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Waterborne Platooning

A Viability Study of the Vessel Train Concept

Alina P. Colling

WATERBORNE PLATOONING – A VIABILITY STUDY OF THE VESSEL TRAIN CONCEPT

Dissertation

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at Delft University of Technology
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To Matei, Laura and my parents.

Thank you for the support and love.

An artist impression by: Marlies Rintelmann

PREFACE

The last four years have certainly not been the way I anticipated them when I embarked on this journey. This had largely to do with a global pandemic, but also with the fact that I learned to understand what research and realistic expectations are. I feel very fortunate to have been part of an international consortium such as NOVIMAR was from its opening event in June 2017 to its closing event in October 2021.

I would like to start by thanking Robert for entrusting me to work on this research. I am grateful for your patience, freedom and the input you have given me throughout this journey. Thank you for staying engaged until the finish line. My gratitude also goes to Edwin for his speedy feedback and collaborations be it for deliverables, stakeholder meetings or my thesis. I also feel blessed to have been able to engage with so many knowledgeable people that were the NOVIMAR partners.

My time researching at the university was also very much shaped by my colleagues at the MTT Department in particular in SDPO. Early on in the PhD Chris gave me the opportunity to be involved in some side projects, which guided me through my first collaborative papers and where I learned a great deal. Thank you for that Chris. Sharing the office at the end of the hallway, B-3-330, with Sietske, Carmen and Harleigh have led to truly memorable moments, countless quotes and discussions over homes, pets, life and occasionally some research as well. I also very much appreciate the time each of you have given to help proofread my conference and journal articles.
Thank you to all other MTT and SDPO PhDs colleagues for sharing your research and discussing our experiences along the journey, so that I was always reminded that I was not alone on the journey. In particular thank you to Qinqin, Zongchen and Pranav for sharing new perspectives and teaching me more about Chinese and Indian culture. I cannot miss acknowledging Erik, for always being available for a coffee chat, IT support and for keeping me updated on the happenings when I returned from my trips or my longer periods away.

Early on in my PhD I was truly immersed in Dutch culture while being part of the BSS board II, which together with the dancing I learned there, became a large part of my motivation and helped me have a good work-life balance in the first two years. During COVID my attention shifted towards the 3ME PhD council. Throughout this challenging time, we managed to flourish into a well working team, even though it was mostly virtual and only got to meet once in person. I would like to thank every single member of the council for the cooperation and hard work you put in to support our PhD community and for giving me the opportunity to learn and grow as the president.

Undoubtedly, my friends in Delft are the main reason for having experienced such a memorable time. All the laughs, cries, animated discussions, cocktails, dinners, dances, runs, escape rooms, game nights, cinema visits and shared adventures during tips. Thank you: Mohsen for your loyalty and inspiring confidence; Leonoor for motivating me with your hard work and resourcefulness; Mousa for being a social anchor; Kaushik for your positivity; Marieke for your open-mindedness; Cantika for your groundedness and curiosity; Pranav for motivating me to network and Fardin for your willingness to debate. Each of you helped me reflect on my life and actions regularly. Claudia and Sai, you have given me reality checks with the non-academic world on a regular basis, and I am grateful for that. Tris, Maria and Catherine, I am grateful for staying in touch and thank you for always being supportive from the far.

I am more than appreciative for all the opportunities my parents have given me, that have certainly lead me to complete this PhD! Without the support you provided and the grit you instilled in me I would not be at this stage in my life. I felt very fortunate to have been able to live with you during the majority of the COVID time. Thank you for accommodating Matei and me for so many months. It was not only great to live under the same roof again, but it also certainly ensured my timely completion of this research, by allowing me to purely focus on my work. Laura, the journey along the PhD made me take note that we are more similar than I realized. I have learned to heed your advice. Thank you for sending me the most appropriate card anyone could have found to describe my PhD research at a time where it was sorely needed!

Last but not least, Matei. You have been the person that has been following my journey the closest and have seen all the ups and downs. It helped very much to have someone by my side that has walked this path before me, to put some perspective into my reasoning and to listen. Thank you for being my travel buddy and the person I can count on no matter the circumstances. I am so very much looking forward to continuing our adventure together in Norway!

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Alina Colling
Delft, September 2021

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LIST OF NOTATIONS

A1:	operating regime that allows 14 h operations
A2:	operating regime that allows 18 h operations
a:	FV sailing time restriction outside of VT
B:	operating regime that allows continuous operations or vessel beam (m)
BC:	Base Case
b_r:	number of bridges on the route
b_o:	maximum required bridge opening along the route
C_b:	block coefficient
CBA:	Cost Benefit Analysis
C_c:	crew cost (€/ year)
c_{CO_2}:	CO2 content per litre of fuel (t/l)
c_{con}:	cost of road congestion (€/v-km)
$\mathrm{C}_{\mathrm{construction}}$:	construction cost of a vessel (€)
C_{Ex}:	external cost of pollutant at p (€)
$C_{Ex_{CO_2}}$:	external cost of pollutant CO2 emission (€)
C_{fee}:	annual VT contribution fee cost (€/ year)
$\mathrm{c}_{\mathrm{fixed}}$:	fixed cost coefficient
C_{fuel}:	fuel cost (€)
C_{FV}:	annual follower vessel cost (€/year)
c_{int}:	bonus payment for international operations (€/day)
$C_{int.soc}$:	transport cost including internalization of emission cost (€)
C_{LV}:	annual LV cost created by providing the leading service (€)
$\mathrm{C}_{\mathrm{maintenance}}$:	cost of vessel maintenance (€)
C_{mc}:	cost of monitoring crew (€)
C_p:	cost of the pollutant (€/t)
C_R:	annual reference vessel cost (€)
C_{shore}:	shore coordination cost(€)
$\mathrm{c}_{\mathrm{variable}}$:	variable cost coefficient
C_{VT}:	annual VT technology cost (€)
C_{VTO}:	VT operator cost (€)
c_w:	annual wage of crew role j (€/year)
$\mathrm{c}_{\alpha,\beta,\gamma}$:	building cost coefficients for dry bulk vessels
D:	annual number of operating days or propeller diameter (m)
D_{g}:	average daily demand (t/day)
d:	VT trip distance (km)
d_g:	variance of daily demand (t^2 /day)
d_{aft}:	spacing between VT aft and bridge at closing initiation (m)
d_{FV}:	FV distance (km) i.e. $d_{out} + d_{in}$
d_{front}:	spacing in front of VT when the bridge should already be fully opened (m)
d_{in}:	distance of the FV spent in the VT (km)
d_{out}:	distance the FV spends sailing on its own (km)
d_r:	distance between road vehicles (% vehicle length)
d_{sw}:	safety distance factor between vessels
ECDIS:	Electronic Chart Display and Information System
e_p:	emission rate of the respective pollutant in (g/kWh)

List of Notations

F_s:	total available fleet size
FV:	Follower Vessel
f_c:	rate of fuel consumption (t/h)
GT:	gross tonnage
h_c:	holding cost (fraction of value /year)
i:	original sailing regime of the reference vessel (A1/A2 B)
I:	departure interval of the LVs (h)
IENC:	Inland Electronic Navigation Charts
IWT:	Inland Waterway Transport
K:	safety factor
$1 + k_1$:	form factor
k_1:	pre-incident density (vehicles/km)
k_2:	incident density (vehicles/km)
k_c:	capacity (dissipation) density (vehicles/km)
k_j:	jam (incident) density (vehicles/km)
L:	vessel length (m) or lead time (days)
l:	variance of lead time (days^2)
LV:	Lead Vessel
L_{LV}:	LV length (m)
L_i:	length of FV i
M:	required fleet share
m:	market share of VT implementation (%)
MCR:	maximum continuous rating
n:	number of follower vessels in VT
n_c:	number of crew members at role j
η_d:	drive train efficiency
η_p:	propeller efficiency
η_H:	hull efficiency
n_{FV}:	required number of FVs per LV
n_{LV}:	number of LV in the transport system
n_{min}:	number of FVs in VT to make it economically viable
o_x:	number of open bridges at a specific section x along the route
O:	total annual operating hours (h)
P:	power requirements at operating speed (kW)
p:	array of pollutant (CO, HC, PM, NOx, SOx, CO2)
P_b:	effective break power of engine
P_{br}:	relative break power
P_E:	effective power
P_{eng}:	installed power (kW)
p_{ex}:	percentage employment-related cost
P_{FV}:	annual productivity of the FV (t/year)
p_{fuel}:	fuel price (€/t)
p_m:	profit margin of VT operator
P_p:	effective propulsion power (kW)
P_R:	annual productivity of the reference vessel (t/year)
P_s	effective shaft power (kW)
p_s:	number of annual single vessel passages
Q:	maximum allowed queue length until next crossing (km)
q_1:	pre-incident flow rate (vehicles/h)
q_2:	incident flow rate (vehicles/h)
q_3:	capacity flow rate (= qmax) (vehicle/h)
q_{max}:	maximum flow rate (vehicle/h)

R:	resistance (N) or reference vessel conditions
R_A:	model-ship correlation resistance (kN)
R_{app}:	resistance of appendages (kN)
R_F:	frictional resistance (kN)
R_{total}:	total resistance of a ship (kN)
R_w:	wave-making resistance (kN)
r:	number of roles the crew is composed of
r_h:	operating restrictions due to holidays (days)
r_w:	operating restrictions due to high/low water (days)
s:	length of the section between bridges
SCBA:	Social Cost Benefit Analysis
SFC_{eng}:	specific fuel consumption of the engine (g/kWh)
$SFC_{optimal}$:	specific fuel consumption at 75% MRC (g/kWh)
SFC_{added}:	added specific fuel consumption (g/kWh)
S_{FV}:	FV net savings (€)
s_{bo}:	number of saved bridge opening per year
s_{con}:	savings due to congestion reduction (€)
s_w:	waiting time savings for road users (h)
$\mathrm{St}_{\mathrm{transit}}$:	stock in transit cost (€)
$\mathrm{St}_{\mathrm{safety}}$:	safety stock cost (€)
T:	vessel draft (m)
T_{B+A1}:	annual operating days of the FV in/outside of the VT (h/year)
T_B:	annual operating hours at operating regime B (h/year)
T_i:	annual operating hours at operating regime i (h/ year)
TSC:	Transition Stage Case
t:	trip time (h) or thrust deduction factor
t_1:	incident duration (h)
t_2:	queue dissipation time (h)
t_l:	time for lock passage (h)
t_p:	time spent in port (h)
t_{p_s}:	time for a single vessel passage (h)
t_r:	time spent resting (h)
t_s:	time spend sailing (h)
t_t:	return trip time (h)
t_w:	VT waiting time due to VT departure (h)
$t_{o\&c}$:	opening and closing time of the bridge (h)
t_{VT}:	opening time for the VT bridge passage (h)
u_1:	queue build-up rate (km/h)
u_2:	queue dissipation rate (km/h)
V:	cargo capacity of the vessel (t)
VT:	Vessel Train
VT_p:	number of participants
v:	vessel velocity (km/h) or value of the good (€/t)
v_c:	speed of river current (km/h)
v_{VT}:	operating speed of VT (km/h)
v_R:	operating speed of the reference vessel (km/h)
v_{lim}:	limited operating speed of VT at bridge passage (km/h)
w:	wake fraction
X:	number of propellers
Z:	age of the vessel
Δ_{crew}:	change in annual crew cost (€)

Δ_{fuel}: change in annual fuel cost (€)
Δw: speed corrector
ΔC_{st}: change in stock cost due to VT operation changes (€)
∇: the displacement of the vessel
ρ: density of MGO or MDO (~0.89 t/m3)

EXECUTIVE SUMMARY

Introduction

The research presented in this thesis is a viability study of the Vessel Train (VT) concept that identifies the boundary conditions and the operating requirements needed for its implementation. The VT waterborne platooning concept consists of a fully manned lead vessel (LV) that is digitally linked to a number of follower vessels (FV), for which it assumes navigational control. Moving the navigational tasks to the LVs, allows the FVs to reduce the size of their crew, and therefore also lower the associated crew cost. Whilst part of the train, the remaining crew on the FVs can either rest, or take care of non-navigational related tasks on board. The FV crew is also able to navigate the vessel on its own, for a short period of time, to its destination, meaning, the FVs can tag along, and leave the train when needed.

The VT concept aims to reduce the operating cost of the FVs. This improves the competitiveness of waterborne transportation, whilst simultaneously addressing crew shortages in waterborne transportation. The research in this thesis aims to answer the following question:

What are the conditions for economic viability of the Vessel Train?

This is answered by addressing the following five sub-questions:

1. What aspects of the vessel operations are altered when sailing in a platoon?
2. What are the VT properties influenced by in *the IWT and the Short Sea Sector?*
3. How can the viability of a VT transport system be assessed?
4. How do variations of the VT properties influence its performance?
5. How do geographical and spatial differences influence the possible implementations of the concept and its viability?

In this summary, the answers to these sub-questions are provided within the chapter descriptions. Which means sub-question 1 and 2 are answered as part of the background section and chapter 3 summary; sub-question 3 is answered as part of the chapter 4 summary; sub- question 4 is answered as part of the chapter 5 summary, and the final sub-question is answered in the chapter 6 summary.

Background

The background chapter starts by providing an overview of the automation technology development of the short sea and inland sectors. Here, two paths towards achieving autonomous waterborne transport are introduced: autonomy through incremental vessel type implementation, and incremental technology development. Afterwards, the focus shifts to the platooning concept. First, prior research on waterborne platooning is presented, before diving into a comparison between truck and vessel platooning.

The comparison identifies business cases, accessibility, traffic safety, environmental and economic similarities and differences between the two applications. The most important differences are identified within the business model; where truck platooning gains financial benefits through fuel cost savings. This is something that cannot be achieved through waterborne platooning. Instead, the focal point of waterborne application lies in cost savings achieved by needing fewer crew members. Both transport modes achieve improvements in productivity through the use of platoons, one by switching leading vehicles, whilst the other ensures that the LV allows FV to sail through resting times in restricted operating regimes. Lastly, waterborne platooning is a simpler application of the concept, as aspects like platoon matching, are less complex with fewer route options and transport units.

Identifying VT Features

Chapter 3 identifies the VT specific features, as well as the business model features, that need to be considered when deciding on a VT service concept. The main VT specific features, related to the operations, are concerning slower VT operating speeds that have to adapt to the slowest member of the train, and the idle times of vessels. Continuously operating vessels, i.e. short sea vessels or inland vessels operating at a B regime, experience longer waiting times before departure. Inland vessels that currently operate under a restricted operating regime, counter this additional idle time, by sailing through their resting periods, improving their productivity. Another characteristic feature of the VT, is a reduced crew. The automation of navigational tasks only expects to reduce the short sea crew size by three crew members (a second officer and two deck boys), which means with two rotating crews, a reduction of six crew members annually. In inland navigation, the crew size reduction is set by the CCNR minimum crewing requirements. This indicates that at most, four crew members can be reduced, but dependent on the reference vessel type and the operating regime, this can mean there are no crew member reductions and there is only an improvement in productivity. The fact that some crew members remain on board, allows the FVs to operate under their own navigational control, for a short period of time outside of the VT. The removal of crew members means that the vessels who participate in the VT and operate continuously, also lose flexibility and rely on the departure and destinations of the LVs.

The automation level of the VT control system is also a vital part of the VT features, as without it, the platoon cannot be created. Depending on the situation, the level of automation of the system reaches up to level 3; this is identified as conditional autonomy. The control system is mainly composed of the RadarPilotVT and the ArgoTrackPilotVT, which operate in either assisted guidance or automatic guidance mode, to be able to deal with static and dynamic encounters. The investment cost for the control system is expected to be € 80.000 with the potential requirement of additional monitoring crew on board of the LV, in the early stages of the concept's implementation. The LV type, be it a cargo-carrying or a dedicated LV, is also a very important aspect of the VT. A dedicated LV, a vessel with the sole purpose to lead trains, needs to compensate its entire operating cost by the FV contribution fees, whereas a cargo LV uses the leading service as a secondary source of income. This means the dedicated LV is less likely to achieve an economically viable condition for all parties. To perform special manoeuvres such as lock passages, it is expected that the FV crew takes back this responsibility.

To be able to set up the VT viability assessment, and the VT business model features, including the business structure, the service concept and the contract length have to be considered. The business model has to ensure a reliable, predictable, but also as flexible a service as possible. Three main business structures were considered in the VT development: 1) The company-internal VT coordination, 2) the platform based- leading service, and 3) the peer-to-peer VT service. In terms of the service concept, there are three alternatives: An on-demand service, i.e. tramp operations where the FV can tag along if the VT were to pass by at a suitable moment, a prescheduled service, i.e. liner operations, or a custom pick up on-call service- similar to an Uber service. The final business feature related to the length of the contract is only relevant for the leading as a service as it pertains to the payment schemes. Only a long term contract is able to accommodate both continuously operating vessels and vessel currently operating under a restricted operating regime. Hence, the most appropriate set-up for the VT that allows for a reliable and predictable service, is a prescheduled VT in which the individual trains are led by cargo-carrying LV. The VT concept is assessed for both a single company business structure and a third party platform service, dependent on the business structure of the application area.

The Vessel Train Cost and Assessment Model

Chapter 4 explains the foundation of the VT cost model and presents the assessment structure, as well as the detailed calculations. The model's main target is to provide results that allow the economic viability of the VT concept. The economically viable conditions are achieved when both of the following conditions are met:

1) the transport cost of the VT user is equal or lower than that of the currently sailing reference vessels;
2) the combined cost-saving of the FVs are greater than the cost created by providing the VT service.

These economically viable conditions are important from the perspective of the direct stakeholders, i.e. the VT operator and the FV operator. However, the economic viability also has to be assessed from the perspective of the shippers and society as a whole. If this is not beneficial for both parties, this becomes more challenging to implement.
In this section, a literature review of the social cost-benefit analysis has been conducted to review a large number of cost elements. A filtering method is then applied to ensure only the most relevant cost elements for the VT concept, are included in the model. These include depreciation, investment, insurance, crew, maintenance, fuel, VT dues, emission and cargo-related cost. The detailed calculations for each of these cost elements are described for both the short sea, and the inland application. Finally, the last section of this chapter verifies and validates the core methodologies used in this model.

Application Cases Studies

Chapter 5 focuses on the application cases of the two sectors. The first part of the chapter states the common factors found in both cases: the VT control system cost, the single company versus platform based cost, two sub-cases that mimic different maturity levels of the VT technologies; the base case (BC) and the transition stage case) and the cargo-related parameters.

The short sea application case is set on a 926 km trip between Hamburg and Le Havre. This vessel train route passes by the largest European ports and is therefore likely to have vessels joining the train, for at least part of the journey. The vessels assessed as part of the case study, aim to mimic different segments by assuming four types of vessels: a large and fast vessel (12.600 t, 34,2 km/h), a fast and small vessel (9.100 t, 30,5 km/h), a slow and large vessel (14.000 t, 24,1 km/h) and a small and slow vessel (2.100 t, 21,3 km/h).

The results comment on the effects of the productivity change, the total cost savings, as well as the cost savings per tkm and the required fleet share made up by the liner system participants. In the short sea case, the main benefit is not through crew cost reduction, but rather through the fuel savings of the slow steaming of the vessels. This means, that under fully matured VT technology, the faster vessels benefit much more by achieving up to 26 % cost reduction, whilst smaller and slower vessels are able to achieve at most a 3 % reduction. In the Transition Stage Case, that assessed the early-stage implementation requirements, the cost reductions reduce down to 19 % for faster and larger vessels, whilst smaller vessels do not achieve viability, as they experience a cost increase compared to the reference vessels. The internalization of external emission cost enhances the cost-benefit for the FV operators, however, when

the logistics cost are considered, these cancel out the savings created by the VT implementation. Furthermore, the results of the sensitivity analysis, were not able to convincingly conclude that the VT benefits from only automating the navigation tasks are large enough to guarantee an application of the VT, for all vessel types in the short sea sector.
In contrast, the inland application case is able to demonstrate viability. The inland application case is set on a 325 km trip between Antwerp and Duisburg, which is the waterway with the densest traffic and greatest cargo volumes in Europe. The three vessels types that are investigated in the case study are a CEMT class V, IV and II vessel.

A VT applied to the IWT sector, manages to achieve a maximum transport cost reduction of between 30 % and 51 %, depending on the vessel type and operating regime, of the reference vessel conditions. These cost reductions are either achieved through crew cost-savings or improvements in productivity of the vessels, allowing them to sail through resting times. The vessel savings can far surpass the VT compensation cost that needs to be paid to the VT operator, which means a single FV is sufficient to achieve economic viability. This means that the entire liner service requires a total of 26 participants, which are less than 1 % of the currently operating self-propelled vessel fleet on the Rhine. Such as fleet share is realistic for the implementation of the concept. The TSC conditions causes the cost reduction to be lower, with at most 17 % to 32 % cost reduction, and the minimum number of FVs per VT to rise to at least two, and up to five FVs per VT. However, overall, the total fleet share still stays below 1%. The sensitivity analysis assesses different influence factors, and concludes that compared to a reference vessel operating at a B regime, the influence factors rank as follows: 1) Crew cost, 2) VT operator cost, 3) departure intervals, 4) fuel price fluctuations, 5) route length. Compared to a reference vessel, that operates under an A1 operating regime, the importance of these factors change to the following: 1) route length, 2) crew cost, 3) VT operator cost, 4) departure interval 5) fuel price fluctuations.

Impact of the Geographical and Spatial Context on the VT Viability

The focal points of this chapter are the comparison of the geographical application differences in the Danube and the Rhine corridors and determining the attractiveness of smaller inland vessels by assessing the VT's implementation in urban areas, when interacting with bridges. The final part of the chapter, comments on the global application potential of the VT concept, by providing an overview of the inland navigation sector.

The main geographical factors, when comparing the Rhine and the Danube corridor, are the route length, the crew cost and the traffic density on the rivers. The crew cost savings in the Danube are expected to be 80% lower than the ones found on the Rhine. This can be compensated for by long distances and frequent departure intervals. However, the increased supply of self-propelled vessel transport volumes that would be created by such a transport system is much more than the demand currently requires. Further, inconveniently spaced locks that require the FV crew to take over navigational responsibility every few hours, can eliminate the navigation benefit created by the VT.

To investigate urban area penetration with the VT, a case study of Amsterdam in investigated. It concludes that spatial limitations from bridge passage in urban areas require road traffic to at least allow a traffic jam creation of 400 m with a maximum traffic intensity of 550 vehicles/h. The waterborne infrastructure should also allow for a minimum bridge spacing of 400 m, so that a VT, with at least one FV, can pass ly, without creating additional traffic obstructions.

In a global comparison of waterways, aside from the European waterway, only the US and Chinese traffic densities, fleet size, and technological developments, would allow for the potential implementation of the VT. It has been concluded that even though the navigation on the Yangtze can be an appropriate area for the VT implementation, the Rhine corridor is the most appropriate location. Due to its high wages, current regulatory set-up that ensures for productivity increases, and a governmental incentive to subsidize technological development in the IWT sector.

Conclusions and Points for Further Research

This final chapter of the thesis answers the individual sub-questions that were stated in the introduction. The answers to the individual sub-questions are provided within the summaries of the chapters.

The conclusion states viable business cases can be identified for the short sea and inland sector, through providing a liner service with cargo carrying LVs. This allow the FVs to reduce their transport cost, via crew cost savings or through improving productivity. The short sea cases can however not guarantee viability for all types of vessels and does not create its main benefit through the crew cost reduction but through fuel savings of slow steaming operations. The IWT sector is more suitable, because it has larger savings for different types of vessels under varying conditions. Yet, the study on geographical influence factors has shown that low crew income along the Danube makes it difficult for the VT to achieve economic viability and needs longer routes with clustered locks passages to be viable. Additionally, a VT can only be implemented in an area with a fleet that is composed of a large number of self-propelled vessels, and a large traffic density.

Even though positive business cases were identified, these cases are not the only requirement for the VT concept implementation. The vessel operator's trust and willingness to cooperate with their competitors in addition to expertise in logistics and platform management are aspects future VT operator needs. Also, knowledge on how to achieve regulatory bodies to approvals for such a business is of impotence for a VT to be able to set-up a VT transport system.

There are several areas for further research, including a more detailed study of the cargo flows in order to estimate a modal shift of the overall network-wide implementation of the VT and the adaptation of the VT concept for push convoys to reach a larger number of potential participants. Regulations also need to be adapted, before some concept steps can be taken towards identifying appropriate cost allocation strategies.

CHAPTER 1: INTRODUCTION

The rising ownership and use of private and commercial road vehicles [1] are causing a worsening of congestion across Europe. In Germany, one of the top five worst-affected countries, drivers waste upwards of 40 h per year in traffic jams, resulting in average congestion costs of around € 3.000 per driver [2]. One way to help alleviate this is to move the cargo that is currently transported via the road, towards another mode of transport.

In contrast to the roads, most waterways are underutilised and have a large potential for additional transport capacity. The cargo transport via ships is less polluting and is more energy-efficient due to the large cargo capacities of vessels [3], [4]. Short sea and inland ships emit on average, respectively 9 % - 17 % less CO_2 and 25 % - 34 % less NO_X than road transport [5]. Achieving a modal shift from road to water can therefore not only help reduce congestion, but also improve the environmental footprint of transported cargo.

To achieve this modal shift, waterborne transport needs to become more competitive, by reducing its transport and logistics cost. This can be achieved by improving the productivity of the vessels or alternatively, by reducing the operation cost, of which crew cost forms a significant part. Automation technologies can help lower the crew cost by reducing the number of tasks that have to be performed by crew members, and thus reducing the size of the crew. In order to achieve this benefit, a waterborne platooning concept referred to as the Vessel Train (VT) is developed, where the navigation tasks of the ships that follow one another in the platoon, are automated.

The research presented in this thesis is a viability study of the Vessel Train concept. It identifies the boundary conditions and the operating requirements for its implementation. This introductory chapter presents the current situation in the European short sea and inland navigation sectors in section 1.1, followed by a description of the waterborne platooning concept in section 1.2. The research questions are provided in section 1.3. and section 1.4., which delineates the scope of the study. The chapter ends in section 1.5. with an outline of the thesis structure.

1.1. Waterborne Transport Challenges Related to the Vessel Train

Inland Waterway Transport (IWT) and Short Sea (SS) shipping are the waterborne transport sectors that are in competition with other transport modes, such as truck and rail transport. The technological advancement of the control systems, as well as the digitalisation of processes, are improving the efficiency and performance of land-based modes of transport. Systems such as automated emergency braking have improved the safety of trucking; topographical adaptive cruise control has reduced the CO_2 emissions, whilst other systems provide support in advanced routing decisions to avoid traffic congestions [6]. These developments have improved the services and competitiveness of road-based transport. In order for waterborne transport to stay competitive, actors within this sector must work towards enhancing processes to cut cost using available technologies.

1.1.1. High Crew Cost

One way to improve the competitiveness of the waterborne transport sector is to reduce the transport cost of vessels. A significant contributor to the operating cost of vessels is the crew cost. This can reach up to 50 % of the cost for seagoing vessels [7] and up to 70 % for inland vessels [8]. Additionally, the shortage of qualified crew members [9]–[11] causes the hiring of crew to become increasingly challenging and expensive [12]. This is due to several factors, including; younger professionals are less interested in spending months on end at sea, or in the inland navigation sector, to live onboard of a vessel [13]. Additionally, the sector is struggling to retain skilled workers. The workforce typically spends less than 10 years on board of vessels, before choosing to move to a shore-based job [14]. It is expected that automation technologies can help reduce to the number of tasks on board of vessels, and with it, reduce the minimum crewing requirements on board [15].

1.1.2. Slow Integration of Technology

The innovations in the waterborne transport sector are not always clearly observable, given the complex interactions of different modules and sub-systems on board of vessels [16]. However, latency in the integration of automation is observed in the maritime sector compared to other transport sectors. This can be accredited to many different reasons. In air transport, a failure can quickly result in a catastrophic event and loss of life, which is less the case in waterborne transport. The lower-risk nature of ships allows for a lack of standardisation. The lack of standards has led vessels, even with similar mission profiles, to be designed with different technical specifications. This makes it more challenging to develop solutions that suit vessels across the entire industry. Another reason, is that smaller commercial perspectives for the development of a technology for the relatively small number of units within a worldwide fleet of about 92 000 ships [17]. In comparison, the millions of trucks on our roads create a much larger commercial incentive for the development of innovations in the road sector. The capital intensity required to purchase a vessel [18] and the long timeframe involved in the construction of newly built vessels, cause the lifespan of vessels to be fairly long with an average age of 20 years [19]. The long lifespan of vessels means that it can take several decades for major automation technologies to reach across the entirety of the waterborne transport sector.

Most vessel operators are only driven to innovate when forced to do so by the implementation of new regulations. The complex ethical issues that need to be resolved with the integration of new technologies cause regulatory change to take a long time to be fully implemented. Technological improvements only occur in increments [16]. This is why innovative concepts like fully autonomous ships [20], [21] will take a long time to develop in the sector. A platooning concept where human operators still have a key role may be a more short-term solution that benefits from new automation technology.

1.2. The Vessel Train Concept

The Vessel Train (VT) waterborne platooning concept consists of a fully manned lead vessel (LV), that is digitally linked to a number of follower vessels (FV), for which it assumes navigational control. Moving the navigational tasks to the LVs allows the FVs to reduce the size of their crew whilst lowering the associated crew cost. Whilst part of the train, the remaining crew on the FVs can either rest or take care of non-navigational related tasks on board. The FV crew is also able to navigate the vessel on its own, for a short period of time to its destination, which means the FVs can join or leave the train when needed, as illustrated in Figure 1.

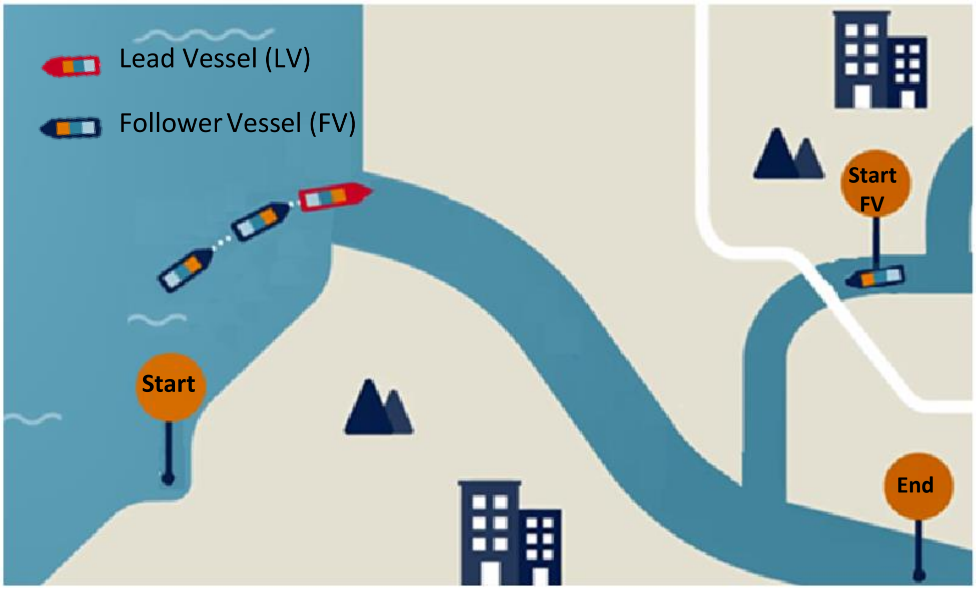


Figure 1: The Vessel Train Concept [22]

The VT bypasses important challenges that fully autonomous ships are facing, whilst still achieving the benefits of reduced crew size. The challenges lie in the ability to obtain situational awareness of the vessel, communication and maintenance tasks [23]. Additionally, it circumvents policy and liability issues in case of accidents, since humans are kept in control of the platoon. The concept can thus be seen as an incremental step to allow existing vessels to transition to a higher level of automation.

In contrast to seagoing ships, inland ships do not have to operate 24 hours per day. They can also choose to only operate 14 or 18 hours per day, which allows them to operate with a smaller crew. If the navigation-related tasks are taken over by the lead vessel, they can keep sailing while the crew is resting, thus allowing 24-hour operations with a crew for only 14 or 18 hours. This implies a very significant productivity increase for the ship.

1.2.1. VT Concept Objectives

The main objective of the concept is to improve the competitiveness of the vessels that use it. This is aimed to be achieved by lowering crew cost, but also by improving the productivity of the vessels, in case of inland ships. Additionally, reducing the crew size addresses the challenge of crew shortages that waterborne transport is currently facing.

The reduction of transport cost, particularly small inland vessels, aims to improve their attractiveness. The objective is to ensure that these vessels are kept operational and enhanced in use to allow waterborne access to smaller waterways closer to urban areas. This can also improve the accessibility, and develops the waterborne service provided. Ultimately, the overall improvement of a ship's competitiveness should be large enough to create a modal shift from road to waterborne transport.

The VT concept was funded and investigated within the framework of a H2020 project called the NOVel Iwt and Maritime transport concept (NOVIMAR). This PhD thesis focuses on establishing the viability of the VT concept in terms of identifying the conditions of economic viability for the VT users and the required number of participants for the VT operators. Therefore, the research solely looks at the waterborne side of the transport chain. Some of the results from the NOVIMAR project are used as input data for this research.

1.3. Research Question

A waterborne platoon can come in many different shapes and application purposes. When developing the Vessel Train a variety of questions arise surrounding the set-up of the train: How do the VT operations compare to conventional waterborne transport operations? Who are the users and the organisers of the VT service? How and where does it operate?

This thesis studies these aspects and identifies the requirements and provides guidelines for the implementation into to existing waterborne transport system. This research is composed of both a design and an assessment of the VT concept.
The main question that is answered is:

What are the conditions for economic viability of the Vessel Train?

To help answer this main question the research is broken down in five research sub-question (RQ). RQ 1 are formulated to be the following:

RQ 1 ***What aspects of the vessel operations are altered when sailing in a platoon?***

The first research sub-question leads to the second, which is aimed at developing an understanding of the challenges created by the operational and business structural changes of the integration of the VT concept. The second sub-question RQ 2 is hence formulated to be:

RQ 2 ***What are the VT properties influenced by in the IWT and the Short Sea Sector?***

These VT properties reach from LV types, over crew size, to individual sailing capabilities of FVs. The awareness of how these VT properties influence one another and are influenced by external factors forms the foundation to build an assessment model. This research question also identifies the scope of this research, which is focused on both the short sea and the inland sector. These have been chosen as they are assumed to have different operating conditions and thus having different conditions of viability.
The second sub-question asks:

RQ 3 ***How can the viability of a VT transport system be assessed?***

The answer to this question provides the performance indicators of the concept, as well as the review and selection of relevant cost models. Here, welfare economic factors are also taken into consideration in order to determine the external costs of the transport system. This sub-study concludes by presenting the calculation methods of the VT cost model that allows the viability of various case studies and scenarios to be assessed and hence solve RQ4.

RQ 4 ***How do variations of the VT properties influence its performance?***

The answer to RQ 4 studies the results of case study applications for the short sea shipping and IWT sector, which include the VT viability requirements. These viability requirements include operating restrictions ranging from identifying the viable operating distance, number of participants and departure interval to the required market share. Furthermore, this part of the thesis also presents a sensitivity analysis of the VT cost model results in order to understand the effects of uncertainties surrounding the input data of the case studies.

The final research sub-question broadens the application focus of the concept and recognises how different geographical locations may hinder or aid the concept's implementation. RQ 5 is worded as:

RQ 5 ***How do geographical and spatial differences influence the possible implementations of the concept and its viability?***

The answer to this question includes geographical differences in terms of countries/regions of operations and addresses infrastructural challenges such as dealing with bridge passage in urban areas.

1.4. Contribution

This thesis has scientific contributions to the development of a new transport system, but also managerial contributions for a potential VT implementation. Each of these contributions is explained in this section.

1.4.1. Scientific Contribution

The scientific contribution of this research lies within the investigation of a new application concept for the waterborne transport mode. The research identifies the main factors and drivers for the implementation of the waterborne platooning concept that were not known before. This research proposes a design for the set-up of this concept that considerations multi-disciplinary aspects. It is assessed the concept's performance in a structured manner using a project assessment methodology and has recorded the viable and non-viable operations. The research thus uses a scientific approach that breaks a complex problem down into its most important components. Conference articles [24] and [25] have been written that describes the new characteristics and expectations of the concept.

The study of the technical viability of road-based platooning and the truck fleet coordination for these platoons has been extensively studied [26]–[30]. Truck platooning, however, has a different business environment than waterborne platooning. Truck platooning is taken as an inspiration to learn from for the waterborne application. This thesis contributes to the field of the general platooning concept research by identifying the differences between the road and the waterborne application of the concept. Waterborne platooning focuses on the crew size reduction rather than the fuel cost savings as chapter 2.3 elaborates.

