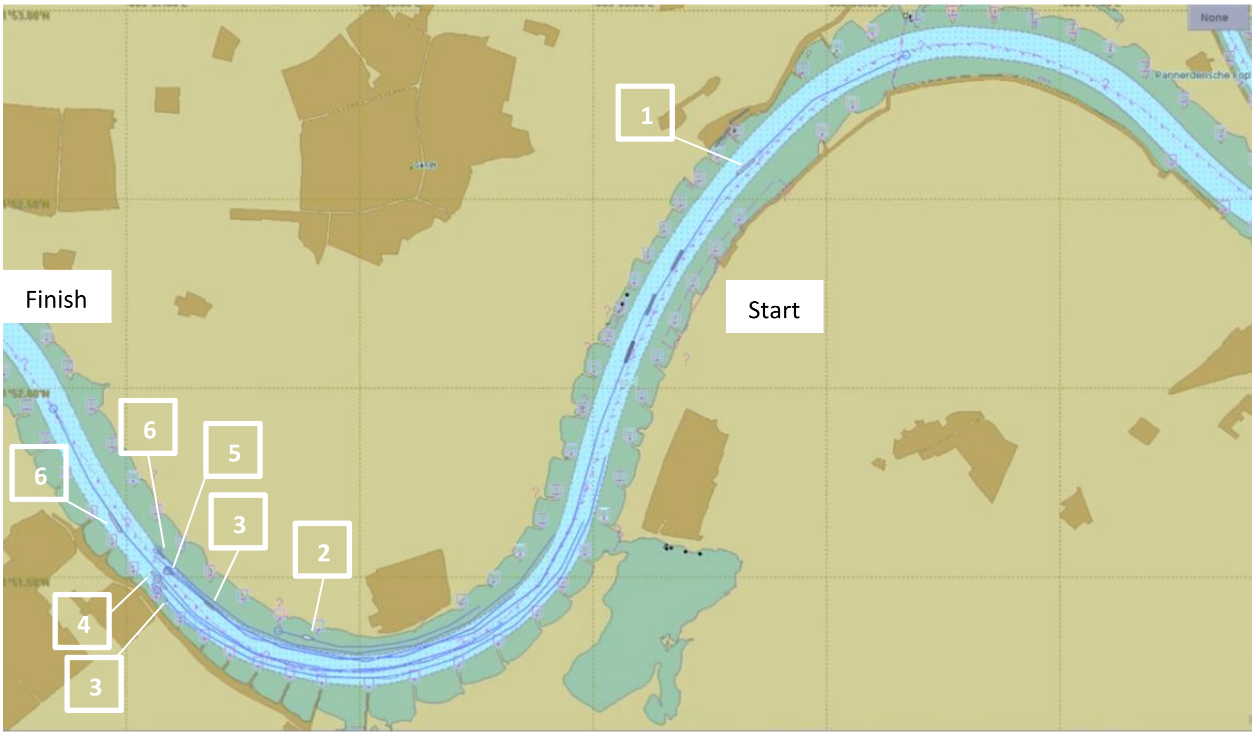


Figure 17: Scenario E

This scenario creates a highly complex navigation situation, by letting 6 to 7 vessels closely together taking the bend upstream. The goal for the VT is create safe passage and when necessary, communicate with the traffic.

Scenario F; Overtaking in a bend

The VT sails downstream.

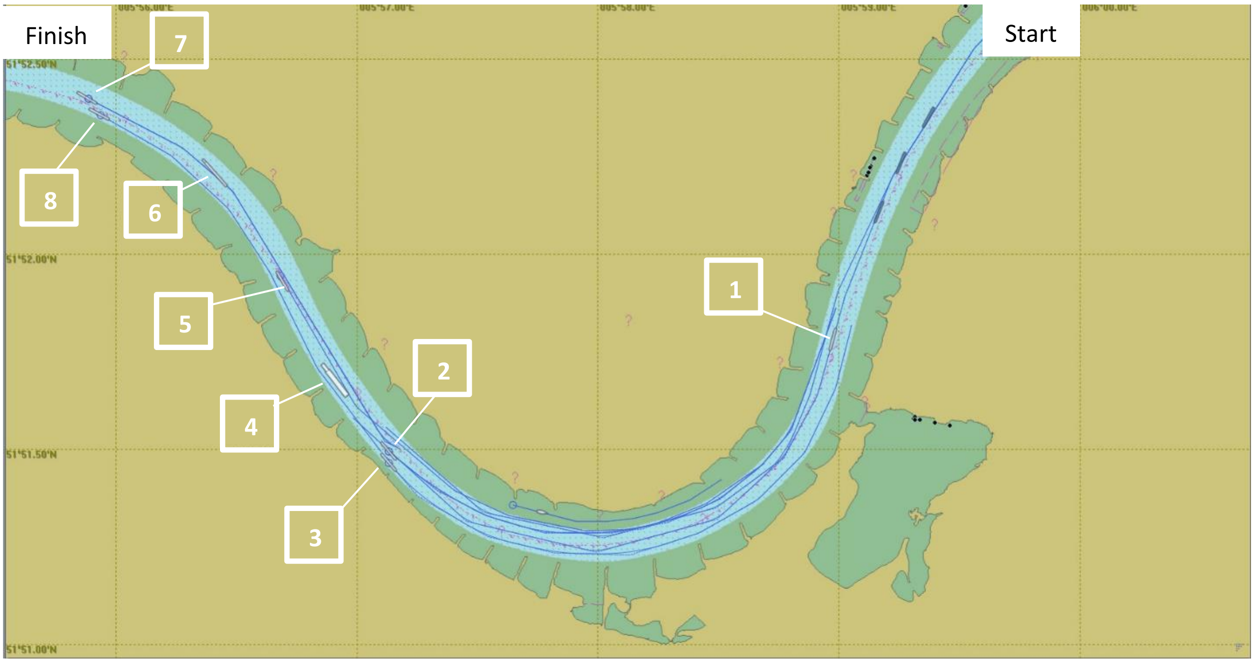


Figure 18: Scenario F

The VT needs to cope with a slower vessel (1) going downstream, whether it safe to overtake or not. Several vessels are sailing upstream: vessel 2 is overtaking 3 in the bend. After that, a large pushtow (4) navigates the bend; the VT needs to account for the extra space required by the pushtow unit. Vessel 6, 7 and 8 are relatively easy to cope: they stay on starboard side.

Scenario G and H

The VT sails upstream.

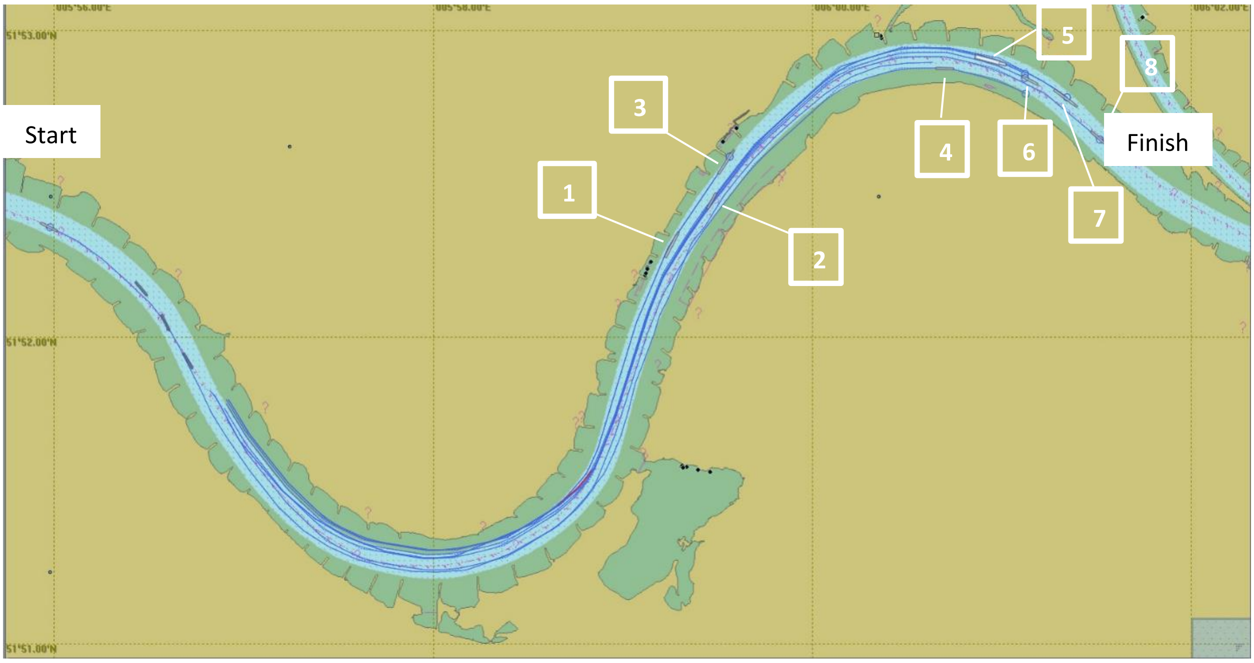


Figure 19: Scenario G

The VT meets a large cluster of vessels going downstream, vessels 4, 5, 6, 7 and 8. The goal is creating a safe passage, and estimate if the VT needs the attention of the FV after an emergency. Vessel 1, 2 and 3 are relatively easy to cope with, but are there to urge for immediate action after an emergency. Scenario G: propulsion break don of the second follower vessel. Scenario H: propulsion break down of the lead vessel.

Skippers

Twelve inland skippers varying in experience, age and nationality (German and Dutch) participated in the simulator experiment. The participants mean age was 46 and varied from 30 to 61 years. All received a briefing and were trained to operate the control system before starting with simulator sessions. The participants were divided into three teams (A, B, C) with each 4 (3 + 1 reserve) skippers. Team A simulated only one day and, teams B & C simulated two days. Team A and C were Dutch inland skippers, team B were German inland skippers. All were experienced inland skippers and sailed with CEMT class V vessels across Europe. During a simulator run one skipper sailed the lead vessels. Two skippers were available on the follower vessels for coupling and decoupling. After coupling they were asked to observe and give their feedback from the follower vessel point of view. The reserve skipper was observing on the lead vessel. In five days, the described scenarios were sailed in random order. Difficult scenarios were repeated.

4.2.3 Free sailing model tests (T3.5.4)

After extensive preparations, in February 2020 the vessel train was tested and demonstrated with scale models (scale 1/16) in the controlled environment of DST's large shallow water basin (L × B × T: 200 m × 9.8 m × 1.28 m). The test campaign was planned, prepared and carried out by Argonics and DST. The water depth was set to h = 0.313 m corresponding to a full-scale depth of 5.0 m. For some tests current was generated and barriers were installed to mimic cross-currents at groynes or tributaries and changes in current velocity. The used length of the basin for the tests was about 150 m due to required space for the carriage, the harbour area and the current injector nozzles. The current was generated by two pumps pumping the water from the downstream end of the basin via a parallel tank system to the current outlet at the basin’s upstream end.

Two scale models of single-screw large Rhine vessels (L × B × T: 110 m × 11.40 m × 2.80 m at full-scale) with identical bow shapes but different aft bodies were equipped with propulsion and steering gear as well as remote control equipment like batteries and Wi-Fi for wireless data transmission. The following vessel was additionally equipped with a turn rate indicator for the autopilot. An optical tracking system (Qualisys) installed on the towing carriage was used to mimic the GNSS functionality of the full-scale system by referencing the vessels position relative to the carriage. Figure 20 shows the principal setup without the carriage which was used to follow up the vessel train with the optical tracking system and remote-control accessories only.

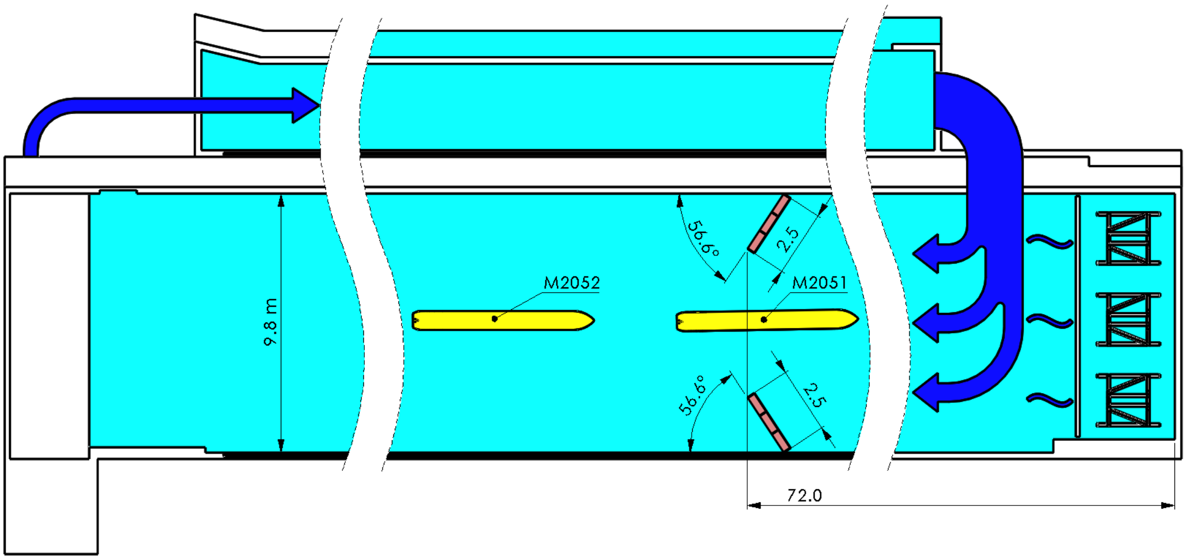


Figure 20: Overview of the basin with models, current generation scheme and barrier/groyne installation

Communication

In general, the communication between the control system, the follower vessel, the carriage position and the motion tracking system has been realised by a central local area network (LAN) on the carriage using the transmission control and internet protocol (TCP/IP). The content of all communications between the systems has been realised by using sentences according to the Standard 0183 of the National Marine Electronic Association (NMEA 0183). Basically, the input of the TrackPilotVT are the motions and positions of both vessels inside the basin. The motion data are scaled to full scale (orange block in Figure 21) and transmitted via different Transmission Control Protocol (TCP) sockets for each vessel to the track pilot. An overview of the used scales and interaction between the different systems is given in Figure 21.