There is existing research on multi-vessel co-operation in both the IWT [31]–[34] and the sea going transport sector [35]–[37] that resembles the application of the VT concept. Yet, the main focus of the existing body of literature deals with technological developments such as the control system of autonomous vessels, the hydrodynamics, the wave-making resistance reduction and the improvement of safety when moving in artic waters. This research adds to the excising research by not only focusing on the technological side but also considering the economics of this system by looking into the potential cost savings of this new concept. This economic side of waterborne platooning has not yet been investigated by any prior research. Two scientific articles were published which address the economic viability for the short sea [38] and the inland sector [39].

Several innovation projects have looked at improving the inland navigation sector by means of adapted barge concepts [40], [41] which have similar aims to the VT concept. The VT, however, focuses on the application of self-propelled vessels, hence targeting different markets and businesses. This research builds upon some of the main inland navigation cost models [8], [41], [42], and short sea cost models [12], [43] which are adapted to implement the VT characteristics. Furthermore, many of these IWT concepts are directed exclusively towards the most developed waterways in Belgium and Netherlands. Thereby, another scientific contribution of this research is the investigation of the differences in implementation potential between the Rhine and the Danube corridor in [44] and even other global areas in chapter 6.4.

A more detailed description of the related background work mentioned in this section is provided in chapter 2. The scientific contribution can thus be summarized in three journal publications and six conference publications that are listed at the end of this thesis on page 165, as well as eight NOVIMAR deliverables [45]–[52].

1.4.2. Managerial Contribution

The results obtained from this research can also be used with a managerial purpose, guiding businesses for the market uptake of the VT concept. Additionally, this research is aimed to raise awareness towards policy makers, of challenges the incremental technology implementation of this autonomous navigation system entails to create viable business conditions.

1.5. Scope of the Study

The scope of this research includes the assessment of the waterborne platoon viability for self-propelled cargo vessels operating in European inland and coastal waters. This excludes the use of all other types of self-propelled vessels such as service vessels or deep-sea vessels. While an explanation of the basic working of the control system is provided in this manuscript to aid the reader's comprehension, no further analysis of the control system and its performance is done as part of this research. The economic assessment of the concept assumes that all technical systems related to the VT operations work as intended. The same holds for safety-related issues that may arise through the VT implementation.

This research offers a rationale behind the boundary conditions for VT features such as maximum or minimum VT size, minimum distance spent in the VT, or the maximum number of lock passages that a route should involve. These should be viewed as guidelines to set up their own versions of a VT. The research does not provide ready-made solutions for vessel operators to apply to their business, nor does it help optimise their operations using the VT on specific routes or in different markets.

Finally, a benefit can be obtained through the internalization of the emission cost when a modal shift towards waterborne transport can be achieved with the help of the cost reduction of the VT. Such modal shifts are also related to many market factors related to the overall transport network rather than the VT. This thesis presents specific case studies and does not study the correlation of cargo flows via different modes of transport. Hence, potential modal shift emission benefits achieved through the internalization of these cost are considered out of the scope of this research.

1.6. Outline of the Thesis

Figure 2 illustrates the structure of this thesis. Chapter 2 starts by placing the navigation automation of the VT into the context of technological development in both the SS and the IWT sectors. It continues by revealing an overview of prior research within waterborne platooning and truck platooning applications. Here the parallels, as well as differences between the concept application for the different modes of transport, are identified.

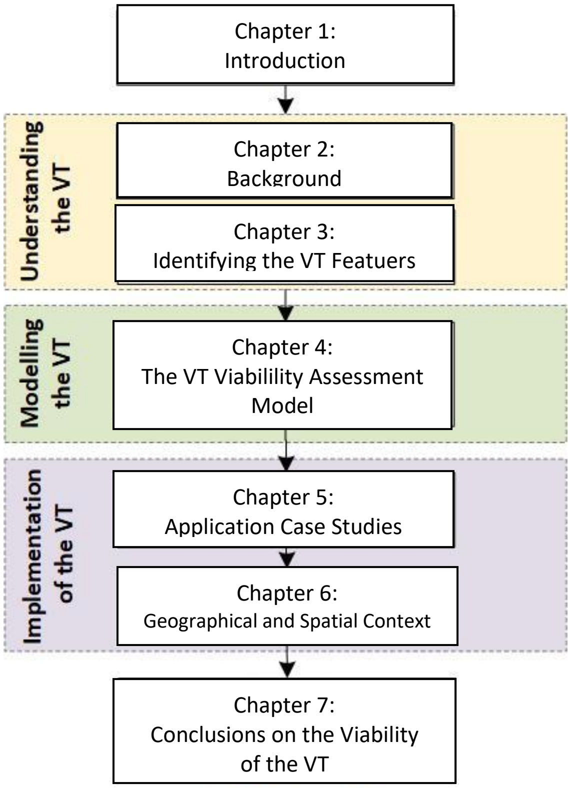


Figure 2: Outline of the Thesis

Chapter 3 explores the VT specific differences to conventionally sailing vessels and clarifies the core implementation differences between the IWT and the SS application. This chapter lies out the advantages and the new challenges of the VT concept, being the added waiting times, the reduced speed, the investment cost requirements and the loss of operating flexibility for continuously operating vessels.

Chapter 4 describes the methodology used in the viability assessment of the concept. It starts by providing a literature overview of cost models and cost-benefit analyses, which have served as a basis for the VT cost model development. In this section, all relevant parameters are discussed and a shortlist of parameters is developed that includes the parameters that are integrated into the VT cost model. The later part of the chapter elaborates on the practical model requirements, the structure and the data sources used. It finishes by providing validation of the model for the current vessel operation.

Chapter 5 applies the model to two main case studies in the IWT and the SS sector with different sub-scenarios that represent increasing development stages of the VT control system. This chapter presents the input data for each case study as well as the results. These results include minimum FV operating distance, the percentage of cost-savings, the required number of participants and an estimate of the total number of crew members saved with the transport system. Each case study also incorporates a sensitivity study to illustrate the effects of different parameter variations and finishes by commenting upon the perspectives of the cargo owner and society. These are addressed by internalising external costs and benefits created with regards to changes in the air pollution and the total logistics cost of cargo caused by the VT operational changes.

Chapter 6 addresses the implications of applying the VT in different geographical locations. This includes a detailed comparison of the geo-economic differences of the Rhine and Danube corridor. Here the changes in the VT operating requirements, i.e. the route length and departure interval are identified that will allow an application of the concept under these different geographical environments. The second topic in chapter 6 addresses the challenges of spatial requirements when penetrating urban areas in VT formation. It presents a case that studies the VT to bridge interactions and its effects on road users. The final aspect of the VT application area study provides a literature overview of the global application potential of the concept. Here the varying potential of inland waterways is vetted. It identifies the VT application potential in the US and Chinese IWT market but concludes that the Rhine corridor is the most appropriate application area for the early-stage implementation of the concept.

Chapter 7 concludes by formulating summarised answers to each of the five research questions. It also identifies the VT concept achievements from this research and lists points for future research. Based on the presented outline, the answers to the five research questions are presented as follows: Research questions 1 and 2 are addressed in chapters 2 and 3, research question 3 is answered in chapter 4, research question 4 can be concluded from the results presented in chapter 5 and research question 5 is focused upon in chapter 6.

CHAPTER 2: BACKGROUND

This chapter provides an overview on the state-of-the-art of automation technology and autonomous vessel development. It helps place the VT concept within the context of these developments. Additionally, the background also addresses the concept of platooning and identities the difference between road- and waterborne platoons.

The structure of the chapter is the following: section 2.1 provides insights into the navigation-related automation developments of the short sea sector, while section 2.2 provides that of the inland navigation sector. Both of these two sections serve to explain the setting of technological development in which the Vessel Train concept is placed. Section 2.3. discusses platoons: both waterborne and road-based. It first describes the related research in waterborne platooning in section 2.3.1 and then compares it to truck platooning. In this last section 2.3.2, the commonalities and differences of five value elements, namely the business case, accessibility, traffic safety, environmental and economic performance, are addressed.

2.1. Automation Technologies in the Short Sea Sector

While short sea shipping operations have existed as a form of waterborne freight transport, it was only in the 2000s that the EU [53] and the US administrations [54] have officially defined the term and given political attention to enhance the use of the sector in order to transfer freight transport from road to water [55]. Since then, the European Commission has put much research funding into developing the Motorways of the Sea [56]. Many authors have contributed work to help understand and improve the competitiveness of short sea shipping. Some focused for instance, on economic cost modelling [57], [43], while others performed environmental impact assessments [58], [59], considered policy issues [60] or researched the human element in crewing [61]. An overview of cost-benefit analysis, created to perform concept viability studies or to provide policy recommendations, is presented in section 4.2.1.

In the last decade, the research focused increasingly on unmanned and autonomous shipping through projects such as the ReVolt [62], the MUNIN project [63], the Yara Birkeland [21] or ongoing Autoship project [64]. These projects are helping to paint a picture of the future opportunities and challenges that increased automation and autonomy can bring to the short sea shipping sector. It has been acknowledged that unmanned navigation operations for short sea shipping are quite demanding as the vessels navigate in fairways that are usually more traffic dense than the open ocean. Some experts predict that short sea operations are going to be remotely controlled by a shore control station [65]. In contrast, others expect the operations to eventually become autonomous, where shore control centers are used to monitor operations and only take over in case of emergencies [66]. Additionally, Kongsberg estimates that operating conditions and technical equipment of only 1/3 of the vessel fleet will allow autonomous operation to be possible in the future [67].

Kongsberg has described two pathways to achieve optimised operation and improved competitiveness of the maritime sector through the implementation of automation or autonomous systems. One way, illustrated in blue in Figure 3, is to disrupt the sector with the implementation of new vessels, that accommodate full automation of all sub-systems aboard. Once such systems and operations have proven themselves on small local vessels such as tugs, the development is expanded to progressively larger vessels and ultimately reaching ocean-going vessels [68]. The second approach, illustrated by the brown line, is to improve existing and new built vessels by incrementally enhancing the automation technology on board. This second path allows the sector to reap the benefits of operational improvements that automation technologies bring and also allows the crew and their training to be progressively adopted. Such developments will start before vessels with a high level of autonomy are going to be commercially available on a large scale. Incremental technology implementation also creates technical challenges concerning the compatibility of different sub-systems and may hence not yield the technically most effective solutions. It can also be more difficult from a commercial perspective to create viable business cases for the automation on individual sub-systems [67]. It is hence important that both of these pathways are evolved. While many of the earlier stated development projects work towards the incremental vessel type implementation, this thesis works towards identifying viable business cases for the incremental technology implementation. The incremental technology is the Trackpilot [69] that forms the core technology of the VT semi-autonomous navigation system. Additionally, fully manned lead vessel of the VT concept keeps the human actor in the loop, ready to interfere and ensure situations are dealt with appropriately to the conditions at hand.

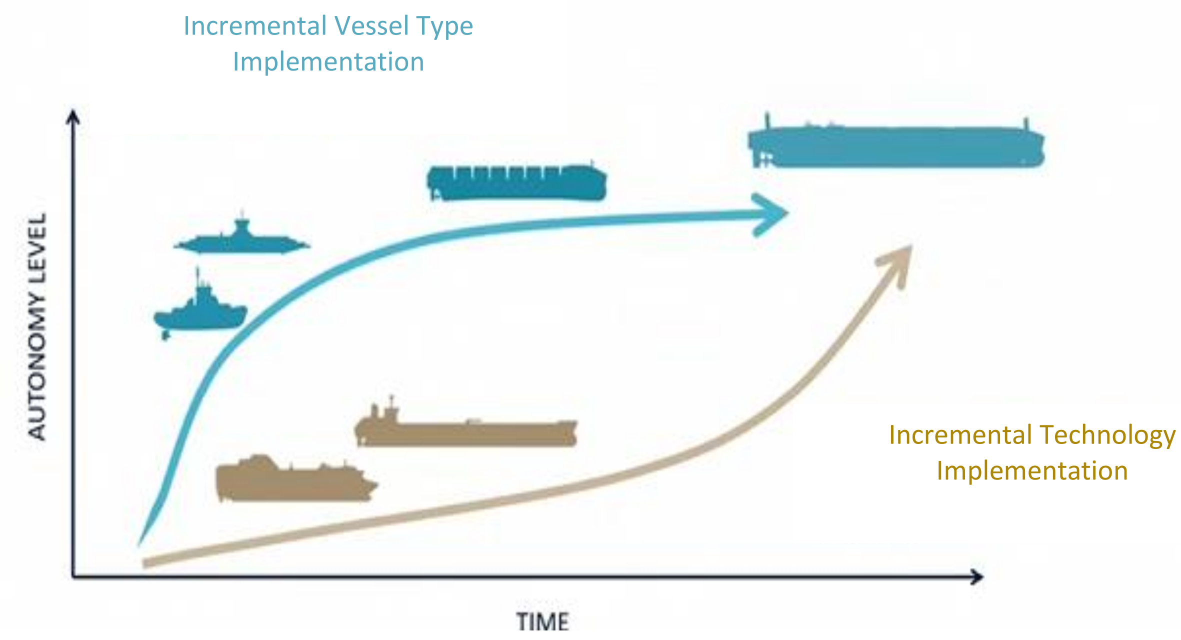


Figure 3: Two Pathways to Higher Levels of Automation in the Maritime Sector [68]

2.2. Related Inland Navigation Research

The initiative for innovations is present within the inland sector, yet there seem to be difficulties for large scale market uptake [70]. The development descriptions on the pathways towards higher levels of automation, introduced in section 2.1., are also valid within the inland navigation sector. There are differences in the environment the inland vessel operate in, that alter the focus of the automation technologies integrated in this sector. These differences involve aspects such as enclosed/restricted navigation, bridge or lock passages, crew size [71] and better network connectivity [72] that can ensure data transfer between vessels or shore. There is hence also a number of R&D projects explicitly targeted at the inland navigation sector.

Autonomous vessels have also been a hot topic in the inland sector. While some research the control of autonomous vessels and have managed to reach the model prototype phase [73][74], others appraise the success and failure factors for the fully autonomous inland vessel [70] or identify regulatory barriers that such vessels are facing [75].

In terms of the progressive technology implementation path, there are a number of projects that work on adopting operations and making use of a variety of technological tools that help improve the efficiency of the existing inland fleet. An example project is the watertruck+ project that piloted physical trials of a barge convoy concept on 18 barges in 2019 [40]. It is the result of prior research performed for the Watertruck Interreg NEW project [40], DSSITP project [76], the BARGE TRUCK project [77] and INLANAV project [10]. The concept is focused on the reactivation of smaller waterways by adapting vessel sizes to the smaller waterways and by reducing the workforce. The principle is simple: decouple the cargo, on the barges, from the pusher where the crew is placed, on while (un)loading operations. The pusher will only operate regionally; hence allowing barge operators to have a daytime job and live in a shore-based home rather than on a vessel. While the idea is simple, the business case is, however, rather complex and requires subsidies to create an incentive for investors to join the initial program [70].

The Watertruck+ project has similar aims to the VT concept, yet the main differences between the two is that the VT can be deployed on large and small currently sailing and future vessels, that still need some form of supervision over longer international distances. The Watertruck+ concept lacks the flexibility to do this. These concepts could evolve complementary to each other, knitting regional and international operations together.

2.3. Platooning

The original meaning of the word 'platoon' refers to a subdivision of soldiers that forms a tactical unit [78]. This definition has been expanded to define the formation of transport units to help develop a more efficient transport system, leading to the reduction of operating cost for different modes of transport. In the past decade, the concept of platooning transport units has been studied for both road-based and waterborne transport. The following section presents the existing platooning research for both modes of transport and compares the aims of their application.

2.3.1. Waterborne Platooning

The idea of vessels moving in a convoy or train is not new. In the late 19th century, operators on the Seine in France made use of a chain attached to the river bed to allow barges to be towed upstream [79]. The “chain–ship” was used as a way to improve competitiveness towards rail transport (Figure 4). Other sources describe convoys of unpowered barges that were towed upstream by a tug using a rope [80], [81].

The navigational difficulties that an encounter of such platoons created and the technical improvements of the steam engines that allowing them to be installed more easily on board of ships, meant that this form of transport concept was short-lived.

The state of technological development now no longer requires physical connections. Instead, one can form wireless connections, passing information between vessels to communicate to a control system and allow vessels to follow each other. Research into multi-vessel co-operation has been performed by Chen et al. [31], [82], which modelled the behaviour of autonomous vessels in complex navigational situations regarding path following, aggregations and collision avoidance. Chen et al. [83], [84] addressed the potential for fuel-saving when placing all-electric autonomous ships in a train by coordinating the vessels' speed such that it meets the optimal speed for all vessels involved in the train. Chen et al. research applied platooning for cargo relocation within ports. Zhang et al. [35] developed a multi-ship following model with the aim to apply it to an ice breaker convoy and hence to allow commercial vessels to operate more safely in frozen waters. It is used to predict the ice resistance, safe speed and safe distance for the vessels operating behind the leading ice breaker.

Other researchers interpret the opportunities of platoons with vessels moving like a swarm. Levants [37] studied the requirements a control system swarming vessels would need. This particularly emphasised the vessels' ability to stay near each other at uniform speeds yet still avoiding collisions. Majid [85] calculates the hydrodynamic interactions between vessels when sailing in V-formation. In 2020 the U.S. Defense Advanced Research Project Agency awarded a contract to look at a concept referred to as the Sea Train. It aims to demonstrate an approach that reduces the wave-making resistance to extend the long-range operations and transoceanic transit for unmanned surface vessels [86].

Figure 4: The "Chain Ship" on the Seine [87]

Even though these sources are based on similar ideas of several vessels moving as a single unit, the intent and use of their ideas is distinctively different from the application of the VT concept. Most of the sources assume a higher level of automation than is currently available on commercially available vessels. More importantly, while the sources provide valuable insights from a control system and hydrodynamic perspective that help to identify the technical potential of platooning, they do not provide concrete insight on the logistic and economic implementation challenges of the platooning concept in the waterborne sector. This research gap is addressed in this thesis via the assessment of the economics behind the platooning applications.

2.3.2. Comparing Road and Waterborne Platooning

Road-based platooning has been the focus of a much larger amount of research than its waterborne counterpart. The most known truck platooning projects are the European project SARTRE, the US project PATH and the two projects set up by the Swedish truck manufacturer Scania (distributed control of a heavy-duty vehicle platoon and iQFleet) [88]. The more extensive research attention for the truck platooning concept causes it to be several steps ahead in development. It has already undergone some physical road trials [26]. The European Automobile Manufacturers Association expects multi-brand platoons to drive across Europe's motorways by 2023 [89].

Figure 5: Road Trials of Truck Platoons [27]

The comparison between the land and the water-based platooning applications serves two points:

1) To illustrate the differences between the two applications and to thereby show that the same concept can have different aims dependent on the circumstances it is applied in.

2) To allow the waterborne concept development to learn from the more developed truck platooning concept and identify possible parallel challenges that were identified from road-based traffic modelling.

The comparison is set around five value elements that have been established by a value case on truck platooning [28]. These value elements, seen in Figure 6, identify the main points of benefit for the platooning concept. All of the value elements are discussed in the upcoming section and their validity for the waterborne application is commented upon.

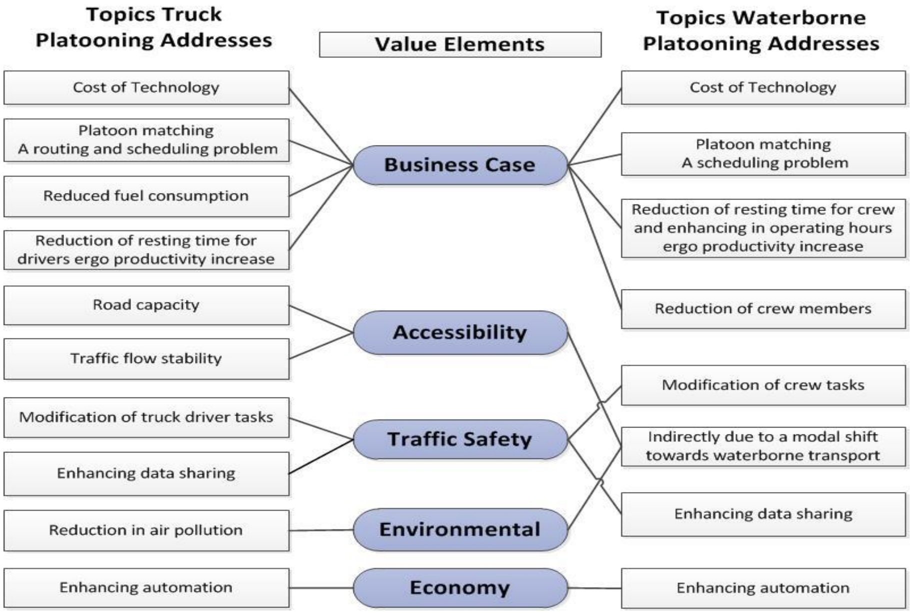


Figure 6: Value Elements for Road-Based and Waterborne Platooning

Business Case

The main business case elements are categorized into financial aspects and platform matching, both of which are explored for the land and the waterborne platooning application.

Financial Aspects

The first value element for the application of platoons on the road or water is the business case created for the user. An important part of this business case is created by financial incentives. The road-based application creates financial incentive by achieving fuel savings as a result of driving in close proximity of the vehicle ahead. This is possible due to the shorter reaction time of the automated driving [26]. The slipstream of the truck ahead lowers the aerodynamic drag the follower truck experiences, which reduces the average fuel consumption of a truck driving in a platoon by up to 14 % [90]. The second financial incentive is expected from labour cost saving which in trucking makes up half of the total annual cost [91]. Even without having driverless trucks operating in the platoon, the platoon can still improve the productivity of trucks. The switching of leading vehicles every few hours allows the trucks to continue moving during the drivers' breaks, in which the truck is usually stationary. This is expected to create a task relief of 50 % for the following trucks [92] and increases the productivity of the platoon by 30 % compared to a conventionally operated truck [26]. Another financial aspect of the platoon that implementation needs to consider is the technological investment cost. A study estimates this to be up to € 20.000 per truck [93].

The direct comparison of these financial features to waterborne platooning reveals some differences. First of all, the fuel-saving benefit is not achieved on the water. Sailing in close proximity behind each other causes vessels to sail in each other's wake. Studies performed on the hydrodynamic interactions between lead and follower vessels [19] [96] conclude that vessels suffer an increase in fuel consumption when sailing closer than one ship length behind the vessel ahead. Additionally, the close proximity also negatively affects the manoeuvrability of the vessels. The ships' stopping ability is much poorer than that of land-based transport, thus requiring a longer safety distance between vessels. Given safety distances

of more than one ship length, the increased power requirements created by the wake of the leader are negligible.
The labour cost reduction and the increase in productivity of the transport units are aspects that apply to both the road-based and to the waterborne application of the concept. The reduction of driver cost is ultimately achieved if the following trucks become unmanned, while the manning cost reduction on ships is achieved in both the short sea and the inland sector by already reducing the need for part of the crew, therefore the ships will not be unmanned. The productivity gains on the other hand, are created for trucks by simply switching lead drivers, but are only achieved in the inland sector that partially operates on 14h or 18h per day operating regimes. More details on this topic are provided in chapter 3. Lastly, investment into the waterborne platooning technology is expected to lie at € 80.000 per vessel according to the developer's estimate [46]. The percentage of the total cost is therefore much smaller for the ships than it is for the trucks.

Platoon Matching

Another important aspect that will allow the full potential of the business case to be reached is to match the participants in the platoon. The planning and coordination of platoons has been subject to numerous research projects, which have been summarised by the review of Bhooplams et al. [30]. The success of the platoon matching is dependent on the number of trucks that have implemented the technology and its setting. The three main situations, found in research are: scheduled planning, real-time matching and opportunistic forming of platoons. Each of these situations respectively represent different manners of creating platoons: before the start of the operation, at the time of departure of the truck or during the trip with trucks in close proximity. The real-time matching and the opportunistic model require a large amount of data sharing between the platoon operators and a large number of participants, making it a difficult model to adapt in an early stage of implementation. The pre-scheduled platoon case does not require either of these, which makes it the most realistic approach for an early implementation of the concept [26].
As road platoons deal with a complex network of roads, as well as potentially millions of trucks, pairing the right trucks becomes a complex routing and scheduling problem. The routing problems create detours for individual trucks to maximise the amount of time spent in a platoon and weigh this against the increasing lead times that are created. The scheduling problems change the departure times to allow trucks to meet the same part of the route simultaneously. It weighs the logistics cost created by waiting times against the benefit created by the platooning. Research on such models made it possible to identify platooning property requirements that allow viable operations for road platoons. For instance, a gap of 1 km should not be surpassed between members of the platoon, so as to allow for the follower to catch up. Additionally, the difference in the speed of the trucks should be 10 km/h for such a manoeuvre to take place. Such action is made increasingly difficult with denser traffic [97].

The situation applicable to waterborne platoon matching are similar to those described for the road. However, the magnitude of the road users is in the millions, whilst vessels on the water are in the thousands only. At the same time, it should also be considered that the end destinations of vessels are limited to a small number of ports. This restricts the route choices for the waterborne platoons significantly, especially for the inland navigation sector, where the platoons will mainly run along the main river arm. The waterborne application thereby eliminates the need for elaborate algorithms to solve the routing problem and only focuses on the scheduling problem. Conclusive traffic flow model results require input data that is often not available, to the same extent, for waterborne traffic assessments. Hence, traffic recommendations such as “catching up distances” are out of the scope of the type of guidelines this thesis provides for the waterborne application. Given that the operating speeds of vessels are much smaller than that of a truck, catching up manoeuvres will take significantly longer on the water. That being

said, it should also be considered that waterborne transport legs typically span longer distances than the average road transport delivery, which allow for longer catching up distances to be made up.
A study that weighs the cost and benefits of waiting times, alike to what was performed for truck platooning, needs to also be done for the waterborne application. The waiting times can create logistics cost for ships just like they do for trucks. The cargo value on board of vessels is on average lower per unit of cargo than that of trucks, yet the ships do transport significantly larger volumes which can have effects on the logistic transport cost.

Accessibility

The second value point of platooning considers the accessibility improvement created by the implementation of the platoon. The implementation of cooperative cruise control installed on trucks allows for faster reaction time and enable the trucks to drive closer to each other, thereby creating more road capacity. Additionally, it avoids unnecessary braking that is often caused by human error and thus also improves the traffic flow [98]. This benefit of technological implementation is, however, not unique to platooning trucks but is also achieved by trucks that may not choose to form platoons.
The merging and exiting procedures of trucks have extensively been studied with a main focus on the leader and the followers of the platoon. Yet, a fairly small about of attention was placed on the study of the platoon interaction with the other vehicles in the transport system [88]. Platooning may have a negative impact on the traffic flow: the gap between the trucks may become too small for other traffic participants to pass in order to enter or exit highways [26].

The aspect of entering and exiting the waterway is not a significant problem for the waterborne application. It may, however, occur that at river mouths or in bends the platoon of vessels do not allow crossings of other vessels between them. It is, therefore, important that for any type of platoon implementation, new regulations are put in place that allow a interaction with the rest of the traffic. The added accessibility that is hoped to be gained from the waterborne platoon is a deeper penetration of smaller inland vessels into urban areas [99]. This is intended to be enabled by improving the competitiveness of smaller inland vessels that can access these smaller urban waterways and hence encouraging the use of these vessels.

Traffic Safety

The value element of traffic safety is improved by platooning as more data is shared between traffic participants concerning their location, which allows systems to better interact with each other. This also means that the role of the driver's changes, requiring them to become supervisors of the system and allowing them to perform other tasks while the control system takes care of the driving. A potential negative impact of a platoon on the traffic safety is that easier monitoring tasks and resting times, occurring inside the moving truck, trick the drivers into thinking they are fit to take over driving again despite actually being tired [28]. Furthermore, integrating platoons into an environment that is not all equipped with the capabilities of platooning may create 'copycats' that mimic the shorter headway maintained without having the actual technologies installed. It can also be expected that unpredictable and unsafe behaviour will be exhibited by third party traffic participants when trying to cut through a "wall" of platooning trucks. It was, therefore, concluded that while the enhancement of the truck technology can enhance safety, the effects of human interaction with his technology can increase the risk of accidents [28].

The system adaptation for the waterborne platoons is likely to meet similar traffic safety conclusions. Given the smaller volume of the transport units and lower traffic density on the water, the accident risk is low compared to road transport [100]. This means the value elements of traffic safety are not a priority in the determination of the concept's viability for the waterborne mode of transport.

Environmental

The environmental value that road platooning brings is obtained via the fuel savings achieved by the reduction in the aerodynamic drag of the trailing truck, as mentioned in the business case. Fuel savings result in fuel emission savings and hence in a societal benefit [28].
This value element is achieved through different means in the waterborne application. The combination of different vessel types in the same train requires the adaptation of the VT operating speed. The faster vessels need to adapt their speed to that of the slowest member in the train. This implementation of a slow steaming regime allows these faster vessels to reduce their fuel consumption and, with it, their emissions. This form of environmental value element is mainly going to be of importance in the short sea sector application where the vessels operate at higher and more diverse speeds than in the inland sector. The environmental value element is additionally indirectly met; if the VT manages to create a modal shift towards waterborne transport, more goods may get transported by this more environmentally friendly mode of transport.

Economic

The final value point is from an economic perspective. The financial aspect of fuel consumption, labour cost reduction and productivity improvements, mentioned as part of the business case, are also counted as economic value points. These benefits improve the competitiveness of trucking and are a result of increasing the standard of automation of the trucks. Therefore the enhancement of automation standards can also be viewed as creating an economic benefit for the mode of transport [28].
While the business case value element did touch upon some commonalities to truck platooning in terms of the transport unit’s productivity improvement and the labour cost reduction, the way to determine the labour cost reduction differs significantly from what is done for trucks.

In contrast to truck drivers, the crew lives on board the ship and does much more than just drive the ship while it is sailing. The crew take care of various tasks ranging from navigation tasks such as watchkeeping and communication to other vessels or shore, cleaning, maintenance, cargo lashing inspections and even catering tasks to ensure all operations onboard can be performed [101]. To determine whether the crew size can be reduced when automating a sub-system on board and if so which crew member is redundant, is not straightforward. This has been researched by the research of Kooij [102]. Crew sizes can vary depending on factors such as vessel size, type, age, the nationality of the crew members, the flags state of the vessel and the choices of the vessel manager [55]. They can reach between sizes as large as 28 crew members for seagoing vessels [55], 11 crew members for short-sea vessels [103] and at least two crew members on small inland vessels [104]. Given these differences in crew sizes, the economic viability of the concept can significantly change depending on the size and operating profile of the vessel.

2.4. Conclusions of Related Research

This background chapter has provided insights into maritime automation-related research in both the short sea and the inland sector, which has helped frame the context of this research. This research investigates realistic implementation challenges for the new navigation technology for current waterborne transport service providers.

Even though the concept of truck platooning has been studied extensively, the waterborne application is based on different value elements, which changes its business application. Yet, comparison to truck platooning provides a useful insight into the expectations that can be set for the waterborne application of the concept. Value elements considered in road-based platoons such as the accessibility, traffic safety and some forms of platoon matching are of less importance for waterborne platooning. This is expected to be the case due to the lower traffic volume, accident risks and route choices of waterborne transport. Instead, the focus for the waterborne study needs to be placed on understanding and quantifying the economic value element that is influenced by the number of crew members that can be taken off the ship, the operating conditions including waiting times, and the business models. This allows for VT requirements guidelines such as the minimum number of participants or sailing time to be determined for future market uptake.

Prior work on waterborne platoons has so far been focused on the control system and hydrodynamic interaction between vessels. Hence, the research gap addressed in this thesis lies in identifying the economic implementation viability of the waterborne platooning concept for different business models in both the short sea and the inland navigation sector. At the same time, it provides insights on the potential that crew size reductions and incremental technology implementation for the waterborne transport mode.

CHAPTER 3:
IDENTIFYING THE VT FEATURES

The previous chapter has created a detailed comparison of waterborne platooning to road-based platooning and has explained the research gap to lie within the economic viability assessment of waterborne platooning. It has also identified the two operating sectors of inland and short sea shipping. This chapter elaborates on the differences between the application of the VT in these sectors and explains the workings of the VT by describing the operational difference of a conventional sailing vessel to the FV operations. Thus, with regards to the research aims, this chapter addresses sub-questions 1 and 2, explaining the aspect of vessel operations and the influences of the VT properties.

Based on the introduction of the concept throughout the last two chapters a VT can be viewed as a transport entity between two predefined destinations that FVs can join and leave when desired, as indicated in Figure 1. The concept needs to allow an enhanced transport service that translates to a transport cost reduction of the transport user.

This chapter serves as an elaborate scoping overview, where relevant operating features are described. It explains how the range of topic areas are narrowed down to the business models and scenario variations investigated in this thesis. This section also summarises the insights gained throughout the project development that help identify the most relevant features affecting the viability of the concept. Important topics covered are the introduced waiting times that causes productivity losses and the technical limitations imposed by the VT technology. Hence, this section emphasises the most important components that are integrated into the VT viability assessment, as well as explains why some components are not considered in the later assessment.

The first part of this section focuses on the VT specific features, reaching from the operation, manning and solo sailing capabilities to the automation level, the choice in LV type and special manoeuvres, in section 3.1. The section finishes with a summary of the most vital aspects of the VT specific features. In the second part of this chapter, section 3.2 explains the possible workings of the VT business model, including choices of business structure, the service concept and the contract length. Based on the information provided, the chapter finishes by summarising the business models that are assessed in the viability study following this chapter.

3.1. VT Specific Features

The VT operations affect certain aspects of current operations more than others. This section discusses all VT specific features that differentiate its operations from conventionally sailing vessels. Figure 7 illustrates the VT influence factors that impact both the FVs and the LVs. These VT features affect the viability of the VT and relate to the vessel operations and types, the manning, solo sailing capabilities outside of the VT, the automation onboard, the investment requirement, the formation of the FVs, the waterways, the type of LVs and special manoeuvres. Not all of these factors are of equal relevance. The importance of each are discussed within this chapter while some less impactful factors such as for instance the depth of waterways are addressed in chapter 6 as part of the application area assessment. Some of these features are affected by the VT application sector, which is why the effect on the short sea and application sectors are explained.

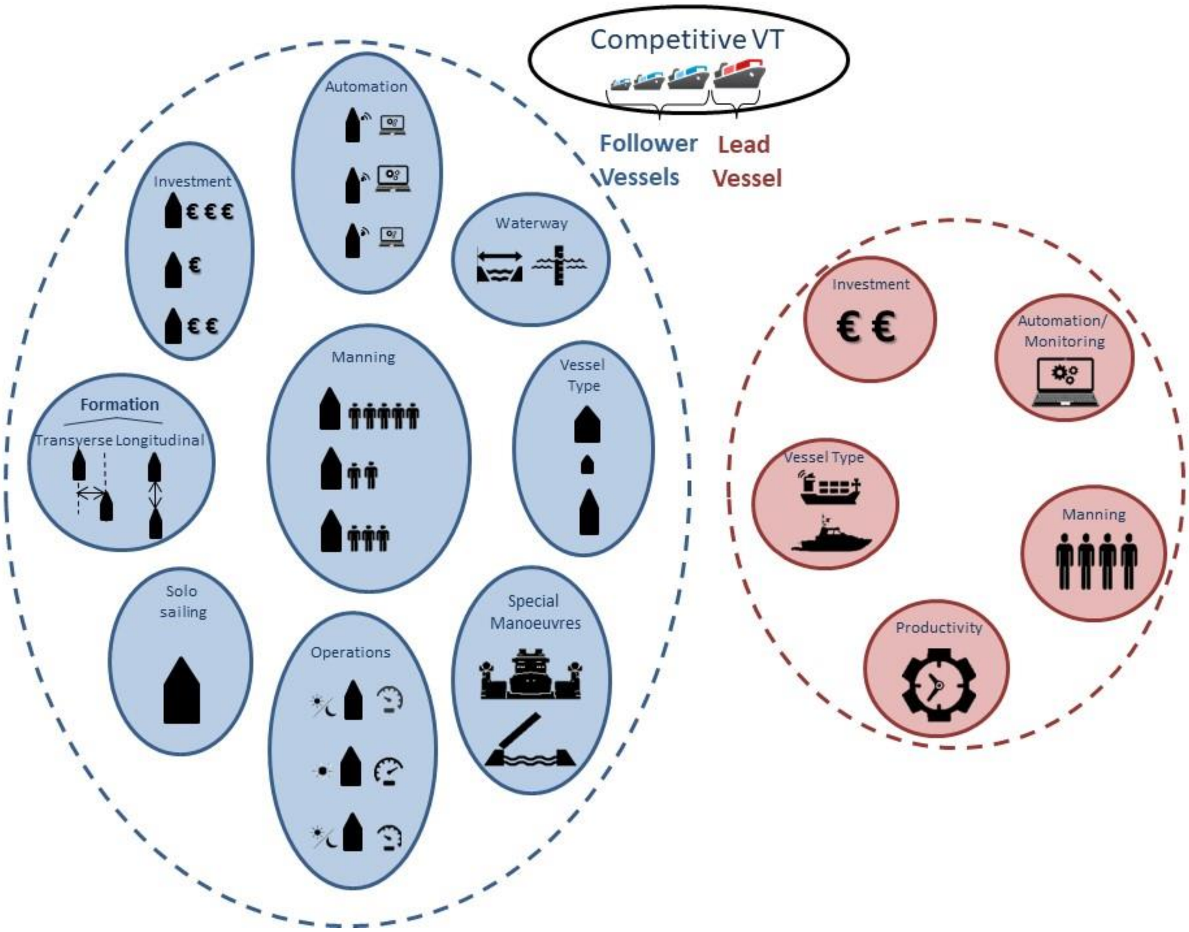


Figure 7: VT Influence Factors

3.1.1. Operations

The VT implementation affects the productivity of a vessel, which is here defined as the amount of cargo transported over the course of a year. The productivity of the vessels changes dependent on the vessel operating speed and the idle time that includes operating regimes and waiting times before the departure of the train.

Speed

When operating within a train, the slowest member dictates the VT operating speed, which means faster vessels suffer an increase in lead time compared to conventional vessels. Even though from a vessel operator perspective, a speed reduction has a positive effect on fuel cost savings, this change in lead time needs to be known when the vessel operator agrees on transport terms with the cargo owner. The vessel-operating speed is imposed by the installed power and size of the vessel. While the adaptation of the operating speed does increase the trip lead time, combining different vessel types in the same train provides more potential for participants to join the train. Varying the vessel types is hence needed to determine which vessel types may or may not be combined in the same VT.

Short Sea Sector

The operating speeds of short sea vessels, as well as their cargo-carrying capabilities, vary significantly. Operating speeds are dependent on the operator's business choices and reach from around 11 knots for small general cargo ships to up 24 knots for fast container feeders. These large variations mean that the potential losses in productivity are significant for the short sea sector.

Inland Navigation Sector

In the inland navigation sector, the main vessel types are dry bulk, tankers and containers. The inland fleet is also composed of a significant fraction of barge convoys. Barge convoys are larger and slower than self-propelled vessels, which influences their manoeuvring capabilities. Achieving the same level of situational awareness as on only self-propelled vessels from the leading vessel can therefore be more challenging. This is why the focus within this study is placed on self-propelled vessels.

The operating speed of different vessel sizes varies between 10 km/h for small peniches that operate in shallow water conditions in regional waterways and 18 km/h for larger vessels that operate on the main rivers [105]. These speeds can further vary depending on the river current going up or downstream.

Vessel Idle Time

Aside from the operating speed variation mentioned in the last section, the productivity of the vessels is affected by the idle time of a vessel. This time relates to added waiting times and a variation in daily operating hours in particular for some inland vessels. Since the VT relies on the coordination of several different ships, there are forcedly waiting times created before the departure of each train, be it for the LV or the FVs. This means that the more individual trips are made by the user, the more often the user has to wait. It also means that the productivity loss due to additional waiting times is strongly affected by the overall duration of a VT voyage. Especially for short trips, productivity loss will be high and, therefore, merits further study.

Short Sea Sector

In the short sea sector, vessels operate continuously. For these operations, the VT implementations create a reduction in productivity via the earlier mentioned speed reduction, but also through extra waiting times that are created during the gathering of the train. These operational restrictions created by the VT implementation on the short sea vessels need to be outweighed by the benefit created through the crew size reduction.

With regards to the journey length, the European coastline potentially leads to trip lengths of several thousand kilometres. However, while there is a potential for long and favourable routes for the VT, many short sea vessels operators make frequent port calls on the way to their final destination. Such fragmented operations are not favourable for the VT.

Inland Navigation Sector

Inland vessels fall under one of three sailing regimes; A1, A2 or B, which allow for 14 h, 18 h or continuous operation of the vessel, respectively [104]. The allowed operating regime of a vessel depends on the number and the skillset of the crew members. The VTs are intended to operate continuously. Thus, while being part of the train, the FVs can also operate continuously with the same crew size they have during their restricted independent sailing operations. The additional crew members needed to allow for these lengthened operating times are navigating the LV. The crew members on board the FVs can rest while they are part of the train.

Compared to a current vessel operating at an A1 or A2 sailing regime, FVs mainly benefit from the VT by increasing the productivity of their vessel without incurring additional crew cost. Contrary to the restricted operating regimes, an inland vessel that currently operates under a B regime will suffer productivity losses when joining the VT, similar to the ones experienced in the short sea sector. The losses due to slowing down are, however, smaller than for the short sea setting as the operating speeds of inland vessels vary less.

Additionally, the IWT generally transports freight over shorter distances, compared to its short sea counterpart, which increases the impact of waiting times. Along the Danube, the longest navigable river in Europe, the average distance of freight transport lies at 600 km, whereas the Rhine, the river with the most cargo flows, the average lies at 200 km [106].

3.1.2. Manning

The last section made it clear that the VT specific operating features can influence a large part of the productivity benefits achieved by the VT. The main cost-benefit, however, is created through the reduction in manning. The crew reduction is, therefore, the most crucial aspect in the VT's economic viability assessment. The VT control system alone only takes over the need to perform the navigation-related tasks during the period in which the FV sails in the VT. All the other tasks still need to be performed to the same standard as they currently are performed. Hence, the crew size reduction is limited to a few crew members. The way in which these reduced crew sizes are determined within this thesis differs depending on the application sector.

Short Sea Sector

The changes in the crew composition onboard the FV are analysed based on Kooij’s work that uses a purpose-built crew analysis algorithm which is based on a greedy algorithm. Using the skills of the crew members and the tasks that need to be performed, the algorithm determines the cheapest crew composition for a given situation [103]. It has been identified that if the crew were to keep the traditional task assignment on board the vessel, only the second officer would become redundant. The workload of some of the remaining crew members would also significantly decrease [103], but none of them can be removed from the ship. If, on the other hand, the vessel operator and crew adopt a more flexible task assignment strategy in which crew members also perform tasks for which they are "overqualified", the crew size can be reduced by two more deck boys. Assuming that two crews are rotating on board to ensure continuous operations of the vessel, up to six crew members could be reduced compared to a standard operating crew.

If we take the crew cost from a Dutch short sea vessel operator as frame of reference, where a second officer costs € 82.900 and a deck boy costs € 15.450 annually, we can expect the six crew members to translate to a cost savings of € 154.400 annually.

Inland Navigation Sector

On inland vessels, in particular the smaller ones, individual crew members have to perform a wider range of tasks compared to the members of the larger crews on short sea vessels. This means the reassignment of tasks is less clear. Additionally, Kooij's research was not performed on inland vessels and can hence her algorithm cannot be used as a foundation for the crew size reduction as it was for the application in the short sea sector. Instead, in the inland sector, the minimum manning requirements from the CCNR [104] at different operating regimes are used as the basis for the crew size reductions. The VT changes the crewing requirements from whatever current operating regime to the minimum crew size at the least demanding regime A1. Table 1 provides the summary of total crew members per vessel size at different regimes and indicates what this translates to in an annual crew size reduction and a crew cost savings for a VT application.

For instance, a class V inland vessel of 110 m that currently operates at a B operating regime reduces its crew size by two crew members when moving from the B minimum manning requirements to the A1 requirements. Additionally, it is expected that all vessels operating at a B operating regime have two crews that rotate to allow continuous operations annually, thereby creating an annual crew size reduction of four crew members. For A1 or A2 regime only a single crew is assumed, as they are not sailing on the weekends and have more idle days over the year. Moving from an A2 to an A1 regime involves a crew size reduction for vessels larger than 86 m, but mainly consists of a cost reduction by requiring less qualified crew members for the smaller vessel sizes. Vessels that already operate in an A1 regime are not able to change their crew size. However, in those instances, the improvement in productivity mentioned in the previous section creates their main benefit.

Table 1: Annual Crew Size Reduction and Crew Cost Savings on FVs

Vessel type and reference vessel operating regime	Minimum crewing requirements	Annual crew size	FV crew size	Annual reduction in crew size on FVs	Crew cost savings
L > 86 m					
A1	3	3	3	0	-
A2	4	4	3	1*	€ 35.100
B	5	10	6	4	€ 389.100
70 m < L ≤ 86 m					
A1	3	3	3	0	-
A2	3	3	3	0*	€ 6.700
B	4	8	6	2	€ 293.600
L ≤ 70 m					
A1	2	2	2	0	-
A2	2	2	2	0*	€ 6.000
B	4	8	4	4	€ 308.000

* cost savings are achieved by replacing a higher-skilled crew member with a cheaper one

3.1.3. Solo Sailing

As discussed earlier the reduction of the crew size on the FVs reduces their ability to sail independently for extended periods of time. A FVs can choose to operate in one of two manners. Either it operates solely along the VT route and thereby does not require solo sailing capabilities, apart from the time it takes to leave to quay and join the VT. Or the FV performs only part of their journey as an FV in a train. The rest of the trip is sailed under the FV crew's own navigational responsibility. If the truck platooning business model presented in chapter 2 is taken as inspiration, the FV could also coordinate its operations with another FV to switch leading roles until the final destination is reached. The early-stages of the VT implementation will require monitoring crew to be present on the LVs to ensure safety and a human in the loop. The switching of leaders would however assume no monitoring crew to be present on either vessel, as else no crew cost savings can be made. Hence, this switching option is not applicable in the early-stage concept implementation and is thus also not researched in any further detail.

Short Sea Sector

The vessels operating in the short sea sector as part of the VT need to adopt a business strategy that accepts a loss of flexibility. As soon as the crew size is reduced, the vessel can no longer operate continuously on its own. The crew will be restricted to sailing the vessel for a single shift (8 h) before they have to rest. Having an initial or final destination that cannot be reached within this 8 h timeframe is not only problematic because of the loss in productivity created by the resting times, but also because a short sea vessel cannot stop and drop anchor anywhere. The vessel would either have to find a sheltered place to anchor or manoeuvre into the closest port, which in either case is a significant operational effort to allow the crew to rest. It is thereby not recommendable for FVs in the short sea sector to operate outside of the operational area covered by the VT service.

Inland Navigation Sector

Inland vessels that currently operate under a B regime will, similarly to the short sea vessels, lose the flexibility to operate outside of the VT. However, the conditions for the inland vessels are more favourable because the vessels can operate for 14 hours per day at the A1 regime and have much easier opportunities for sheltered mooring and resting places along the waterways, as this is already a common practice for this sector. Vessels currently operating at A1 or A2 regime view the opportunities of the VT as an increase in flexibility and do not suffer any negative consequences by the use of the VT.

3.1.4. Automation

The last three subsections have covered the main VT features that are focused upon within this research. A feature that has not been developed as part of this research, but that is the core part of the VT implementation is the automation technology of the VT control system. The following section is intended to provide the understanding of how the automation feature of the VT works.

The technology installed onboard has been designed such that it can be applied to both the short sea and the inland sector. The highest automation level achieved with the technology implementation is a CCNR's level three, conditional automation. This level of automation indicates that all standard navigation tasks, i.e. steering, adjustment of the propulsion system and the monitoring of the navigational environment, is performed automatically by the system. In exceptional conditions, a human will be requested to intervene. In situations with high traffic densities or environmental conditions such as wind or currents, the automation level may reduce to two on the LVs. In this level of partial automation, the LV operator will indicate the most appropriate course of action which the system will follow. To ensure a timely manual fall-back performance the FV crew needs to be present on the bridge in those circumstances even though actions are still performed without the interference of the FV operators. Both the partial and the conditional automation level are described in Table 2. In an emergency situation, the control would fully go back to the crew on the FV.

Table 2: CCNR Definition of the Level of Automation [107]

	Level	Designation	Vessel command (steering, propulsion)	Monitoring/ responding to the navigational environment	Fall-back performance of dynamic navigation tasks	Remote control
Boatmaster performs par or all of the dynamic navigation tasks	2	**PARTIAL AUTOMATION**	👤🚢	👤🚢	👤	remote control is possible. It may have an influence on crew requirements (number or qualification).
	the context-specific performance by a navigation automation system of both steering and propulsion using certain information about the navigational environment and with the expectation that the human boatmaster performs all remaining aspects of the dynamic navigation tasks					
System performs the entire dynamic navigation tasks (when engaged)	3	**CONDITIONAL AUTOMATION**	🚢	🚢	👤🚢	
	the sustained context-specific performance by a navigation automation system of all dynamic navigation tasks, including collision avoidance, with the expectation that the human boatmaster will be receptive to requests to intervene and to system failures and will respond appropriately					

VT Control System

This section provides a brief overview of the underlying VT control systems upon which the VT concept is based. The information and illustrations are taken from the NOVIMAR deliverable [108] written by the developers of the VT control system at Argonics [109] and Innovative navigation [110].

The installed systems are the same for both the LV and the FV as seen in the schematic of Figure 8, with the main difference created by the right to accept coupling by the LV. The control system is composed of standard sensor and communication devices available on a vessel (i.e. depth sounding, AIS, GNSS device, RADAR, ROT & RPM controllers, VHF etc.), processing components (i.e. generic message handlers, position estimator, multi-sensor tracker, etc.), the human to machine interface and the control components which are specific to the VT. These two components that form the forefront of the VT features are the RadarPilotVT and the ArgoTrackPilotVT. As the technology is based on radar, night, fog and most other weather conditions can be navigated. The radar pilot uses a filter that ensures a high level of accuracy, which is equivalent to that of surveillance radars. The RadarPilotVT layers the radar video, tracks, AIS, and VT specific information and compares it to the ECDIS chart information to identify the location of each vessel. The ArgoTrackPilotVT makes use of this RadarPilotVT information and ensures the vessels stay on the defined tracks and keeps the distance to a successor's vessel. It hence has control over the rate of turn (ROT) and the engine rotations per minute (RPM) controllers onboard the vessels.

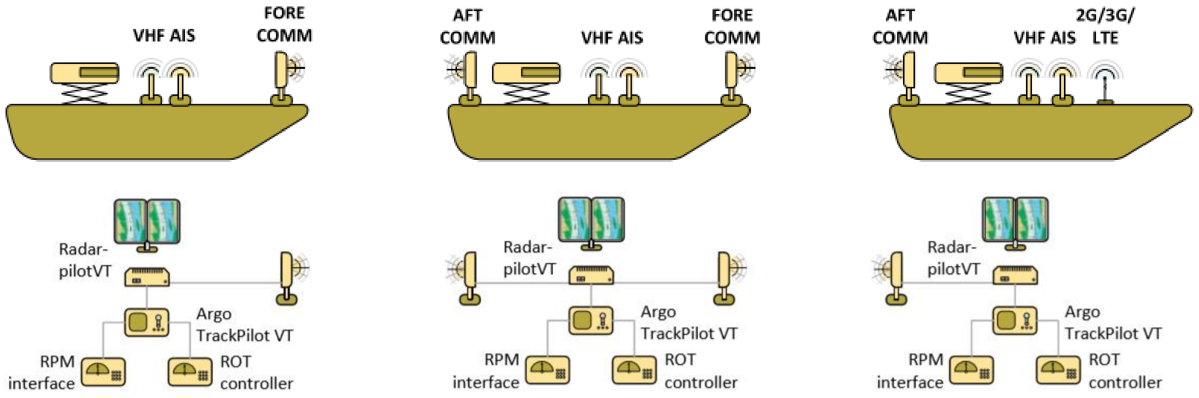


Figure 8: VT Control System [108]

The developers have chosen to perform the inter-vessel communication via direct antenna as it provides sufficient reach for sea-going and inland navigation and has a fairly low-cost impact. All data traffic is routed through successor's vessels before it joins the LV. The longer the communication distance between the vessel, the more narrow becomes the reception angle of the antenna, and thus the antenna needs to be directed specifically towards the location of the FVs. This method of communication requires the available bandwidth of 1 Mbit, which allows up to ten FVs to be part of the train as a bandwidth of 100 kBit/s is assumed to be reasonable [48]. This length can be enhanced if needed with additional technology. While the VT control system is designed to work without supervision, the regulatory bodies are likely to request monitoring crew member on board of the LV. These monitoring crew estimates are one additional crew member for up to two FVs in the train and two crew members for VT lengths longer than two.
The track creation and the adjustment of the FV position is made automatically by the ArgoTrackPilotVT, the activation of the coupling procedures requires manual activation by both parties, which communicate with one another about the coupling request via VHF.

The LV operator can choose to operate in one of two VT operations mode to deal with different static and dynamic situations. These are the assisted and automatic guidance mode.

Figure 9: VT Control System Assisted Guidance Mode [108]

In *assisted guidance* mode (see Figure 9) the FVs sail on the identical path that the LV has sailed upon. This gives the LV operator the freedom to manually steer the VT around stationary objects. At the same time, it also requires the LV helmsman to have a good understanding of the sailing capabilities of each FV.

In *automatic guidance* (see Figure 10) the LV operator can offset the position of a specific FV with respect to a guiding line to ensure the FVs stay within a predefined fairway. The FV lateral offset can thus immediately be adjusted. This ensures the VT can handle encountering traffic.

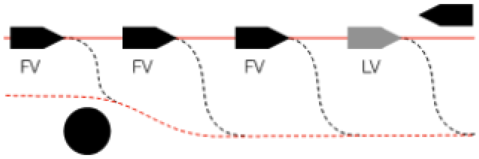


Figure 10: VT Control System Automatic Guidance Mode [108]

3.1.5. Investment

Knowing the set-up of the VT control system enables an estimate on the VT feature related to the investment cost to be identified. The investment cost for the soft- and hardware of the RadarpilotVT and the ArgoTrackPilotVT are estimated by the product developers to be € 40.000 - € 60.000. On top of that, a specific component is not included in this cost estimate. This is a 3 – axis antenna that can be directed towards specific follower vessels. Such an antenna at the state of development in 2019 costs € 40.000 on its own. Thereby bringing the total VT control system investment cost to € 80.000 - € 140.000 dependent on the number of antennas on the vessels.

3.1.6. LV Type

All VT features described so far have been directly related to the FV performance. The final VT feature is, related to the LV operations, deciding upon the role of the LV within a train. The LV type is a feature that for certain VT business model also influences the viability of the FVs using the VT service.

The choice for the LV type is the most VT-related feature aside from the VT control system. An LV could either be dedicated or cargo carrying. The dedicated vessel refers to a vessel whose sole purpose is to provide a service of leading other vessels. It can be any type of vessel, e.g. a refit cargo vessel or a fast crew supplier. A cargo LV acts as a normal cargo ship but allows FVs to tag along to generate additional income. As a result, only the additional cost of the monitoring & control equipment and associated crew or VT waiting time-related cost would have to be compensated for by the FVs. The benefits and drawbacks of both vessel types have been assessed in [25] are summarised in Table 3.

Table 3: Benefits and Drawbacks of Different LV Types

LV Type	Benefits	Drawbacks
Dedicated	• Available when needed (suitable for both liner and tramp services) • Flexibility in choice of sector (IWT or SS) application, since operating speeds can adapt to any vessel type	• Costlier for the user, since the total LV operating cost has to be compensated for by the FVs
Cargo	• The income from cargo partially covers the operating cost of the LV, which means the FVs need to compensate for smaller expenses	• Availability restricted by loading of the cargo (not suitable for liner service) • Less attractive to FV due to more restrictions in destination and departure • Additional space is required onboard for the VT monitoring personnel

Cargo LVs can be existing vessels that are refitted with the VT control system technology. A project from Marine Technology students at Delft University of Technology has performed a first concept vessel design (see Figure 11) for a dedicated LV for the short sea sector. It resulted in a 34 m vessel design that is operated by seven crew members at 15 knots (kn), over a trip distance ranging 1000 nm, with an estimated vessel value of € 1 million [111].

Figure 11: Dedicated Short Sea LV Design

The dedicated vessel has all the same cost elements as the cargo vessel and more, since the FVs also have to compensate for the general operation of the vessel. The capital (depreciation, interest), insurance and maintenance cost are significantly higher than for the cargo LV. They are based on the investment cost of the VT technology and the investment cost of the ship. The two operational cost elements that are added to the dedicated vessel are the operating crew and the fuel cost. An overview of these cost elements is provided in Table 4. The (✓) of the cargo vessel indicates that these cost elements are relevant but only related to the VT technology cost, not over the entire operations of the vessel. The X indicates that the cost is not relevant for the VT, as it is a cost covered by the cargo transport. The dedicated short sea vessel is required to operate at faster speeds and also has a larger annual operating cost than its inland counterpart, which is why it is used as an example of comparison. A summary of all cost in either LV type is provided in Table 4 and its relative cost breakdown is shown in Figure 12.

Table 4: Cost Element Comparison Dedicated and Cargo LV

Cost elements	Dedicated	Cargo
Ship investment	✓	X
VT technology investment	✓	✓
Operating crew cost	✓	X
Monitoring crew cost	✓	✓
Fuel cost	✓	X
Capital cost	✓	(✓)
Interest cost	✓	(✓)
Maintenance cost	✓	(✓)
General cost	✓	X
Total annual cost	**€ 2.635.700** [111]	**€ 204.200**

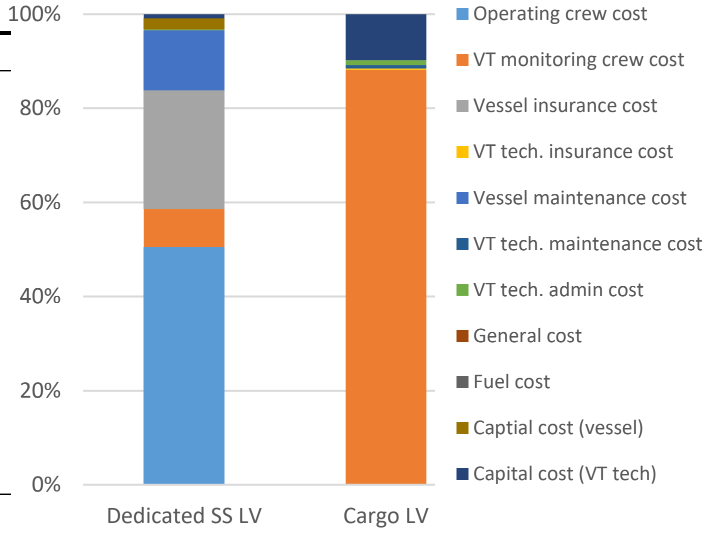


Figure 12: Relative Cost Breakdown of LV Types

The rough operating cost estimations of € 2,6 million annually obtained from the short sea vessel design is 13 times larger than the expected cost a cargo-carrying LV needs to be compensated for. Section 3.1.2 the crew cost savings have been identified to be around € 150.000 for the SS sector and € 390.000 for the IWT sector. The high operating cost of a dedicated LV would even under best-case conditions that allows FVs to fully benefit from these crew cost savings with no negative side effects, to rely on six other vessels to join per vessel train. Choosing between the dedicated or cargo LV is a trade-off between service reliability and cost. Given the difference in magnitude, a business model with the smallest viability threshold is going to operate with a cargo-carrying LV. Details on the VT related cost of the cargo-carrying vessels found in Table 4 are elaborated on in chapter 5.

3.1.7. Special Manoeuvres

A final feature that has not yet been addressed is special manoeuvres. These are identified as lock and bridge passages, which mainly affect the inland sector. The special restriction will require a procedure to be put in place to allow the VT to navigate the waterways without significantly disrupting third-party waterway users. Such a procedure concerning lock or bridge passage, but also any type of encounter with other vessels, can create added lead times. Encounters such as overtaking procedures can take longer than for conventional vessels with the higher traffic density the VT creates within a specific stretch of the route. Bridge and lock passage procedures on the other hand are directly influenced by the size of the crew and the level of automation on the FVs. The determination of a maximum waiting time for a certain VT length allows the identification of routes that may be more appropriate for the VT use. Especially waterways with a large number of locks like the Rhine-Main-Danube connection may lead to significant delays for a VT.

3.1.8. VT Specific Feature Summary

This section has presented the main VT features that influence the viability of the concept which need to be considered in the viability assessment of the VT concept. While the description of for instance the LV type has shown the clear cost-benefit of a cargo-carrying vessel, the description of other features is also indicative of the variation and sensitivity analysis requirements of the viability assessment. These include a variation in operating regime, vessel types and its operating speeds, as well as in waiting time and VT operating cost with and without monitoring crew members. An analysis of the FVs spending part of their trip sailing on their own navigational control including resting times is also needed, as well as a sensitivity study on the effect of crew cost variation that affects the savings. Finally, the special manoeuver feature becomes of relevance when studying the application areas of the VT concept.

3.2. VT Business Model Features

The way in which the VT operates can take many different shapes. The business case needs to ensure a reliable, predictable but also as flexible of a service as possible. The choice between using a cargo and dedicated LV, that helps the flexibility of the service, has already been addressed as part of the characteristic VT specific features. There are also other operational aspects that need to be decided before setting up a business model that can be used in the VT viability assessment. The relevance of these different operational business model features are deliberated and preselected within this section so that the service meets the key transport requirements of being predictable and reliable yet also flexible.

3.2.1. Business Structure

The decision regarding the form in which the different entities of the VT (the organiser, the LV and the FVs) interact is strongly influenced by the local market and sizes of the businesses that serve it. Three main business structures were considered in the VT development: 1) The company-internal VT coordination, 2) the platform based- leading as a service and 3) the peer-to-peer VT service.

The company internal or single company structure requires one organisation to set up VTs composed of their own vessel fleet. In such a structure, the coordination is likely to be easier than for a third party organiser, as there are no competitiveness-related information restrictions.

The platform-based business structure in which leading is a service to third party users allows businesses to make use of the LVs to improve their competitiveness in exchange for a fee. This VT organiser can take the shape of a company that coordinates and operates the LVs, i.e. a company that owns and operates a small fleet of vessels. Alternatively, the VT operator is an independent agent that sets up contracts with vessel operators to perform the LV service. The agent would thereby serve as a matchmaker between LVs and FVs. This service is organised in the form of an online platform upon which information is exchanged and bookings are made. This third party coordinative business does create additional administrative cost such as shore offices. A single company that already coordinates its own vessels will not experience such additional shore offices as it is already incorporated within the corporate operations.

Having many individual businesses participate in such a transport system increases the complexity of the business model. For instance, figuring out insurance and liabilities for such collaborations is so far uncharted territory for insurance companies in the waterborne transport sector [112]. An additional entry barrier is also the reluctance for companies to share their data with potential competitors to ensure more effective collaboration in fear of negatively impacting their competitiveness. This problem is not unique to the waterborne transport sector. Many studies have proven the advantages of information and data sharing in the transport sector [113]. Yet, there is still a lack of trust between individual actors in the sector [114]. This lack of trust is, in particular, the case for small captain owner businesses towards larger shipping companies. Vessel owners view the third party agent option as a better and likely more trustworthy business model [51]. To ensure for trust to be placed into the early-stage business model, it needs to introduce a simple and transparent service.

The peer-to-peer VT business structure in which the participant's alternate navigational responsibilities is inspired by the truck platooning application and can technically also be achieved with the developed control system. It is a structure in which all participants are service users and providers simultaneously. This allows the vessels to gain flexibility in reaching their destination compared to the first two structures, as each FV only needs to find one other vessel that intends to reach the same or close-by destination. However, it requires all crew members on the vessels to have the skillset to become LV operators, meaning that the total number of crew members may reduce, but it does not address the lack of qualified crew members that need to be addressed. Additionally, this structure relies on a fully matured VT control system that has proven itself and does not require additional monitoring crew. It is therefore not suitable for a gradual development of the concept. For this reason, the peer-to-peer VT business structure is not pursued any further within this research.

3.2.2. Service Concept

The service concept of the VT can be set up in one of three manners. An on-demand service, i.e. tramp operations where the FV can tag along if the VT were to pass by at a suitable moment, a prescheduled service, i.e. liner operations, or a custom pick up on call service, similar to an Uber service [51].

The advantage of the on-demand service is that it reduces the waiting times of participants. The potential cost savings that a well-organised on-demand service brings make this an attractive business model feature especially if a solid user base is formed for the service [51]. The liner service does create longer average waiting times for the FVs, but builds more reliability as it guarantees a departure at a predetermined time. This is in particular important for short sea vessels with reduced crew size and IWT vessels at a B regime that rely on the departure of an LV and without which these vessels have limited operating conditions.

The uncertainty of the tramp service could be addressed by creating a staff pool of flexible crew members that are allocated to vessels in order to enable the ship to operate on its own. Such solutions would create an even more complex business model, which drifts away from the core crew reduction the VT concept aims to facilitate. Knowing that the core weakness of the liner operations lie within the waiting times, it is important to demonstrate and determine a minimum departure frequency for the VT concept dependent on the operating sector.

The custom pick up creates its service by not only picking up the client at its desired location but also delivering it to the desired destination as well. This means that a dedicated LV is needed to provide such a concept, as a cargo-carrying LV is bound by its cargo destination. The cost comparison of section 3.1 has established that for this viability assessment the cargo-carrying LV will be used, implying that it always has a predefined destination port. Hence, the Uber service concept is also not taken further within this research.

3.2.3. Contract Length

The final business model feature is the contract length. It influences the payment strategy of the VT service. This is only of relevance for the VT as a service business structure, as a single company that uses the VT within the coordination of its own fleet does not need to consider paying its own services. A VT service as a business that is set up to use a payment charging per km or per journey may be cheapest for the user for short term use, yet it requires the VT and the FV operator to carefully weigh their choices for every journey, which creates added workload and is economically also riskier for both parties [51]. At the same time, such short-term decision making is only possible for vessels that only have an increase in productivity to gain and do not reduce their crew size, i.e. IWT vessels currently operating at an A1 and

A2 regime. Any other vessel that reduces its crew size, cannot easily hire crew members on a trip-by-trip basis. Therefore, joining a VT is a decision taken for several months or even years. In those circumstances, a subscription payment scheme comparable to the mobility service subscription [115] is most realistic. This form of contract can be compared to a shipping pool [116] that shares the LV expenses with all participants and simultaneously improve their own productivity.

Based on these building blocks, different business models have been set up and reality checked with stakeholder in a workshop have been performed. These stakeholders including vessel owners, brokers, waterway authorities and logistic service providers. The workshop concluded that vessel operators find the single company model the most realistic, whereas all other actors find the platform based third party coordinator the most progressive and hence adaptable solution [51].

This information overview and based on the fact that this research should identify the viability requirements for both the short sea and the inland sector application, the business model studied hereon forward are liner services, led by cargo-carrying LVs for both a single company structure, as well as a third party platform structure that assumes an annual subscription fee to be paid by the FVs.

3.3. Summarizing the VT Features

This section has elaborated on the key elements of the VT concept and its differences to conventionally sailing vessels. It has shown the VT operational differences to lie within the VT operating speed adaptation based and the idle time of the FVs. The explanation of the LV type and the VT business model options concluded that the most appropriate set-up of the VT allowing a reliable and predictable service is a prescheduled VT in which the individual trains are led by cargo-carrying LV. The FVs join and leave the train wherever it is most suitable for them. The VT concept is assessed for both a single company business structure and a third party platform service, dependent on the business structure of the application area. The information presented in this section addresses sub-questions 1 and 2 of chapter 1, identifying not only the VT operational changes but also how these differ, between the short sea and the inland sector. Chapter 4 presents the model used to calculate the cost changes between the reference vessel and the FV conditions. This model is used in chapter 5 to assess the viability of the VT and the sensitivity of the VT features as well as the input parameters.

CHAPTER 4:
THE VESSEL TRAIN VIABILITY ASSESSMENT MODEL

This chapter describes the foundation of the VT economic viability assessment. The VT's viability is defined as achieving the same or lower transport cost for the VT users and identifying a reasonable number of FVs needed to ensure that the VT service cost are covered. Throughout this chapter established cost models from short sea and IWT sectors are studied, merged and adopted to ensure the effects of VT feature variation presented in chapter 3 can be quantified. The main challenge of this chapter is to tailor the VT cost model to include the most relevant and impacting cost features for the VT, without excessively increasing the complexity of the model by including every possible influence factor of waterborne transportation systems. Creating a shortlisted number of cost elements ensures to keep the focus on the changes that the VT concepts bring to the vessel operators while still considering the perspectives of the cargo owner and society. The focus of this chapter is thus to address sub-question 3 by explaining how the viability of the VT is assessed first theoretically and later via the description of the structure and detailed calculation used in the assessment model. Parts of this chapter have been published in the NOVIMAR deliverables 1.2 and 2.2 [45], [50], as well as journal articles [39], [44], [117].

The chapter is structured as follows: First, the model requirements are laid out in section 4.1. Then section 4.2. gives an overview of project evaluation methodologies and the literature sources from which cost elements have been gathered and studied. Section 4.3. describes a shortlisting procedure that allow to identify the most impactful cost elements for the VT. The resulting shortlist is compared to literature

sources to demonstrate its completeness. Section 4.4. dives deeper into explaining the individual shortlisted cost elements and the way they are merged together into the model framework.
The description starts by identifying the VT operating speeds that are needed to calculate the trip of individual participants. Then the productivity of the reference and FVs can be determined as indicated. The trip time and the productivity of the individual vessels are used to determine the transport cost of the reference and the FV vessels. These calculations start by explaining the capital cost, including the vessel building cost, the VT control system investment, the depreciation and the interest cost. This is followed by the operational cost that requires resistance predictions to be made, to determine the fuel consumption and the vessel's fuel cost. Next, the crew cost calculations are described as well as the repair and maintenance cost. The last operating cost elements for which assumptions are elaborated are the insurance and the administration cost. Once all these cost elements are calculated, it is possible to determine the net savings of the FVs. The following step includes the VT operator cost when integrating different business model options into the calculations. Here, it is also explained how the number of participants per VT and the total required fleet share is determined. It moves on to explain the external cost created from the perspective of society by changes in pollutions from the VT operation and brings in the perspective of the cargo owners by explaining the calculations behind the changes in cargo-related cost. Finally, the chapter finishes by commenting on the validity expectation of the outputted results and from the VT cost model.

4.1. Requirements of the VT Cost Model

The model's main target is to provide results that allow the economic viability of the VT concept to be assessed. The economically viable conditions are achieved when both of the following conditions are met:

1) the transport cost of the VT user is equal or lower than that of the currently sailing reference vessels;
2) the combined cost-saving of the FVs are greater than the cost created by providing the VT service.

These two conditions are the economically viable conditions from the perspective of the direct stakeholders, i.e. the VT operator and the FV operator. However, the economic viability also has to be assessed from the perspective of the shippers and society. If the concept does not reveal benefits, for both of these actors, it also becomes more challenging to implement.

The model needs to be generic enough to accommodate a range of case assessments that permit the identification of both viable and unviable conditions. It should hence allow for various vessel types, operating conditions (i.e. operating speeds, journey length), varying maturities of the technology implementation and business models to be analysed. The assessment of best and worst-case scenarios enables trends to be recognised that can develop an indication of the VT service operating requirements. The requirements are not aimed at concluding the optimal operating conditions for the specific case studies but need to be indicative of reasonable VT applications. Sensitivity analyses are also applied to the case studies in chapter 5 are used to help draw conclusions.

The introduction of this thesis stated the main aim of the VT concept, the improvement of the competitiveness of the FVs. The key performance indicator (KPI) for the analysis is thus the cost reduction per tonkilometer (tkm) achieved by the FVs. This KPI is the main output of the model.

4.2. Literature Review of Cost Assessments

There are a number of methodologies with which cost assessment can be performed. This section provides a brief explanation of the most relevant of these methodologies, as well as a description of cost assessment found in literature with specific emphasis on maritime transport applications.

4.2.1. Project Evaluation Methodologies

Investment or concept development projects can be assessed using a variety of tools. For this research cost-effectiveness analysis (CEA), cost-benefit analysis (CBA) and social cost-benefit analysis are of relevance. All three are tools to evaluate and support decisions making and provides insights for policymakers [118], [119]. A CEA is an evaluation tool in which the output is not necessarily expressed in monetary terms. It is a measure of all quantifiable influence factors, however, some benefits or negative effects are left to be expressed in qualitative measures. The CBA goes further than a CEA and quantifies all cost and benefits in monetary terms, this is why CEA can be viewed as a subset of a CBA [120].

The structure of a CBA is formed around technical feasibility, financial, economic and risk assessments and takes into consideration demand and customer benefits but purely from a private perspective. When the assessment is extended to addresses welfare economic aspects and no longer purely looks at the private components but also at the public effects on society then it is classified as a SCBA [118].

CBA is a tool that is particularly used in high capital intensity transport infrastructures projects [121]. Taking inspiration from such large scale infrastructural project is mainly done to gain an understanding of the wide variety of detailed influence factors included in these assessments. These are road construction-related investment projects that have access to a large amount of data from road traffic. This allows for complete SCBAs to be set up that focus on the benefits per car in terms of time savings, savings on wear and maintenance of the vehicle, fuel savings, accident avoidance as well as improved comfort for the user.