For the data conversation a real-time software application has been developed, which is aware of the current carriage position to determine the vessels position not only relative to the carriage, but in relation to the whole basin. During this operation the position is converted to virtual GPS coordinates corresponding to a Rhine stretch close to Mannheim. The change of the position and heading between each time step has been used to derive the vessel's speed and turn rate. The follower vessel has been equipped with an advanced gyrocompass and motion sensor (Octans/iXblue), to resolve a more consistent signal of the turn rate than provided by the derivation of the Qualisys system.

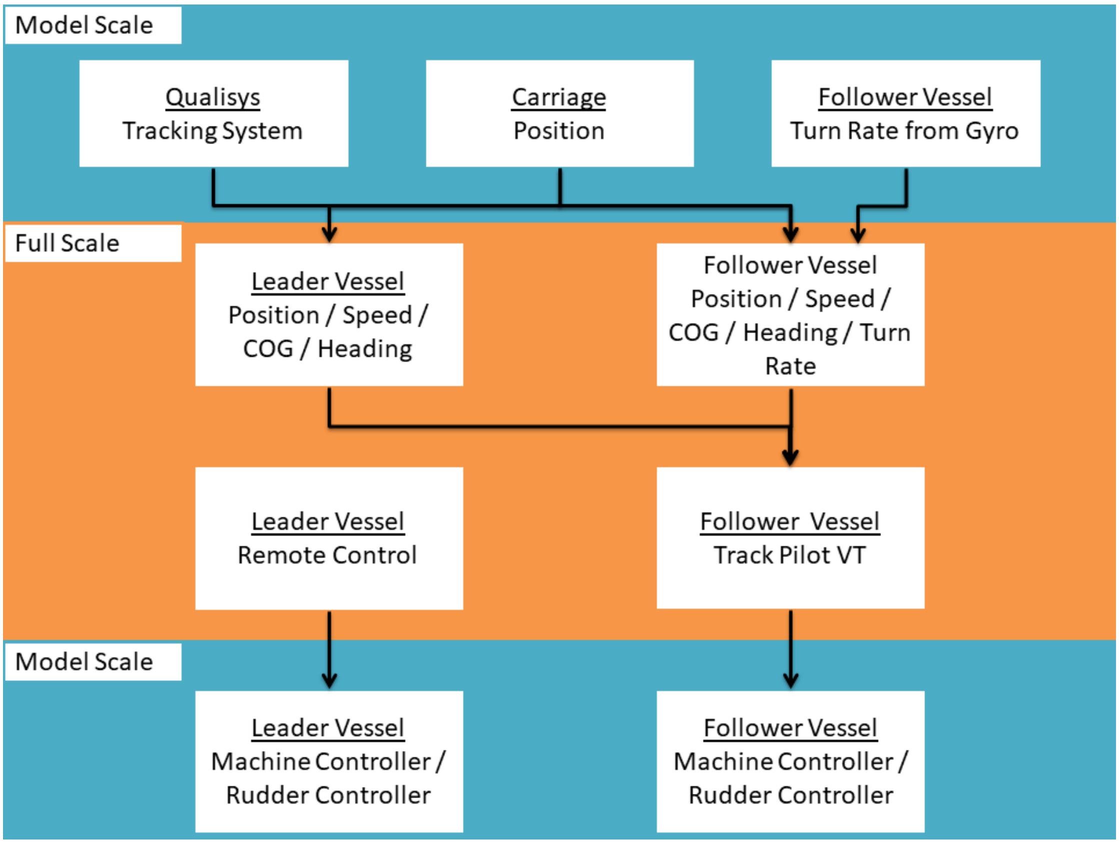


Figure 21: Single Line Diagram of Communication

The TrackPilotVT is developed for full scale application. Therefore, all motion data from the sailing models had to be converted to full scale. Since time scales with the square-root of the scale factor, all modules have to run four times faster than at full scale. The software application developed by DST has been used to gather the data from the optical tracking system, apply the conversion functions and provide the data to the TrackPilotVT via Ethernet using the NMEA 0183 standard in real-time. An overview of the applied conversion functions is given in Table 4.

Table 4: Overview of scale factors

Measure (model scale)	Scale factor to full scale	Unit
Spacings	λ	m
Time	$\frac{1}{\sqrt{\lambda}}$	s
Angular velocities (e.g. turn rate)	$\sqrt{\lambda}$	$\frac{deg}{min}$
Velocity	$\sqrt{\lambda}$	$\frac{m}{s}$

Optical Tracking System

The optical tracking system was installed at the front of the carriage observing a defined measuring volume in reference to the carriage. The measuring volume depth of the tracking system was increased to about 25 metres by using active markers on both models (Figure 22). This proofed to be sufficient to track two ship models of a length of approximately 7 metres leaving some room for variations of the longitudinal distance in between them in front of the carriage. The system was set up to a robust tracking in the waterplane area to archive 100 % coverage and not tuned for highest accuracy. A tracking resolution of 3 mm was achieved, which is less than 5 cm in full-scale. The achieved resolution in full scale is more accurate than with commercial GNSS receivers on board.

The positions of both models were captured in real-time with the tracking system, added to the carriage position, converted to virtual GPS coordinates using the given scale factors by the DST software application and finally fed into the TrackPilotVT for automatic guidance. These virtual GPS coordinates were placed on a river stretch close to Mannheim where the scaled model basin dimensions fit in. Figure 23 shows the bounding box and the centre line of the scaled and projected DST's large shallow water basin (L × B full scale: 3.200 m × 160 m) on the inland Electronic Chart Display and Information System (ECDIS). The changes of position and heading between each time step were used to derive the ship speed and turning rate for the leader. The follower vessel was equipped with a high-end inertial measurement system to provide a better signal quality of the turning rate for the TrackPilotVT. The output rate of all channels was 10 Hz which was high enough to obtain smooth motions from the vessels using real time filters while the capture rate of the optical tracking system was 100 Hz. Furthermore, the TrackPilotVT designed for full scale applications had to act four times faster during the model tests according to the law of scale.

Figure 22: Carriage with Optical Tracking System and both vessels sailing in front

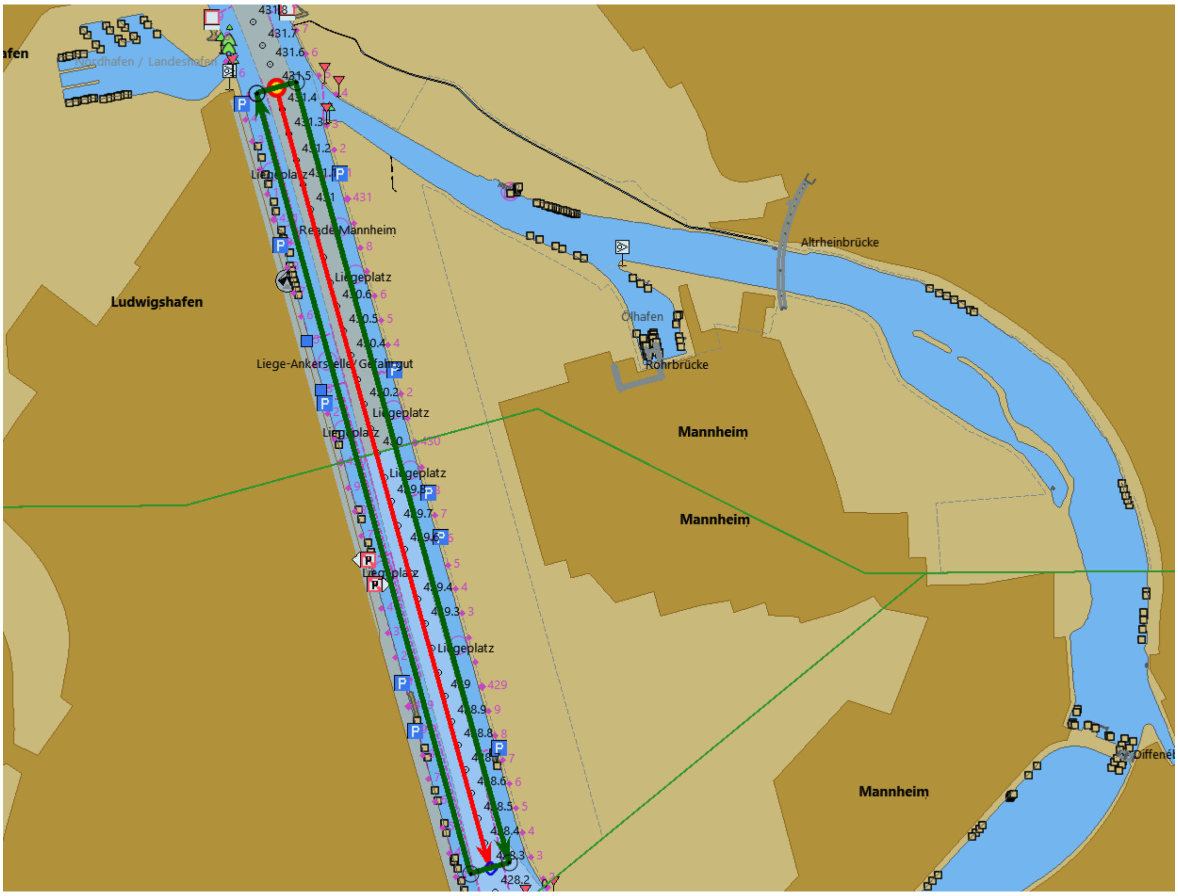


Figure 23: Projection of the DST basin to a bend of the river Rhine near Mannheim

Model equipment

The leader vessel (M2051) was manually remote controlled while the follower (M2052) used the TrackPilotVT developed within NOVIMAR. The manoeuvring characteristics of M2052 were derived in extensive computations by project partner MARIN in T3.4. Both vessels were equipped with the same propeller, nozzle and rudder to achieve similar manoeuvring characteristics except from their different hull designs. The used nozzle was designed with a plain and well known 19A profile. A similar simple approach was used for the propeller. Inland vessels show significant differences in manoeuvrability due the installed thrusters, propulsors and rudder systems. Therefore, the single-screw models were equipped with simple single-area rudders, posing increased challenges for the helmsman and the TrackPilotVT. The vessel train was, therefore, demonstrated with ships of poor manoeuvrability serving as a worst-case scenario.

Environmental Conditions

The set flow velocity has been documented with a 3D inductive flow measuring probe at the height of half the measuring distance. If the adaptive barriers were used, a significantly increased flow velocity was recorded, as expected. The archived undisturbed flow velocity was set to 0.2 m/s for most of the tests. Varying the barriers, a flow velocity up to 0.44 m/s was measured by the probe approximately 20 m downstream of the barriers. Each barrier element was 2.5 m long and set up to specific angles (see Table 5) to the basin’s boundaries to achieve different flow velocities and cross currents.

Table 5: Configurations of the adjustable barriers

	Angle left	Angle right
Large angled adjustable barriers right hand side	-	65.0°
small angled adjustable barriers right hand side	-	57.3°
small angled adjustable barriers both sides	57.3°	57.3°

A webcam was installed to observe the vessel train manoeuvring in front of the carriage. The webcams video signal was aligned with different views of the TrackPilotVT graphical user interface (GUI) and recorded during the tests. The behaviour of the vessel train and the appearance on the control system can be analysed from these captures (Figure 24).

Figure 24: screenshot of GUI including video stream and ECDIS view

The robustness of the experimental setup provided excellent conditions to investigate the behaviour of the vessel train and TrackPilotVT extensively. This led to a large number of different tests with TrackPilotVT at scale models.

4.3 Deviations from the plan

During preparations for fast-time simulations the effort to implement a fast-time simulation environment was evaluated. It turned out that the effort of implementation would not be worth the time saved compared to real time simulations. Therefore, it was decided to replace the fast-time simulations by a similar set of real-time simulations.

According to the original plans full mission bridge simulations for T3.5 were foreseen at MARIN while for T5.3 simulations were planned with the simulator at DST. Since the implementation of the command and control modules were both complex and elaborate and both IN and ARG had no task in WP5 it was decided to join forces of WP3 and WP5 on MARIN’s simulator in a combined simulator session.

5 RESULTS

5.1 Introduction

This chapter describes the results of the subtasks. Results of the first set of full mission bridge simulations were used for development of operational procedures and further development and fine tuning of the TrackPilotVT and RADARpilotVT. The description in this chapter focuses on the results of the second set of full mission bridge simulations and the model tests.

5.2 Results sub-task T3.5.3 Simulator demonstrations

This paragraph describes the results of the simulation of each scenario by summarizing the timeline and the main observations. The observations are based on comments from the simulator instructors during the runs, observations from the skippers observing on the follower vessels, the observer on the lead vessel and the interviews/debriefing with the skippers after each simulation run.

Scenario B; Encountering traffic in bend Nijmegen

Start condition:

- Not coupled
- Sailing downstream
- 200 metres distances between the VT vessels
- All same speed: 15 km/h
- FV operators stay on the bridge, though they do not have an active navigational task

Summary of the simulation (run 1)

During the coupling procedure, the speed differences between the vessels became too large because the LV was accelerating and going too fast for the followers. The LV operator noticed the difference and communicated with the FV if the speed needed to be adjusted. The VT passed first the downstream vessel on starboard side. After that, two upstream vessels passed the VT. One of the vessels came close to FV2, which was anticipated by the LV: the LV operator moved the track to starboard side (40 metres) to create more space for the encountering upstream vessels. Nevertheless, the second upstream vessel still came close to FV2 – distance within 20 metres. Next, the LV anticipated for taking over an inland vessel on starboard side by moving the VT track, in automatic mode, back to port side. At the same moment, the LV started with the right bend while a large pushtow unit just passed the LV and now passed FV1. As a result of adjusting the track, the VT moved to the centre line of the river with FV2 coming too close to the pushtow unit. The VT operator with his decision to adjust the track did not account for the drift angle that FV2 needed to follow the bend. FV2 and the pushtow unit passed each other with only a few metres separation distance. After several minutes, the VT increased the speed to speed up the overtake manoeuvre of the vessel on starboard side. The LV operator moved the track to the centre line of the river. While LV was overtaking the vessel, traffic was coming out of the Maas Waalkanaal and crossed the river to the other side and sailed about hundred metres upstream before turning to port following the bend. The LV operator communicated via VHF to verify the voyage plan of the outgoing vessel, and the LV operator decided to lower the speed and moved the VT further to port side – as a result the outgoing vessel had more space to cross the river. After passing the outgoing vessel, the VT was ordered by the simulator instructor to decouple.

Summary of the simulation (run 2)

Coupling between FV1 went well, however, FV2 was coupled with a large separation distance to FV1 (450 metres) due to lack of attention of the operators. The TrackPilotVT automatically reduced the separation distance to 300 m, by speeding up FV1. The VT passed the first downstream (small) vessel with sufficient distance. Next, the LV communicated with the VTS to inform about the traffic situation, and switched to assisted (manual steering) resulting in a manoeuvre with each vessel in the VT following the past LV track. However, due to a large distance between the predefined track (in automatic mode) and the past LV track, FV2 steered strong to port side. This movement was observed by the FV2 operator and he decided to take over control by switching off the TrackPilotVT. The LV did not immediately recognize this. It took more than a minute before the LV communicated with FV2.

Meanwhile, two upstream vessels were passing the VT on a collision course with FV2. The encountering vessels were moved by the instructor to prevent a collision, because the FV2 operator could not prevent a collision. After passing the vessels, the FV2 turns on the TrackPilotVT again. Next, the VT passed a new upstream vessel on starboard side (outside the corridor border of the VT).

The VT speeded up to 20 km/h to overtake another downstream vessel on starboard. As a result, the FV1 could not keep up and the LV slowed down a little. A small vessel was leaving the Maas Waalkanaal to the Waal and crossing to the other side of the river. The LV steered to the port side, to create more space for the vessel crossing the river and reduced the speed a little bit more. The VT passed the outgoing vessel with a large distance. Hereafter, the LV decoupled successfully.

Summary of the simulation (run 3)

The VT coupled well. The VT operator frequently communicated with VTS post, informing about coming traffic. The VT operator switched to assisted mode, but gets a strong ROT to port side. Switched back to automatic, but the vessel already initiated a strong turn to port and almost collided with the large pushtow unit. FV2 collided with the large pushtow unit, because of the track that was too close – not adjusted enough to starboard side. However, there was still space to do so. After that, LV switched to assisted mode, and stayed in that mode. Passed several vessels with sufficient passing distance, switched back to automatic mode. Decoupled the vessel train after all vessels were passed successfully.

Summary of observations during the runs:

- Communication with VTS is needed to coordinate traffic and anticipate future scenarios.
- Higher communication activity level is required to gather information to project/predict future navigational states of the complete VT.
- Overtaking vessels while encountering other vessels is impossible due to limited control. The TrackPilotVT does not allow the vessels to be steered individually. This was a design decision.

Overtaking should not be allowed for a coupled vessel train. If overtaking is unavoidable, e.g. if the minimum safe manoeuvring speed of the VT is higher than the speed of the vessel in front, the vessel train should be decoupled and the skippers of the individual vessel should be called on the bridge.

- FV operators should intervene by taking over control when the situation gets too complex. However, it can be difficult to predict when a navigational situation evolves beyond the available means of control.
- LV operator workload is higher because of active monitoring of the track and speed keeping of each FV.
- Display of information for monitoring can be improved to support the LV operator better:
    - Information on engine status of the FVs is not easy to capture. The numbers are currently too small.
    - Display the track for the whole VT, including the FV. The FV track is not displayed yet on the RADARpilotVT interface (This was added later on in the simulation week and tested).
- Monitoring the FV by the LV with surrounding traffic is a very demanding task.
- The performance of automatic distance keeping is sensitive for speed differences when sailing downstream; location and speed should be quite accurate before sending a couple request. The coupling procedure is more sensitive for failures when going downstream.
- RADARpilotVT interface: In assisted mode, the couple line (can) overlap the past LV track displayed, which makes it harder to distinguish the two lines.
- Changing between automatic to assisted guidance can lead to unwanted situations when there is a significant gap between the predefined track and the past LV track in dense traffic situations.
- The ability to put off the TrackPilotVT with one button is handy in emergency situations.
- Active communication with surrounding traffic and VTS is vital for an informed decision about navigating the VT.
- LV operator needed an extra explanation on how to monitor the system and see whether the follower vessel can retain distance and track.
- The user system interaction indicates that the operators are not fully familiarised yet with the concept or system. Therefore, they are not fully aware of the risks and sensitivities in operating the train, such as changing between automatic and assisted mode, creating more errors. This stresses the need for proper training.
- When changing from automatic to assisted mode, the LV operator gains manual rudder control of the vessel. In one of the runs, the rudder tiller was not in a neutral position, but at a maximum angle to port side. As a results the rudder changed to port side the moment the LV operator changed from automatic to assisted mode. It is important to include in the procedures to take immediate control of the rudder after changing from automatic to assisted mode or put the rudder tiller already at the desired angle before changing the control mode.

Scenario C; Downstream of Nijmegen

- Not coupled
- VT sailing upstream
- 150 metres distance between VT vessels
- All same speed: 15 km/h
- FV operators stay on the bridge, though do not have an active navigational task
- With weather condition fog (sight limited to 500 metres)

Summary of the simulation

FV1 closed in on LV, FV2 stayed more behind. They started with the coupling procedure, communicated about the correct distance and supposed that FV1 would stay at the correct distance (which he did not, because of having higher speed then the LV). FV1 requested for coupling, and asked LV to speed up. That worked well, FV2 coupled too. And the voyage continued — there was another short explanation to the LV operator included of how the TrackPilotVT interface works.

After a few minutes, a downstream vessel passed the VT. The vessels stayed on the starboard side of the river and did not conflict with the VT track. The LV operator communicated with VTS and agreed the upstream sailing vessel to pass starboard – starboard (blue sign). LV communicated again with post-Nijmegen to be informed on upcoming traffic further downstream. The VT let the encountering vessels pass on safe distance with the use of TrackPilotVT. The operation went well. After that, the VT decoupled successfully.

Summary of observations during the run:

- The LV lowered speed due to reduced sight.
- Operator misses AIS information, to know which vessels are coming.
- The LV operator felt compelled to limit the track offset, because he did not know how each FV would be affected.
- LV frequently communicated with the VTS and surrounding traffic to agree on passing each other.
- The couple procedure when going upstream is easier than when going downstream. Upstream allows more variance in the distance and speed between vessels amid coupling.

Scenario D; Meeting traffic in a long bend

Start condition

- Not coupled
- Sailing upstream
- 200 metres distances between vessels
- All the same speed: 10.5 km/h
- FV operators stay on the bridge, though do not have an active navigational task
- Emergency introduced at the end of the scenario

Summary of the simulation (run 1)

The LV operator started with the coupling procedure for FV1 and FV2, which went well: within 70 seconds, both vessels were coupled. After two minutes, LV moved the track 5 metres to starboard and after returned the track to the current LV position, to get a better feeling on how the vessels reacts on an offset. Then the LV moved the track again to starboard, with 10 metres. After a few minutes, VT got an order from the simulator instructor to decouple and couple again; meanwhile, the VT was encountering/passing/crossing a downstream vessel on portside. During the decouple and couple procedure, FV1 made an error by selecting the passing upstream vessel to couple instead of the lead vessel. When the LV accepted the decouple request of FV1, the LV TrackPilotVT was turned off automatically (not according to the design). The LV encountered at a later stage three downstream vessels on portside, of which one was overtaking another vessel needing more space. The LV anticipated and created a larger offset to starboard side (35 metres).

Shortly after, the VT was slowly catching up an upstream vessel. Three vessels passed the VT with more than 30 metres separation distance. The LV operator zoomed out on the radar, to get an overview, and repeated that several times throughout the voyage. The LV increased the speed to have the rest of the train pass the upstream vessel more quickly (speeds up to 11 km/h). The LV was now passing the upstream vessel and was on the same track as the encountering downstream vessel. The downstream vessel moved a little bit to the side and passed with sufficient distance. The LV operator checked again the radar by zooming out: sees vessel coming down further on the line. The LV moved the track back to starboard with 10 metres – now 5 metres to port from the centre line of the river. When the upstream sailing vessel has passed FV2, the simulator instructor communicated an emergency from another upstream sailing vessel that was still in front of the LV. The rudder was stuck, and the vessel started to drift towards the centre line of the river, crossing the track of the VT. The LV operator reacted immediately by starting the decoupling procedure. In the end, the LV almost crashed into the emergency vessel, due to the sharp bend of the emergency vessel.

Summary of the simulation (run 2)

The coupling procedure did not go well, because the LV made an error by coupling with the FV1 before the FV1 requested for coupling. As a result, the LV started to follow FV1, instead of the other way around. Simulation was restarted and the couple procedure was executed again; this time FV1 coupled with a lower distance of 100 metres instead of the planned 150 metres. The voyage went smoothly with an average speed of 10 km/h and sailing on automatic mode. The VT met three downstream vessels in the bend, and adjusted the track to starboard to create more distance for the encountering vessels. After passing the downstream vessels, the VT closed in a vessel ahead on starboard side and took over by adjusting the track to port side. This went well and no other vessel were coming downstream that may have a conflict with the track of the VT. At the end, the VT decoupled in a proper way according to the procedures.

Summary of the simulation (run 3)

The LV and FVs communicated well about the speed and distance before executing the coupling procedure. The coupling procedure went well. The LV operator zoomed out on the ECDIS map, to capture a larger navigational area. The VT encountered three downstream vessels close after each other, one vessel was going to starboard (right side of the river) and crossing over coming from the left side. The VT moved the track a little to port side. The LV had one vessel ahead on starboard side with lower speed. The VT overtook the vessel. An emergency was introduced on the vessel ahead and it communicated to the LV that the vessel lost control. The LV suggested to pass on starboard side and the LV warned the FV to monitor the situation. The LV ordered to start to uncouple, this went well – still 200m away from the emergency vessel. The vessel was on the right side of the river and the VT could pass easily.

Summary of the simulation (run 4)

The FV operators left the bridge after coupling. The coupling procedure went well, the VT passed the other traffic with sufficient space. LV communicated with FVs to check if speeds were okay; the operator did not use the RPM display information. A downstream sailing large pushtow unit narrowed the available space for the VT. The pushtow unit passed the FV1 very close, the distance was around 10 metres - while the LV had the space to alter the track to starboard. Further on, the VT passed three vessels at the same time (one on starboard side going upstream and two on port side going downstream,) again FV1 passed the vessel closely, while there was space to alter the track. The operator decoupled the VT in line with the procedures.

Summary of observations during the runs:

- The VT sailed in the automatic mode, almost during the entire simulation.
- Couple and decouple procedure are error prone to select the wrong vessels, for LV and FV operator. Interface allows to select the wrong vessels, which could directly lead to hazardous situations.
- RADARpilotVT interface: when a FV requests for decoupling, it shows two lines: the original yellow coupled line and a red dotted line for the indication of the decoupling request. It can be confusing having both lines at the same time.
- Automatically turning off or on of the LV TrackPilotVT when the LV operator accepts a couple or decouple request can be confusing; no warning is given when the TrackPilotVT gets on or off. An alert or clear notification would help alert the LV operator.
- The LV needs to zoom out and in to get a good understanding of the navigational situation; the current simulator setup does not provide enough information, an extra screen covering a larger navigational area would be helpful.
- The LV operator could have solved the emergency better by ordering all operators to take over control by turning off their TrackPilotVT, instead starting decoupling procedure.
- System should not allow erroneous selections of vessels, once the LV is defined.
- LV operator does not understand the system sufficiently to operate it well; procedures are not well known, such as the need for matching speed and stick to the planned distance before starting to couple.

- The VT handled the situations largely with ease. Only a few track adjustments were needed to get an unhindered path/track for the VT.
- Instead of decoupling in the emergency situation, the VT could have just put off the TrackPilotVT for each vessel.
- Despite the extra explanation on the system, the operators are still reluctant to put off the TrackPilotVT to regain control instead of the more time consuming decouple procedure.
- The concept is (still) difficult to understand for the operators: the meaning of TrackPilotVT off and on while being coupled.

Scenario E; Meeting with traffic in a narrow bend

- Not coupled
- Sailing downstream
- 150 metres distances between vessels
- All same speed: 15 km/h
- FV operators stay on the bridge, though do not have an active navigational task

Summary of the simulation (run 1)

The LV added an extra ring on the radar, set it to 150 metres to better observe the distance between the LV and FV1. The LV is located at starboard 70 metres from the centre line when accepting the couple request of FV1; the LV's TrackPilotVT automatically turns on and the track is displayed on the RADARpilotVT, which is by default placed on the centre line of the river line. As a result, the system steers the LV strongly towards the track placed in the centre of the river, to reduce the gap of 70 metres. Five upstream vessels in the bend were close to each other and encountering the VT. The VT had only a small corridor to sail in between the upstream sailing vessels. The LV adjusted the track – in automatic mode. Nevertheless, the LV and FV1 almost collided with an encountering vessel that sailed in the middle of the river; the VT did not set the offset large enough to create sufficient distance to the encountering vessels. After the VT passed several upgoing vessels, it coupled with the FV2. FV2 almost hit the last passing vessel, due to the track that was placed close to the middle line. Thereafter, the VT decoupled, which went smoothly.

Summary of the simulation (run 2)

The VT coupled well, passed first the downstream sailing vessel on portside. In the right bend, the VT encountered three vessels (two upstream on both side of the river, and one downstream vessel). The VT passed in between with sufficient passing distance to all vessels. The VT had some difficulty in passing the vessels while staying in automatic mode. Best would be to switch back to assisted mode or call upon each FV operator. The VT decoupled successfully.