Each of these methodologies can be done for retrospective (ex post) or prospective (ex ante) analysis. In particular the ex-ante analysis, used for the assessment for prospective innovations such as the assessment performed in this thesis, rely on the setting of a large number of assumptions which adds subjectivity to the results. It is thus important to perform sensitivity analysis as part of the assessment process to ensure a realistic understanding of the results to be covered. The assessment approach for each of the three assessment methodologies described above follow a similar process steps which have been summarized by [119] as follows:

1. Set the framework of the analysis
2. Decide who's cost and benefits shall be recognized
3. Identify and categorize cost and benefits
4. Monetize cost where possible
5. Quantify benefits in terms of units of effectiveness (for CEA), or monetize benefits (for CBA)
6. Discount costs and benefits to obtain present values
7. Compute a cost-effectiveness ratio (for CEA) or a net present value (for CBA)
8. Perform sensitivity analysis
9. Make recommendations where appropriate

These steps are followed in the VT cost assessment of this thesis and are referred back to at respective locations within the text. The following sections of this chapter will make it clear that the assessment performed for the VT viability assessment is an extended cost-effectiveness analysis. The VT viability assessment goes beyond a cost-effectiveness analysis as it not only calculates the cost-effectiveness ratio in terms of cost per tkm of each vessel, but draws its main results from the differences in cost-effectiveness ratios between the current and the VT conditions. It uses the savings made per FVs as its main viability indicator, which makes it resemble a CBA. However, only the most relevant cost elements are integrated in the assessment, which means not all cost and benefits are quantified on a monetary basis, nor are all demand related components considered, as they are related to a wider network assessment. The assessment can thus not be considered complete CBA nor SCBA.

4.2.2. Example Application of Cost Analysis Methods

To ensure that all relevant cost elements are included in this research, a large number of cost assessment methods ranging from infrastructural projects, over transport projects from other modes of transport, to maritime transport-related projects are studied. This section presents a selected number of cost assessments as points of reference and describes the cost structures which form the foundation of maritime cost models.

Maritime transport-related cost assessment methods are numerous [10], [122]–[128]. The ATOMOS IV project is used as an example as it resembles the VT concept with regard to the automation of navigation. ATOMOS IV assessed whether or not it is worthwhile for a vessel owner to refit an Ice breaker with the ATOMOS system [127]. The system is a complete navigational bridge package consisting of the hardware of a bridge console (i.e. panels, joysticks, etc.) that are connected via an automation solution allowing any of the bridge equipment and alarm systems to communicate and exchange data with a network. The project acquired detailed cost estimations on the equipment that needs to be installed and topics such as the retraining cost of the crew. The study has also quantified a direct safety benefit by the technology towards accident cost reduction. The study deals with the refit of vessels; hence the ship-related capital cost factors were not needed to be integrated into their assessment.

An analysis that takes the automation of vessels further than that of navigation tasks, is the cost assessment performed by the MUNIN project. The project is the first large scale investigation of the technical feasibility and commercial viability of unmanned merchant ships [129]. While remote navigation through a shore control station receives their main research focus, they also describe how the new vessel design translates into cargo-carrying benefits or air resistance reduction [63].

Grønsedt (2014) conducts a financial cost assessment on the feasibility of transporting containerised goods between Rotterdam and Yokohama using the Northern Sea Route as an alternative to the Suez Canal Route, since transporting goods via the NSR reduces the travel distance up to 35%. The analysis is focused on the annual operations between two specific ports for which the number of trips is calculated based on the operating performance, comparable to the way it is performed in the VT cost model. To determine the adaptation of the route, it is also assessed whether an investment in an ice-strengthened containership appropriate is worthwhile.

In the maritime sector factors such as added waterway maintenance requirements due to the higher waterborne traffic density, sound or light pollutions near ports or the effects of natural habitat disturbance are not included in monetary terms in SCBA. This is due to the fact that standardised data is not available to the same extent compared to the gathered data for road-based operations. While there is literature that addresses external factors such as light, sound, vibration pollution, oil spills or erosion effects due to frequent ship passage [126], many of these components are not quantified such that they can be applied in more general terms. Instead, most studies mainly focus on calculating the external cost in terms of emissions, accidents or congestions at locks and ports as these are the largest external cost contributors and can be calculated based on the ship operations [123], [131] and logged accident reports.

4.3. Determining Relevant Cost Elements

Based on the cost assessment methodology described in section 4.1.2., steps 1-3 are described within this section as it identification of relevant cost elements included in the assessment. Thus the methodology used to shortlist the most relevant components is described, followed by a comparison of this shortlist to related research projects.

4.3.1. Identifying the Relevant Cost Parameters for the VT

The study of prior research described in the last section combined with the VT features given in chapter 3 resulted in a list of cost elements that can play a role in the assessment of the VT. In this section, a summary of the elements and their relevance is specified. However, not all of these cost elements are incorporated in the final model, as they have varying impacts and relevance for the VT concept. Even though there are many factors that have an influence on the waterborne transportation system, it is important to find the balance between the model complexity and impact of factors to develop a sufficiently complete model that enables accurate case study assessments to take place. Therefore, this section explains the filtering method used to shortlist the cost elements, summarises the shortlisted components and compares the integration of these components to other studies.

Filtering the Cost Elements

At the beginning of this project, a study has gathered a long list of cost elements that have been considered in prior research the most relevant of which have been described in section 4.2.2. Yet, not every cost element used in other cost assessments is necessarily of relevance for the VT concept assessment. It is needed to filter the cost elements for their relevance and impact on the VT concept. The filtering ensures research effort is targeted on components that contribute to the final goal of understanding the performance and behaviour of the VT and not get side-tracked by the assessment of general features of the waterborne transport sector.

A prioritisation method has been applied to filter the list of cost elements based on application relevance for the VT concept and data availability on the quantification of each element. The method has a four-stage evaluation.

- To narrow down the list to only elements that have a clear impact, the first stage identifies the possible impact of the individual cost elements compared to the overall expected cost and identifies the relevance for the VT concept. A judgement based on descriptions from references is made to determine the either large/low impact.

- The second stage determines whether there is sufficient data available to calculate the impact of an element. Sufficiency of data is identified by one or more sources that provide values that form a solid basis of using the value as input assumptions for the model. The result answers for this stage are thus: yes or no.

- The third stage ensures that the calculations needed to obtain usable results are feasible within the context of this thesis. A calculation of high simplicity would be a situation in which standardised values can be used for cost estimations. A calculation with high complexity requires the interpretation and processing of large amounts of data together with numerous calculation steps.

- The fourth categorisation takes all the scores from the previous stages into consideration. It is the prioritisation criterion. Here the three options are: 1) The cost element is always included into the assessment, 2) the inclusion of the cost element is dependent on the business case application, or 3) the cost element is not included in the assessment.

Figure 13 gives an overview of the type of scores given for each decision stage. The purple diamond describes a special stage of the categorisation. There are cost elements that are known to have a large impact on the model but do not have any data to refer to, since they are directly related to the new concept. In such cases, an assumption is set that is mostly based on experts' opinions. The impacts of such cost elements are further investigated throughout the assessment to understand the effects a misestimating may have on the viability of the overall concept.

Going through this filtering process not only shortlisted all relevant cost elements that are presented in the next section, but also gathered all information needed to calculate each element and combine them in a structured cost model. These calculations are presented in section 4.4.

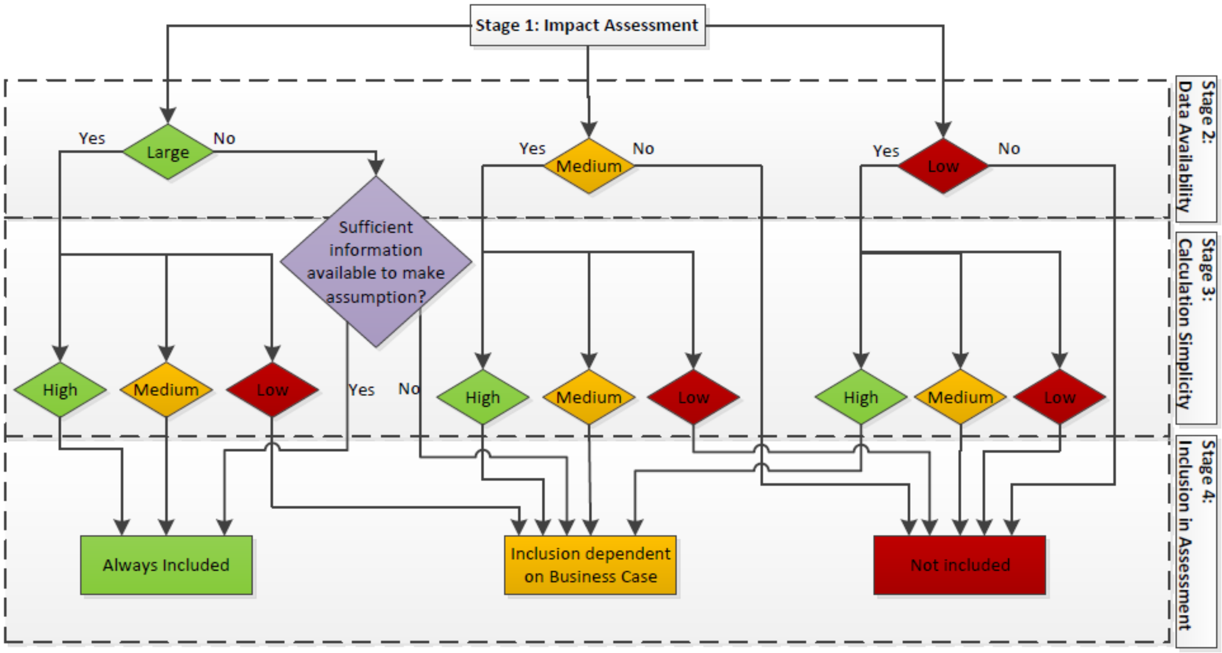


Figure 13: Cost Elements' Prioritisation Method

List of Cost Elements

The filtering procedure of the cost element was a broad study made for the NOVIMAR project that can be found in the project's deliverable 1.2 [45]. The summary of this long and detailed assessment is presented in Table 5. It includes slight adjustments tailored to the purpose of this thesis. The overview descriptive the cost elements together with their level of prioritisation for the VT model. The list includes all cost elements from the perspective of the FV, LV operators, society and cargo owners. It only provides a very brief description of the elements to give an understanding of why they have or have not been integrated into the model. A detailed description of the elements included in the model is provided in section 4.4.

Table 5: Summary of Cost Elements

Cost Structure	Cost Element	Comments	Prioritisation Always 2 Dependent 1 Not 0
Capital Cost	Depreciation cost	The depreciation is split into the ship and the VT control system technology depreciation, which are depreciated at a different rate and are dependent on the VT investment cost and the vessel value.	2
	Interest cost	Just like for the depreciation, the interest cost has to be considered for both the vessel and the VT control system.	2
Operating Cost	Insurance cost	It is to be expected that the addition of automation will decrease the number of accidents and casualties, but at the same new types of risks are created (cyber); hence the overall, the insurance cost are kept as they are currently.	2
	Crew cost	As chapter 3 described elaborately, the crew size and respective cost is an essential element for the VT concept. These cost vary significantly dependent on the sector and the geographical application of the concept.	2
	Repair & maintenance cost	The repair and maintenance cost is calculated for both the ship and the VT control system. The design of the vessel is not expected to change due to the crew reduction [132], hence the maintenance and repair is remaining the same.	2
	Back office cost	Various sources have made cost estimated for shore control stations. These as such do not hold. The VT does not need a shore control centre that is found in many autonomous shipping assessments. Yet, dependent on the business model, the VT operator may require a back-office from which the coordination of the matching can be done. This office can make up a significant part of the operating cost of the VT business.	1
	Black/greywater	Water and waste management will reduce with smaller crews. However, this environmental improvement and cost reduction is negligible compared to other cost elements.	0
	Waste management		0
	Lubrication & stores cost	The cost of lubrication and stores is dependent on the vessel age and maintenance. Yet, just like it was seen for the maintenance, there is no trend that allows estimation. Given that this is not an element that is actively influenced by VT operations and it is making up a smaller contribution than maintenance, it is not included in the model.	0
	Training cost	Understanding the qualification requirements of the crew interacting with the automation technology is an important aspect of the concepts' development. However, it is not possible to accurately predict this cost with the current state of the control system development. This can only be clearly addressed as a source of uncertainty within the implementation of the concept.	0
Voyage Cost	Fuel consumption and cost	Fuel consumption is dependent on the operating conditions of vessels, and the fuel cost additionally on the price of the fuel. The fuel cost is one of the main contributors to a vessel's operational cost and can be estimated based on proven calculations methods.	2
	VT dues	VT dues are the fees that need to be paid by the FV operator to the organiser of the VT. Dependent on the business model, this cost may be internal within a company. It is expected to be a long term cost over the duration of several months or annual.	2

	Port dues	Port dues are charged for ship-related services and for crew-related services. They are dependent on the size of the vessel and the geographical operation of the port. The crew-related port dues may be slightly lower with a smaller crew, however, these changes are negligible. Optimisation procedures such as pre-sorting are changes in the cargo handling that can have an effect on the port dues. These “additional building blocks” developed by work packages of the NOVIMAR project lie outside the scope of this research and are hence not added to the VT model.	0
	Bridge, lock passage cost and canal fees	Fairway dues (which do not exist in the Netherlands and on the Rhine) for Flanders are very low. These fees are not impacted by the VT concept.	0
Cargo related Cost	Logistics cost	The logistics cost are split into stock in transit, safety and cycle stock. Some of these stock types are influenced by a change in the lead time of the goods. This is an aspect that the additional waiting times and VT operating speed influence.	1
External Cost	Air pollution cost	The emission of ships is the most important environmental external cost factor and can be calculated based on the fuel consumption. However, not all of the gases are equally relevant, which is the reason why a prioritisation has been set to SOx, NOx, CO2, PM, CO and HC.	2
	Congestion cost	Congestion cost calculations due to a higher traffic density are calculated using speed-flow relations of the traffic. These are not available for waterborne traffic and congestion on the waterways is considered negligible. However, congestion effects on the road traffic caused by the VT, through for instance, passing a bridge, can be assessed with the available data.	1
	Waiting time cost at locks and port	The simultaneous arrival of a number of vessels at a lock or a port may cause congestions for the VT users as well as third parties. This is an issue that asks for regulations and planning solutions for the local facilities. This resembles the port or lock scheduling problems that are studied in operations research and is thus not included in the VT specific research of this work.	0
	Infrastructural decay of waterways	Hydrodynamic and CFD tests of the VT, performed by MARIN, concluded that the vessel needs to operate at a far enough distance apart to avoid any negative effects on the power requirements or steering [94]. Hence, the vessels in the train will not affect the waterway infrastructure or the natural habitats in any other way than the conventional operating vessel.	0
	Impact on natural habitat		0
	Water pollution	Water pollution is mainly a problem with oil spillage in ports and water discharge of seagoing vessels. There are no concrete monetary guidelines on how these discharges reflect within societal cost.	0
	Sound pollution	Even though this topic may be of importance, especially when considering delivering more goods into urban areas, it is very difficult to be calculated. Real data are needed and are usually either not recorded or available.	0
	Light pollution	Similar to sound pollution, light pollution may become particularly relevant when considering delivering more goods into urban areas. It is very difficult to be calculated since real data are needed and are usually either not recorded or not accessible.	0
	Accident cost	Accidents can cause high external costs. However, large accidents are fairly rare in waterborne modes of transport. So, the assessment of such circumstances is kept for a later stage in the model development.	0

Comparison of Shortlist

The shortlist presented in Table 5 indicates the most important component for the VT concept. To illustrate how these components compare to other assessments, Table 6 illustrates the use of each cost element in a variety of sources. Most of the sources have been described within the literature review of this thesis. The comparison shows that the main difference lies in the number of external cost factors included. These are either extremely application case-specific and can therefore not be translated to the VT operations [36] or qualitative [10], [126].

Table 6: Comparison of Shortlisted Cost Elements to Other Studies

Cost Element	Sources									
	VT model	[14] **Blauwens**	[36] **Lyridis**	[10] **Miola**	[24] **Van Hassel**	[28] **Beelen**	[29] **Hekkenberg**	[16] **Grønsedt**	[18] **Kretschmann**	[35] **Verberght**
Depreciation - ship cost	✓	X	X	X	✓	✓	✓	✓	✓	✓
Depreciation- automation technology cost	✓	na	✓	na	na	na	na	na	✓	✓
Interest cost	✓	X	✓	X	✓	✓	✓	✓	✓	✓
Insurance cost	✓	X	✓	X	✓	✓	✓	✓	✓	✓
Crew cost	✓	X	✓	X	✓	✓	✓	✓	✓	✓
Maintenance & repair cost	✓	✓	✓	X	✓	✓	✓	✓	✓	✓
Fuel cost	✓	X	X	✓	✓	✓	✓	✓	✓	✓
VT dues	✓	na	na	na	na	na	na	na	na	na
Emission cost of SOx, NOx, CO2, VOC and PM	✓	X	X	✓	✓	X	✓	X	X	✓
Cargo related cost	✓	✓	X	na	✓	✓	✓	X	X	X
Congestion cost	✓	X	X	X	✓	X	X	X	X	✓
Back office cost	✓	na	✓	na	✓	na	na	na	✓	✓
Lubrication & stores cost	X	X	X	X	X	✓	X	X	✓	X
Training cost	X	na	✓	na	✓	na	na	✓	✓	✓
Port dues	X	X	X	X	X	✓	X	✓	✓	✓
Wastewater and waste management cost	X	X	X	✓	X	X	X	X	X	X
Bridge, lock passage cost and canal fees	X	X	X	X	X	✓	X	✓	✓	X
Water pollution cost	X	X	✓	✓	X	X	X	X	X	X
Accident cost	X	X	✓	✓	✓	X	X	X	✓	✓
Waiting time cost at locks and port	X	X	X	X	✓	X	X	X	X	X
Waterways decay and impact on habitats	X	X	X	✓	X	X	X	X	X	X
Sound pollution cost	X	X	X	✓	X	X	X	X	X	X
Light pollution cost	X	X	X	✓	X	X	X	X	X	X

Legend:

✓: Included in the source or model

na : Not applicable means that it is only of relevance for the respective concept

X : Excluded in the source or model

4.4. Vessel Train Model Calculations

This section describes the way in which the cost elements are brought together into the structural framework of the VT cost model. It details the cost estimation methods used with the available data and explains the equations used for each element.

4.4.1. Model Framework

The viability assessment is primarily done for private entities, i.e. the vessel operators, future VT operators and shippers to identify if the VT is a viable solution for them. However, also the public perspective is added in the assessment by including emission cost. This can help determine whether public support sources could be used to help the VT concept take off.

Figure 14 is a visual representation of the structural framework of the model and the assessment performed with its results. The model starts by calculating and merging the cost elements of each FV type with their respective reference vessel cost and the LV/ VT operator cost. These calculations are based on the return trip time, hence the speed, distance, operating regime, water current speed and departure frequency of the VT operations. They not only include the transport cost calculations, but also the external cost. The cost are calculated for a range of input data that are brought together in the assessment to identify the viable operating requirements. When a case is able to identify viability requirements, these are used as implementation guidelines. If the viable conditions cannot be identified or only for highly restricted operations, the original input data will be adapted within reason to assess whether alterations can be made that enable economic viability. In the case that different development stages indicate drastic viability differences, the external cost benefits help determine if temporary government subsidies can help support the concept temporarily.

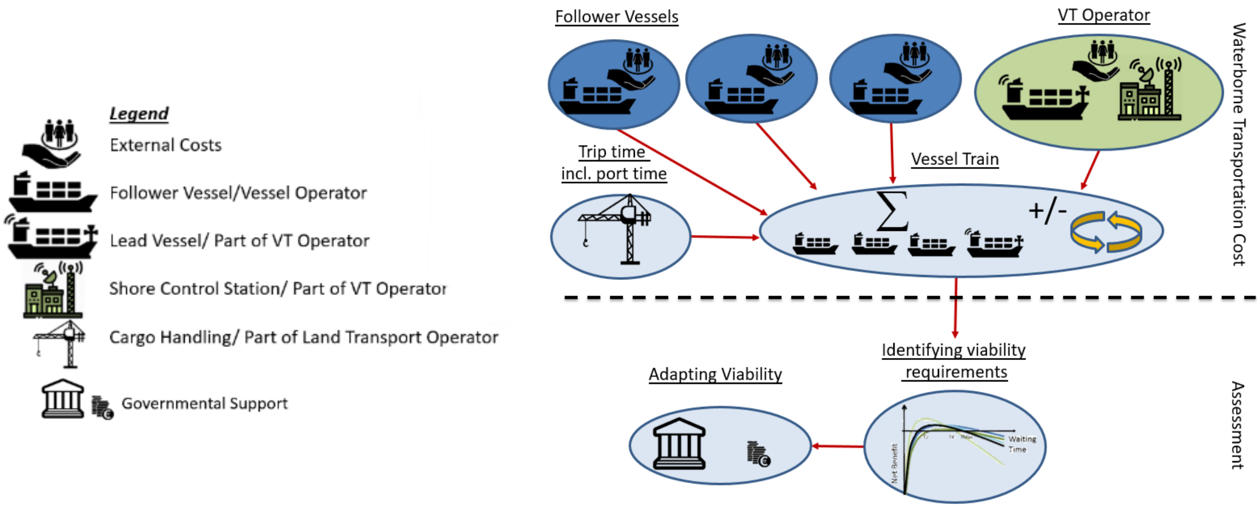


Figure 14: Structural Framework of the VT Cost Model

4.4.2. Data Sources and Calculation Methods

Before diving into the detailed cost calculations, it needs to be clarified how different components are brought together. This section explains steps 4-6, which were listed in the assessment method of section 4.2.1.

In section 3.3 it was concluded that the assessment should be performed for a liner service. This implies that the VT sails round trips on a fixed route, ensuring a departure at a given interval. Using this and a fixed number of LVs, the VT sailing speeds can be deduced. Once this speed is known, the return trip time can be determined. Next, the productivity of the reference vessel and the FV are computed, to determine the cost per ton of the respective vessel. The reference vessel is specifically needed to determine the maximum FV cost at which the cost per tkm is at least equivalent to the reference conditions.

Knowing the voyage time makes it possible to determine the fuel consumption and the fuel cost as well as the external cost created by pollution emission. The fuel cost, together with the other operating cost elements and the capital cost form the transport cost of the reference vessel. This transport cost is used together with the productivities of the vessels to determine the FV net savings. Finally, the first key performance indicator (KPI), the cost reduction per tkm, for the viability of the FV operator is determined by converting the net savings to a cost reduction per tkm.

The viability for the VT operator is identified by establishing the VT operator cost dependent on the applied business model. Once both the FV and the VT operator cost are known, the required number of participants per LV can be determined, which is for the platform-based model equivalent to the contribution fee of the FV participants. The required FVs and the number of LVs along the liner route are then compared to the total fleet size to obtain the second performance indicator: the required fleet share for a viable application.

The last steps include the societal and cargo related cost into the model. These calculations use the earlier mentioned fuel consumption and power requirements to determine the external cost created through emission pollution, as well as the benefits created through the VT implementation. The cargo-related cost calculations use the earlier determined trip time together with cargo related input data to identify the difference in safety stock and stock-in-transit caused by the changed lead time when using the VT.

The following order of parameter calculation steps summarize the structure of the VT cost model:

1. VT operating speed
2. Return trip time
3. Productivity
4. Transport cost (capital and operating cost)
5. FV net savings
6. Integrating the business model
7. External cost
8. Cargo related cost

The flow chart in Figure 15 illustrates how the input data and calculation steps that were described above merge together from the reference, FV and the VT operator perspective to determine the output of the cost model. The output obtained by this model and hence the results presented in the application cases of chapter 5 provide a step-by-step evolution of first the productivity changes, then the FV cost savings, ultimately leading to the KPI’s of cost per tkm compared to the reference vessel and the required fleet share. These KIP’s are then also influenced by the internalization of external cost and the consideration of the cargo-related cost that will be discussed in the final part of the assessment.

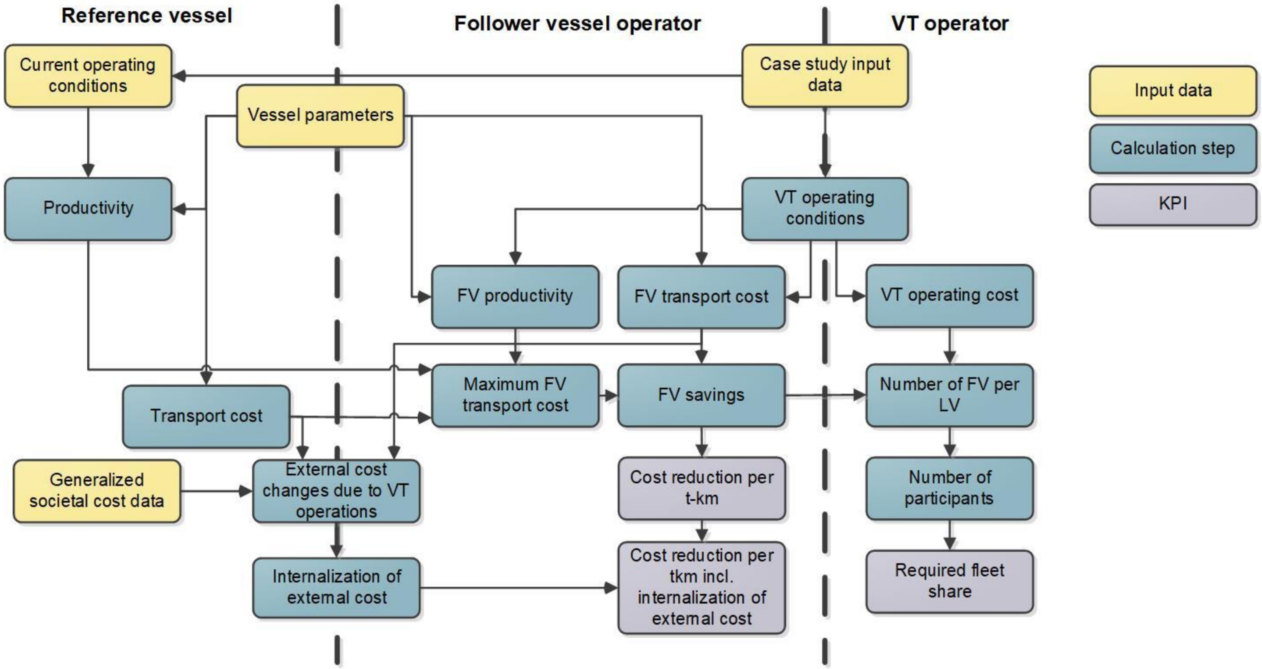


Figure 15: Calculation Dependencies of Calculation Elements

VT Operating Speed

As was explained in the introductory description of this section, the determination of the VT operating speed is the first step of the VT model calculations. The VT operating speed is calculated using equation 1, which is derived from knowing that the number of LVs is the return trip time of the LV divided by the departure interval. This VT operating speed is determined based on the return trip time of the lead vessels that are assumed not to incur any waiting times before the departure of the VT. The departure interval of the train is set within the case study. The number of LVs in the transport system are determined such that the operating speeds of the VT are as close as possible to the operating speeds of the reference vessels. The lock passage time and river current speed that are included in equation 1 are set at 0 in the short sea calculations, which simplifies its VT operating speed calculations.

$$v_{VT} = \begin{cases} \dfrac{2d}{In_{LV}-2t_{p_{LV}}} & ; \boldsymbol{for\ short\ sea} \\ \dfrac{d}{In_{Lv}-2(t_{p_{LV}}+t_l)} + \sqrt{\dfrac{d^2}{\left(In_{LV}-2(t_{p_{LV}}+t_l)\right)^2} + v_c^2} & ; \boldsymbol{for\ IWT} \end{cases} \qquad \text{Equ. 1}$$

Where:

d: VT trip distance (km)

n_{LV}: required number of LVs in the transport system

t_l: time for lock passage (h)

I: departure interval of the LVs (h)

$t_{p_{LV}}$: time the LV spent in port (h)

v_c: speed of river current (km/h)

Return Trip Time

With the VT operating speed known, the voyage time for a return trip can be determined. The first part of the trip time calculations is to determine the amount of time that vessels spend sailing ($\boldsymbol{t_s}$) with no operating restrictions. The VT operations change the sailing times of the FVs while they are part of the train, as they need to adapt to the operating speed of the other vessels in the train. Once navigating under their own control outside of the VT, the FVs can adjust their operating speed. Equation 2 provides all variations of the sailing time calculations for reference and FVs.

$$\boldsymbol{t_s} = \begin{cases} \dfrac{2d_R}{v_R}\,;\ \boldsymbol{for\ short\ sea\ ref.\ vessel} \\ \dfrac{2d_{in}}{v_{VT}} + \dfrac{2d_{out}}{v_R}\ ;\boldsymbol{for\ short\ sea\ FV} \\ \dfrac{2d_R v}{v_R^2 - v_c^2}\quad ;\ \boldsymbol{for\ IWT\ ref.\ vessel} \\ \dfrac{2d_{in}v_{VT}}{v_{VT}^2 - v_c^2} + \dfrac{2d_{out}v_R}{v_R^2 - v_c^2}\ ;\boldsymbol{for\ IWT\ FV} \end{cases} \qquad \text{Equ. 2}$$

Where:

d: VT trip distance (km)

d_{in}: distance of the FV spent in the VT (km)

t_s: return trip sailing time (h)

v_R: operating speed of the reference vessel (km/h)

d_R: ref. vessel & FV distance (km) i.e. $d_{out} + d_{in}$

d_{out}: distance the FV spends sailing on its own (km)

v_c: speed of river current (km/h)

v_{VT}: operating speed of VT (km/h)

Once the sailing time is determined, the return trip time is calculated using equation 3. The reference vessel of the short sea case simply adds the port times (including time spent on actions such as (un)loading, berthing, bunkering) to the sailing time. The inland and the VT conditions restrict the operations of the FVs. Therefore, additional resting time needs to be added dependent on the operating regime and the restricted operating hours per day (t_o). The IWT reference vessel case also needs to consider lock passage time (t_l)., thereby adding it together with the port time (t_p). Finally, the return trip times of FVs also include the VT waiting time. Time spent at a terminal depends on aspects such as berthing times, the type and amount of cargo (un)loaded, the capacity of the terminal equipment or even the waiting time required for bunkering. Hence, it is assumed that it is not possible for a follower vessel to plan the time at which it is ready to join the VT such that this coincides with the departure time of the VT. This means a uniformly distributed arrival pattern of FVs at the location where they join the VT is assumed, which makes the average waiting time (t_w) to be half the departure interval of the LVs.

$$\boldsymbol{t_t} = \begin{cases} t_s + 2t_p\ ;\ \boldsymbol{for\ short\ sea\ ref.\ vessel} \\ t_s + \dfrac{\frac{2d_{out}}{v_R}}{t_{o_a}}\left(24 - t_{o_a}\right) + 2\left(t_p + t_w\right) ;\boldsymbol{for\ short\ sea\ FV} \\ t_s + \dfrac{\frac{2d_R v}{v_R^2 - v_c^2}}{t_{o_i}}\left(24 - t_{o_i}\right) + 2\left(t_p + t_l\right) ;\ \boldsymbol{for\ IWT\ ref.\ vessel} \\ t_s + \dfrac{\frac{2d_{out}v_R}{v_R^2 - v_c^2}}{t_{o_a}}\left(24 - t_{o_a}\right) + 2\left(t_p + t_l + t_w\right) ;\boldsymbol{for\ IWT\ FV} \end{cases} \qquad \text{Equ. 3}$$

Where:

a: FV sailing time restriction outside of VT

t_l: time spent in locks (h)

t_p: time spent in port (h)

t_w: VT waiting time due to VT departure (h)

i: original operating regime of ref. vessel

t_o: restricted operating time per day (h)

t_t: return trip time (h)

Productivity

With the trip time calculated, it is now possible to determine the productivity of the vessels. The productivity of the vessel is measured in terms of the amount of cargo (in tons or TEU) transported annually between a set origin and destination. The formula to calculate the productivity is expressed by equation 4 for both the reference vessels and the follower vessels, simply varying the input based on their operating conditions. The total number of annual operating hours differ for the FV and reference vessel. The restricted operating speeds inside of the VT and the restricted number of sailing hours when operating under their own navigational control, cause the annual number of operating days to change. These number of operating hours are also influenced by holidays and days of restricted operating conditions due to weather conditions. The latter is mainly an issue for inland navigation as high or low water can limit the navigation on the rivers. This topic is discussed in more detail in chapter 5.3.4.

$$P_{FV\ or\ R} = \frac{O}{t_t} 2V \qquad \textit{Equ. 4}$$

$$O = \begin{cases} 24(D_i - r_{hw} - r_h) & ; for\ ref.vessel \\ 24\left[\left(\frac{d_{in}}{d_R} D_B + \frac{d_{out}}{d_R} D_a\right) - r_{hw} - r_h\right] & ; for\ FVs \end{cases} \qquad \textit{Equ. 5}$$

Where:

B:	operating regime that allows 24 h operations	*D:*	annual number of operating days
O:	total annual operating hours (h)	$P_{FV or R}$:	annual productivity calculated respective to the ref. or the FV (t/year)
r_h:	operating restrictions due to holidays (days)		
r_w:	operating restrictions due to high/low water (days)	*V:*	cargo capacity of the vessel (t)

Transport Cost

The previous sub-sections have shown how to determine all the operational parameters needed for the transport cost calculations of the vessels. The transport cost calculations of the reference vessel is used to find the maximum allowable FV cost. The flow chart in Figure 16 shows the calculation components. The difference in calculations between the reference vessel and the FVs are in the operating conditions and the fact that the cost for the VT control system is not included for the reference vessel. The cost calculations are presented by category, i.e. first capital then operational cost. Each cost element starts with the description of the reference vessel cost and then adds the requirements of the VT operations.

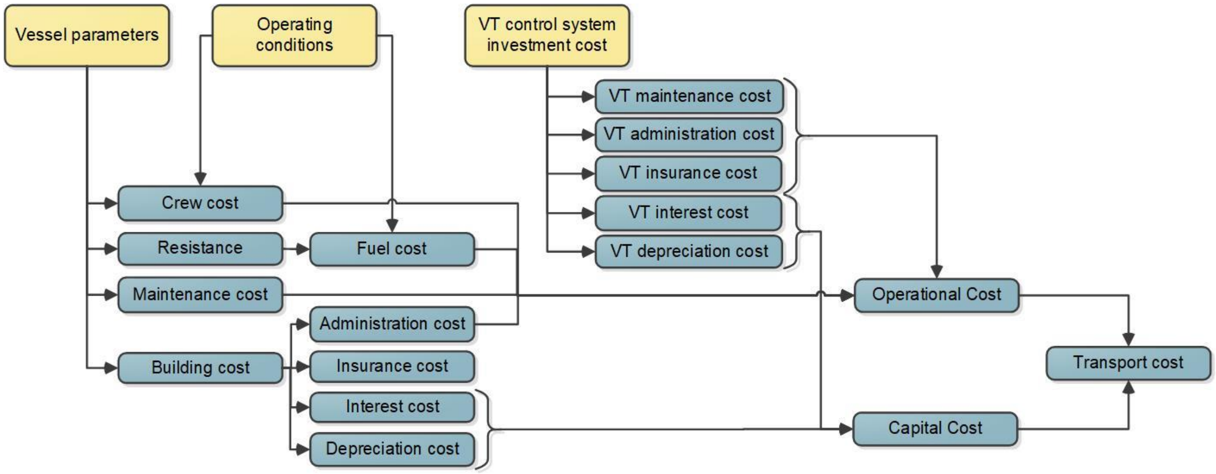


Figure 16: Flow Chart of Vessel Cost Calculations

Capital Cost

As is illustrated by Figure 16 the first large cost element category is the capital cost which is composed of the depreciation and the interest cost of both the vessel and the technology. These capital cost elements are mostly determined as a function of the new building price of the vessel or of the VT technology cost, which is a common approach that is commonly adopted by e.g. [10], [42], [70], [127], [133].