Summary of observations during the runs:

- Extra training/explanation was given during the simulation on the consequences for control in using the TrackPilotVT when switching between assisted and automatic mode.

- The track is only displayed after the TrackPilotVT turns on; this can lead to a large offset with the current position. One can resolve this by adjusting the track to the current position of the LV.
- In total 6 lines visible: two corridor lines, one line for the middle line, one present track line, one past LV line and couple line.
- Trackline with decouple line is confusing: both are red dotted, making it difficult to distinguish (this was changed afterwards).
- No distinction between display icon on the RADARpilotVT for coupling and decoupling; the operator is only reminded once when the LV goes back to the VT menu to select the correct accepting mode (for decoupling or coupling). If the LV forgets to do this, the icon does not remind the operator what will happen: accepting a coupling request, or couple the LV to a FV which is very dangerous.
- Furthermore, the menu buttons do not deviate for a LV or FV, because a vessel needs to able to control both. It is advisable to change this, to reduce the likelihood of mode/selection errors.
- The simulation run confirms that with the present control modes it is too difficult to cope with multiple moving vessels as traffic. The VT should have an unhampered corridor on the river to sail safely.

Scenario F; Overtaking in a bend

- Not coupled
- Sailing downstream
- 150 metres distances between vessels
- All same speed: 15 km/h
- FV operators stay on the bridge, though do not have an active navigational task

Summary of the simulation (run 1)

FV1 could not keep up with the LV and the distance between LV became larger than 150 m up to more than 240 metres. FV2 called upon LV to reduce speed. The LV reduced speed to let the FVs catch up. While doing this, FV1 overshoot his setpoint of 150 metres, due to a higher speed than the LV. FV1 came too close and lowered RPM. As a result, FV1 lost rudder control and started drifting off course to the other end of the river (corridor border of the VT). Meanwhile, the LV increased speed again. FV2 was closing in on FV1 fast. Once FV1 reached the correct distance (150 m), FV1 regained control. FV2 coupled successfully. VT overtook a vessel on starboard side and moved the track to port side. The LV asked FV2 to uncouple, FV2 did not respond; did not know how to put TrackPilotVT off. Meanwhile the VT encountered new vessels, LV almost collided with a (large pushtow unit)) encountering vessel, because the track was altered too late to starboard side. In the end the VT passed the large pushtow with very close distance (10 metres). After that, the VT uncoupled successfully.

Summary of the simulation (run 2)

Coupling went well, although FV2 seemed to lose control and turned to starboard – TrackPilotVT is turned off. FV2 wanted to decouple (although not necessary to do so). FV2 sailed independently with TrackPilotVT off and chose a different route to pass the upstream vessels. A cluster of three upstream vessels came up. FV2 coupled again, successfully. LV zoomed out on the RADARpilotVT, to get a larger area and to see what traffic was coming towards the VT. VTS communicated which vessels were coming and VT agreed with the pushtow unit to pass green to green (starboard-starboard, blue sign). The VT needed to squeeze in between the upstream vessels. The LV operator zoomed in again, to get a better look on the track. There was another vessel upstream that was crossing the track of the VT. The LV moved the track too late to starboard resulting in a near collision. Decoupling went well.

Summary of observations during the runs

- Switching between assisted and automatic mode should be avoided with dynamic objects. Assisted mode is designed to avoid static objects.
- When the LV switches off the TrackPilotVT, when automatic mode is selected, the FV will still keep the predefined track while the LV steers manually. The display of the track on the RADARpilotVT disappears when the TrackPilotVT is turned off by the LV. This is an unwanted system state in reality.
- The operators are still not sufficiently familiarised with the system, more training is needed to let the operator understand the system.
- Even after familiarisation, it is too difficult to overtake in dense traffic moving vessels and account for encountering traffic that conflicts with the VT track.
- LV reports that it would be helpful to have information of the rudder angle of the FV’s to monitor the performance of the control system.

Scenario G (emergency)

- Not coupled
- Sailing upstream
- 150 metres distances between vessels
- All the same speed: 15 km/h
- FV operators stay on the bridge, though do not have an active navigational task
- Emergency with FV2 at the end of the simulation

Summary of the simulation (run 1)

Coupling went well, there was more active communication between the operators during the couple operation. The VT slowed down after coupling with FV1 because they went too fast and had to wait for FV2 to catch up. FV2 coupled well. Three vessels were going downstream, two on starboard and one large pushtow unit on port side. The VT needed to be in the middle of the river to pass them all. However, after the three vessels a downstream vessel sailing came in the middle. While the VT was passing the three vessels, the LV anticipated for the last downstream vessel in the middle of the river by moving the VT trackline to starboard. However, at the same time, the large pushtow unit still needed to pass FV1 and FV2. Due to the offset of the trackline, and a turn of the large pushtow to retain course in the bend, FV1 and FV2 almost collided with the pushtow (few metres distance). After the pushtow is passed, the simulator instructor introduced an emergency by putting off FV2 TrackPilotVT and warned the LV operator. The LV called upon the FVs and started the decouple procedure successfully.

Summary of the simulation (run 2)

Coupling went smoothly, correct distance and matching speed. The VT encountered several downstream vessels, but the LV coordinated well via VHF and stayed clear from other vessels. No special manoeuvring was needed. LV zoomed out and scrolled over the map to get an idea of what was coming. The VT passed two vessels with sufficient distance. At 34 minutes, the simulator instructor introduced an emergency, turned off the FV1 TrackPilotVT, and warned the LV. The LV alerted the FV crew, a little more than a minute later the FV1 operator returned to the bridge and started the decouple procedure. The speed had dropped to 2.8 km/h. The FV regained controls, and after that the simulation ends.

Summary of observations during the runs

- During coupling procedure: not paying enough attention to speed differences.
- Operators are still not familiarised with the system.
- Not paying attention to what happens to FV: reacts on the navigational situation for the LV, not to the FV.
- The emergency procedure was time-consuming, it took two minutes before the vessels were decoupled.

Scenario H (emergency)

- Not coupled
- Sailing upstream
- 150 metres distances between vessels
- All the same speed: 15 km/h
- FV operators are not on the bridge after being coupled
- Emergency with the main engine of the LV at the end of the simulation

Summary of the simulation:

The VT coupled successfully. The LV steered to the right side of the river to create space to pass a large pushtow unit. A cluster of downstream vessels passed the VT (green to green). At 38 minutes, the simulator instructor introduced a failure of the main engine and warned the LV operator. Fifteen seconds later, the LV alerted the FV crew. It took 1.5 minutes to come back on the bridge. The speed dropped below 5 km/h. The LV explained the situations and suggested to decouple the VT. After another minute, the VT was decoupled. After that, the simulation stopped.

Summary of observations during the run:

- It takes roughly two minutes to get back on the bridge and get informed of the emergency, before taking any action. The walk to the simulator from the resting room is approximately 25 seconds.
- The situation could have been resolved better by turning off the TrackPilotVT instead of initiating decouple procedure.
- How fast a FV retakes adequate control and can make an informed decision depends on several factors, for example: the time to get back on the bridge, the time needed to detect the current situation based on the navigational information provided by the equipment, the communication ability and quality between the FV and LV to understand the emergency and the implications for each vessel in the VT. In this scenario, the LV had to explain the emergency several times before the FV fully understood it.

5.3 Results sub-task T3.5.4 Model scale demonstrations

The model scale tests were carried out in the weeks 6 and 7 of February 2020 at the DST in Duisburg. Week 6 was used for preparation of the model ships, installation of the measurement equipment, installation of the vessel train control system and the first trial and tuning experiments. All tests in week 6 were carried out in still water. The tests carried out in week 7 contained experiments with the vessel train consisting of two ships with and without current.

06.02.2020, 07.02.2020: Track control only

The first experiments (number 3 and 4) were used to test and tune the underlying rate of turn controller for the follower vessel. The rate of turn controller implements the commands issued by the track controller. For this reason, it is important to have a well-tuned rate of turn controller. The rate of turn controller was found to be working sufficiently with the settings used at MARIN in November 2019.

Figure 25 shows the performance of the track controller at 50 % throttle. The setpoint change of 30 m is executed smoothly, lateral deviation after the manoeuvre is smaller than 1 m. This corresponds to the behaviour on full scale ships. The settings of the controller for the model scale ships were similar to the ones used on full scale ships and also to the ones used for the experiments at MARIN in November 2019. This confirms that the scaling to the model size works as expected.

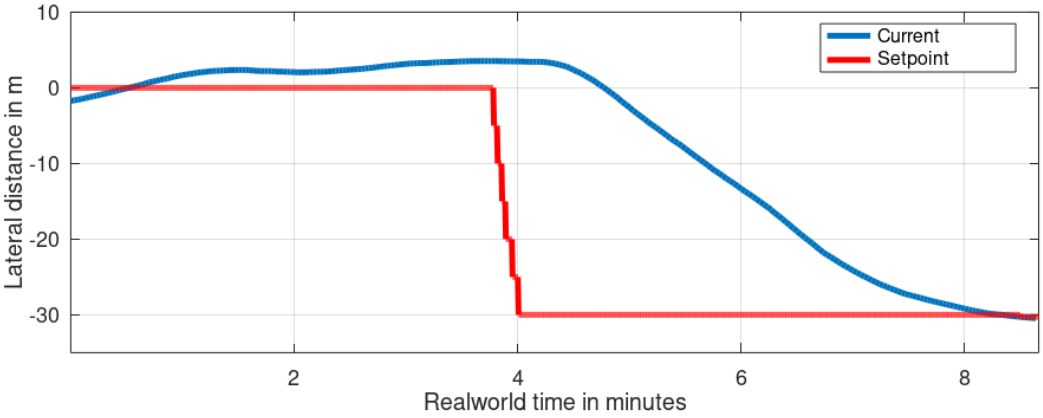


Figure 25: Experiment 9: Lateral control with setpoint change, 50 % throttle

07.02.2020: Speed control tuning

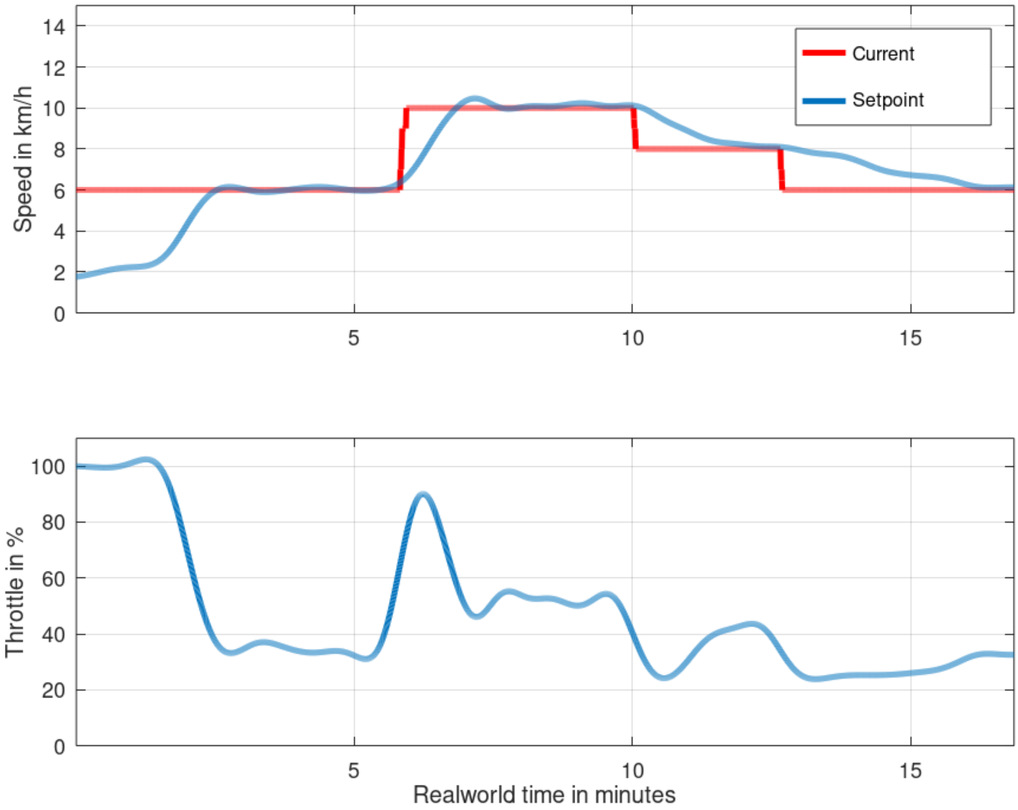


Figure 26: Experiment 10: Speed control test with setpoints 6 km/h, 10 km/h, 8 km/h and 6 km/h

Figure 26 shows the result of experiment 10. This experiment was used to analyse the performance of the speed control loop without any previous tuning. It shows two accelerations and two decelerations. The first acceleration is done well, the second acceleration has 2 km/h overshoot. To improve this, the lookup-table for throttle values was adjusted in a later experiment. Additionally, the throttle output acts too aggressively because the control loop needs to compensate for the wrong values from the lookup table.

The deceleration experiments show that such speed changes take a long time because the minimum value for the throttle output is set to 25 %. The lower value of the throttle is limited to 25 % because below that threshold, safe navigation with active track control is not possible.

11.02.2020 Distance control tuning with current

After the parameters of the speed control loop were adjusted in experiments 15 to 17, the following experiments were used to tune the distance controller. The ships were able to sail at very low speed of ground due to the current. For this reason, it was possible to carry out experiments with longer duration and execute stopping manoeuvres while maintaining full control over the ships. It should be mentioned that we tested the variation of the distance set points and focused on the longitudinal control rather than steady sailing with a realistic and fixed distance.

Figure 27 shows a stopping manoeuvre. Since the reduction of speed on the leader vessel is not communicated to the follower vessel and can only be detected by a decreasing distance, the reaction of the follower vessel is too late and the distance decreases to 50 m (see minute 6). Additionally, the follower vessel cannot reduce its throttle below 25 % because a certain amount of thrust is necessary to maintain stable lateral control.

Figure 28 shows an acceleration of the vessel train while the desired distance is fixed to 50 m. After a delay of approximately 30 s the throttle on the follower vessel is increased as well. During the acceleration the distance increases up to 70 m, then decreases again towards the setpoint. The small increase in speed at the end of the experiment leads to an increased distance of 60 m.

Both acceleration and deceleration could be improved by using a common speed setpoint for both ships. Additionally, the leader vessel should use speed control as well.

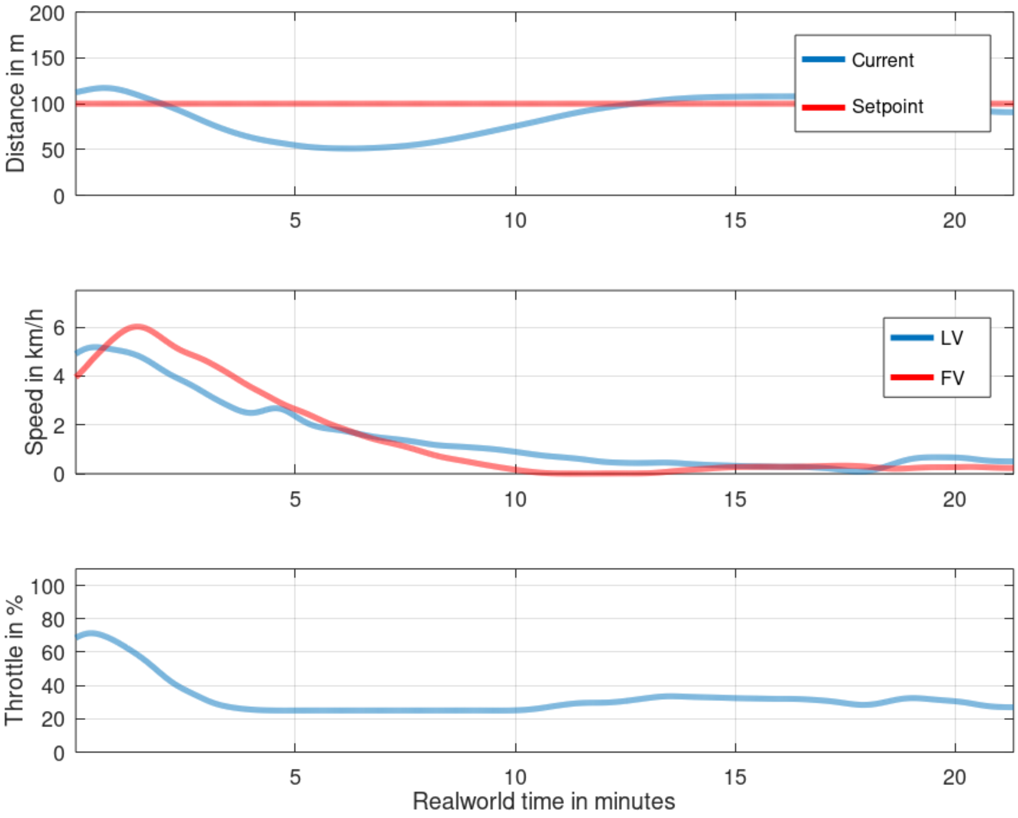


Figure 27: Experiment 27: Vessel train stop manoeuver

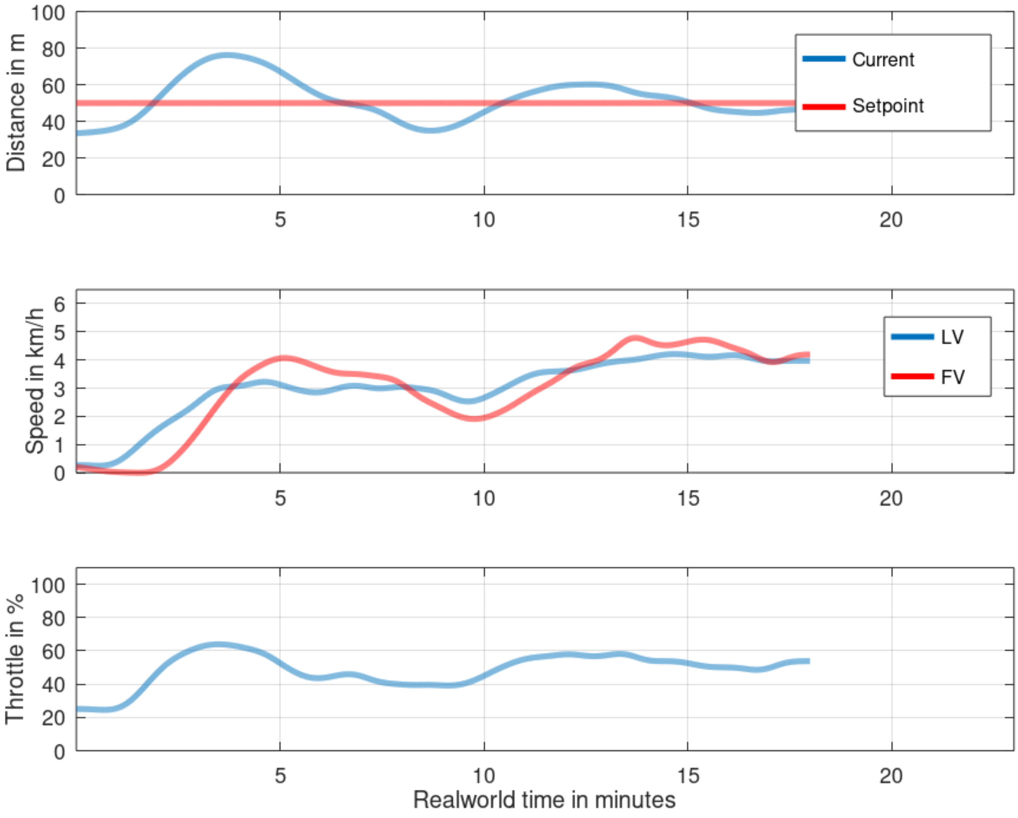


Figure 28: Experiment 28: Vessel train acceleration

12.02.2020 Tests with adjustable barriers

In experiments 29 to 46 adjustable barriers were installed to simulate more difficult current situations like groynes or tributaries. The first two experiments with the vessel train revealed two problems. The first problem was caused by the automatic adjustment of the lateral offset from the guiding line on the follower vessel. The leader vessel was controlled manually without a rate of turn controller and the person controlling it had difficulties keeping the model on a straight path due to the strong influence of the cross currents. The follower vessel tried to follow these lateral movements but was not able to keep its desired course because the strong currents pushed the ship to the side. In these experiments the thrust was not sufficient to generate enough rudder force to turn the ship into the current. This problem was increased by a second effect. When the leader vessel reached the barrier, it was slowed down which resulted in reduced thrust on the follower vessel as well. This led to a loss of lateral control because of the strong current.

These experiments lead to the conclusion that the lateral control loop needed to be tuned to be better suited for these difficult conditions. Thus, the next experiments were carried out with the follower vessel only. Additionally, a fixed lateral distance to the guiding line was used to exclude further excitation of the control by changing offsets.

Experiments 33 and 34 showed oscillations of the rate of turn caused by the rate of turn controller so the next experiments were used to adjust the rate of turn controller. Additionally, the rudder speed of the follower vessel was increased to 40 deg/s to match the rudder speed on full scale ships to further improve the performance of the rate of turn controller.

The behaviour of the vessel train passing a barrier was tested again in experiment 41. Figure 29 shows the lateral distance of the leader vessel (red) and the follower vessel (blue) to the guiding line. It is obvious that both vessels are strongly deviated from a straight path by the current. The arrows highlight the point in time when the ships pass the barrier. The large lateral deviation of the follower vessel at the end of the experiment was caused again by the leader vessel. It was concluded to use a fixed offset to the guiding line for the next experiments.

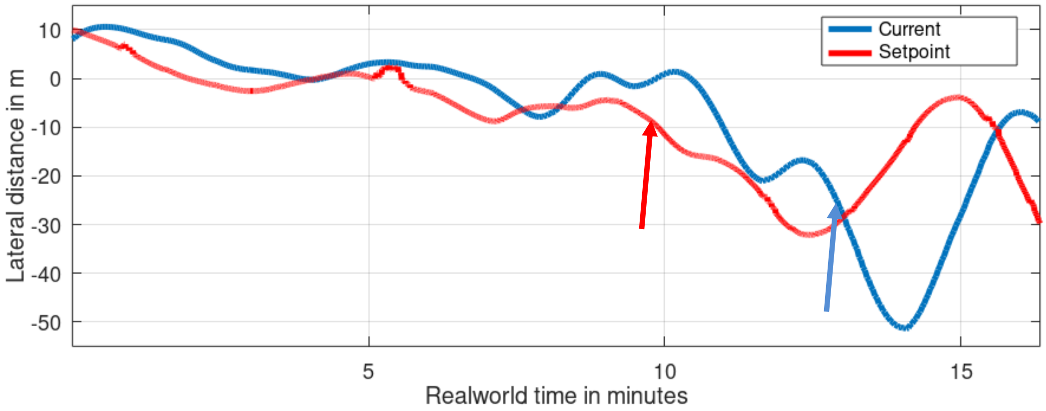


Figure 29: Experiment 41: Vessel train with decreased barrier

Figure 30 shows the distance between the vessels and the speed. The increased current speed at the barrier leads to a reduced speed of the leader and the follower vessel. The distance between the vessels drops to 40 m ahead of the barrier because of the reduced speed of the leader vessel. Upstream of the barrier the leader vessel is able to accelerate earlier and thus the distance increases while the follower vessel is slowed down by the strong current.

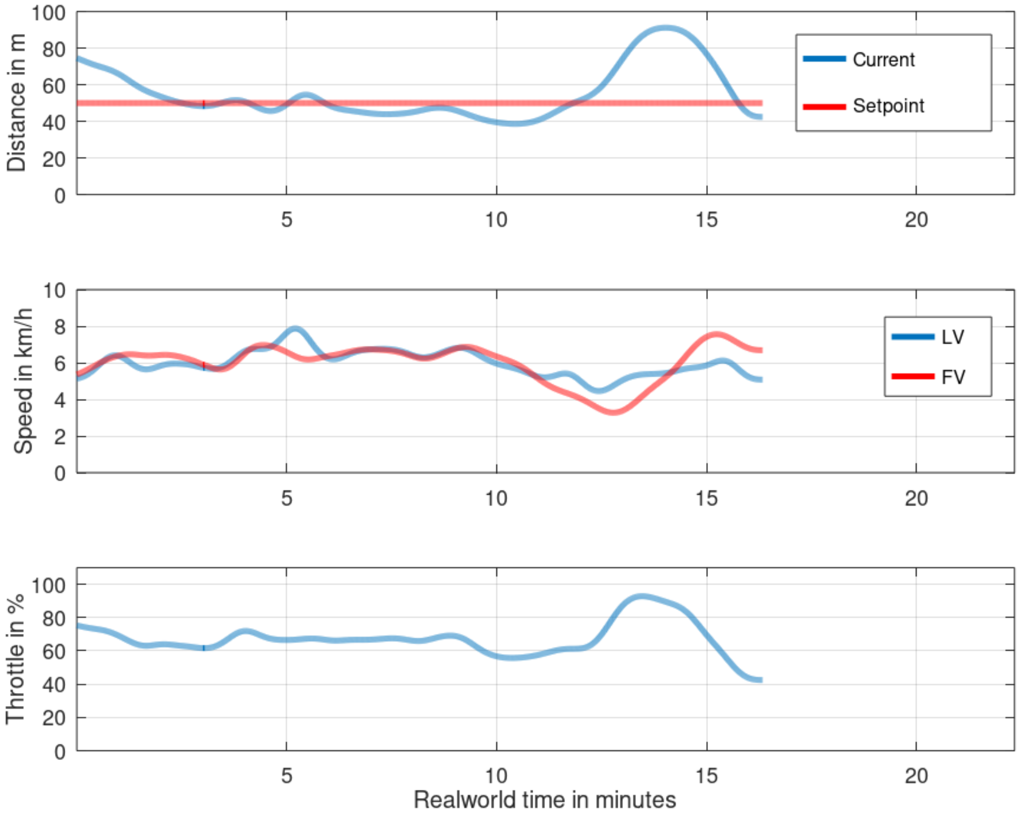


Figure 30: Experiment 41: Vessel train with decreased barrier

Figure 31 shows the results of experiment 42. In this experiment the follower vessel sailed on a fixed guiding line without the leader vessel at 75 % throttle. The barrier was reduced to limit the influence of the current. Even though, the ship experienced an offset of approximately 3 m at the beginning of the experiment, when it was 1000 m downstream from the barrier. At 350 m downstream of the barrier the current pushed the ship nearly 5 m away from the guiding line. When the ship passed the obstacle after 9 minutes, it was pushed away from the barrier 9 m. The controller was able to correct for this offset with 5 m overshoot.

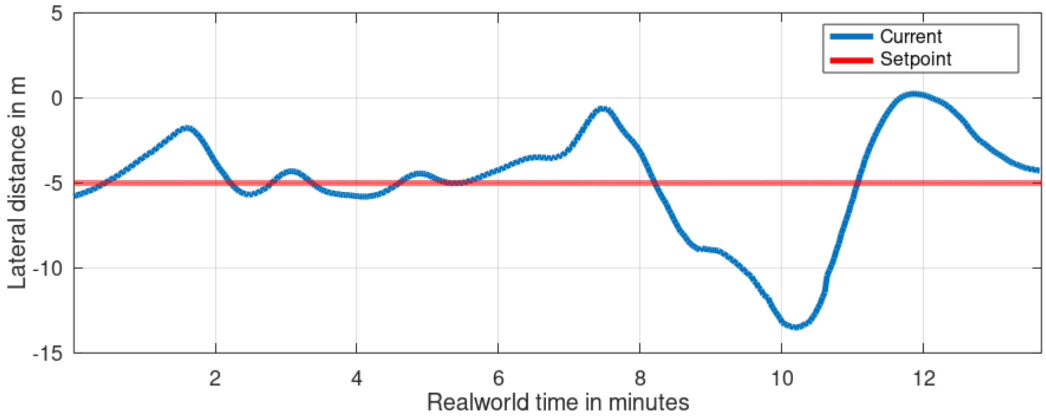


Figure 31: Experiment 42: Distance to track, FV only with 75 % thrust and reduced barrier

13.02.2020 Tests with symmetric barrier

Experiments 44 to 46 were carried out with a symmetric barrier that accelerated the current velocity up to 6,3 km/h. In experiment 44 the follower vessel was able to pass this obstacle but experienced large lateral offsets of up to 23 m. The speed dropped to 0 km/h directly at the barriers, even though the throttle was set to 100 %. The largest deviations occurred several hundred meters downstream of the barriers, closer to the barriers the current was steadier.