I. Vessel Building Cost

To be able to estimate the capital cost of a vessel, the new build cost of the vessel needs to be determined. If the original price of the vessel is known, that is used for the capital cost calculations. If it isn't known, the generic equations deduced from cost estimation models that are based on regression analysis on sample vessels are used. Generalised formulas have been developed for the building cost of short sea and inland vessels.

i. IWT Vessel Building Cost

Hekkenberg has presented a cost estimation method for several different types of inland vessels [42]. It is a generic equation, given in equation 6, in which the constants change dependent on the vessel type and size. The VT concept is mainly targeting dry bulk vessels as these compose the largest share of the fleet. Hence, the cost coefficients used for the calculations of the vessel's construction cost are those of dry bulk vessels.

$$\mathbf{C_{construction}} = \mathbf{c_\alpha} * (\mathbf{LBT})^2 + \mathbf{c_\beta} * \mathbf{LBT} + \mathbf{c_\gamma} \qquad \text{Equ. 6}$$

T	c_α	c_β	c_γ
1,5	-2,36E-02	1,39E+03	3,54E+05
2,0	-1,20E-03	9,67E+02	4,54E+05
2,5	1,50E-02	6,97E+02	5,56E+05
3,0	8,00E-04	6,41E+02	5,65E+05
3,5	-1,30E-03	5,82E+02	5,85E+05

Where:

B: vessel beam (m)

L: vessel length (m)

$c_{\alpha,\beta,\gamma}$: building cost coefficients for dry bulk vessels

T: vessel draft (m)

ii. Short Sea Vessel Building Cost

Martinez-Lopez et al. determine the building cost of short sea vessels using equation 7. It is based on the vessels' gross tonnage (GT) [43] and thereby also takes varying ship dimensions into account. This formula is most representative of a feeder vessel.

$$\mathbf{C_{construction}} = \left(-4\text{x}10^{-8}GT^2 + 0,0029GT - 2,5447\right)\frac{10^6}{1,29} \qquad \text{Equ. 7}$$

II. VT Control System Investment Cost

The capital cost is mainly composed of cost related to the value of the ship, yet a smaller but also relevant cost element for the VT concept very relevant, i.e. the investment cost of the VT control system also needs to be considered. The VT control system investment cost is an estimate of the technology developers. It requires the installation of VT track and the radar pilot soft- and hardware (i.e. antenna or distance sensors) on board of the vessels. These components have been described in chapter 3.

III. Depreciation

The depreciation is calculated based on the above-described investment cost. In general, it is assumed that a ship will take 20 years to fully depreciate [7], [63]. This means that the cost estimates of the VT cost model assume that a ships annual depreciation is equivalent to 5 % of the above-determined building cost.

The depreciation of software can be as short as three years [134]. The VT control system investment cost is a combination of both software and hardware and is thus depreciated over a lightly longer timeframe of 5 years, which is 20 % of the VT control system investment cost annually.

IV. Interest Cost

Alike it was seen for the depreciation cost, also the interest cost is a function of the amount of money that is borrowed from a bank. The interest rates lie between 4.5 % and 5 % of the borrowed sum [41], [135].

Operational Cost

Unlike the capital cost, the operating cost is influenced by the VT operating speed, journey length, port time and departure interval. All necessary components have already been described earlier in this chapter. A large part of the operating cost is composed of the fuel cost, which is determined based on resistance estimations from which the vessel's fuel consumption is deduced. Another important cost factor is the crew cost which is determined next in this chapter, followed by the repair and maintenance cost that is determined based on regression analysis of different vessel sizes. The final two cost elements of this section cover the insurance and the administration cost of the vessels.

I. Fuel Cost

Calculating the fuel cost based on the operating conditions and dimensions of the vessels is essential to allow operational changes and vessel type differences to be assessed for the VT concept. The fuel cost is dependent on the fuel consumption at the operating speed, the amount of time spent sailing, the number of trips performed annually and the price of the fuel, as shown in equation 5.

$$\boldsymbol{C_{fuel} = fc\, t_s \frac{O}{t_t}\, p_{fuel}} \qquad \text{Equ. 8}$$

Where:

C_{fuel}: fuel cost (€)
p_{fuel}: fuel price (€/t)
t_s: sailing time per return trip (h)
fc: rate of fuel consumption (t/h)
O: total annual operating hours (h)
t_t: return trip time (h)

To calculate the fuel consumption of a ship the vessel resistance and power requirements need to be known. All parameters required for this, are explained in the upcoming subsections.

i. Resistance Prediction

To be able to determine the fuel consumption, first the resistance of the vessel needs to be estimated. It was shown in the VT related hydrodynamic tests performed by DST that vessels sailing in close proximity to another vessel increases their resistance. The tests have estimated the vessels in the train to need at least between 2 % - 4 % additional power compared to reference vessels that do not sail in a train [94]. This is only the case up to one ship length distance between the vessels. The safety regulations however do not allow for the vessels to operate at a distance less than one ship length apart. Thereby, even though there can be additional resistance due to the VT formation it is not expected that the resistance of the vessel operating in the VT is calculated differently from a currently operating vessel, as their safty distances will ensure they are far enough apart.

A commonly used resistance prediction method for displacement vessels is that of Holtrop and Mennen (H&M) [136] is used. The most important resistance components are presented in equation 9. The frictional resistance and form factor have been adapted from the H&M resistance prediction method to take shallow water resistance into consideration. For that the RhineShip86 form factor of [137] is used.

This adaption causes minor changes for the deep water conditions, but allows the effects of shallow water conditions to be assessed for inland vessels. It is valid for vessels with transom and a water depth to draught ratio, h/T ≥ 1,2.

$$\boldsymbol{R_{total} = R_F(1 + k_1) + R_{app} + R_w + R_A} \qquad \text{Equ. 9}$$

Where:

R_A: model-ship correlation resistance (kN)
R_F: frictional resistance (kN)
R_w: wave-making resistance (kN)
R_{app}: resistance of appendages (kN)
R_{total}: total resistance of a ship (kN)
$1 + k_1$: form factor

ii. Power Calculations

Next, the resistance needs to be transposed into power requirements at a given speed. This is done by integrating the propeller efficiency (η_p), the drive train efficiency (η_d) and the hull efficiency (η_H)[138]. The effective power, the effective propulsion power, the effective shaft power, the effective engine brake power and the relative brake power are calculated as provided in equation set 10. The hull efficiently is dependent on the speed and propulsion parameters such as the diameter of the propeller.

Effective power: $\boldsymbol{P_E = vR}$
Effective propulsion power: $\boldsymbol{P_p = P_E / \eta_H}$ Equ. 10
Effective shaft power: $\boldsymbol{P_s = P_p / \eta_p}$
Effective brake power of engine: $\boldsymbol{P_b = P_s / \eta_d}$
Relative brake power: $\boldsymbol{P_{br} = Pb / P_{eng}}$

Where :

η_d: drive train efficiency (0,95)
η_H: hull efficiency
P_{eng}: installed power (kW)
η_p: propeller efficiency (IWT: 0,35, SS: 0,5)
R: resistance (N)
v: vessel velocity (km/h)

iii. Hull Efficiency

The hull efficiency of a ship is established using equation 11. It is determined using the wake fraction (w) and the thrust deduction factor (t) of the vessels. The wake coefficient represents the inflow velocity of a propeller which is usually less than the velocity of the ship, while the thrust deduction coefficient expresses the increase in hull resistance caused by the suction of the propeller [139].

$$\eta_H = \frac{1 - t}{1 - w} \qquad \text{Equ. 11}$$

$$\boldsymbol{w = 0,11 + \frac{0,16}{x} C_b^x \sqrt{\frac{\nabla^{\frac{1}{3}}}{D}} - \Delta w} \qquad \text{Equ. 12}$$

$$\boldsymbol{t = 0,6w(\,1 + 0,67w)} \qquad \text{Equ. 13}$$

Where:

C_b: block coefficient
t: thrust deduction factor
Δw: speed corrector
D: propeller diameter (m)
X: number of propellers
∇: the displacement of the vessel

The wake fraction is determined using equation 12, where Δw is a correction factor based on the Froude number (Fn) at the design speed of the vessel. The following holds: if Fn < 0,2 then Δw= 0 else Fn < 0,2 then Δw= 0,1 [140]. Once the wake factor is known, it can be used to determine the thrust deduction factor using equation 13.

iv. Fuel Consumption

Knowing the power requirements of the vessels makes it now possible to calculate the fuel consumption using the specific fuel consumption. The fuel consumption of an engine is usually given at its design speed, which is around 80 % - 85 % maximum continuous rating (MCR). This is the point at which the specific fuel consumption on the engine is at its lowest. If vessels are not operating at their ideal speed, the specific fuel consumption increases dependent on the MRC the vessel operates at. Table 7 provides two sample engines which have been chosen as representative engines for IWT vessels with the Caterpillar 3406E [141] and for SS vessels with the MakM25 E [142]. The data provided in the table are valid for medium-speed engines with fixed pitch propellers connections.

Table 7: Added Fuel Consumption Compared to 85 % MCR (g/kWh)

%	Caterpillar 3406E	%	Mak M25 E
21	18	21	51
26	16	29	36
32	13	43	16
39	9	50	9
46	5	57	6
55	8	75	0
64	0	85	1
75	0	100	3
87	4		
100	14		

Based on these added fuel consumptions, equation 15 is used to calculate the SFC of the engine at a given speed. The hourly rate of fuel consumption (t/h), used in equation 8, is calculated with equation 15.

$$\boldsymbol{SFC_{eng} = SFC_{optimal} + SFC_{added}} \qquad \text{Equ. 14}$$

$$\mathbf{fc} = \mathbf{P_b}\left(\frac{\boldsymbol{SFC_{eng}}}{\mathbf{1000}}\right) \qquad \text{Equ. 15}$$

II. Crew Cost

The crew cost calculations are at the core of predicting the savings benefit of the VT concept. They are determined based on the number of different roles (r) onboard, which determines the number of crew members and the wages of these crew members. The number of crew members is dependent on the size, age and operations of the specific ships. In the inland sector minimum manning requirements are set by the CCRN [104], which serve as guidelines for crew size estimates. Such clear regulations are not available for short sea vessels.

Details on the crew wages are provided in the case study input data of sections 0 and 0. Crew cost is not only composed of crew wages but also of employment-related cost (e.g. rotations, travel arrangement, supplies) and indirect crew cost (e.g. sick pay, social dues, agency fees). It is also assumed that the employment-related cost includes training that teaches the crew the use and interaction with the automation system as part of the standard training and renewal of certification of crew members. These cost are also incorporated into the crew wage calculations expressed by equation 16.

It has been found that in some countries the wages in inland navigation are to a significant part composed of bonus payments (c_{int}) received for every day spent sailing outside of their country of origin. If such bonus payments are not part of the wage calculations, it is set to 1.

$$\boldsymbol{c_c = \sum_{j=1}^{r}\left(n_{c,j}\left(c_{w,j} + \frac{c_{w,j}p_{ex}}{(1-p_{ex})}\right) + n_{c,j}\frac{d_{int}}{d_{FV}}\frac{O}{24}c_{int}\right)} \tag{Equ. 16}$$

Where:

c_c: annual crew cost (€/year)
$c_{w,j}$: annual wage of crew role j (€/year)
d_{FV}: operating vessel of the assessed vessel (km)
O: annual number of operating hours (h)
r: number of roles the crew is composed of
c_{int}: bonus payment for international operations (€/day)
d_{int}: distance spent sailing internationally (km)
$n_{c,j}$: number of crew members at role j
p_{ex}: percentage an employment-related cost

III. Repair and Maintenance Cost

The vessel repair and maintenance cost are not expected to be significantly affected by the VT control system implementation. A large reduction in crew size may cause maintenance tasks not to receive as much attention as they currently do. Yet, the crew remaining on board of the FVs is expected to still be able to perform the maintenance tasks without influencing the maintenance cost. The only annual maintenance cost addition is expected to come from the maintenance of the VT control system, which is set to make up 2 % of the control system investment cost annually.

Determining the maintenance cost of the vessels is still important as it makes up a significant part of the annual operational cost of a vessel. Including these ensure that conclusion can be drawn on the VT benefits in context to the overall cost of the vessels.

The maintenance cost vary significantly per vessel and are therefore difficult to estimate reliably [8]. They depend on the maintenance choices of the vessel owners and the age of the vessel [7], [43]. The results of two studies are used to determine the repair and maintenance cost for the inland [42] and short sea vessel [43].

i. IWT Vessel Repair and Maintenance Cost

Equation 17 estimates the repair and maintenance cost for the ship and its engine based on the dimension of the vessel. The formulation is split into two parts, a fixed and a variable cost, for both of which a constant is estimated. These constants have been adapted for inflation (2021), making them 5,5 €/m^3 for the fixed cost (c_{fixed}) and 0,01 €/kWh for the variable ($c_{variable}$) constant. The variable cost are calculated based on the operating conditions of the vessels.

$$\mathbf{C_{maintenance} = c_{fixed}LBT + c_{variable}t_s\frac{t_t}{O}P_{eng}} \tag{Equ. 17}$$

Where:

B: vessel beam (m)
$c_{varible}$: variable maintenance cost coefficient
P_{eng}: installed power on vessel (kW)
t_s: sailing time per return trip
O: annual number of operating hours (h)
c_{fixed}: fixed annual maintenance cost coefficient
L: vessel length (m)
T: Vessel draft (m)
t_t: return trip time

ii. Short sea vessel maintenance cost

The short sea maintenance cost estimation is based on a regression analysis that calculates the cost using the age of the vessel (Z) and its construction cost ($c_{construction}$) [43].

$$\mathbf{C_{maintenance}} = \left(\frac{\mathbf{1,20Z^2 + 25,10Z - 194,24}}{\mathbf{100}} + \mathbf{1}\right)\frac{\mathbf{0,82}}{\mathbf{100}}\mathbf{c_{construction}} \qquad \text{Equ. 18}$$

III. Insurance Cost

The NOVIMAR research partners have conducted four interviews with insurance companies and asked them to comment upon the impact of the VT navigation system on the insurance costs. All discussions concluded that less insurance premium is expected due to the less crew on board being at risk and as a result the less risks for crew claims. However, increased insurance costs due to the additional (unknown at the present time) IT system-related additional risks (exposure to cyber risks) is it also to be expected. Initially, costs are expected to increase from 5 %-10 % and after some years, when the technology proves itself to be safer/less claims active, insurance costs might decrease by about 10 % [45].

According to MARSH, the insurance cost the machinery and hull insurance equals to 0.5 % - 1 % of the ship value. The insurance cost is case-dependent, so similar to the depreciation cost this is set to 0.75 % of the vessels new built cost [42] lying within the MARSH insurance range. This percentage is also used for the insurance cost of the VT technology cost.

IV. Administration Cost

Administration cost includes any type of overhead cost involved in the operations of the vessel such as vessel registration cost, management fees or sundries. This can in particular, for short sea vessel sum up to a considerable amount of the operating cost over the course of a year. Based on vessel operating cost records [143] these administration cost estimates to an annual cost of 2 % of the vessel's value. The VT control system cost assumes the same percentage for the administration cost, yet with respect to its investment cost figure.

FV Net Savings

Now that the calculation of all cost components of the reference and follower vessels have been explained, it is possible to deduce the FV net savings when using the VT. To do so, first, the maximum allowed FV cost is determined. This is done by taking the transport cost of the reference vessel (C_R), which is the sum of all the elements described prior in this chapter and considering the change in productivity caused by the VT conditions. To ensure that the FV transport condition are at least equivalent to the reference operation, the FV cost is determined based on the change in productivity and the reference vessels cost using equation 19.

$$\mathbf{C_{FV}} = \frac{\mathbf{P_{FV}}}{\mathbf{P_R}}\mathbf{C_R} \qquad \text{Equ. 19}$$

Where:

C_{FV}:	maximum FV cost (€)	C_R:	reference vessel transport cost (€)
P_{FV}:	FV productivity (t/year)	P_R:	reference vessel productivity (t/year)

Only the crew and the fuel cost are influenced by the VT implementation. Therefore, when calculating the cost savings (Eq. 20) achieved by the FV, only the fuel and crew cost changes (Δ_{crew}& Δ_{fuel}) are included. All other elements are covered by the reference vessel cost. Finally, the annual cost of the VT control system (C_{VT}) is the sum of the depreciation, interest, insurance, maintenance and admin based on the VT investment cost.

$$\mathbf{S_{FV} = C_{FV} - C_{R} + \Delta_{crew} + \Delta_{fuel} - C_{VT}}$$

Equ. 20

Where:

C_{FV}:	maximum FV cost (€)	C_R:	reference vessel transport cost (€)
C_{VT}:	VT control system cost (€)	S_{FV}:	FV net savings (€)
Δ_{crew}:	change in crew cost between reference vessel and VT conditions	Δ_{fuel}:	change in fuel cost between reference vessel and VT conditions

Integrating the Business Model

The net savings of the FVs represent the benefits of the vessel operators that decide to use the VT. Another stakeholder's benefit that needs to be considered is the VT operator. This benefit is dependent upon the FV benefits outweighing the cost created by VT operations and hence also indicates the number of FVs required. The calculation method used to determine the required number of FVs differs dependent on which business model is applied.

The business model may either have an influence on the FV cost savings that is calculated using equation 23 or on the number of FV needed to join the VT, ensuring the VT organiser at the least breaks even with the service it provides to the FVs. Based on the business model descriptions provided in chapter 3, equation 21 provides the VT organiser cost.

$$\boldsymbol{C_{VTO}} = \begin{cases} \sum \boldsymbol{n_{LV}(C_{VT} + C_{mc})} & ;\boldsymbol{for\ single\ company} \\ \boldsymbol{(\sum(n_{LV}C_{VT} + C_{mc}) + C_{shore})(1 + p_m)} & ;\boldsymbol{for\ platform\ based} \end{cases}$$

Equ. 21

Where:

C_{mc}:	cost of monitoring crew (€)	C_{shore}:	shore coordination cost(€)
C_{VT}:	VT control system cost (€)	C_{VTO}:	VT operator cost (€)
n_{LV}:	number of LVs	p_m:	profit margin of VT operator

Dependent on the technological development maturity of the control system, an early stages implementation may require additional monitoring crew members on board of each LV. This additional monitoring crew cost (C_{mc}) is added in the cost of both the single company and the third party platform-based business model.

Single Company

The single company operations need to satisfy the constraint set by equation 22, where the net savings of all FVs in the fleet (fleet size minus the number of LVs) needs to outweigh the VT operator cost (C_{VTO}). Hence, some vessels for which the VT may not be beneficial would be able to use the VT because vessels with larger benefits can cover the cost for the less beneficial ones. The minimum required FVs per LV for the single company business model is defined by equation 23.

$$\boldsymbol{C_{VTO} \leq\ n_{FV_f} S_{FV}}$$

Equ. 22

$$\boldsymbol{n_{FV} = \min \sum_{j=1}^{f} S_{FV,j} \geq \frac{C_{VTO}}{n_{LV}}}$$

Equ. 23

Where:

C_{VTO}:	VT operator cost (€)	n_{FV_f}:	number of FV in the fleet of the single company
n_{LV}:	number of LVs	S_{FV}:	net savings of FV (€)

Platform-Based

The platform-based business model uses a third-party agent to coordinate the VT operations. This creates additional back-office coordination and profit margin cost compared to the single company model. The back office coordination cost includes the rental of office spaces, software licenses, updates and other overheads related to office equipment that in a single company model would already be covered by the excising back office. The platform is assumed to be coordinated and maintained by four shore-based workers with transport planning and IT skills in a back office. Additionally, the coordination agent also requires a profit margin (p_m). Equation 24 assumes that the VT cost for the LVs is covered by the VT coordinator.

$$\boldsymbol{S_{FV} = max\, C_{fee}} \qquad \text{Equ. 24}$$

$$\boldsymbol{n_{FV} = \frac{\frac{C_{VTO}}{n_{LV}}}{C_{fee}}} \qquad \text{Equ. 25}$$

From the viewpoint of the VT platform operator, the net savings is the maximum possible contribution fee that can be asked from the FV. However, the actual contribution fee that the FV are charged is dependent on the VT operators pricing strategies, which is not further taken into consideration in this research. Instead, equation 25 uses the maximum contribution fee to determine the minimum number of FVs required for break-even operations from the perspective of the VT operator.

Required Fleet Share

Now that the required number of FV per LV are clear it is possible to determine the required market share for the VT liner service operation. First, the required number of participants for the transport system have to be determined. Knowing the minimum number of FV(n_{FV}) from last section, allows for the number of participants (VT_p) to be determined using equation 26.

$$V\boldsymbol{T_p = n_{LV} + n_{LV}n_{FV}} \qquad \text{Equ. 26}$$

The number of VT transport system participants, in turn can then provide an indication on the required fleet share (M) of the VT concept. This is done by calculating the size of the VT fleet compared to the total available fleet size (F_s) in the region, see equation 27. A high required fleet share may mean that even if a theoretical break-even point can be achieved, practically, it is unlikely because a new concept is unlikely to take over a significant share of the fleet.

$$\boldsymbol{M = \frac{VT_p}{F_s} 100} \qquad \text{Equ. 27}$$

External Cost

The calculation descriptions up to now all only included the perspective of the FV and the VT operator. This section focuses on the calculation methods to determine the cost and benefits for society and internalizes these for the FV operator to assess the changes in cost savings.

The operations of the vessels give rise to a number of impacts that are not directly borne by the people that reap the benefit of the transport user [144]. The cost created are called external cost. Section 4.2.2. explained why the VT cost model mainly focuses on the emission cost. The external cost of road congestion cost will also be briefly addressed when studying urban area penetration of the VT.

Changes in operations create improvements to society as less emissions are created due to slower sailing, but may simultaneously have negative effects such as longer lead times for the transport users. The internalisation of external cost is a policy tool that is based on the idea: If customers were to be charged for this additional effect on society, it would naturally opt-out the overall less beneficial modes of transport [145]. Hence, this means the operation changes can also create benefits to the transport user.

Emissions

The main air pollutant considered are carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), particular matter (PM2,5), carbon dioxide (CO_2) and sulfur oxides (SO_x). The first four of these components are calculated using equation 28. Among these pollutants, NO_x is by the largest contributor. The cost of the pollutant (C_p) may vary dependent on the operations, North Sea, rural or urban areas. This is, in particular, the case for PM, which affects the respiratory system of people in the vicinities of where it is emitted.

$$\mathbf{C_{Ex_p} = \frac{P t_s \frac{O}{t_t} e_p}{1x10^6} C_p} \qquad \text{Equ. 28}$$

Where:

C_{Ex_p}: external cost of pollutant p (€)
C_p: cost of the pollutant (€/t)
e_p: emission rate of the respective pollutant in (g/kWh)
P: power requirements at operating speed (kW)
t_s: sailing time per return trip (h)
t_t: return trip time (h)
O: annual operating hours (h)

The calculation of the CO_2 and SO_x emissions are determined based on the fuel consumption of the vessel (see equation 29). Since January 1st 2020, the IMO has set a sulphur limit of 0,5 % in maritime fuels [146]. Hence, this value is used to calculate the SO_x emission for both short sea and inland vessels.

$$\mathbf{C_{Ex_{CO_2}} = fc\ t_s \frac{O}{t_t} \rho c_{CO_2} C_p} \qquad \text{Equ. 29}$$

Where:

$C_{Ex_{CO_2}}$: external cost of pollutant CO_2 emission (€)
C_p: cost of the pollutant (€/t)
c_{CO_2}: CO_2 content per litre of fuel (t/l)
e_p: emission rate of the respective pollutant in (g/kWh)
fc : fuel consumption (t/h)
t_s: sailing time per return trip (h)
t_t: return trip time (h)
O: annual operating hours (h)
ρ: density of MGO or MDO (~0,89 t/m^3)

The emission rates and cost of pollutant used for the external cost calculations presented in Table 8 [100], [144], [146], [147]. All cost have been inflation corrected to 2021.

Table 8: Emission Rates and Cost of Pollutants for External Cost Calculations

<table>
<tr><td>Pollutant emission rate</td><td>CO
(g/kWh)</td><td>HC
(g/kWh)</td><td colspan="2">PM
(g/kWh)</td><td>NOx
(g/kWh)</td><td>SOx
(% of fuel)</td><td>CO2
(t/l)</td></tr>
<tr><td>IWT (CCNR Stage II)</td><td></td><td></td><td colspan="2"></td><td></td><td></td><td></td></tr>
<tr><td>130 ≤P_{eng}<560</td><td>3,5</td><td>1</td><td colspan="2">0,2</td><td>6</td><td>0,5</td><td>0,003</td></tr>
<tr><td>P_{eng}>560</td><td>3,5</td><td>1,3</td><td colspan="2">0,7</td><td>7</td><td>0,5</td><td>0,003</td></tr>
<tr><td>Short Sea</td><td>0,33</td><td>0,5</td><td colspan="2">0,3</td><td>13,2</td><td>0,5</td><td>0,003</td></tr>
<tr><td rowspan="2">Cost per pollutant</td><td colspan="2">VMVOC (€/t)</td><td colspan="2">PM (€/t)</td><td>NOx</td><td>SOx</td><td>CO2</td></tr>
<tr><td colspan="2">(CO & HC are part)</td><td>Rural</td><td>Urban</td><td>(€/t)</td><td>(€/t)</td><td>(€/t)</td></tr>
<tr><td>IWT (EU average)</td><td colspan="2">1.785</td><td>32.043</td><td>80.094</td><td>12.130</td><td>11.675</td><td>28,5</td></tr>
<tr><td>Short Sea (North Sea)</td><td colspan="2">2.394</td><td colspan="2">29.412</td><td>6.783</td><td>8.664</td><td>28,5</td></tr>
</table>

Internalization of Emission Cost

In order to, also take into consideration the perspective the societal benefit created from the changes in emission of the VT implementation, the emission cost have to be internalized for the transport users. Thus the next step in determining the effects of the VT operating changes is to internalize the external cost that were calculated via equations 28 and 29. By adding the emission cost to the minimum FV transport cost, i.e. excluding the savings and hence the possible contribution fee it needs to pay, the maximum FV cost savings compared to the conventionally sailing vessels can be identified.

$$C_{int.soc} = \begin{cases} C_{FV} - \mathrm{S_{FV}} + \sum_{j=CO}^{p} C_{Ex_j}; for\ FV \\ C_R + \sum_{j=CO}^{p} (C_{Ex_j})_R \ \ ; for\ reference\ vessel \end{cases} \qquad \text{Equ. 30}$$

Where:

C_{Ex}:	external pollution cost (€)	$C_{int.soc}$:	transport cost incl. internalization of emission cost (€)
p:	array of pollutants (CO, HC, PM, NO_x, SO_x, CO_2)		

Cargo Related Cost

The final stakeholder's perspective that has not yet been described is the one of the cargo owner. Cargo related or logistics cost are composed of the cycle and safety stock, as well as the stock in transit. All of these are heavily predisposed by the operational choices of the individual shippers. However, the safety stock and especially the stock in transit are also influenced by changes in lead time, which are caused by the VT waiting times and altered operating speeds. This is why only the safety stock and stock in transit are included in this model. Equations 31 and 32 describe the stock in transit and the safety stock, respectively [148]. These are combined and compared to the reference vessel conditions in equation 33, to determine the additional cargo-related cost suffered by the cargo owner due to the changed operating conditions.

$$\mathrm{St_{transit}} = (L\, v\, \frac{h_c}{365}) \qquad \text{Equ. 31}$$

$$\mathrm{St_{safety}} = (\frac{1}{P}\, v\, h_c\, K \sqrt{(L\, d_g) + (D_g^2\, l)}) \qquad \text{Equ. 32}$$

$$\Delta C_{st} = \left(St_{transit} + St_{safety} \right)_{FV} - \left(St_{transit} + St_{safety} \right)_{R} \qquad \text{Equ. 33}$$

Where:

ΔC_{st}:	change in stock cost due to VT operation changes (€)	$\mathrm{D_g}$:	average daily demand (t/day)
d_g:	variance of daily demand (t^2/day)	h_c:	holding cost (fraction of value /year)
FV:	FV conditions	K:	safety factor
L:	lead time (days)	l:	variance of lead time ($days^2$)
P:	productivity (t/year)	R:	reference vessel condition
St_{safety}:	safety stock cost (€)	$St_{transit}$:	stock in transot cost (€)
v:	value of the good (€/t)		

4.5. Cost Model Validation

This chapter has introduced the most impacting cost elements for the VT and has described the detailed calculation method used to compute these components within the VT cost model. Even though many of the equations that were discussed in the last chapter are based on validated cost models of other literature sources, it is still important to check if the results from this model provide plausible results.

The full validation of the VT model output are not possible as they are highly influenced on the case study and as the VT concept does not exist in the waterborne transport sector yet. It is very difficult to obtain accurate cost data from vessel operators that would be representative for similar operations. However, it is possible to cross-check if certain components that significantly influence the cost model result are indeed plausible compared to existing vessels. These include the crew cost, the building cost upon which the capital cost estimations are based, as well as a ships speed power curve that is used to calculate the fuel consumption.

The topic of crew cost and their savings has already been addressed in chapter 3 and will again be briefly picked up in the input data descriptions for the application cases in chapter 5. As the sources for these calculations are either directly taken from industry for the short sea case or from regulatory guidelines, it can be said that these are validated.

4.5.1. Building Cost

The building cost that are calculated based on regression analysis, can however be validated. The calculated building cost of short sea vessels range between € 4 million and € 16 million as indicated in Table 12 of the short sea case study information. A TU Delft internal short sea ship database shows that the investment cost of general cargo vessels from which a sample of nine costs were available between € 5,9 million and € 22 million. Container feeders, for which the price of six vessels were available, range between € 6 million and € 18 million and roro vessel, for which the investment cost of eight vessels range between € 30 million and € 72 million. Given this comparison to real short sea vessel prices, it can be said that the calculated estimate fall within a plausible range for general cargo and container feeders, even though the smaller vessels prices seem to be trending lower. The verification also shows that the calculations are not representative for short sea roro vessels.

The building cost of IWT vessel class V, IV and II vessels are calculated to be € 2,48 million, € 1,8 million and € 1,09 million respectively. A report from EICB in 2011 indicated the vessel cost to lie at € 3,5 million, € 2,5 million and € 1,2 million respective to a Class V, IV and II vessel [149]. Given the fact that building cost can fluctuate dependent on the state of the market [42], and these EICB values are from a time close to the price peak, the at most € 1 million difference to the model calculations can still be considered reasonable estimates.

4.5.2. Speed-Power Estimations

The H&M resistance calculation methodology that was described in section 4.4.2. was developed and validated for displacement sea-going vessels [136]. To verify that the calculation results used in this thesis are indeed within a plausible range Table 9 presents the power requirements of two sample short sea vessel types that are introduced within the case study. It shows that the power requirements at their design speed are within a reasonable range, as they are at 74 % and 80 % maximum continuous rating of the engine.

Table 9: Verification of Power Requirements of Short Sea Vessels

Market Segment	Fast and large	Fast and small
Length (m)	153	100
Beam (m)	21,5	20,4
Installed power (kW)	8.000	7.800
Capacity (t)	12.600	9.100
Design speed (km/h)	34,2	30,5
Power requirements at operating speed (kW)	5.949	6.285
MCR at design speed (%)	74 %	80 %

To ensure that this resistance estimation method would also take confined waters of rivers into considerations the form factor calculations have been adapted. Figure 17 compares the VT model resistance estimation at a 5 m water depth to a real Johann-Welker-type vessel from [150] at a 4 m and a 5,8 m water depth. The curves do not match at faster speeds due to the fact that the described method does not correct for the retardation effect of the shallow water on the wave-making resistance. However, this is only creating significant changes at high speeds and very shallow water depths. In the case studies of chapter 5, the maximum operating speed does not surpass 16 km/h and no very shallow waters are considered. Therefore, the described method is also applicable for inland vessels and Figure 17 validates this to be the case.

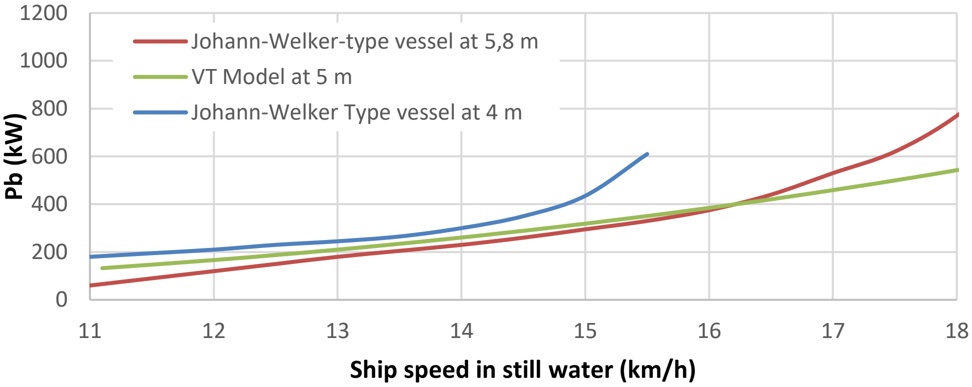


Figure 17: Speed-Power Curve Verification of a Class IV Inland Vessel

4.6. VT Viability Assessment Model Summary

This chapter has provided an overview of the calculation methodology integrated into the VT assessment model, as well as its structure and the reasoning why certain cost elements have not been integrated into the VT assessment. It provided a detailed overview of the calculation method of all the cost elements that are deemed to have large enough of an impact on the VT operations to be included. Knowing the set-up and calculations of the VT assessment model it can be concluded that this assessment approach is an extended cost-effectiveness analysis. It goes beyond a cost-effectiveness analysis as it not only calculates the cost-effectiveness ratio in terms of cost per tkm of each vessel, but draws its main results from the differences in cost-effectiveness ratios between the current and the VT conditions. It uses the savings made per FVs as its main viability indicator, which makes it resemble a CBA. Even though the cargo and societal emission cost components are included in the VT viability assessment, other demand-related components and some of the cost and benefits from both private and societal standpoints are not expressed in monetary terms. This thereby means that it is not considered a complete CBA or SCBA.

The chapter finished by giving an indication of the result validity, by verifying the vessel prices of both short sea and inland vessels and the speed power curve of a class IV inland vessel. Thereby, showing that the main cost estimations are founded on plausible estimates.

This VT assessment model allows for a full economic viability assessment of the VT operations to be made. The next chapter introduces the case studies and the input data that compare the concept's application in different transport sectors. The model is also used in the study of effect from application areas of the Danube case in chapter 6.

CHAPTER 5: APPLICATION CASE STUDIES

This chapter applies the VT cost model that has been detailed in chapter 4 to study the viability of the VT concept application in a short sea and in an inland shipping case. The viability assessment is performed by presenting step-by-step the VT model calculation results. First, the productivity changes the FVs experience are commented upon. This knowledge is then used to explain how the savings can compensate for some of the losses in productivity. The achieved savings are then translated into a cost per tkm that is compared to the VT operator cost to determine the minimum VT length. Based on this information, the last part of the viability assessment concludes the required fleet share for an implementation. On top of the viability assessment, the case studies also include a detailed sensitivity that enhances the understanding of the effects of variations in the input data on the viability of the VT concept. Finally, the case studies also explain how including the societal and cargo related cost can further increase or diminish the benefits of the VT concept. The aim of the application cases is not only to identify the minimum viable operating conditions for different stages of VT market implementation and but also to figure out if the concluded results are robust and representative even with the uncertainties of the case study input assumptions. This part of the thesis answers the third research sub-question identifying how the variations of the VT properties influence the concept's performance.

The information presented in this chapter is based on the information published in articles [39], [117] and NOVIMAR deliverable 1.5 [48]. This chapter is structured as follows: First, the non-case sensitive input data and case assumptions are presented, which concern the VT control system cost, the business model cost but also assumptions that are made concerning different stages of implementation of the VT. Then the short sea application case is introduced in section 5.2.1 by providing the case study route, the main vessel-related parameters and crew cost data, followed by the description of the VT operating conditions and the cargo-related parameters. Before diving into the results of the assessment, the cost breakdown of all reference types is illustrated that helps explain some of the behaviours seen later in the assessment. Section 5.2.2 dives into the results and subsequently identifies the VT requirement for viable operations that represent the 7th step of the CEA assessment listed in section 4.2.1. Then, the 8th step of the CEA is performed with a sensitivity analysis section 5.2.3. Next, the assessment is extended to further stakeholders, namely society and cargo owners in section 5.2.4. Finally, the case study is taken to closure by summarising the main conclusions drawn from the short sea assessment in section 5.2.5. The inland case study follows the same structure as was just described for the short sea case.

5.1. Non-Generic Input Data

To start with there are some input data that are common for both the short sea and the inland case. This data concerns the VT control system cost as well as the scenarios that are set for both sectors. These scenarios involve the business model cost, i.e. difference between the single company and platform-based model but also the maturity of the VT technology, the implementation stage of the VT concept maturity and the cargo-related parameters used to calculate the logistics cost. Each of these are discussed in the hereon following sections.

5.1.1. VT Control System Cost

Chapter 4 elaborately explained the cost factors that go into the calculation of the annual VT cost. Each of the five cost elements, depreciation, interest, insurance, maintenance and administration cost, are based on the € 80,000 investment cost estimate of the VT control system presented in chapter 3. Table 10 summarises the cost breakdown of the VT control systems cost elements.