13.02.2020 Emergency stop

In experiment 50 two emergency stops were executed. The vessel train was set up with a distance of 100 m between the vessels at 9 km/h. The follower vessel used a fixed distance to the guiding line.

At the start of the emergency manoeuvre, the engine on the leader vessel was reversed to 100 %. The vessel train control system reversed the engine automatically when the distance between the vessels fell below 80 m. The engine stayed in reverse for 48 seconds. The follower vessel was able to stop at a distance of 40 m to the leader vessel. Then both vessels used the engine to maintain manoeuvrability. The thrust of the leader vessel turned the follower vessel to portside and induced a lateral offset of 40 m. The control system of the follower vessel was able to compensate the lateral offset, it was not necessary to switch off the control system.

In the second part of the experiment, the setup was exactly the same. The speed of the vessels was at 8 km/h. The engine of the follower vessel was reversed for approximately 20 seconds. This time, the leader vessel did not use its engine when the follower vessel was very close, so the follower vessel was not deviated by thrust from the leader vessel. The remaining distance between the vessels was 34 m (see Figure 32). The deviation from the track was less than 10 m. The control system was able to safely keep the follower vessel on the fairway. There was no immediate need for intervention by the skipper of the follower vessel. The leader vessel was able to stop after approximately 76 m, the follower vessel after approximately 64 m (see Figure 33).

The detection of an emergency stop using a threshold leads to a delayed reaction of the follower vessels and a reduced distance between the vessels at the end of the emergency stop. This problem must be resolved by a simultaneous emergency stop command for all vessels issued by the leader vessel.

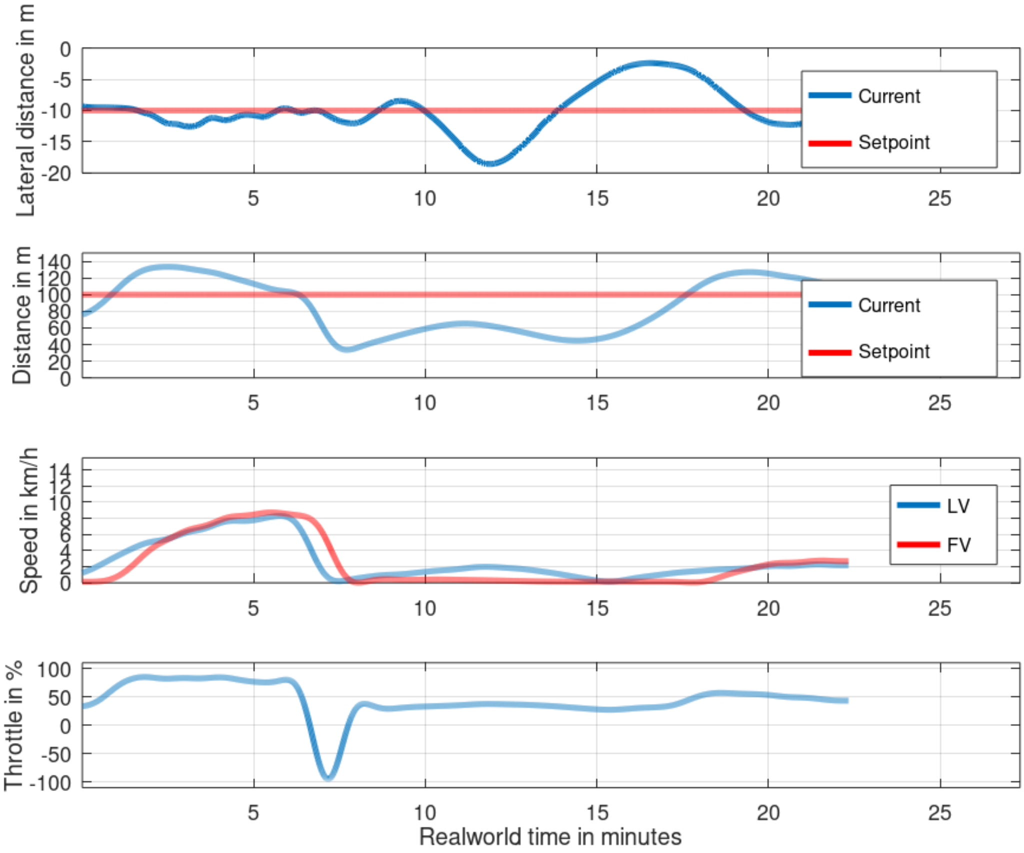


Figure 32: Experiment 50: Emergency stop 2

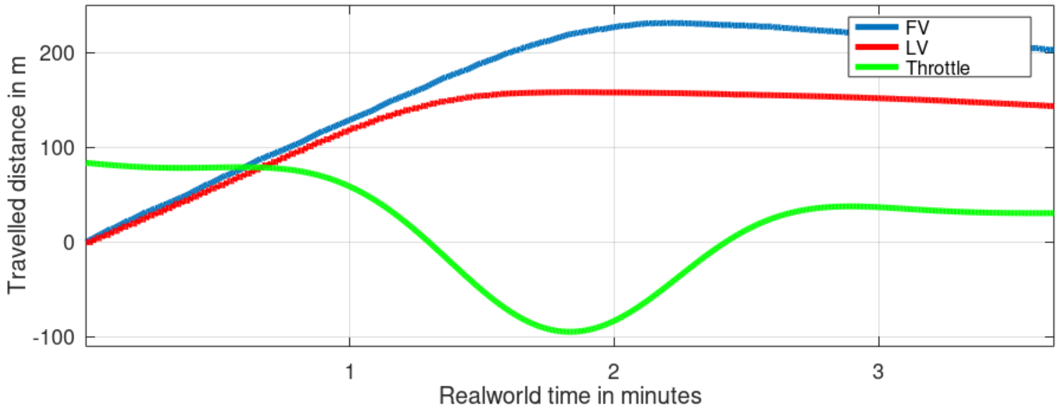


Figure 33: Experiment 50: Emergency stop 2, travelled distance

6 ANALYSIS OF RESULTS

6.1 Summary of results

Simulator demonstrations

The vessel train, composed of one lead vessel and two follower vessels and with hardware-in-the-loop was demonstrated with real-time simulations on the river Waal. All participating skippers acted both on the lead vessel as operator and follower vessel as operator/observer. The simulator allowed to provoke challenging situations which could be used to derive valuable input for further development steps. The skippers used the command and control system to navigate the vessel train. The skippers successfully coupled and decoupled the system when all the vessels had approximately the same speed and reached the setpoint of 150 metres.

The automatic mode and assisted mode of the control system worked as designed. The skippers used the predefined track in the automatic mode successfully and were able to move the track to starboard or port through the TrackPilotVT interface. In assisted mode, the follower vessel followed the past track of the lead vessel on the straight stretches and in the bends with minimal offset on the river. Changing between the automatic mode and assisted mode could lead to unexpected behaviour in case of a large offset to the new track when switching. To handle this the TrackPilotVT offers the possibility to adjust the tuning of the lateral control to the skippers need.

When going upstream the vessel train followed the track with a minimal offset. When going downstream it was experienced that:

- The control system was more sensitive for speed changes and sometimes lead to loss of control of the follower vessels. This was fixed during the simulator tests by increasing minimum throttle setting. The rate-of-turn-controller of the simulator was not able to cope with small thrust as opposed to commercial solutions.
- When the lead vessel reduces speed in downstream manoeuvres, the follower vessels sometimes overshoots the distance setpoint. As the system tries to recover the sailing distance, the rate of turn of the propeller is slowed down to a minimum to reduce speed, which in return leads to lower rudder force and loss control. The settings of the TrackPilotVT were fine-tuned during the simulations to avoid overshoots.
- Coupling procedure is sensitive for speed changes when going downstream.

Settings for current speed are important for a correct working control model. Settings were adapted during the simulations.

The participating skippers stressed that the concept of automatically following a past track or predefined track set out by a lead vessel is very promising, although they agreed that the control system and the vessel train concept requires further improvement before they are ready for full market uptake. Based on their experience they recommended:

- In more complex traffic situations with traffic going upstream and downstream on a bendy river, the navigational control of the follower vessels should be returned from the lead vessel to the follower vessel in order to avoid collisions with other traffic. This recommendation is based on scenarios when the skippers tried to navigate the vessel train between oncoming traffic and slow traffic going in the same direction. Instead of returning control the LV could have resolved the situation by slowing down and waiting for the oncoming traffic to pass. These procedures need to be included in the training for VT skippers.

- The reaction of the controller was different from what a skipper would expect. E.g. according to some skippers, the control of the rate of turn was not in line with how they would steer themselves. As a result, the rate of turn and the vessels motions were difficult to predict for the skippers. Further tuning of the control system and a short-term prediction of the path of the follower vessels on the navigation system of the leader vessel is recommended.

Improvements include:

- Further develop the control system interface with a human centred design approach to enable safe use, to enhance the usability and to create an effective human-automation collaboration, that fits the needs, abilities and limitations of automation and the human operator.
- Improve or extend the control abilities to cope with a wider range of complex traffic situations and use a user centred design approach to make sure the controls fit the human strengths, abilities and takes into account limitations.
- It was possible in the tested version of the system to take back control at the FV without informing the lead vessel. This should be made impossible.
- Exclude the possibility to enter unwanted system states, such as coupling with the wrong vessel, to prevent immediate danger when operators err.
- Provide adequate alerting to the VT operators for any vital system change that is tailored to the operational phase. For example, alert the LV operator when the TrackPilotVT of a FV is turned off.
- Ensure easy understandable and accessible information to monitor the system effectively for both the LV and FV operator.

A more detailed discussion on improvements is included in D5.2.

Model scale demonstrations

With some improvements of the control system following the results from the simulator, extensive model scale tests were performed. During these tests the complexity was increased in a step-wise manner to improve the longitudinal (speed/distance) and lateral control. After testing and tuning parameters with the follower alone, the vessel train was navigated through the test stretch many times varying the vessel and current speeds, the set distance between the vessels, the manoeuvring of the leader and the flow regimes at the barriers. Especially, for boundary conditions changing in time and space the control performance was improved significantly. In upstream navigation it was possible to keep the vessel train in a steady state at a speed over ground of zero.

The scale model experiments showed that the vessel train control system is able to steer the ship safely in all upstream conditions except extreme current conditions. In the case of emergency and normal stops simple improvements to the rate of turn controller and the lateral control could be used to further improve controller performance. Both acceleration and deceleration could be improved by using a common speed setpoint for all ships with the leader also using speed control. This should include a centralized emergency stop signal. This way speed changes of the leader vessel caused by varying current conditions would be reduced and thus distances between all vessels would vary less.

When sailing downstream the vessel train control system in its current setup it is not able to handle normal and emergency stops because there is no rudder force to steer the ship if the throttle is reversed. In day to day operation with a single manual controlled vessel the skipper will use the bow thruster to control the vessel (almost all lager vessels are equipped with a bow thruster) or in case of a small vessel make a turn. To be able to deal with this problem in a VT it is required to include a bow thruster in the control strategy. The following block diagram shows the developed scheme, which will be further investigated in Task 3.6.

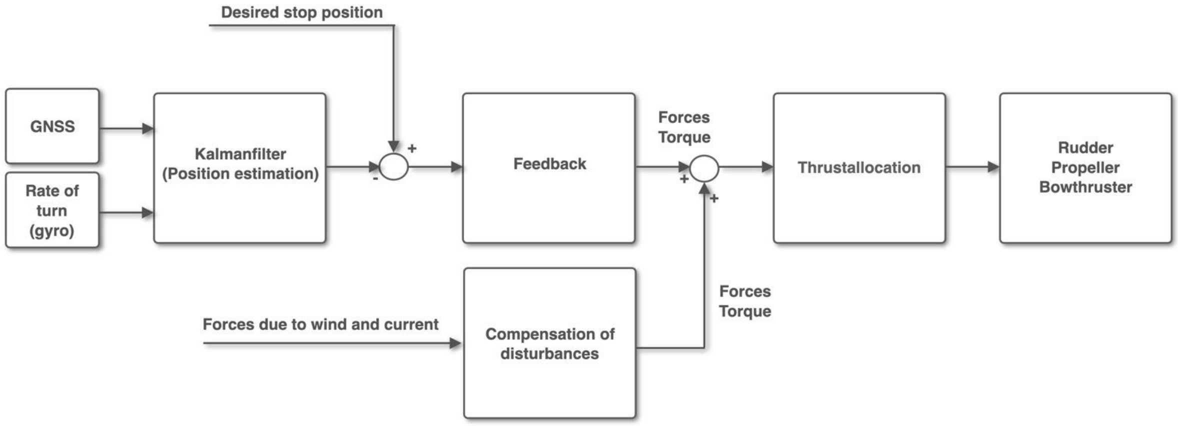


Figure 34: Block diagram for the control strategy to improve stopping performance

6.2 Analysis of results

The main objective of this task was to demonstrate the vessel train concept for the scenarios outlined in D3.1. Both the results of the simulations and the model scale demonstrations show that it is technically feasible to sail with the VT on inland waterways, however, the tested prototype system cannot solve the same dynamic traffic situations as a single vessel could and therefore limits the navigational areas where the VT could sail safely, without any changes on regulations and procedures, e.g.:

- Avoid overtaking in dense traffic areas;
- Stay on the right side of the fairway;
- Decouple in heavy traffic and call the skippers of the individual vessel to take over control.