Table 10: Cost Breakdown of the Annual VT Control System Cost

Cost Elements	Depreciation	Interest	Insurance	Maintenance	Admin	Total
Annual share of investment cost	20%	5%	0,75%	2%	2,5%	
Values	€ 16.000	€ 4.000	€ 600	€ 1.600	€ 2.000	**€ 24.200**

5.1.2. Single Company vs. Platform-Based

The VT transport system as was described in chapter 3 is a liner operation of cargo-carrying LVs that depart at regular intervals and operate between two specific destinations. Dependent on the business structures of the market players, the single company or the platform based coordination may be more appropriate. Both of these business models have been explained together with other influential factors in chapter 3, Table 11 and the text below explain the cost estimates associated with each business model.

Rental of office spaces and software licenses, updates and other overheads are estimated to be € 50.000, where € 10.000 is the expected annual fee for offices and screens in the common office of control centres of the port of Antwerp. While this equipment is also needed when coordinating ones own fleet in the single company model, it is expected that a large transport company already has an established back office that does not have to be purposely dedicated to the LV coordination but merges into the day to day business operations that are already occurring.

Instead, the coordination and maintenance of the platform-based model is performed by four shore-based workers with transport planning and IT skills. It is expected that the employees will each cost € 60.000 annually, thereby adding € 240.000 per year to cover the shore-based workforce. Finally, it also assumes that the VT organiser also operates the LVs and has a profit margin of 20 % on the total cost [151]. While a margin of 20 % may seem high, this may have to cover any margin for the LV operators if they are contracted. These are dependent on the VT companies pricing strategies, which will not be considered at this stage of the development of the concept. Additionally, it can also be viewed as a risk and profit margin given that there is a fair amount of uncertainty in the business concepts cost estimations.

Table 11: Cost Difference Between Business Models

Cost Items	Single company	Platform-based
Annual VT control system cost per LV	€ 24.200	€ 24.200
Shore offices and equipment	-	€ 50.000
Shore coordinators	-	€ 240.000
Profit margin	-	20 %

5.1.3. Transition Stage vs Matured Implementation Stage

Two levels of technology and implementation maturity are assumed within each case study. The difference between these cases shows the evolution of the concept and allows to concludes general insights into the viability of the transition stage of the VT concept's implementation. It also helps conclude whether governmental subsidies can help the concept in the early stages of implementation.

Base Case

The Base Case (BC) represents the conditions in which the VT is well-established in the future maritime transport system. The reasoning behind it being named "base" is that this represents the way the concept is intended to operate in its final state. If it does not show to be viable in these conditions, it is also not going to be viable in any more challenging conditions. The BC implies that the technology is matured fully and does not require active monitoring. Furthermore, it also means a large number of participants are involved with the concept, enabling a short departure interval.

Transition Stage Case

The Transition Stage Case (TSC) is more challenging than the BC, since the early stages of the VT implementation will not have as large of a client base participating in the transport system. It assumes longer departure intervals and the need for monitoring crews on the LVs that ensure safe VT control system operation. Two additional crew members are thus put on board of each LV. Two crews are expected to rotate on board of the vessel throughout the year to allow continuous operation of the VT. These monitoring crew members are expected to cost € 45.000 per year, which is similar to a second officer on a cargo ship (later explained in Table 14). It is expected that the navigation skillset of a second officer is similar to what is expected of the monitoring crew. In total, these cost sum up to an estimated VT monitoring crew cost of €180.000 per year.

Cargo Related Parameters

The last common parameters are related to the cargo. While some of the values required in the logistics cost calculations presented in chapter 4 are annual cargo volumes are determined in the individual sector case studies, the parameters provided in this section are general assumptions of the cargo owner operating choices.

The logistics cost calculations assume a supply chain setting with a single supplier and single receiver [152], which means all cargo on one vessel belongs to a single client. This is the worst case in terms of the logistics cost created. The variance of the lead time estimates are all setting samples of lead times of +/- 10 % for both the LV and the FVs. The daily demand variance is set to 0. The safety factor is a parameter that is set to 2, and the annual holding cost, which is a fraction of the cargo value per ton, is set to 10 % [42].

To ensure uniformity in the results, container capacity measured in TEU, are converted to metric ton where 1 TEU weighs is 14 tons. The cargo value chosen lies within the expected value of a container (€14.000 per TEU), this is higher for dry bulk commodities such as steel products are usually only worth half this value [55].

5.2. Short Sea Case Study

This case study illustrates the VT concept implementation in the short sea sector. The information presented in this section is based on the article "Waterborne platooning in the short sea shipping sector". There are five sea shipping regions in Europe which are the Black sea, the Mediterranean, the Atlantic ocean, the North sea and the Baltic sea. It is a diverse sector in which there are companies owning hundred-vessel fleets but also captain-owned vessel operators [153]. This means both the single company and the platform-based business model are of interest in this sector.

Section 5.1 starts by listing the input data used in the VT cost model, before it provides an overview of reference vessel cost breakdown and productivities. The results in section 5.2.2, first describe the effects of the VT on the FVs' productivity, then move to the savings achieved and then convert these into a cost per tkm that is compared to the reference vessel conditions when it sails conventionally without the VT. These also allow VT operating requirements to be identified. Section 5.2.3 perform a sensitivity analysis for a variation in waiting times, crew cost, route length, solo leg and the fuel price. Finally, section 5.2.4 adds the societal and cargo owner perspective by calculating emission and logistics cost.

5.2.1. Case Description

The case description includes the chosen route, vessel parameters as well as other vessel-related input data. This is followed by detailed information on the number of crew members and their related cost.

Route

The short sea case study route operates between Hamburg and Le Havre (see Figure 18), which is a one-way length of 500 nautical miles (926 km). This area is chosen because of its high traffic density, leading to a large number of potential customers (i.e. followers). AIS data analysis from MARIN [154] shows

Figure 18: Case Study Operating Area

around 10.500 ship passages annually in front of the Dutch coast. This vessel train route passes by the largest European ports and therefore likely to have vessels joining the train for at least part of their way to their destination. The passage in front of the large ports allows the FVs to reach their destination port without trouble. The FVs can join the VT at any port along the route. The assessment assumes that FVs operate on a fixed sub-section of the trip all year round. The results are presented for a range of distances at 100 km intervals.

Main Vessel-Related Parameters

The dimensions and properties of the four assessed FV types are based on actual vessels and presented in Table 12. Each vessel is intended to be a sample of one market segment. The vessels are classified into one of the four categories based on their operating speed and size. The speeds of the different vessel types are picked such that smaller and larger differences in operating speeds can be assessed. The differences in vessel sizes have been picked in order to see the effect of productivity variations.

The vessel data has been taken from a TU Delft internal vessel database. The vessels could both dry bulk, general cargo or container vessels. To ensure uniformity in the results container capacity, measured in TEU, is converted to metric ton where 1 TEU weighs is 14 tons.

Table 12: Input Data for Four Sample Vessel Types

Reference Number	**I**	**II**	**III**	**IV**
Market Segment	**Fast and large**	**Fast and small**	**Slow and large**	**Small and slow**
Vessel Type	Feeder	General Cargo	General Cargo	General Cargo
Length (m)	153	100	137	89
Beam (m)	21,5	20,4	21	13,6
Draft (m)	9,3	11,1	11,3	7,2
Cb	0,8	0,7	0,8	0,7
Gross tonnage (t)*	9.100	6.500	8.950	2.850
Installed power (kW)*	8.000	7.800	4.350	1.800
Capacity (t)*	12.600	9.100	14.000	2.100
Operating speed (km/h)	34,2	30,5	24,1	21,3
Vessel construction cost	€ 15.900.000	€ 11.500.000	€ 15.600.000	€ 4.130.000

* rounded to the nearest 50

Aside from the vessel dimensions, power and capacities, there are also other parameters that are vessel dependent and have an influence on the cost and productivity of the operations. The port times are of particular importance for the productivity of the vessels. The port time estimate is taken as a standard turnaround time from the review of maritime transport [17]. There the average time in port for all ship types is stated to be 23,5 hours. It is, however, to be noted that the port times for different carriers can differ significantly. While dry bulk carriers typically spent about 2 days in port, container vessels only need on average 0,7 days.

Another parameter to consider is the specific fuel consumption, which plays an important role in the fuel cost estimation and hence also in the assessment of the effects of slowing down, which is one of the effects of sailing in the VT. The specific fuel consumption is determined as a function of engine loading, as defined by MAK M25E [142], which sets the specific fuel consumption, at 85 % MCR, to 185 g/kWh and provides the added fuel consumptions at different engine loads. All further data requirements for the calculations of the FV cost are provided in Table 13.

Table 13: Input Data for FV Cost Calculations

Input Item	Generic for all FVs
Annual VT system depreciation	5 %
Annual Interest	5 %
Annual Insurance	0,75 %
Annual Administration	2,5 %
Operating days per year	360
Port time (h/journey)	23,5
SFC (g/kWh)	185
Fuel price (€/t)	560

Crew

The crew aspect of the input data has three aspects: 1) the number of crew 2) the wages of the crew members 3) the expected reduction of the number of crew members achieved by the automation of the navigation tasks on the FVs. The first two aspects are summarized in Table 14 for all vessel types, while the latter of these aspects has been identified in chapter 3 to amount to € 154.400 annually.

Crew wages significantly vary dependent on the flag state of the vessel but also the nationality of crew members [55]. The uncertainty and effects caused by crew cost variation are further discussed in section 5.2.3 as part of the sensitivity analysis of this case study. Crew cost are composed of wages as well as employment-related (e.g., rotations, travel arrangement, supplies) and indirect cost (e.g., sick pay, social dues, agency fees). The wages and crew numbers have been obtained from a Dutch shipping company. It is assumed that two crews rotate on board of the vessel annually to allow continuous operations. An additional 30 % is added on top of the wages to cover the employment-related and indirect cost [12].

Table 14: Input for Crew Number and Crew Role (rounded to the nearest € 100)

Crew role	Original Sailing Crew			
	I/III	Annual Cost	II/IV	Annual Cost
Captain	1	€ 99.400	1	€ 99.400
Chief Engineer	1	€ 99.400	1	€ 99.400
Chief Officer	1	€ 82.800	1	€ 82.800
2nd Engineer	1	€ 82.800	1	€ 82.800
2nd Officer	1	€ 46.400	1	€ 46.400
Bosun	1	€ 26.500	1	€ 26.500
Cook	1	€ 29.800	1	€ 29.800
Deck Boy	4	€ 61.800	3	€ 46.400
Total cost for a single crew	**11**	**€ 529.400**	**10**	**€ 513.500**
Total cost for two crews	**22**	**€ 1.058.800**	**20**	**€ 1.027.000**

Source: Author's composition based on Dutch industrial partner

VT Operating Conditions

As described in section 5.1.3 the case study assessment is split into two scenarios, the Base Case and the Transition Stage Case. This section describes the specific input data differences that are set for each of these scenarios, which are deemed appropriate for the short sea application of the VT.

Base Case

Based on a waiting time cost assessment performed in NOVIMAR deliverable 1.3 it was concluded that the waiting times for larger vessels should not surpass 8 h, while for smaller vessels the waiting time should not surpass 27 h. Hence, the departure intervals for the respective development cases were picked such that they fit into each of these two timeframes and at the same time do not create any additional waiting time for the LVs for the round trip departures. The short sea BC sets the VT departure interval of 6 h. The operating speeds for the VT are selected to be as close as possible to the current operating speeds of the different vessel types without surpassing their design speed. The number of LVs to achieve the required departure interval at those speeds is indicated in Table 15, ranging from 17 to 24 LVs. This number of LVs in the transport system provides the last parameter needed to calculate the platform-based compensation cost.

Table 15: VT Speeds and LV Requirements under Base Case

LV return trip time (h)	144	126	108	102
Speed (km/h)	19,1	23,5	30,3	33,6
Number of LV’s	24	21	18	17
Compensation cost for platform business model (€/LV)	€ 43.500	€ 45.600	€ 48.400	€ 49.500

Transition Stage Case

The TSC also explores longer intervals and adds monitoring crew cost. A departure interval of 21 h is used. This departure interval increases the waiting time from 3 h to 10.5 h. The decrease in departure frequency causes fewer LVs to be needed over the same distance as in the BC. The TSC only allows for three speeds (see Table 16) that create conditions in which the LV would not need to wait. The TSC drops the required number of LVs to five to seven LVs.

Table 16: VT Speeds and LV Requirements under the Transition Stage Case

LV return trip time (h)	147	126	105
Speed (km/h)	18,5	23,5	31,8
Number of LV's	7	6	5
Compensation cost for platform business model (€/LV)	€ 78.800	€ 87.200	€ 98.500

Reference Vessel Cost Breakdown

Now that all the input parameters have been presented, the focus can be shifted to the cost calculations of the reference vessel. These are not only the basis for the FV cost determination as was described in chapter 4, a study of the cost breakdown can also help explain some of the VT behaviour that is later observed in section 5.2.2. The cost breakdown presented in this section is respective of each of the four reference vessel types at their original operating speed, continuously operating along the entire length of the route (925 km).

The pie chart in Figure 19 allows for a direct comparison between each of the four vessel types. The largest variations are identified in the magnitudes of the crew and the fuel cost. While the crew cost makes up the largest share for the slowest vessel IV with 44 %, the fastest vessel I only has a crew cost share of 12 %. The fastest vessel has the highest fuel cost, with 62 % of its total cost, while the slowest vessels' fuel cost only makes up 30 % of the vessels cost.

One can deduce from this cost comparison that slow and small vessels are going to benefit the most from the VT specific cost-saving caused by crew reduction, whereas the larger and faster vessels are going to see their main benefit from the fuel consumption reduction when they adapt to the slower VT operating speeds.

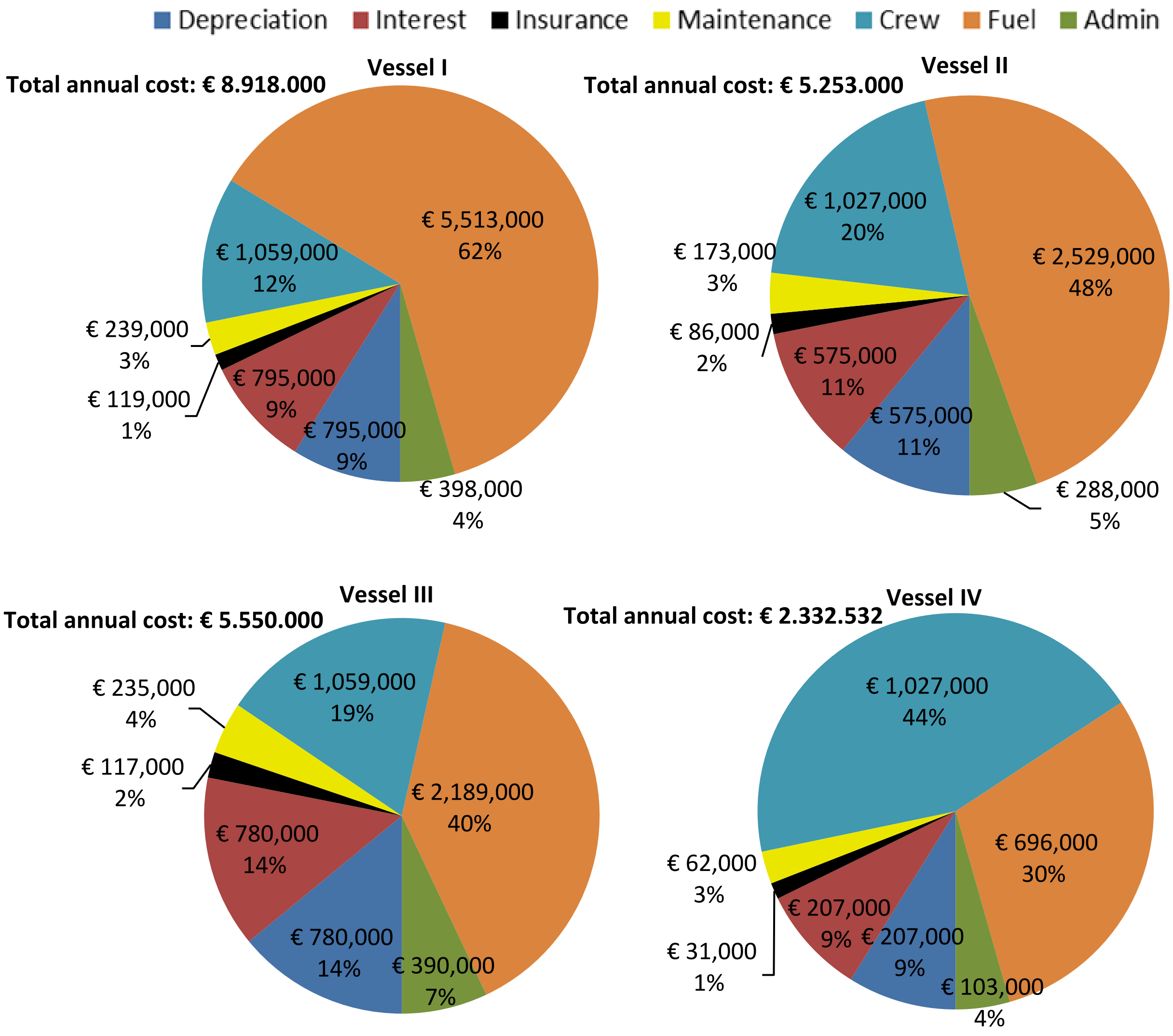


Figure 19: Cost Breakdown of Vessels I-IV

5.2.2. Results and VT Operating Requirements

The results presented in this chapter start by giving the changes in productivity when the FVs sail in and outside of the VT. Then, the productivities are used to determine the net savings of individual FVs, which allows minimum operating distances for FVs within the VT to be identified. The required number of FVs per VT can then be quantified by converting the savings into tkm and comparing these values to the VT cost that needs to be outweighed. By associating the FV cost to the reference vessels, the percentage cost reduction created by the VT is shown. Based on the FV per VT, the required number of participants in the liner service are determined and with it the required market share, which also ensures the VT operator to break even with their cost. Therefore, each of the calculation steps presents a new insight into the determination of the VT operating requirements.

All results presented in this section include a black vertical line that denotes the separation point of the FV from the VT. Before that line, all distances are fully spent as part of the VT while after that line the FVs spend part of their trip under their own navigational control.

Productivity Change

The assessment of the productivity change for the FVs provides insight into the effects of the increased waiting times and slower operating speeds of the VT. Before looking at the productivity changes, however, we first need to need to see the reference vessel conditions to which the FV operations are compared.

5.2.2.1.1. Reference Vessel Productivity

Figure 20 shows the productivity of the reference vessels with increasing trip distances. The longer the trip, the less cargo is moved, since the vessel spends more time sailing and achieves fewer trips. Vessel III has the largest cargo capacity and is over short distances the most productive. However, the longer the trips the better faster vessels make use of their speeds to achieve improved productivities relative to vessel III. Of course, this depends on the definition of productivity if this is set in terms of tkm, the conditions improve the longer the sailing distance as less idle time is created in ports.

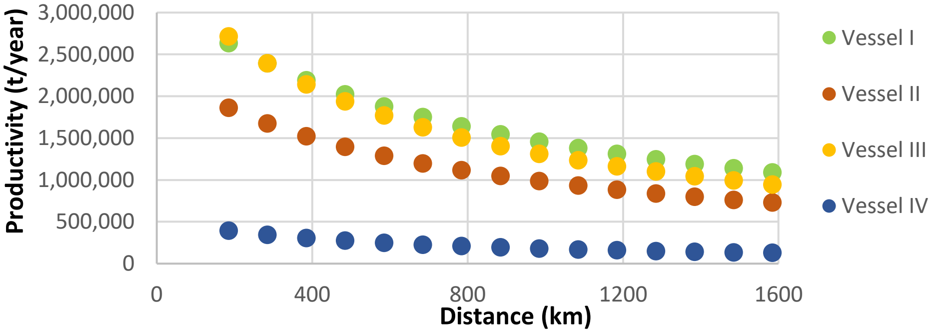


Figure 20: Reference Vessel Productivities

FV Productivity Change

With the reference vessel productivities provided in Figure 20 we can now discuss the relative productivity change for the FVs. All plots presented demonstrate the results of the respective vessels when sailing in the VT, up to the black vertical line, and outside of the VT, past the black vertical line, as illustrated by the arrows in the vessel I plot of Figure 21. The productivity changes in both the BC (Figure 21) and the TSC (Figure 22) of all short sea vessels indicate negative productivity as the added waiting time and the reduced speed forcibly causes longer trips than the reference vessel that operates continuously.

The commonality that becomes apparent when looking at the productivity is that it decreases as soon as the FV leaves the train. This is due to the fact that the FVs encounter resting times with the reduced crew size and can no longer sail continuously. Even though the vessel will be able to operate at its reference operating speed, which may be higher than the VT operating speed, this improvement in productivity cannot counteract the 16 h resting times per day (if we assume that the remaining navigation crew can only operate for 8 h).

Base Case

It can be seen from the plots of vessels I-II in Figure 21 that at speeds closest to the reference operating conditions, the productivity of the vessels slightly improves the longer they stay part of the train. Longer trips mean fewer trips annually, hence also fewer hours spent waiting for the train to depart. The productivity reduction of the vessels are at least 5 % compared to the reference vessel and at most 33 % if they are only sailing in the VT and follow the slower VT operations.

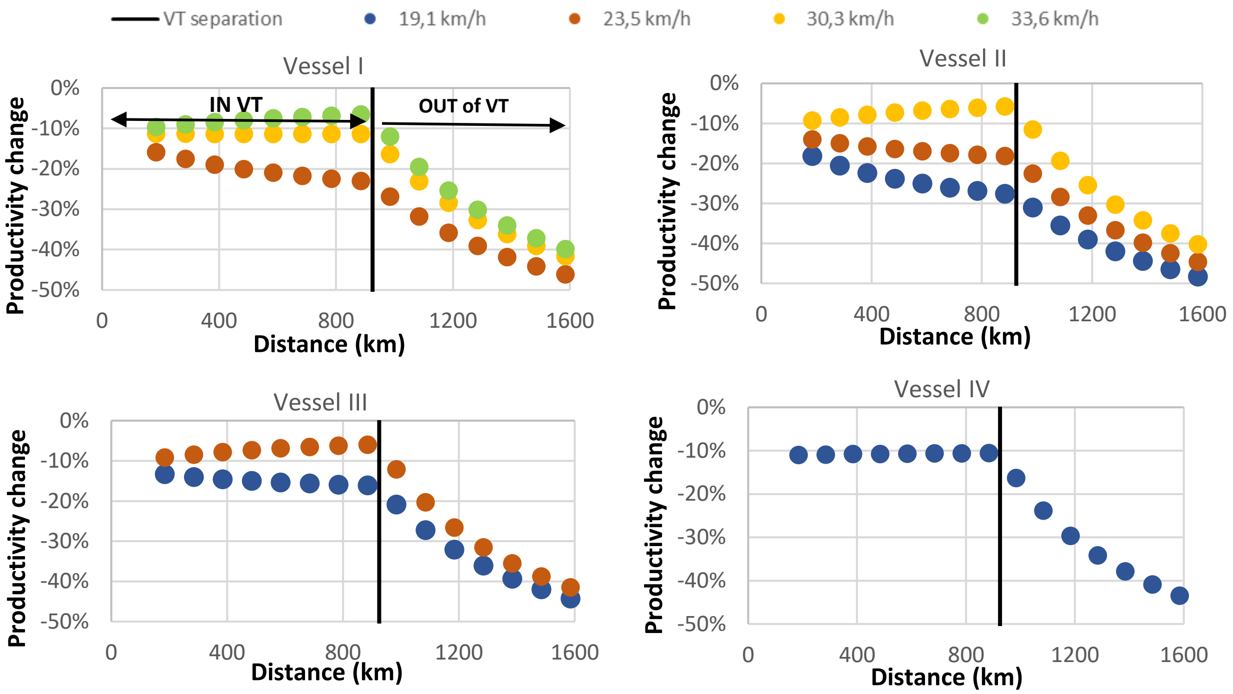


Figure 21: Effect of VT Implementation on Short Sea Vessel Productivity for the Base Case

Transition Stage Case

The longer waiting times of the TSC result in fewer annual return trips, which causes a drop in productivity for the short distances of about 15 % compared to the BC. This can be seen when the 23,5 km/h conditions are compared for both vessel I and II. The longer the waiting times become the more important it is for FVs to use the train for longer routes.

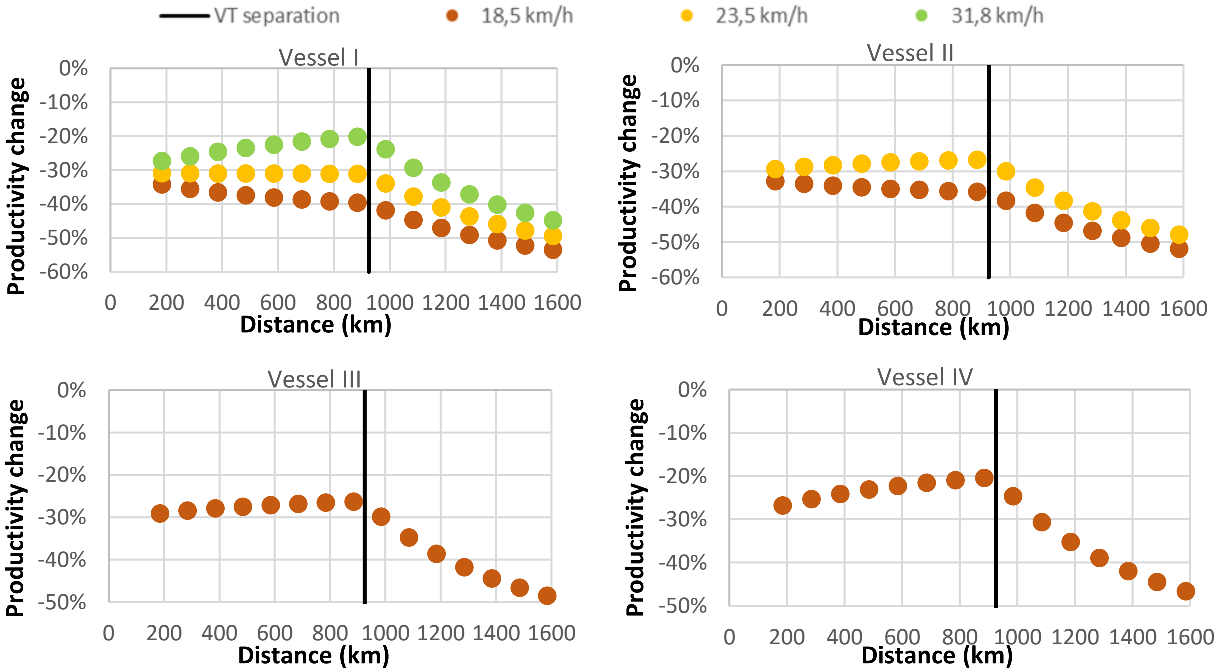


Figure 22: Effect of VT Implementation on Short Sea Vessel Productivity for the Transition Stage Case

Savings

When the changes in productivity observed in the previous paragraph are combined with the reduction in crew cost, the additional cost of the VT system and the changes in fuel consumption, net savings become clear. These savings are in the attention of this section.

Any negative savings in Figure 23 for the BC and Figure 24 for the TSC indicates that the annual VT control system cost are larger than the achieved benefits of the VT. It thereby does not provide any benefit for the VT participants. The comparison of the operating speeds for both the BC and the TSC allows to conclude that the savings created due to the fuel savings at slow steaming operations is of significantly greater importance than the savings created through crew cost savings. This is the case as in either implementation stage the conditions closest to the reference vessel operating conditions are not or barely able to create savings for the FVs, even when they are operating fully in the VT for the entire length of the journey. Only those vessels that sail significantly slower than their normal sailing speed achieve significant savings. Presenting the total savings is of interest to gauge the magnitude of the total savings potential but does not provide the final answer to the viability assessment as they do not show the effect of fewer transported tons.

Base Case

The fuel cost savings due to slowing down leads to annual savings of up to € 1,5 million for vessel I. These large savings allow the FV to be able to operate up to 28 % of its time outside of the VT and is still able to break even with the current operating conditions. Such large savings are however only experienced by vessel I. Even with fuel savings at slower VT operating speeds, the other vessels achieve at most € 400.000 per year for vessel II, € 185.000 for vessel III and € 70.000 for vessel IV.
In particular, for vessel IV the journey length of the FV sailing becomes less important. Yet, due to the lack of built-up savings over the length of the trip vessel II-IV are barely or not at all able to operate outside of the train without making losses.

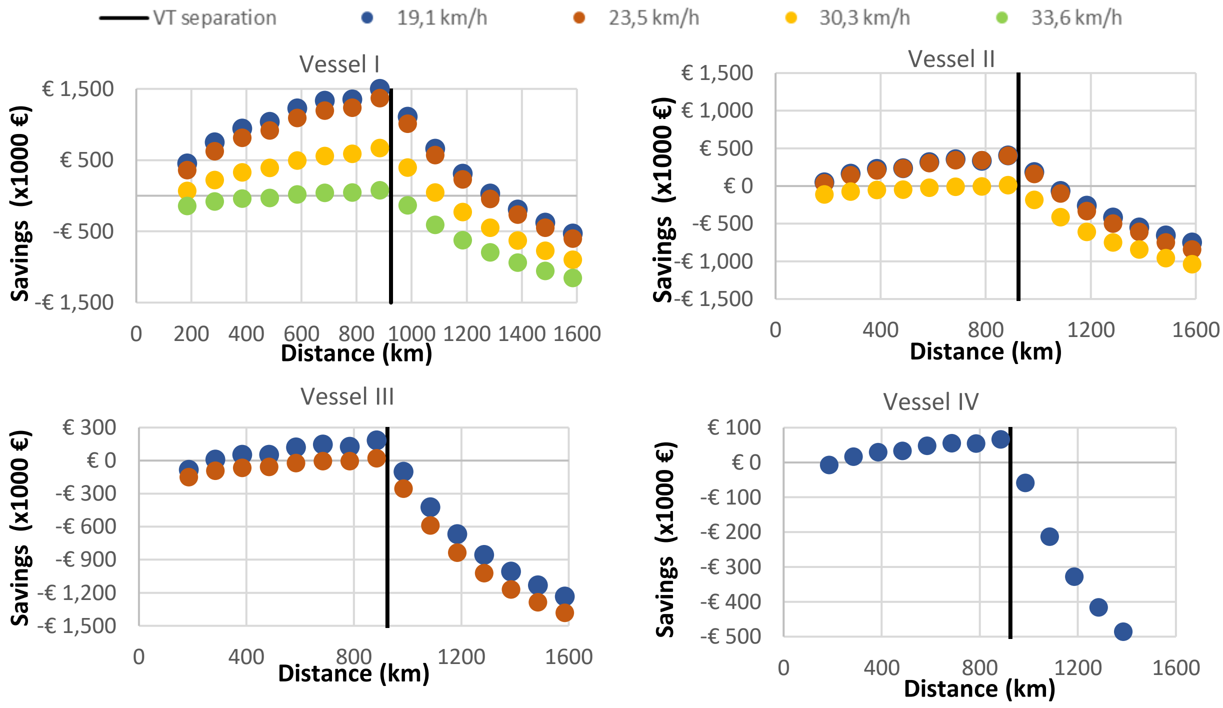


Figure 23: Short Sea FV Savings for the Base Case

Transition Stage Case

When making the same analysis for the TSC, it becomes apparent that the longer waiting times of the TSC cause most conditions that were viable in the BC, to tip into losses. Vessel I that was in the BC able to make up to € 1,5 million if the vessels stay as part of the VT for the entire route length, is now only able to make € 0,8 million. The 31,8 km/h condition of the TSC is no longer able to achieve positive savings even though it achieves more fuel cost savings than the 33,6 km/h condition in the BC. Vessel II, that in the BC was still able to achieve up to € 400.000 of savings is now at the same VT operating conditions only able to make € 130.000. Both vessels III and IV are not able to achieve any benefits of the VT in these early-stage conditions, as seen in Figure 24.

Looking at the conditions in which savings are achieved in the BC or the TSC they mostly surpass the investment cost of the VT control system. This means in viable conditions, a return on investment can already be expected in one year.

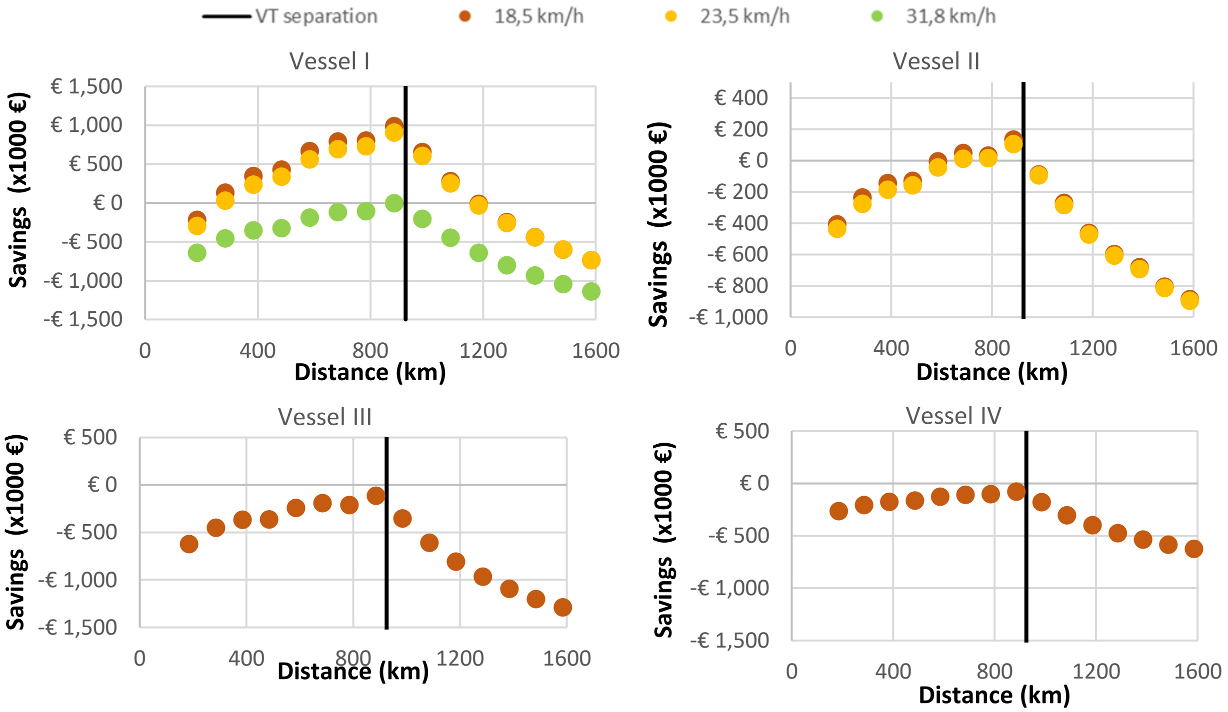


Figure 24: Short Sea FV Savings for the Transition Stage Case

Cost per tkm

The total cost savings do not allow for an accurate comparison to be made between the different vessel types, for that to be possible, the savings need to be converted into their respective savings per tkm. This is why the transport cost reduction is considered the main KPI output from the VT cost model.

The results presented in this section first translate the savings into a cost per tkm and compare these to the compensation cost that needs to be paid by the LVs to the VT operators per LV. This then indicates the number of FVs at a specific operating condition per LV. Finally, the cost per tkm is compared to the total transport cost of the reference vessels to illustrate the cost savings the VT is or is not able to bring.

The compensation cost that is converted to cost per tkm is representative of the largest cost requirements of any VT operating condition so as to determine the maximum FV requirements. This means that for both business models, the compensation cost at the slowest operating conditions are taken as that would mean the largest cost per tkm values.

Base Case

The vessel I plot in Figure 25 clarifies that the savings the vessel achieves, in any slow steaming conditions, are significantly higher than the LV compensation cost. It is only at VT operating conditions of 33,6 km/h that more than one FV will be required per LV. Vessel types I and II achieve sufficient savings to largely outweigh the compensation costs at slow steaming operations. At the operating conditions closest to their reference operations, viable conditions are only achieved on the full route length of the VT and then even below the compensation cost requirements of either type of business model.

A difference in the business model application can be observed for the savings range achieved by vessel IV. The single company surpasses the compensation cost after 300 km in the train, whereas for the platform based model, a single FV would be able to compensate for the cost by itself after 500 km as part of the train. Before these distances are achieved, the VT operator is reliant on more than one FV to participate per LV. These operating conditions are illustrated by the blue shaded area on the vessel IV plot of Figure 25. While these operating conditions are still fully viable, the pricing strategies of the VT operator within this region has to be chosen carefully to ensure that the FV operators are still benefiting and the FV operators are interested in joining the VT.

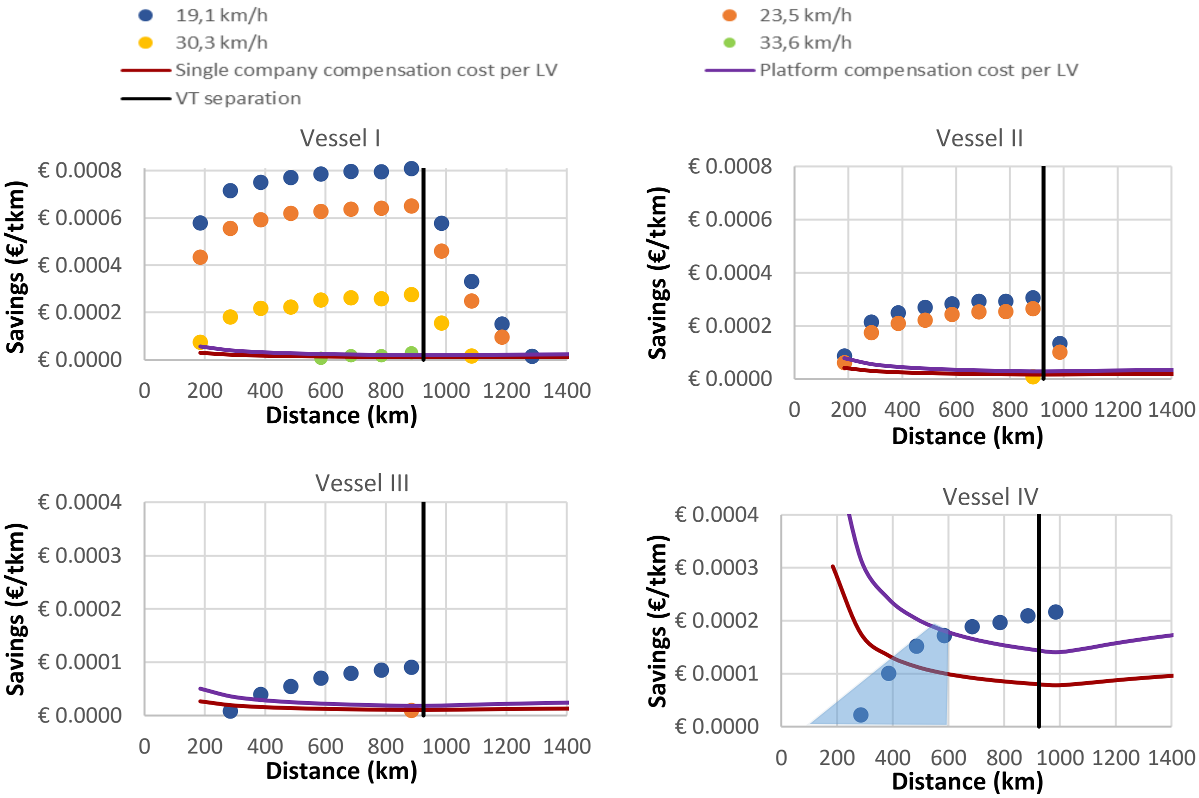


Figure 25: Comparing Short Sea Cost Savings to Business Model Compensation Requirements for the Base Case

To provide the means to identify the VT length requirements, the bar charts in Figure 26 illustrate the number of FVs for all viable conditions. The slower vessel types have less representative operating conditions as they can only operate in the conditions that their original vessel speeds allow. On top of that, the bars are only representative of economically viable conditions, which explains why the range of results represented by the bars diminishes for the slower and smaller vessels. All presented results including the FV requirements are of course, dependent on the distance intervals chosen within the assessment data set. The 100 km intervals used to make these plots, shows that no more than five FVs are needed in the BC at points of viable conditions.

This VT length of five FVs has been identified to be the maximum technically feasible length of the VT with the currently developed VT solution. This is number can still be increased with added redundancies in the VT communication and using different means than AIS, however, this is not further researched within the development of the VT concept [48]. This value of five vessels is based on trial tests that demonstrate a good direct vessel to vessel communication for real-life conditions to be achieved over a distance of up to 3,5 km [155].

Figure 26: Required Number of Short Sea FVs per LV for the Base Case

The vessel I plot of Figure 27 makes the clear transport cost reduction (up to 26 % at 19,1 km/h) visible if it stays as part of the train for the entire length of the trip. For vessel II this reduction only reaches up to 10 %. The largest cost reduction of 3 % - 4 % for vessels III and IV are not distinguishable on the plots. In those cases, only the significant reduction of productivity, once the FVs have left the VT, becomes noticeable as that increases the transport cost compared to the reference vessel.

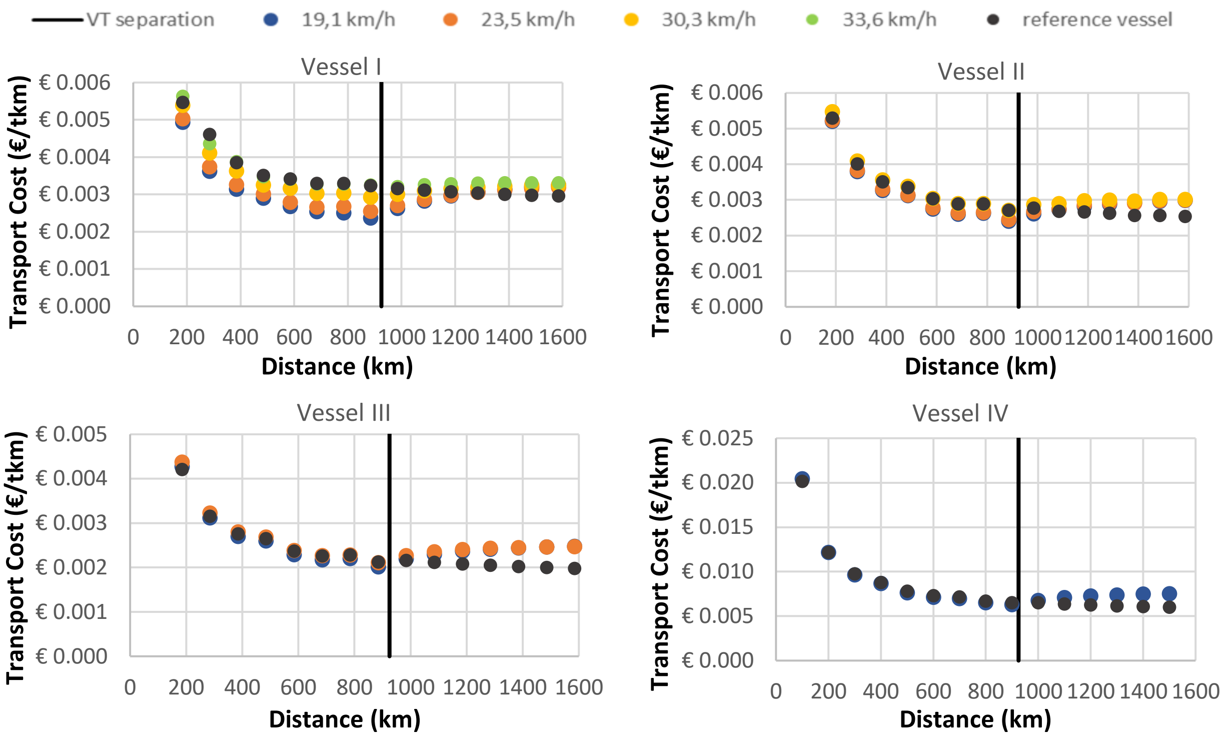


Figure 27: Comparing Transport Cost Reduction of FV to Reference Conditions for the Base Case

Transition Stage Case

The previously presented cost savings description showed that the TSC is only able to achieve economically viable conditions for vessel I and II. Vessels III and IV are not able to benefit sufficiently from the fuel cost savings and cannot outweigh the VT cost with their crew cost savings alone given that they experience a loss in productivity. This is why only vessels I and II are represented in the plots of Figure 28, Figure 29 and Figure 30.

The cost-saving comparison of the business models in Figure 28 illustrates a more notable difference between the single company and the platform-based model than was previously seen in Figure 25 of the BC. In the TSC conditions, only vessel I is still capable of compensating for the LV cost with a single FV. The viability of vessel II shrinks to an operating range of 600 km to the full VT route length.

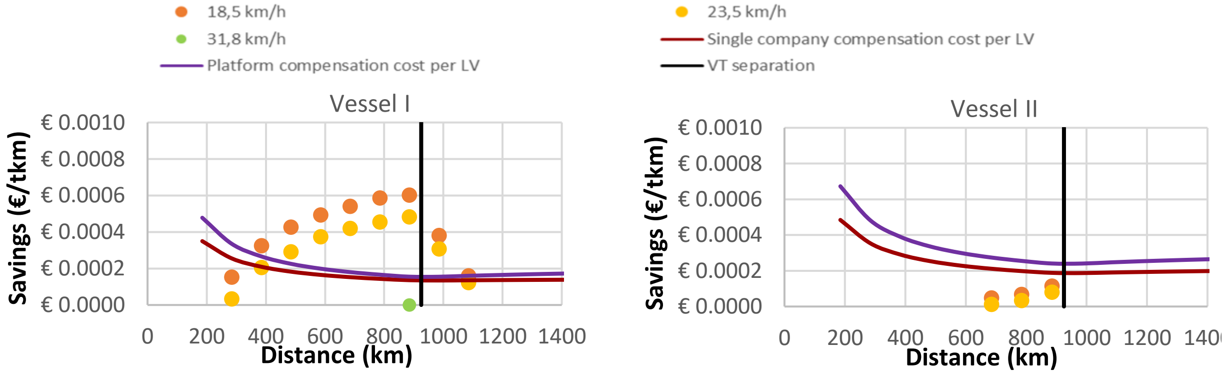


Figure 28: Comparing Short Sea Cost Savings to Business Model Compensation Requirements for the Transition Stage Case

The TSC requires up to 11 FVs per LV for a vessel type I that stays in the train for at least 300 km, whereas up to 24 FVs per LV for a vessel type II that stays in the train for 700 km for the VT operator to break even. Such a high number of FVs not only lie above the maximum technical VT length restrictions of the currently developed system but are also questionable from a practical application perspective. Given that a single train is part of an overall VT transport system, a VT with 11 FVs would require 77 vessels to operate along the same route.

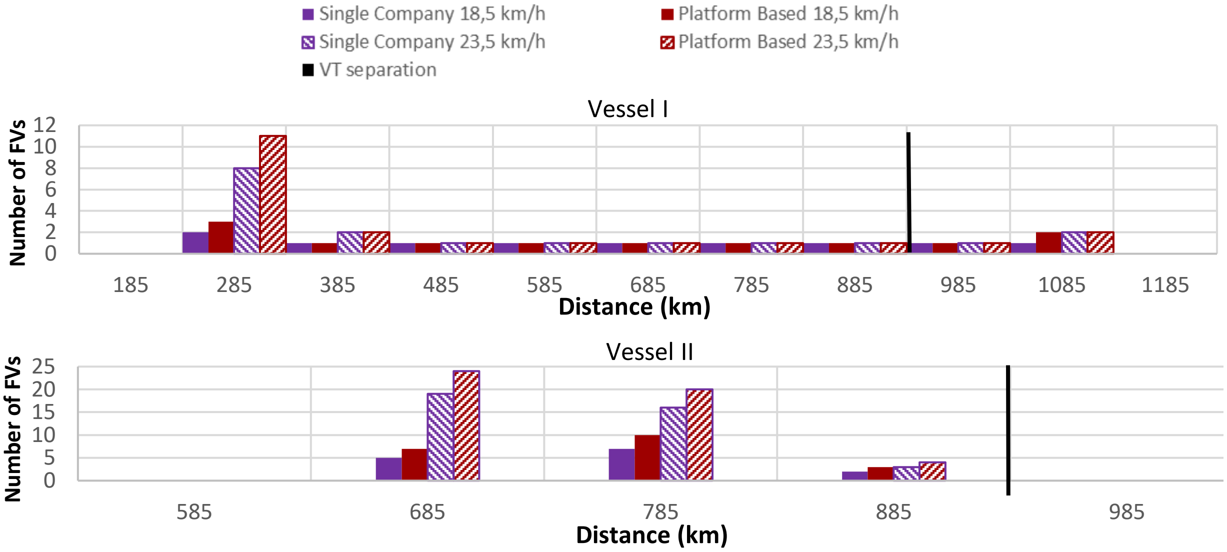


Figure 29: Required Number of Short Sea FVs per LV for the Transition Stage Case

Similar to Figure 27 of the BC, Figure 30 makes the cost savings due to slow steaming for vessel I visible. However, the cost savings for vessel II within the VT route are no longer distinguishable. Table 17 summarises the maximum transport cost reductions of the BC and the TSC for the best cases (i.e. where much reduction can be achieved due to slow steaming) and the worst cases (i.e. where the benefits are mainly achieved through crew cost savings only). The values show significant differences between vessel types, making it clear that convincing the smaller and slower vessel operators to join the train for comparatively small benefits is unlikely.

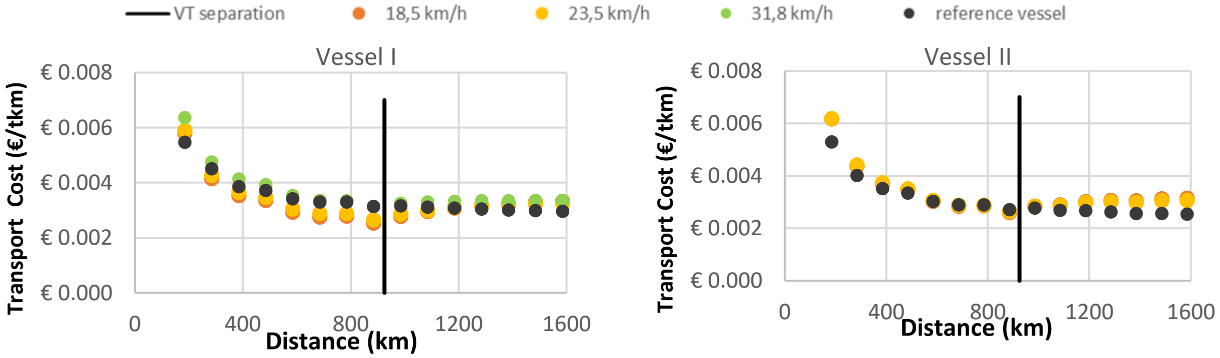


Figure 30: Comparing FV and Reference Transport Cost to Conditions for the Transition Stage Case

Table 17: Summary of Maximum Transport Cost Reduction Achieved by VT Implementation

Implementation stage	Vessel I fast and large		Vessel II slow and large		Vessel III fast and small		Vessel IV slow and small
	Best	Worst	Best	Worst	Best	Worst	
BC	26 %	1 %	11 %	< 0,5 %	4 %	< 0,5 %	3 %
TSC	19 %	< 0,01 %	4 %	3 %	-	-	-

VT Requirements

The results that were presented and discussed so far make it possible to conclude a set of VT requirements that FVs need to meet, in order to achieve economically viable operations in the VT. Table 18 lists the requirements for the distance spent in the VT, the percentage of the trip sailed in the VT, the VT length, the required number of participants and hence also the fleet and market share required for an implementation. The cells marked as not applicable (NA) are conditions in which no viable conditions were identified or in which no second worst-case assessment was performed. The first part of Table 18 is a summary of the assessment observations made throughout this sections 5.2. The bottom part of Table 18 identified the fleet share requirements, which are explained in the next subsection.

Fleet Share Requirements

To determine the fleet shares the number of vessels up to 21.000 GT and with owners from the North and Baltic sea countries are filtered out from the world fleet register listing [156]. This narrowed the fleet size from a total European owned fleet of 4.525 vessels to 3.059 originating in the North and Baltic sea. While it is not guaranteed that these vessels operate with similar crew sizes than set in the assessment, the likelihood that these crews operate with relatively high incomes is there.

When composing a train of vessels from different cargo types, the required fleet share lies between 2 % - 5 %. If the chemical and oil tankers are removed from the available fleet, the required share increases to 2 % - 6 %. From the implementation perspective of a VT operator or an FV operator, the required market share should be as low as possible as that means that these stakeholders are less reliant on other parties to ensure an economically viable VT application. Thus, a required market share of 2 % - 5 % is a realistic requirement for the implementation of a new transport concept. However, if the required market share would be representative of the actual market share this would point towards the VT only serving a niche market, which from an impact perspective of the concept is not desired. To truly make a difference and allow modal shifts to be created due to the VT implementation, the VT will have to penetrate a much larger share of the market. An example is provided in the congestion cost benefit case study of chapter 6.

Table 18: VT Requirements for Short Sea Applications

VT requirement	Stage	Vessel I		Vessel II		Vessel III		Vessel IV	
		Best	Worst	Best	Worst	Best	Worst	Best	Worst
Distance spent in VT	BC	-	590 km	-	773 km	220 km	746 km	139 km	NA
	TSC	224 km	859 km	-	703 km	NA	NA	NA	NA
Percentage time required to be spent in VT	BC	89%	75%	89%	100%	91%	100%	NA	~100 %
	TSC	82%	~100%	100%	NA	NA	NA	NA	NA
VT length	BC	1 FV	4 FV	1 FV	4 FV	1 FV	5 FV	1 FV	3 FV
	TSC	1 FV	11 FV	2 FV	24 FV	NA	NA	NA	NA
Number of participants in VT transport system	BC	48	85	48	90	48	144	48	96
	TSC	10	72	21	150	NA	NA	NA	NA
Total fleet share	BC	2%	3%	2%	3%	2%	5%	2%	3%
	TSC	<1%	2%	1%	5%	NA	NA	NA	NA
Total fleet share (excl. dangerous goods)	BC	2%	4%	2%	4%	2%	6%	2%	4%
	TSC	<1 %	3%	1%	6%	NA	NA	NA	NA

5.2.3. Sensitivity Analysis of VT Influence Factors

The results of the short sea case study are influenced by the input data assumptions. While the result section already provided an overview of effects caused by VT operating speed or VT compensation cost variations, there are a number of other influential factors whose uncertainty can cause significant changes to the viability of the results. This section is intended to help understand the effects of such variations, allowing an overall conclusion to be drawn on the VT applicability in the short sea sector.

Even though there are many factors whose variation can influence the outputs calculated in the last section, reaching from port times, environmental conditions, to solo sailing capabilities, not every factor is studied as part of this sensitivity study. The assessment performed in the first part of this case study already investigated variation in vessel types and operating speeds. This analysis focuses on the sensitivity of operating choices, i.e. departure intervals and route length that can be defined by the VT operator as well as the two factors that mainly influence the cost benefits created, i.e. crew cost and fuel price. The fuel price is an extremely volatile factor that cannot be influenced by the FV or VT operators. It is however important to understand if the dependence on the fuel price is large enough to eliminate the viability of the concept.

Given that vessel I has shown to provide the widest range of results, it has been chosen as a sample case to demonstrate the effects of parameter variations analysis.

Waiting Time

The comparison between the BC and the TSC varies two influence factors simultaneously: the VT compensation cost and the departure intervals and hence waiting times for the FVs. Figure 31 focuses the variation purely on the waiting time variation for different trip lengths spent as part of the VT. The plot shows that while a trip length of 100 km can only allow for a waiting time of 1 h, an FV that intends to stay as part of the VT for a 900 km trip can instead wait up to 4 h. Therefore the viability changes within a waiting time window of 3 h across an 800 km distance variation. This mainly shows the large negative effect of longer waiting times, which implies the need for frequent departure and thus a large number of participants in the system.

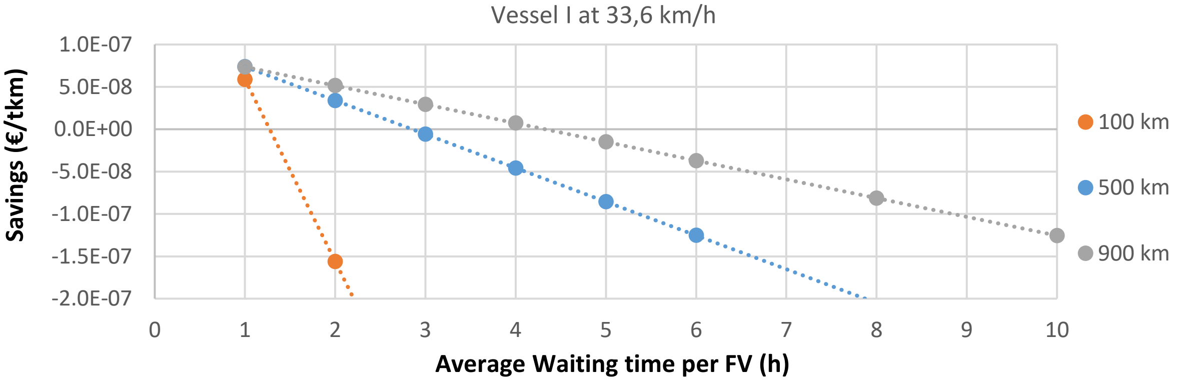


Figure 31: Waiting Time Variation for Vessel I

Crew Cost

The uncertainty related to not only the number of crew members on board, but also their wages has already been mentioned at several points throughout chapter 3 and in the input data description of this chapter. The bar chart in Figure 32 is a visual representation of the variation in crew wages for higher-skilled crew members from different sources. These show a crew variation of up to 90 % lower than those that were used in this assessment. Figure 33 illustrates that a reduction of crew cost of 20 % or even 70 % can tip the balance between viable and non-viable conditions close to the reference operating speeds. This implies that the VT is only potentially attractive to operators with high-wage crews.

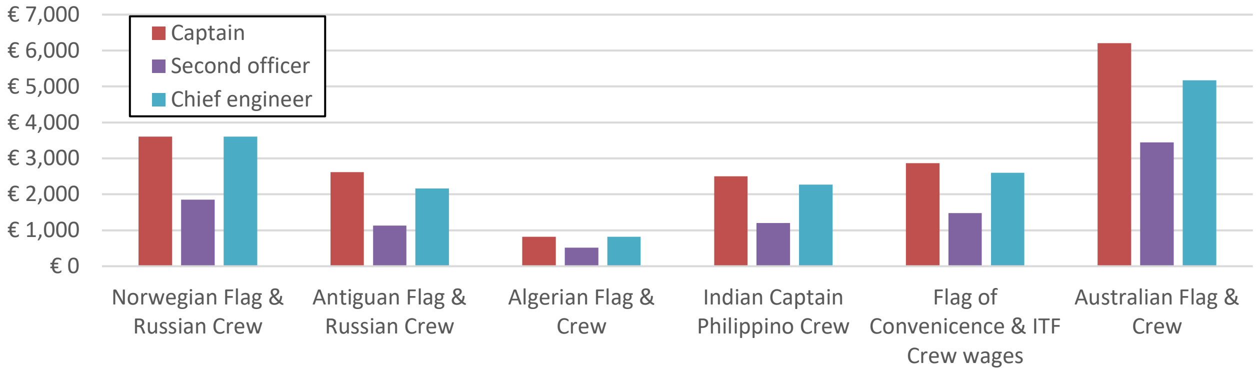


Figure 32: Comparison of Crew Salaries [12], [55], [157], [158]

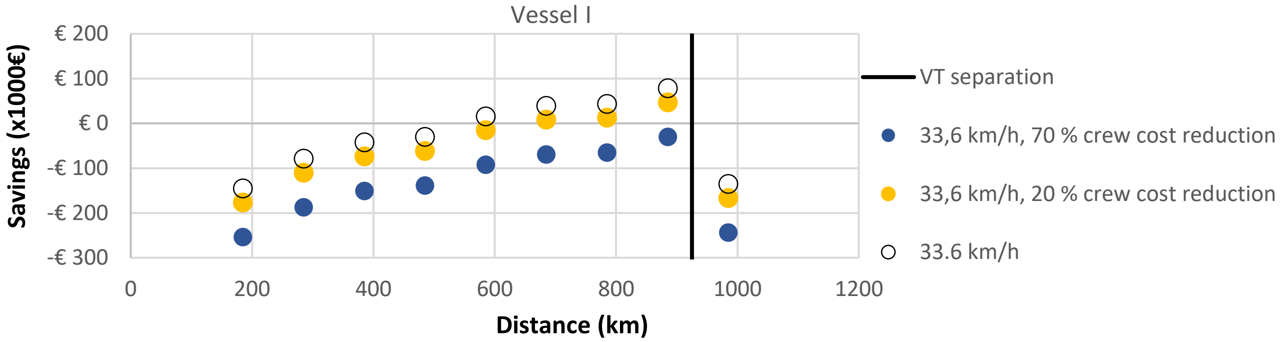


Figure 33: Variations in Crew Cost

Route Length

An increase in VT route length results in larger total savings as fewer trips are performed annually and hence less waiting times are created. The higher savings also allow the vessels to operate outside of the train for longer distances. As seen from Figure 34, the effects for the slow steaming vessels are larger with an increase of up to 57 % of savings, while for VT operations at faster speeds, the savings increase by 14 %. If this is turned into a cost per tkm the reduction at the VT separation points of the two route lengths are 4 % at the 23,5 km/h operating speed and 39 % at the 33,6 km/h operating speed.

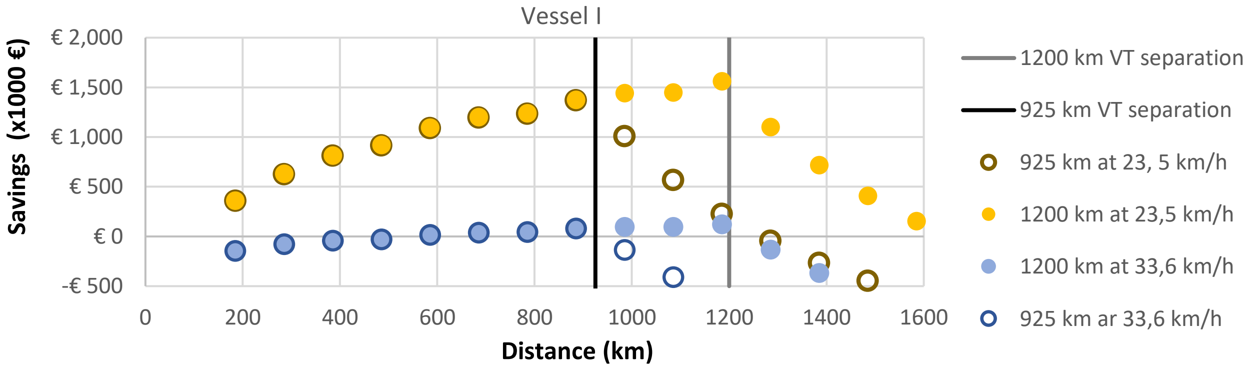


Figure 34: VT Route Length Variation for Vessel I

Fuel Cost

Finally, the variation of the fuel cost is the most important variation factor for the VT implementation as the concept's viability for SS applications hinges on the slow steaming benefits. Based on the MGO price fluctuation [159] two extreme costs of 660 €/t and 230 €/t were chosen for this assessment. Figure 35 shows that without the fuel cost-benefit created by high fuel prices, the productivity reductions at slow VT operating speeds naturally also leads to less favourable conditions than the operations closer to the original reference speeds of the vessels.

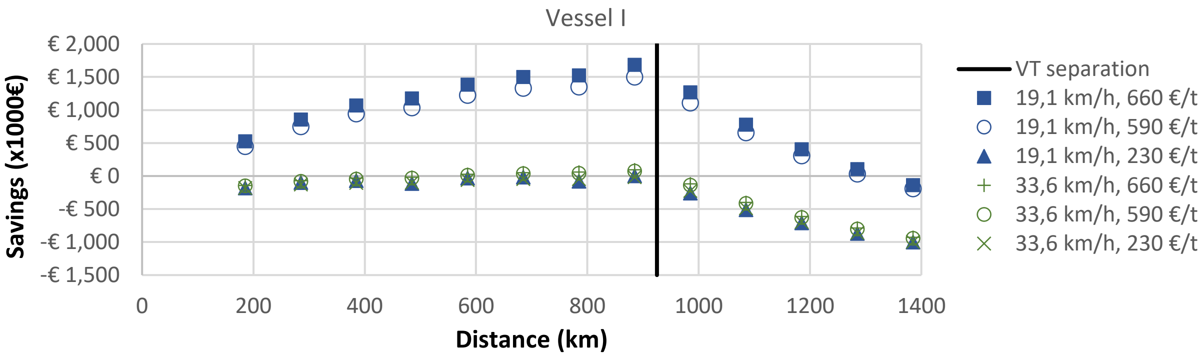


Figure 35: Variation in Fuel Price for Vessel I

Summary

Table 19 summarises the largest variations performed in this sensitivity analysis and its effects on the cost reduction of vessel I. The fourth column of Table 19 compares the impact of 1 % of the variation of each of the factors. While this is not a fully objective comparison since some factors can vary significantly more than others, it is at least indicative of the most impacting factors. The appraisal shows that the fuel price is by far the most important being 7,5 times more influential than the route length. The increase in waiting times is the third influential factor, while the variation in crew cost has the smallest impact on the cost reduction.

This means that even though the uncertainty around the crew cost can be significant, dependent on the vessel operator, it is much more important to focus on adjusting the VT operation i.e. departure interval and route length that are in control of the VT operator. Even though uncertainty around the fuel price can also impact VT implementation, this is a factor that will affect all operators no matter whether they are located in or out of the VT. It can therefore be concluded that since the fuel savings play such an important role in the VT implementation, the vessels productivity variations caused by the VT are much more important than any crew cost savings that only play a secondary role in the concept implementation in the short sea sector.

Table 19: Comparison of Sensitivity Analysis Results for the Short Sea Application Case

Item	Variation from BC	Effect on Vessel I savings (€/tkm)	Savings changes per 1 % item variation
Waiting time (h)	+ 50 %	- 9 %	- 0,18 %
Crew cost (%)	- 70 %	-7 %	- 0,10 %
Route length (km)	+ 30 %	7 %	0,23 %
Fuel price (€)	- 11 %	-19 %	- 1,72 %

5.2.4. Integrating Other Stakeholders

Now that the viability for the VT and FV operators have been thoroughly investigated for the short sea application case, the focus needs to be placed on two other stakeholder groups that can still be influenced by the VT implementation. This section adds external emission cost and cargo related logistics cost to demonstrate the effects of the VT integration on society and the cargo owners.

Society- Emissions

Effects of slow steaming operations do not only provide economic benefit through fuel savings, it is also used as a tool to reduce emission. Slow steaming has frequently been studied, e.g. [160]–[162] and is also implemented by operators such as Maersk [163] and COSCO [164] along certain routes as a solution for fuel cost saving and greener operations. Even though slow steaming is only feasible with high bunker prices and powerful market-based solutions such as tax levers [165], many people expect that slow steaming becomes the norm in the future, as it is a way to meet environmental regulations [166]. While a number of studies and politicians call for mandatory slow steaming to be installed by the IMO, maritime experts express concern with such an approach. They argue that it would not only artificially reduce decarbonisation, as the carriers would lose incentive in investing into better technologies on their vessels, but also risks creating a reverse modal shift onto other modes of transport [167], [168]. It is hence not a surprise that when internalising the emission cost and thus including the social perspective, significant cost benefits can be identified due to the implantation of the VT.

Figure 36 is a sample of the external emission cost calculated for vessel I, which are internalised in Figure 37. The FV emission cost of Figure 25 are representative of the slowest VT BC operating conditions. While the emission cost of the reference vessel stays constant throughout the journey, the emission cost per FV rise after separating from the VT. This is caused by the FV being able to increase its speed to the reference vessel operating speed and thus causes the emissions to rise.

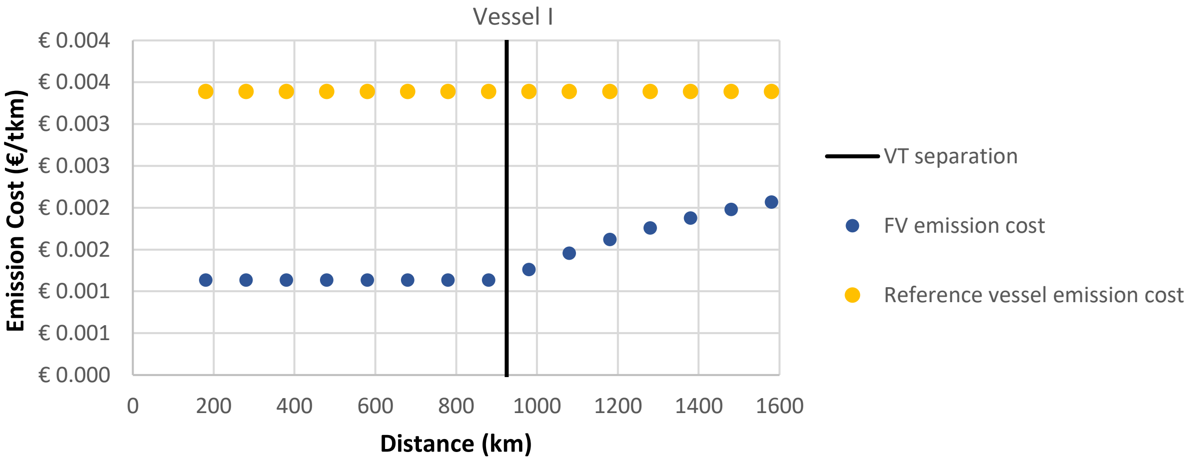


Figure 36: Example Emission Cost for Vessel I

The plots in Figure 37 show the effect of internalising the emission cost compared to the reference vessels at the slowest VT operating speed of the BC. Even though the internalisation causes the cost per tkm to rise for the FV operator, the transport cost of vessel I - III with internalized societal cost further reduces compared to the reference vessel by up to 46 %, 32 % and 13 % respective to the vessel types. This improvement is much larger than the cost difference without the internalization of emissions that only achieved a maximum cost reduction of 24 %, 11 % and 5 %. Vessels IV do not experience such benefits.

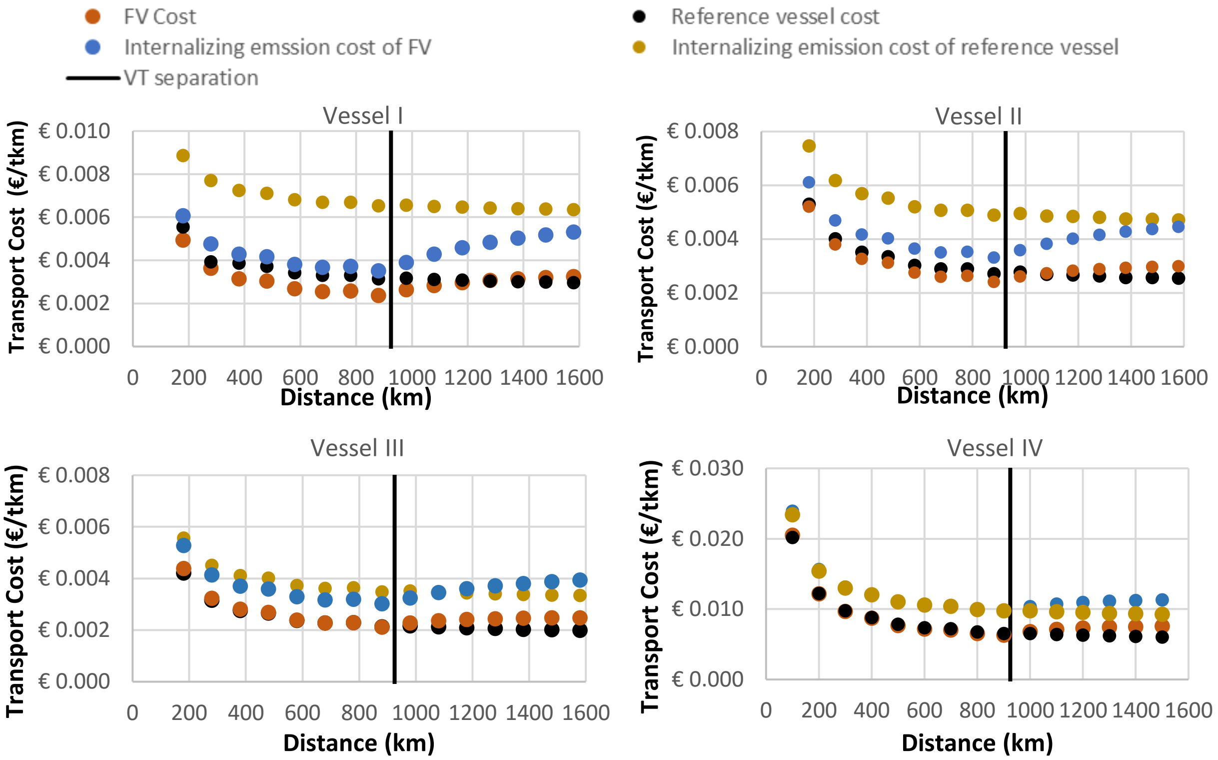


Figure 37: Internalising Emission Cost

Cargo Owners- Considering Stock in Transit and Safety Stock

Contrary to the positive effects the internalisation of external emission cost have brought, from a cargo owner perspective the slower operations are a negative consequence. The slower speeds and added waiting times increase the lead times of the goods, which hence increase the stock in transit cost and safety stock cost. As a reminder the cargo value is set to 1000 €/t, which is high for bulk commodity values but representative for containerized goods. The holding cost is set to 10 % annually and the safety factor is set to 2. The variance in lead time is taken from samples with a variation of 10 % and the daily demand variance is set to 0.