The obtained results of the simulator tests were input for the human impact assessment of Task 5.2 and also provided as feedback for further development of the command and control system.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The scale model experiments showed that the vessel train control system is able to steer the ship in all upstream conditions except extreme cross flow conditions conditions: the tested vessel train configuration was unable to pass a test stretch with local cross flow of approximately 50 % of the mean flow velocity. In the case of emergency and normal stops simple improvements to the rate of turn controller and the lateral control could be used to further improve controller performance. Both acceleration and deceleration could be improved by using a common speed setpoint for all ships and a centralized emergency stop signal with the leader vessel also using speed control. This way speed changes of the leader vessel caused by varying current conditions would be reduced and thus distances between all vessels would vary less. The idea behind is that the longitudinal control would be simplified when the LV uses speed control instead of constant/manually set engine rate and the FVs know the common speed setpoint. With this approach the speed control of the FVs primarily controls the speed and only secondary the distance. The stopping performance would be improved when all vessels are aware of an emergency stop and the FVs do not need to react on a sudden significant reduction in distance.

When sailing downstream the vessel train control system in its current setup it is not able to handle normal and emergency stops because there is no rudder force to steer the ship if the throttle is reversed. To be able to deal with this problem it is recommended to include a bow thruster in the control strategy.

The simulator experiments showed that it is technically feasible to sail with the VT, however the lead vessel operator tasks become more complex. There are several operational limitations. The main limitation is that the VT cannot cope with everyday dynamic situations on the tested navigational area in the same way as a single vessel (IWT setting with dense traffic), because VT vessels once part of a VT cannot be manoeuvred independently from the rest of the VT. This way of controlling was a design decision for the controller to make manoeuvring the VT as easy and predictable as possible. This limitation can be overcome if overtaking is avoided in heavy traffic for a coupled vessel train and if the vessel train stays as far as possible on its own side of the fairway. In situations when this procedure does not work the vessel train must be decoupled and the skippers of the individual vessel must be called on the bridge and take over control.

The operational window can be extended by further developing the control abilities, operational procedures and the level of training and experience of the vessel train operator. This is further elaborated as part of T5.2.

Envisaged improvements towards market uptake include:

- Further develop the control system interface with a human centred design approach to enhance the usability and to create an effective human-automation collaboration, that fits the needs, abilities and limitations of automation and the human operator.
- Improve or extend the control abilities to cope with low speeds and stopping when going downstream, use a centralized speed control and emergency stop.

- Increase training to enable operators to be able to predict the behaviour and performance of the control system.
- Exclude the possibility to enter unwanted system states, such as coupling with the wrong vessel.
- Provide improved alerting to the VT operators for any vital system change that is tailored to the operational phase. For example, alert the LV operator when the TrackPilotVT of a FV is turned off.

A more detailed discussion on improvements is included in D5.2.

7.2 Recommendations

It is recommended to require a bow thruster as standard equipment of a vessel in a VT and include a bow thruster in the control strategy to extend the capabilities of the control system and extend the operational window to downstream manoeuvres.

The tested prototype of the man machine interface is subject for further improvement (see 6.1) to increase system performance, and/or extending the operational boundaries for navigation.

A short-term prediction of 5 to 10 minutes of the path of the follower vessels on the navigation system is recommended.

8 ANNEXES

8.1 Annex A: Public summary

The NOVIMAR project researches the vessel train (VT), a waterborne platooning concept featuring a manned leader ship and a number of followers which are virtually connected and follow at feasible distance by means of automatic control. The vessel train concept is a totally new approach for inland waterway and short sea transport. Before the vessel train concept is deployed in a full-scale environment with actual ships and surrounding traffic iterative development and improvement is required. Besides desk studies the performance of the systems needs to be assessed in controlled environments. Here direct numerical simulations, full mission bridge and physical model tests can be used. Task 3.5 focussed on the testing and demonstration of the vessel train in the full mission bridge simulator and by means of physical models in a towing tank.

The simulator experiments showed that it is technically feasible to sail with the VT, however, there are some operational limitations. The main limitation is that the VT cannot cope with everyday dynamic navigational situations on the tested navigational area in the same way as a single vessel (IWT setting with dense traffic), because VT vessels once part of a VT cannot be manoeuvred independently from the rest of the VT. This way of controlling was a design decision for the controller to make manoeuvring the VT as easy and predictable as possible. This limitation can be overcome if overtaking is avoided in heavy traffic for a coupled vessel train and if the vessel train stays as far as possible on its own side of the fairway. In situations when this procedure does not work the vessel train must be decoupled and the skippers of the individual vessel must be called on the bridge and take over control.

The tested prototype of the man machine interface is subject for further improvement to increase system performance, and/or extending the operational boundaries for navigation. As an important addition it is recommended to include a short-term prediction of 5 to 10 minutes of the path of the follower vessels on the navigation system.

The scale model experiments showed that the vessel train control system is able to steer the ship in upstream conditions except extreme cross current conditions. In the case of emergency and normal stops simple improvements to the rate of turn controller and the lateral control could be used to further improve controller performance. Both acceleration and deceleration could be improved by using a common speed setpoint with the leader vessel also using automatic speed control. This way speed changes of the leader vessel caused by varying current conditions would be reduced and thus distances between all vessels would vary less.

When sailing downstream the vessel train control system in its current setup it is not able to handle normal and emergency stops because there is no rudder force to steer the ship if the throttle is reversed. To improve the stopping performance a dedicated control strategy including bow thrusters was developed. It will be further investigated in Task 3.6.

Name of responsible partner: MARIN

Name of responsible person: Dick ten Hove

Contact info (e-mail address etc.): d.t.hove@marin.nl

8.2 Annex B: Table of experiments

Number	Date	Time	Ship(s)	Description
1	05.02.2020	13:27:00	LV	Test run with model M2051 only, used as LV
2	05.02.2020		FV	Rigid body calibration of model M2052
3	06.02.2020	14:24:00	FV	Test and tuning of rate of turn controller
4	06.02.2020	14:41:00	FV	Test and tuning of trackpilot
5	06.02.2020	15:03:00	FV	Test and tuning of trackpilot
6	06.02.2020	15:29:00	FV	Test and tuning of trackpilot, test of speed control
7	07.02.2020	09:45:00	FV	Test and tuning of trackpilot
8	07.02.2020	09:49:00	FV	Test and tuning of trackpilot; throttle 30 %; 30 m lateral offset to PS for track control
9	07.02.2020	10:09:00	FV	Test and tuning of trackpilot; throttle 50 %; 30 m lateral offset to PS, then 40 m lateral offset to SB
10	07.02.2020	10:34:00	FV	Test and tuning of trackpilot and speedcontrol; speed setpoints 6, 10, 8, 6 km/h
11	07.02.2020	11:38:00	LV+FV	Test and tuning of trackpilot and distance control; distance setpoint 150 m
12	07.02.2020	12:25:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
13	07.02.2020	13:19:00	LV+FV	Test and tuning distance control; distance setpoint 500 m
14	07.02.2020	13:37:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
15	10.02.2020	13:08:00	LV+FV	Test and tuning distance control; distance setpoint 100 m
16	10.02.2020	13:27:00	LV+FV	Test and tuning distance control; distance setpoint 100 m
17	10.02.2020	13:44:00	LV+FV	Test and tuning distance control; distance setpoint 100 m
18	11.02.2020	08:29:00	LV+FV	Recalibration of Qualisys positioning system
19	11.02.2020	09:31:00	LV+FV	Test and tuning distance control; distance setpoint 100 m
20	11.02.2020	10:47:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
	11.02.2020	11:05:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
21	11.02.2020	12:01:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
22	11.02.2020	13:33:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
23	11.02.2020	13:35:00	LV+FV	Test and tuning distance control; distance setpoint 150 m
24	11.02.2020	13:48:00	LV+FV	Test and tuning distance control; distance setpoint 150 m

25	11.02.2020	14:04:00	LV+FV	Test and tuning distance control; distance setpoint 150 m; current velocity -0.8 m/s
26	11.02.2020	15:00:00	LV+FV	Test and tuning distance control; distance setpoint 150 m;
27	11.02.2020	15:16:00	LV+FV	VT stationary in current with varying distance setpoints: 100 m, 50 m, 100 m, 50 m. Varying lateral distances.
28	11.02.2020	16:24:00	LV+FV	VT stationary in current with varying distance setpoints: 50 m, adjustment of lateral control. Slowly backwards with current.
29	12.02.2020	09:31:00	LV+FV	Introduced adjustable barriers simulating groynes or tributaries; Distance setpoint 50 m; Throttle 50 %
30	12.02.2020	10:17:00	LV+FV	Distance setpoint 50 m; Throttle 90 %
31	12.02.2020	11:04:00	LV+FV	Removed barrier, Distance setpoint 50 m; Current velocity -1.1 m/s
32	12.02.2020	13:05:00	LV+FV	With barrier; FV only; Throttle 50 %
33	12.02.2020	13:31:00	FV	With barrier; FV only; Throttle 75 %
34	12.02.2020	13:49:00	FV	With barrier; FV only; Throttle 75 %
35	12.02.2020	14:13:00	FV	With barrier; FV only; Throttle 100 %: Test autopilot performance
36	12.02.2020	14:51:00	FV	With barrier; FV only; Throttle 100 %: Test autopilot performance
37	12.02.2020	15:08:00	FV	With barrier; FV only; Throttle 100 %: Test autopilot performance
38	12.02.2020	15:22:00	LV+FV	With barrier
39	12.02.2020	15:50:00	LV+FV	With barrier; Experienced skipper on LV
40	12.02.2020	16:09:00	LV+FV	With barrier
41	12.02.2020	16:36:00	LV+FV	With reduced barrier; skipper A. Lutz
42	12.02.2020	16:57:00	FV	With barrier; FV on a fixed guiding line; Throttle 75 %
43	13.02.2020	09:07:00	FV	With increased barrier; FV on a fixed guiding line; Throttle 75 %
44	13.02.2020	09:33:00	FV	With two barriers; FV on a fixed guiding line; Throttle 50 % - 100 %
45	13.02.2020	10:11:00	LV+FV	With two barriers; FV on a fixed guiding line; Distance control active
46	13.02.2020	10:31:00	LV+FV	With two barriers; FV on a fixed guiding line; Distance control active
47	13.02.2020	11:00:00	LV+FV	No barriers; Test of distance control, going backwards
48	13.02.2020	11:38:00	LV+FV	Test of emergency stop; Distance setpoint 200 m; LV from 75 % ahead to full astern
49	13.02.2020	13:13:00	LV+FV	Test of emergency stop; Distance setpoint 150 m; LV from 75 % ahead to full astern

50	13.02.2020	13:48:00	LV+FV	Test of emergency stop; Distance setpoint 100 m; LV from 75 % ahead to full astern
51	13.02.2020	14:23:00	FV	FV downstream, emergency stop
52	13.02.2020	14:53:00	LV	LV upstream, manual control
53	13.02.2020	14:59:00	LV	downstream, manual stop
54	13.02.2020	15:10:00	LV	downstream, manual stop
55	14.02.2020	09:41:00	FV	Acceleration test: throttle 100 %; Stop test: Throttle 0 %
56	14.02.2020	10:01:00	FV	R-Manoeuvre: Rate of turn 20 deg/min, rudder 12 deg, throttle 50 %
57	14.02.2020	10:16:00	FV	R- Manoeuvre: Rate of turn 20 deg/min, rudder 30 deg, throttle 50 %

8.3 Annex C: MARIN Simulators

MARIN

MARIN simulators

MARIN (Wageningen) operates three different types of real-time simulators for research, consultancy and training purposes of professional mariners. The simulators can be used separately or combined in the same scenario. The steering controls can be easily adapted to the specifications of the simulated vessel. At MARIN the following 6 real-time simulators are available:

- Full Mission Bridge I (FMBI): Especially suitable to simulate large ocean-going vessels.
- Full Mission Bridge II (FMBII): A flexible facility, capable of simulating a wide range of vessels.
- Four Compact Manoeuvring Simulators (CMS): Smaller simulators that can be used to simulate all kind of tugs and smaller vessels.

MARIN operates full mission ship manoeuvring simulators at three different locations:

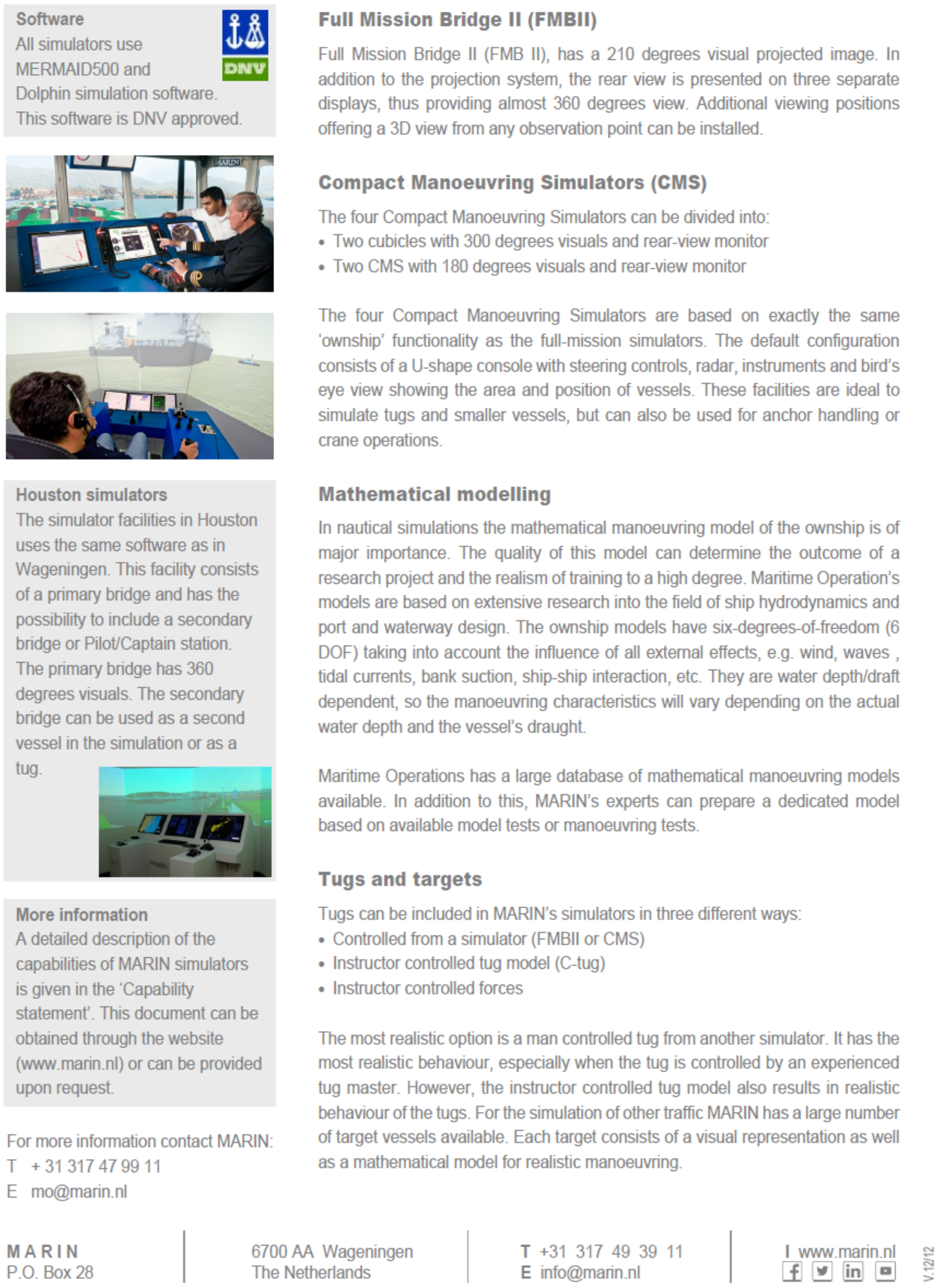
- MARIN: Wageningen, The Netherlands;
- MARIN USA: Houston, USA.

- Depending on the wishes of the client research projects, consultancy and maritime training can be done on each of these locations.

FMBI, bridge house with cylindrical projection wall

Full Mission Bridge I (FMBI)

This is a fully equipped bridge with 360 degrees visual projected scenery. A mock-up of a real ship bridge is located in the centre of a cylindrical projection wall on which the graphics image is projected. The diameter is 20m and the bridge house is approximately 8m by 6m. The bridge is equipped with realistic consoles and instrumentation, including bridge wing consoles. Bridge and console layout can be adapted according to client wishes or research needs.



Software
All simulators use MERMAID500 and Dolphin simulation software. This software is DNV approved.

Houston simulators
The simulator facilities in Houston uses the same software as in Wageningen. This facility consists of a primary bridge and has the possibility to include a secondary bridge or Pilot/Captain station. The primary bridge has 360 degrees visuals. The secondary bridge can be used as a second vessel in the simulation or as a tug.

More information
A detailed description of the capabilities of MARIN simulators is given in the 'Capability statement'. This document can be obtained through the website (www.marin.nl) or can be provided upon request.

For more information contact MARIN:
T + 31 317 47 99 11
E mo@marin.nl

Full Mission Bridge II (FMBII)

Full Mission Bridge II (FMB II), has a 210 degrees visual projected image. In addition to the projection system, the rear view is presented on three separate displays, thus providing almost 360 degrees view. Additional viewing positions offering a 3D view from any observation point can be installed.

Compact Manoeuvring Simulators (CMS)

The four Compact Manoeuvring Simulators can be divided into:
- Two cubicles with 300 degrees visuals and rear-view monitor
- Two CMS with 180 degrees visuals and rear-view monitor

The four Compact Manoeuvring Simulators are based on exactly the same 'ownship' functionality as the full-mission simulators. The default configuration consists of a U-shape console with steering controls, radar, instruments and bird's eye view showing the area and position of vessels. These facilities are ideal to simulate tugs and smaller vessels, but can also be used for anchor handling or crane operations.

Mathematical modelling

In nautical simulations the mathematical manoeuvring model of the ownship is of major importance. The quality of this model can determine the outcome of a research project and the realism of training to a high degree. Maritime Operation's models are based on extensive research into the field of ship hydrodynamics and port and waterway design. The ownship models have six-degrees-of-freedom (6 DOF) taking into account the influence of all external effects, e.g. wind, waves , tidal currents, bank suction, ship-ship interaction, etc. They are water depth/draft dependent, so the manoeuvring characteristics will vary depending on the actual water depth and the vessel's draught.

Maritime Operations has a large database of mathematical manoeuvring models available. In addition to this, MARIN's experts can prepare a dedicated model based on available model tests or manoeuvring tests.

Tugs and targets

Tugs can be included in MARIN's simulators in three different ways:
- Controlled from a simulator (FMBII or CMS)
- Instructor controlled tug model (C-tug)
- Instructor controlled forces

The most realistic option is a man controlled tug from another simulator. It has the most realistic behaviour, especially when the tug is controlled by an experienced tug master. However, the instructor controlled tug model also results in realistic behaviour of the tugs. For the simulation of other traffic MARIN has a large number of target vessels available. Each target consists of a visual representation as well as a mathematical model for realistic manoeuvring.

MARIN
P.O. Box 28

6700 AA Wageningen
The Netherlands

T +31 317 49 39 11
E info@marin.nl

I www.marin.nl

V.12/12

8.4 Annex D: Long List of Situations and Manoeuvres

HAZID

ID.	**HAZID description**	**WP 3 solution?** **(Y/N)**	**If no, why not?** **If yes, how? (technical solution / procedure and solution description**	**Demonstration (simulation / model / full scale)**
1.1.1	Loss of propulsion of lead ship	Y	Technical solution to be implemented. All vessels in the train will receive an alarm requesting the crew to attend to the navigation bridge. At the same time the speed is reduced to a minimum or stopped. Following that each vessel will proceed on manual individual manoeuvring. For downstream going vessel trains no solution is implemented technically. The procedure will be described in a report.	Possible to demonstrate in simulations.
1.1.2	Loss of propulsion of one of the follower ships	Y	Technical solution to be implemented. All vessels in the train will receive an alarm requesting the crew to attend to the navigation bridge. The leader vessel will decide for the vessels in front of the emergency vessel if they slow down. The	Possible to demonstrate in simulations.

ID.	HAZID description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
			vessels behind the emergency vessel will be reduced to minimum speed or be stopped. The ships behind the emergency vessel will continue manually and contact (VHF) the leader vessel if they can re-join the train. For downstream going vessel trains no solution is implemented technically. The procedure will be described in a report.	
1.1.3	Loss of steering gear on lead ship	See 1.1.1		
1.1.4	Loss of steering gear on follower ship	See 1.1.2		
1.1.5	Heavy traffic	Y	Technical solution implemented. Follower ships will follow the same path as the leader vessel. This will not always be possible for instance with encountering traffic, in that case the leader vessel will sound an alarm on the relevant follower vessels. Solutions to that will	Possible to demonstrate in simulations. Path following approach will be possible to demonstrate on model and full scale too.

ID.	HAZID description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
			not be implemented in a technical solution but the procedure will be described in a report.	
1.1.6	Narrow, shallow, low waters and / or bendy waterways	Y	Technical solution implemented. Follower ships will follow the same path as the leader vessel. The captain of the leader vessel will remain in the fairway, he is responsible for the path when leaving the fairway.	Possible to demonstrate in simulations and model scale.
1.1.7	Passing bridge	Y	Technical solution implemented. Follower ships will follow the same path as the leader vessel.	Possible to demonstrate in simulations, model scale and at full scale.
1.1.8	Floating objects	See 1.1.5		
1.1.9	Marine wildlife (e.g. whales, squids, carcasses)	N	See 1.1.5	We do not expect whales in the river.
1.1.10	Different ships manoeuvring capabilities	See 1.1.6 We assume all vessels will comply to regulations regarding manoeuvring.		

ID.	**HAZID description**	**WP 3 solution?** **(Y/N)**	**If no, why not?** **If yes, how? (technical solution / procedure and solution description**	**Demonstration (simulation / model / full scale)**
		ARG control system on follower vessels checks for navigability of the path, if this is not possible an alarm will sound on follower vessel and leader vessel.		
1.1.11	Different ships speed	Y	Vessels with very similar speeds will be in the same train. If the speed is much lower, the vessel will not be allowed in the train. The slowest vessel dictates the speed of the train. Follower vessels can announce that they cannot follow anymore, they will then have the possibility leave the train or the leader vessel reduces the speed of the complete train.	Possible to demonstrate in simulations
2.1.1	High winds	Y	Technical solution will be implemented. Alarm will be sent to the leader vessel and on the vessel itself if one of the vessels have difficulty keeping the path (for instance if you are off the path more than 10 meters) with the automated steering.	Possible to demonstrate in simulations
2.1.2	Heavy rain	N	We do not believe this affects the manoeuvring of the vessel train.	No
2.1.3	Low visibility			

ID.	HAZID description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
2.1.4	Icing		If the leader vessel does not think it is safe to keep manoeuvring as a train, he will sound an alarm on the follower vessels to take over control.	
2.2.1	Strong current	See 2.1.1		
2.2.2	Swell			
2.2.3	High waves			
2.2.4	Tide			
3.1.1	Actuator / Sensor failure ship – shore connection	N	There is no ship – shore connection. In case of ship-shore connection for remotely controlled vessels, solutions for remotely controlled vessels should be implemented.	
3.2.1	LS-FS connection actuator/sensor failure	N	The leader vessel is not controlling the engine and rudders of the follower vessels directly. In case of a failure see 1.1.2 and 1.1.4	No.

ID.	**HAZID description**	**WP 3 solution?** **(Y/N)**	**If no, why not?** **If yes, how? (technical solution / procedure and solution description**	**Demonstration (simulation / model / full scale)**
3.2.2	LS-FS connection	Y	Technical solution implemented Connection between vessels is monitored by both the leader vessel and the follower vessel. In case of loss of connection both the leader vessel and follower vessel will identify this themselves and an alarm will sound to take over control.	Probably not all aspects. To be discussed with demonstrator leader
3.3	Failure in position fixing	Y	Technical solution implemented. If the GPS connection is lost for too long an alarm will sound on the leader and relevant follower vessel. Follower vessel will take over control.	
3.4	Failure in detection of small objects	N	If we do not detect we will crash into it. Same as for any other ship.	
3.5	Failure in detection of ship / buoy / navigation marks lights, sound and shapes			
3.6	Communication failure with other ships	See 3.2.2		

ID.	HAZID description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
3.7	Failure of ship's IT infrastructure			
3.8	Failure to drop anchor when drifting	See 1.1.1 and 1.1.2 (dropping anchor is not a preferred solution to stop the vessels)		
4.1	Fire on lead ship	N	Fire / flooding alarm will sound and crew is alerted to take action (this is already in place on ships). One of the actions is to decide how to continue in the vessel train.	No.
4.2	Fire on follower ship			
4.3	Flood on lead ship			
4.4	Flood on follower ship			
4.5	Abandon lead ship	See 4.1, 4.2, 4.3 and 4.4		
4.6	Abandon follower ship			
4.7	Man overboard on lead ship	Y/N	Together with the WP 5 input on regulations, a solution will be described in a report how to cope with this to prevent follower vessels to hit the train.	No.
4.8	Man overboard on follower ship			
4.9	Loss of intact stability	See 4.3 and 4.4		
4.10	Temporary loss of electricity	See 1.1.1 and 1.1.2		
4.11	Permanent loss of electricity			

ID.	HAZID description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
5.1	No update (e.g. of nautical publications, weather forecasts...)	N	Offline task, nothing from WP 3 required.	
5.2	No input of voyage plan			
5.3	Incorrect remote monitoring and control (e.g. through situation unawareness, data misinterpretation, SCC capacity overload)	Not relevant to operation of vessel train		
5.4	Incorrect remote maintenance			
5.5	Incorrect maintenance of the VT control system onboard the lead ship	Y	A proposal for version keeping and updating of the software will be written in a report.	
5.6	Incorrect maintenance of the VT control system onboard the follower			
5.7.1	Crew/operator fatigue	N	No automated monitoring of condition of crew is done.	
5.7.2	Crew/operator work overloading			

Special Manoeuvres

ID	Manoeuvre description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
a	Docking and undocking at terminals	N	This will not be done with the vessel being part of the vessel train.	N
b	Passing Locks	N	Passing locks will not be done automatically. When approaching a lock the crew is alarmed. It is up to WP 2 to see if it is a business case to wait and continue as a train.	N
c	Joining & leaving the train	Y	A procedure to ask and accept joining the vessel train will be developed. Each vessel will be manually controlled until both the leader and follower vessels accept the vessel is in the train and the vessel is in position. Procedures will be written in a report.	To be discussed where possible.
d, e, f	Normal sailing in train while under control of the VT system	Y	See all of the above.	Yes in all demonstrators
g	Loss of control in train while under control of the VT control system	See 1.1.1 and 1.1.2		
h	Anchoring in case of calamity	N	This is not a preferred solution in case of a calamity.	No.

ID	Manoeuvre description	WP 3 solution? (Y/N)	If no, why not? If yes, how? (technical solution / procedure and solution description	Demonstration (simulation / model / full scale)
i	Countering calamities including emergency manoeuvres	See 1.1.5		
j	Embarking & disembarking vessels	N	Not automated, the leader vessel can slow the train down to allow for embarking and disembarking.	
k	Navigating outside the train	N	This is not part of the project as we only look at navigation inside the train.	
l	Loading and unloading cargo	N	This will not be done with the vessel being part of the vessel train.	