The plots in Figure 38 makes it visible that the safety stock pays a very small contribution with at most 0,0013 €/tkm and at least 0,0002 €/tkm. It is the stock in transit that is more important cost with cost lying between 0,006 €/tkm and 0,0009 €/tkm, dependent on the trip length, when the lead time of the operating conditions change. To illustrate the comparison of the cargo cost of a conventional and an FV vessel the secondary axis of the plots the percentage cargo cost increase caused by the VT operations. It is inversely proportional to the trend of the productivity changes that was earlier seen in Figure 21. It is therefore understandable that the percentage cost increase for vessel I-II rise, while they are part of the train they need to slow down and then dramatically increase when the vessel leaves the train, as the vessel has to stop for the crew to rest every eight hours.

Figure 38 also compares the reference vessel and the FV cost, including the transport and the two logistics cost parameters that relate to lead time. As only very small differences can be distinguished for vessel I and IV, this indicates that the savings benefit created by the slow steaming is almost entirely cancelled out. As it can be seen at shorter distances, the total VT related logistics cost sum up to be larger than the reference vessel cost, including the safety and transit stock. This difference in percentage cargo cost increase is plotted on the secondary axis. Vessel type I is left with 9 % cost savings when the cargo cost are included, which is 15 % less savings than the 24 % identified previously. Vessel II is left with a maximum of 2 % savings which is down from 11 % in the BC. The FV of a vessel III no longer achieves savings compared to the reference vessel; instead, its VT related logistics cost increase by at least 3 %. Vessel IV is left with a cost reduction of <1 % cost reduction from the prior 4 % achieved without the consideration of the cargo cost.

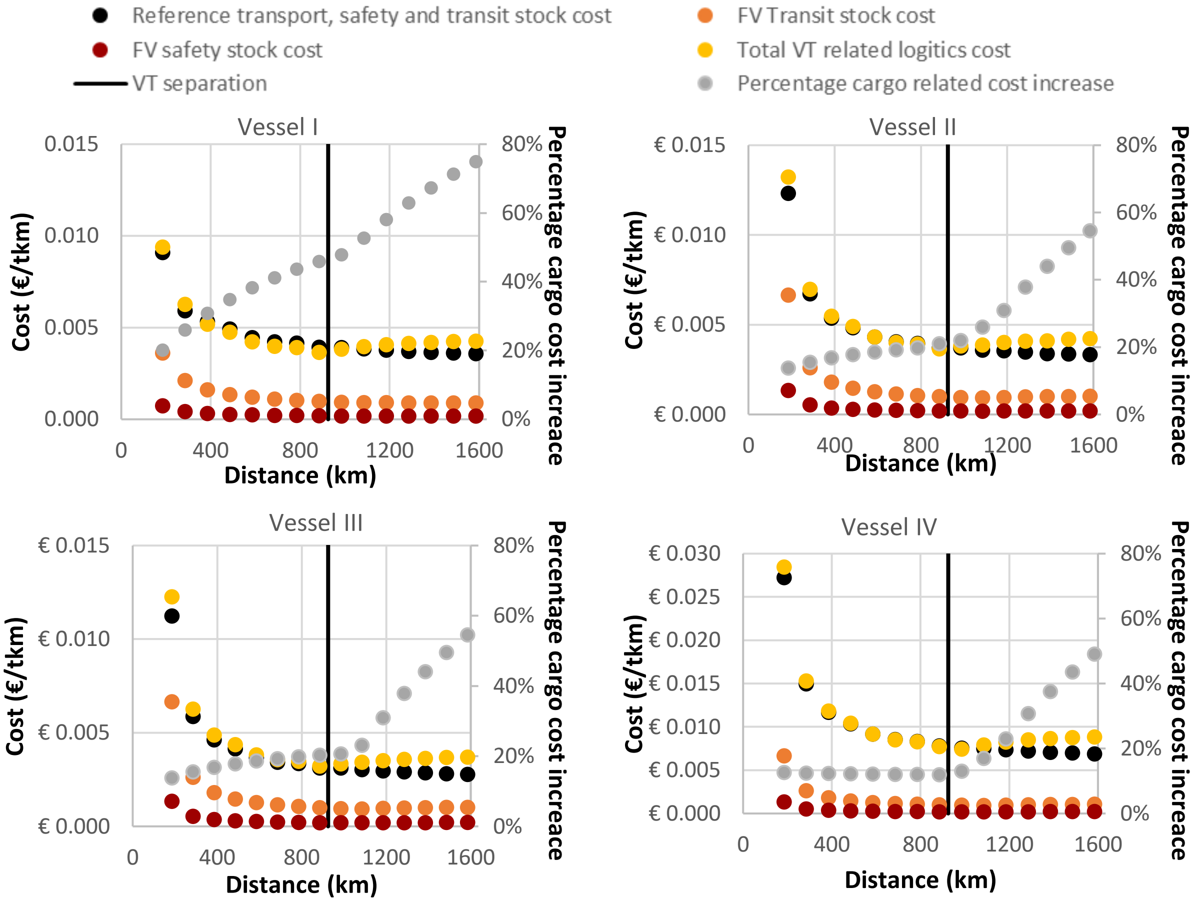


Figure 38: Effect of the VT Operations on Cargo-Related Cost

5.2.5. Conclusions on the Viability of Short Sea Application

In the short sea case study, the original focus of the VT concept to reduce crew cost, can be achieved, but its benefits are small in comparison to the fuel savings. The sensitivity analysis has shown that a 1 % fuel price decrease causes a 1,72 % savings reduction, while a 1 % lowering of crew cost only influences the savings negatively by 0,1 %. The fact that a platoon is only as fast as its slowest member forces the VT concept to adopt slow steaming operations. The benefits achieved through this operational choice are not VT specific and could be adopted by any vessel operator. The added benefit of the crew cost reduction also brings along a restriction in flexibility.

This loss of flexibility means that conditions of the spot market for general cargo vessels are less well represented by the case study. Vessels operating on the spot market have continuously varying route lengths and destinations. This means the added waiting time increases when a trip is split into several port calls. The chosen route is a highly frequented route and passes by a large number of important European ports. Therefore, it is still possible for a vessel that follows a more erratic call pattern to join at any point on this route. The operating area and thereby the flexibility of these vessels is then restricted to the area in which LVs operate.

Even though the BC identified viable conditions for all vessel types achieving transport cost reductions of between 1 % and 26 %, the TSC only showed viability for vessel I with a cost reduction of up to 19 % and for vessel II for a cost reduction of up to 4 %. This means in the early-stage of the implementation and in the conditions assumed via the input data, some vessel types will require subsidies to identify their participation in the VT concept.

The variation between the single company and the platform-based business models does show differences for a range of shorter distances in particular of the vessels III and IV. However, overall the choice of this business model is not the determining factor for the concept's application in the short sea sector. Instead, the sensitivity analysis has shown the variation of the input data with regards to VT operation i.e. route length and departure interval, to be of a more important and controllable factor than the fuel price from the VT operator. Since the automation of the navigational tasks is only able to reduce the crew size by six crew members annually, the savings created through the concept are comparatively small and thus the possible variation of crew wages dependent on the vessel operator become less relevant. Additionally, the analysis has shown how easily uncertain parameters can tip the balance to be economically viable. It can, therefore, at it this point not be convincingly concluded that the VT benefits from only automating the navigation tasks are large enough to guarantee an application of the VT in the short sea sector. This answers sub-question 3 on the effects of VT property variations on the performance of the concept, described in chapter 1 for the short sea scenario.

The slow steaming of the VT operations creates benefits in the reduction of societal cost. If these cost are internalized, vessel I can achieve an additional 22 % cost reduction on top of the 24 % and vessel II can achieve an additional 21 % on top of the 11 % it already achieves through the fuel and crew cost savings. The lead time-related cargo cost can add up to 33 % -82 % of the identified FV transport cost. These cargo-related cost caused by the change in operating regime cancel out close to all benefits created. It is only vessel I that can still achieve a clear cost reduction of 11 %, which is still 15 % less than the savings achieved by the slow steaming. This further emphasizes that the effects of slow steaming are not creating an attractive VT service for the cargo owners. Thus the VT concept is not able to create a convincing business case for the short sea sector.

5.3. IWT Case Study

This second application case is focused on the inland navigation section. As section 3.1 described, there are several parameter differences to the short sea application that are added in this inland case. These are related to lock passage, restrictions in operating days created by environmental river conditions and regulated operating hour restrictions dependent on the size of the crew.

This sub-section is structured in the same manner as the short sea case, starting by giving the input data, followed by a validation of the benchmarked cost model. Then the results are presented, a sensitivity analysis is performed and an analysis is done that integrates the societal perspective and that of cargo owners. Finally, the main conclusions are summarized at the end of the chapter.

5.3.1. Case Description

Some inland navigation operating features can vary significantly depending on the region of application. While this is acknowledged and also elaborated upon in detail in chapter 6, this first inland case study applies the VT concept to the largest European inland navigation corridor on the Rhine. More specifically the lower Rhine, which has the highest traffic density.

The vessel operators along this corridor are fragmented, meaning that the majority of the fleet is operated by small family businesses that are either captain owned, in which case a family lives and works on their vessel [169]. A comparison of the size of businesses based on the number of vessels they operate, subdivided by, country, is provided in Figure 61 of chapter 6. Due to this predominant business structure on the Rhine, the most appropriate business model is the platform-based business model. Nevertheless, for the sake of comparison, this inland shipping case also denotes the differences to the single company model that would need to be adopted in other geographical areas.

Route

The VT service in this case study operates all year round on a regular interval, between Antwerp and Duisburg. This is a route of 325 km length (one way), indicated by the orange arrows in Figure 39. The reason for choosing this area is its high traffic density. The port of Antwerp is one the largest seaports in Europe, which allows large amounts of cargo to be moved along the waterway into the hinterland to Duisburg, which in turn is the world's largest inland port and is a logistic hub in central Europe [170].
To allow FVs to operate outside of the VT past the first 325 km, their route lengths are varied up to a range of 700 km. This means they could reach past the Port of Karlsruhe. The FV can join and leave at any point along the way, i.e., start from Rotterdam, Frankfurt or Karlsruhe to join the VT. The average length of vessel routes on the Rhine is 200 km [171] which lies within the operating distance of the VT.

Figure 39: Operating Area of the Case Study

Under normal water conditions, the current on the Rhine is 4 km/h [172]. This can vary significantly throughout the year. Even though in general, the Rhine has provided more reliable discharge than other rivers, in bad years such as in 2018, 107 days of low water were recorded [173]. On average, about 5 % of days (18) per year are in low water conditions. Suspension of navigation on the Rhine is only expected to occur about 1 % of the time [105].

Main Vessel-Related Parameters

In inland navigation vessels are classified into CEMT (European Conference of Ministers of Transport) classes I – VII. Self-propelled vessels mostly range from classes I-V, while classes VI and VII are mostly push convoy which are not targeted as VT users. In order to perform an assessment that is indicative of a variety of different vessels, three classes have been picked that each fit into a different category of the minimum manning requirements that were introduced in chapter 3 and are presented in Table 1. These are CEMT class II, IV and V vessels. While class II mainly operates on a regional level, the other two larger classes typically operate internationally. The dimensions and technical information of the three sample vessels are summarised in Table 20.

The fuel consumption differs between each vessel class are taken from generic guidelines for IWT vessels for different classes [174]. The fuel price is set to € 590 per ton. The cargo capacity of the vessels is indicated in tons, as that is the cargo unit of dry bulk vessels that make up a large fraction of the Rhine fleet.

Port time for inland vessels are generally quite long since they are not given priority by the terminal operators at seaports and therefore have to wait significantly longer compared to seagoing vessels [175]. Port times depend on the port location, the size of the vessel and the loading or unloading actions. The Dutch government has estimated the shortest and longest port time for inland vessels [176]. The average of these values are used as the port times for the different vessel classes in Table 20. Even though these port times are not VT specific, in combination with the waiting times created by the VT departure intervals, application conditions may be impacted by larger port times.

Table 20: Input Data for Four Sample Vessel Types

Vessel Type	Class V	Class IV	Class II
Length (m)	110	81	54
Beam (m)	11,4	9,5	6,5
Installed power (kW)	1.644	1.063	376
SFC (g/kWh)	210	218	230
Capacity (t)*	2.200	1.500	600
Operating speed (km/h)	16	15	13
Vessel construction cost	€ 2.460.000	€ 1.800.000	€ 1.060.000
Port time (h)	58	54	40

* rounded to the nearest 50

The input values for the vessel cost calculations and the dimensions of the sample vessels are equivalent for the reference ships and FVs. Table 21 provides the annual percentages that make up the capital and administration cost based on the building cost estimates. Additionally, it specifies the number of annual operating days for the continuous operations at a B regime (assuming 5 in-operational days) and for the A1/A2 regimes that only operate on weekdays [104].

Table 21: Input Data for Vessel Cost Calculations

Input Items	Input Values
Interest	5%
Depreciation	Over 20 years, therefore, 5%
Insurance	0,75%
Administration	2,5%
Operating days (B regime) (days)	360
Operating days (A1 or A2 regime) (days)	261
Restricted operations due to environmental conditions (days)	18
Fuel price (€/t)	590

Crew

The last missing cost data that has been touched upon in chapter 3 is the data to calculate crew cost. There are no uniform European wide regulations that identify the size and composition of crews. This usually falls under the responsibilities of the states in which the vessels are sailing [177]. There are, however, minimum crewing guidelines provided by the CCNR [104]. Here the number of crew have been taken from the higher equipment standard means requirements meaning that equipment such as a bow thruster and equipment such as electric coupling winches are available on board. This standard thus needs less qualified support crew. The higher equipment standard was chosen as the developers of the VT control system indicated the need for a bow thruster if they are to navigate on smaller and more demanding waterways [108].

The wages for this case study are taken from a Dutch wage table [178]. This wage table does not include employment-related cost or indirect crew cost. These extra cost are calculated in the same manner as was done for the short sea case by setting these extra cost to be 30 % of the total crew cost [12]. The annual crew cost under different sailing regimes are provided in Table 22 and based on the crew numbers of [104]. It should be noted that the A1 and A2 regimes are assumed to only have one crew operating on the vessel while under B conditions, two crews rotate to allow continuous operations all year round.

Table 22: Annual Crew Cost and Saving for the Different Operating Regimes

Role	Class V			Class IV			Class II		
	A1	A2	B	A1	A2	B	A1	A2	B
Boatmaster									
>86m	€ 39.300	€ 78.600	€ 112.600						
70-85m				€ 38.500	€ 77.000	€ 110.200			
<70m							€ 37.800	€ 75.600	€ 108.200
Schipper									
Helmsman	€ 32.300		€ 46.000						
Boatman			€ 45.500	€ 31.800		€ 45.500	€ 31.800		
Apprentice	€ 28.100	€ 56.200	€ 40.300	€ 28.100	€ 28.100	€ 40.300			€ 80.600
Total crew cost	€ 99.700	€ 134.800	€ 244.400	€ 98.400	€ 105.100	€ 196.000	€ 69.600	€ 75.600	€ 188.800
Total annual crew cost	**€ 99.700**	**€ 134.800**	**€ 488.800**	**€ 98.400**	**€ 105.100**	**€ 392.000**	**€ 69.600**	**€ 75.600**	**€ 377.600**

The variation in minimum crewing requirements results in a crew cost savings between € 6.000 and € 389.100 dependent on the vessel type and reference vessel operating regime as was explained in chapter 3 and is indicated in Table 1.

VT Operating Conditions

Base Case

Just like in the short sea case, BC is set to a VT departure interval of 6 hours. Yet, the slower operating speeds of the inland vessels and the shorter route cause the return trip times to be different and hence also the required number of LVs is different. It is assumed that LVs, will have priority access to terminals and will hence not have as long port times and standard inland vessels. As the LV sails on a fixed schedule, it is assumed that the port times are also prescheduled and that LV have hence shorter port times than a conventional inland vessel that does not continuously operate on the same route. The LV port time of 10 h is set, which is sufficient time to (un)load even a class V vessel.

The VT operating speeds are selected to be as close as possible to the current operating speeds of the different vessel types without surpassing their design speed. The number of LVs to achieve the required departure interval at those speeds is indicated in Table 23, ranging from 11 to 13 LVs. With every LV the amount of compensation cost increases, as every LV has their own VT control system investment cost. Yet, with more LVs the back-office cost per LV reduced. This means for the platform-based VT operator the cost per LV varies by € 4.500 between the operating conditions.

Table 23: VT Speeds and LV Requirements under the Base Case

LV return trip time (h)	78	72	66
Speed (km/h)	12,5	13,7	15,2
Number of LVs	13	12	11
VT compensation cost (€/LV)	€ 56.000	€ 58.000	€ 60.500

Transition Stage Case

To ensure no waiting times are created for the LVs, the departure interval in the transition stage is set to once per day. This departure interval increases the average waiting time from 3 h to 12 h. The decrease in departure frequency causes fewer LVs to be needed over the same distance as in the BC. The longer departure interval causes the VT operating speeds closest to the reference vessel conditions to be pushed apart and hence a slower operating speed is assessed compared to the BC conditions. The TSC drops the required number of LVs to three to four LVs.

Table 24: VT speeds and LV Requirements under the Transition Stage Case

LV return trip time (h)	96	72
Speed (km/h)	10,1	13,7
Number of LVs	4	3
VT compensation cost (€/LV)	€ 356.000	€ 385.000

5.3.2. Reference Vessel Cost Breakdown

Now that all the input parameters have been presented, the focus is once again shifted to the cost calculations of the reference vessel. The cost breakdown presented in Table 25 and Figure 40 is representative of the reference vessel operating at the full journey length of 325 km.

The pie charts in Figure 40 illustrate the cost breakdown of all cost elements that compose the reference vessel cost for vessels operating continuously. It demonstrates the importance of the crew cost for all three inland vessel types, which is different to what was observed for the short sea application where only the smallest and slowest of the vessels had a comparably large share of crew cost. This crew cost-share of the inland vessel also increases with decreasing ship size, making up to 61 % of the total cost on class II vessels. The second most significant cost contributor is the capital cost (deprecation, interest) followed by the fuel cost. This cost breakdown indicates that contrary to the observations made in the short sea application case, the crew cost savings will make a significant impact, whereas the variation in fuel cost cause by altering operating speed will have a much smaller effect.

Table 25 provides the cost breakdown comparison between the two extreme operating regimes B and A1. It indicates that the importance of crew cost at an A1 operating regime diminishes. There the most important cost factors become the capital cost. Yet, even under A1 regime, the crew cost is more important for the smaller vessels than it is for the larger ones.

Table 25: Cost Breakdown under B and A1 Operating Regime

Cost element	Vessel Class V		Vessel Class IV		Vessel Class II	
	B	**A1**	**B**	**A1**	**B**	**A1**
Depreciation	11 %	22 %	11 %	22 %	9 %	21 %
Interest	11 %	22 %	11 %	22 %	9 %	21 %
Insurance	2 %	3 %	2 %	3 %	1 %	3 %
Maintenance	3 %	7 %	3 %	5 %	3 %	5 %
Crew	45 %	18 %	48 %	24 %	61 %	27 %
Fuel	22 %	16 %	19 %	14 %	13 %	11 %
Admin	6 %	11 %	6 %	11 %	4 %	11 %
Total	**€ 1.086.000**	**€ 606.000**	**€ 809.000**	**€ 447.000**	**€ 616.000**	**€ 273.000**

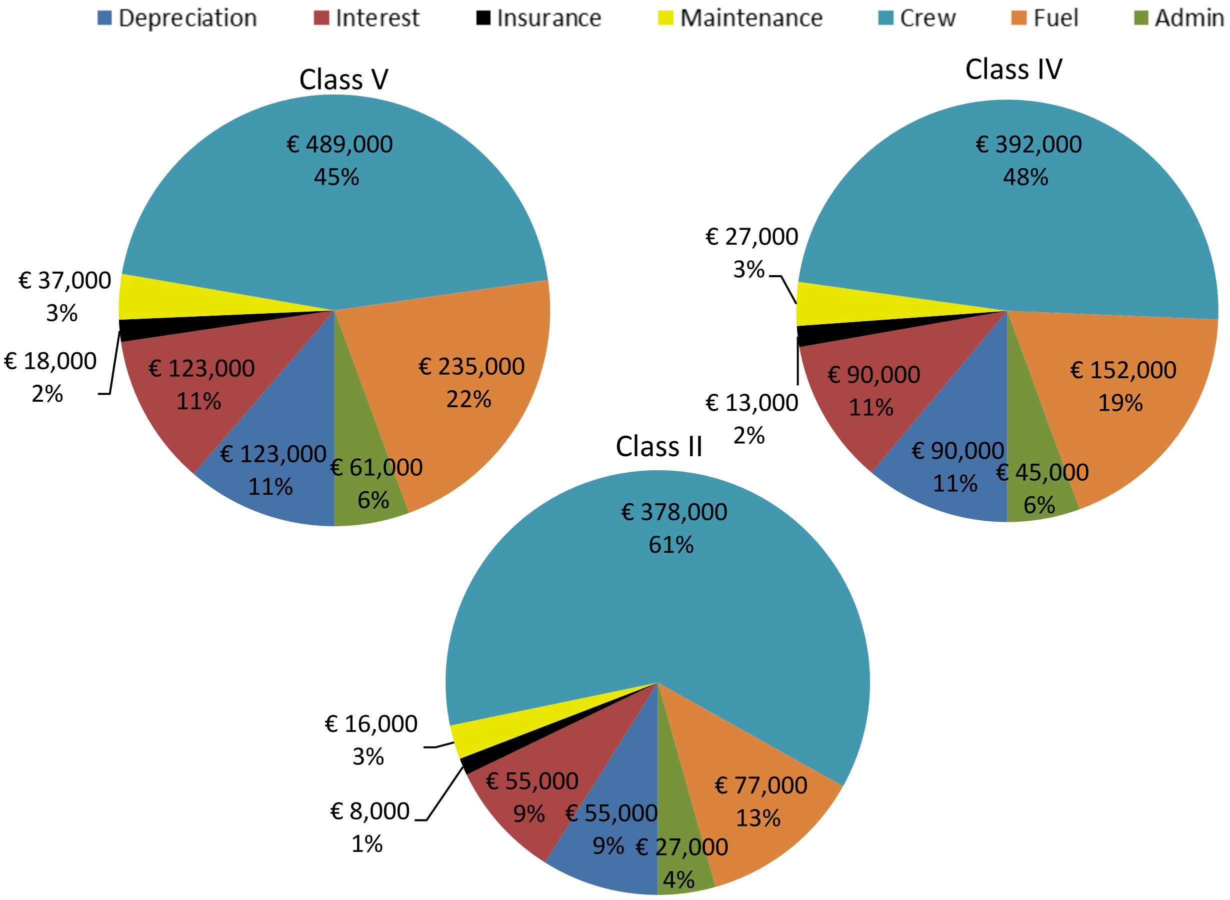


Figure 40: Cost Breakdown under B Operating Regime

5.3.3. Results and VT Operating Requirements

The result section starts by explaining the productivity changes in the two maturity scenarios. These productivities are then used to determine the total FV cost, before converting them into a cost per tkm that allows a comparison to the LV compensation cost of the two business models. This comparison between compensation cost and savings per t–km is used to identify the required VT length. Next, the transport cost reduction achieved by the FVs compared to the reference conditions at a B, A2 and A1 sailing regime is calculated. The section finishes by summarizing the viable operating conditions in terms of minimum VT distance and maximum percentage time spent sailing outside of the VT, as well as identifying the required market and fleet share of the VT transport system.

Productivity Change

Just like in the short sea case study, the inland results first takes a look at the productivity change of the FVs in order to better understand the effects of productivity changes. Before looking at the productivity changes, however, we first need to need to see the reference vessel conditions to which the FV operations are compared.

Reference Vessel Productivity

Figure 41 shows the decreasing productivity of the reference vessels with increasing trip distances. The plot also illustrates the impact of the sailing regime on the vessel types. The operation changes from the B to the A1 regime cause a productivity reduction of 33 % for all vessel types.

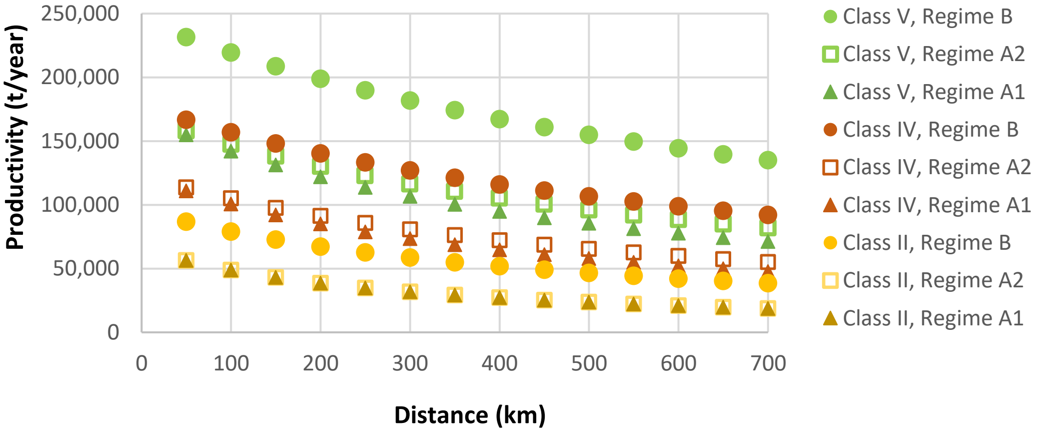


Figure 41: Reference Vessel Productivities at All Sailing Regimes

FV Productivity Change

Figure 42 and Figure 43 illustrate the productivity change of the vessels as a function of the distance travelled for each of the three sailing regimes. Just like in the short sea case study, the black vertical lines on the plots indicate the point of separation of the VT. The most noticeable commonality between the various scenarios is that the productivity of the vessels decreases as soon as they leave the VT. This is due to the fact that under their own navigational responsibilities, the vessels are restricted to an A1 sailing regime.

In both the BC and the TSC, the B regime conditions resemble the productivity changes that have been seen for the short sea vessels, with negative productivity changes. Here longer trips mean fewer trips annually, hence the number of transported tons per year decrease too. The A1/2 regimes, on the other hand, demonstrate clear productivity improvement even at very short distances. This indicates that the added waiting times created are largely outweighed by the reduction in resting times that can be sailed through.

Base Case

In the BC, vessel class II achieve the largest productivity improvements compared to the other two vessel types. For the smaller vessels, a productivity increase of up to 70 % can be expected compared to the reference vessel that operates at an A1 regime. The potential of productivity increase for larger vessels is slightly less, reaching up to 60 %. This increase in productivity for the smaller vessels is caused by different port times. The shorter port times of the smaller vessels allow for more round trips to take place.

The speed variations have different effects depending on the original operating regime of the reference vessel. While for a class V vessel at a B regime, the 2,7 km/h variation causes a change of up to 6 %, at an A1 regime the speed variation causes a productivity change of 10 %. This is caused by the longer sailing time in the VT compared to the reference vessels, which means the slower operating speeds are experienced over a longer time frame.

If a direct comparison to the continuous operations in the short sea application case is drawn, it can be seen that the productivity loss of the IWT vessels with a B regime at short distances is much smaller. This is mainly due to the fact that the inland vessels have longer port times, so relative to the short sea vessels they spend less time sailing, which means less time at slower operating speeds. Secondly, the IWT vessels experience navigation day suspensions which are not taken into consideration in the short sea case study.

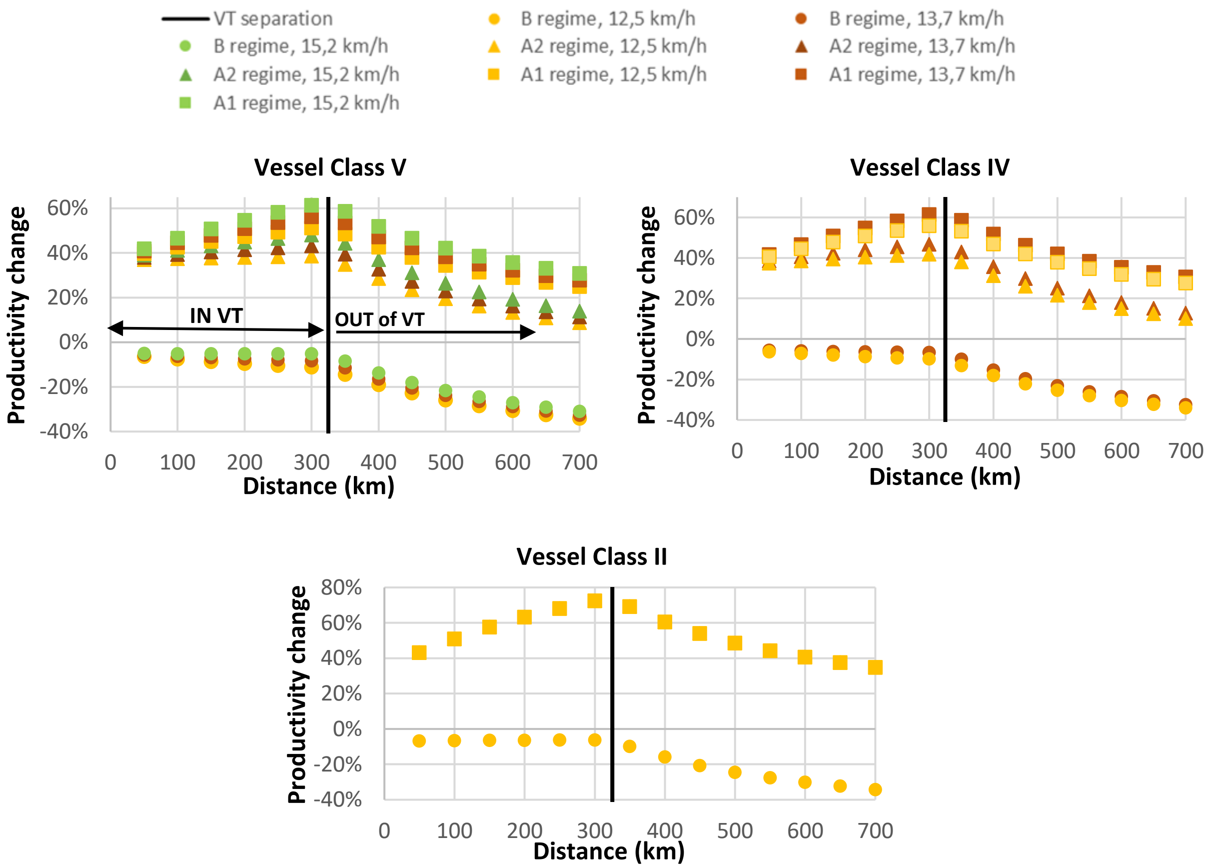


Figure 42: Productivity Change of IWT Vessels at Base Case

Transition Stage Case

The comparison between the BC and the TSC results shows a clear productivity reduction caused by the longer departure intervals. At a B regime, a reduction of productivity of around 10 % can be deduced for the vessel classes IV and V while the FV is part of the train, while for vessel class II a productivity change of close to 20 % occurs.

At first sight, the TSC the VT operating speed variations appears to have a greater impact. However, it should be kept in mind that the variation in the TSC case is 3,6 km/h while the largest speed difference in the BC is 2,7 km/h in the BC. This explains the productivity change of up to 15 % difference between the

10,1 km/h and the 13,7 km/h scenarios of class IV and V TSC compared to the maximum 10 % differences between the two extreme speeds at the BC scenarios.

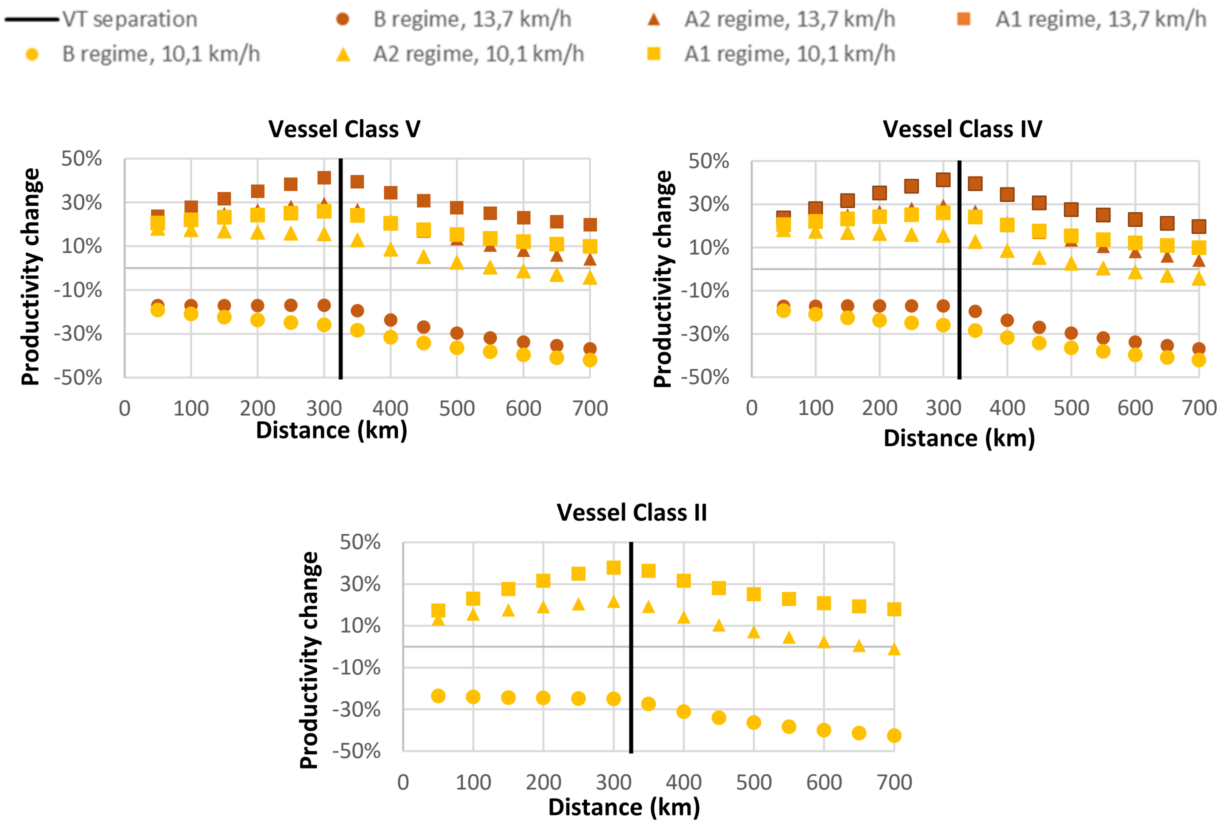


Figure 43: Productivity Change of IWT Vessels at Transition Stage Case

Savings

When moving the attention to the total annual savings achieved by the VT implementation show very different results than were previously seen by changes in productivity. The plots in Figure 44 and Figure 45 depict the FVs positive savings even when spending a large part of the operations sailing under its own navigational control, which is contrary to what was seen in the short sea application. The three operating regimes have been split into three separate plots to ensure the visibility of the data. An additional observation to be made about these results is that there are also no minimum viable distances an FV needs to spend as part of the VT. In a direct comparison between the productivity and the savings, it is noticed that once the FV leaves the VT, the savings reduce at a much steeper rate, in particular for the larger vessels than the productivity presented in the last section. This is due to the fact that the vessels are assumed to accelerate to their original operating speeds once they leave the VT. This increase in speed causes their fuel consumption to increase as well; therefore, the VT benefits diminish faster.

Base Case

The BC Figure 44 shows that the distinction between results at different operating speeds is very subtle, making up at most a difference of € 16.000 for a class V vessel or 5 % of the total FV cost savings. Compared to reference conditions in a B regime, the savings also stay consistent even at short distances, which shows the small effect created by the additional VT waiting times. The savings compared to the A1 or A2 reference conditions increase the longer the FVs stays part of the train, as the benefit of sailing through resting times are increasingly used with the lengthening of the trip.

The comparison of the three operating regimes shows that both the large crew cost savings of continuously sailing vessels and the productivity improvements creating benefits for the vessels that have small or no crew cost savings. The lower savings achieved by the A2 regimes of vessels IV and II shows that the productivity benefit of the A1 regime outweighs the small cost savings achieved by the change of existing crew members to cheaper and less-skilled crew.

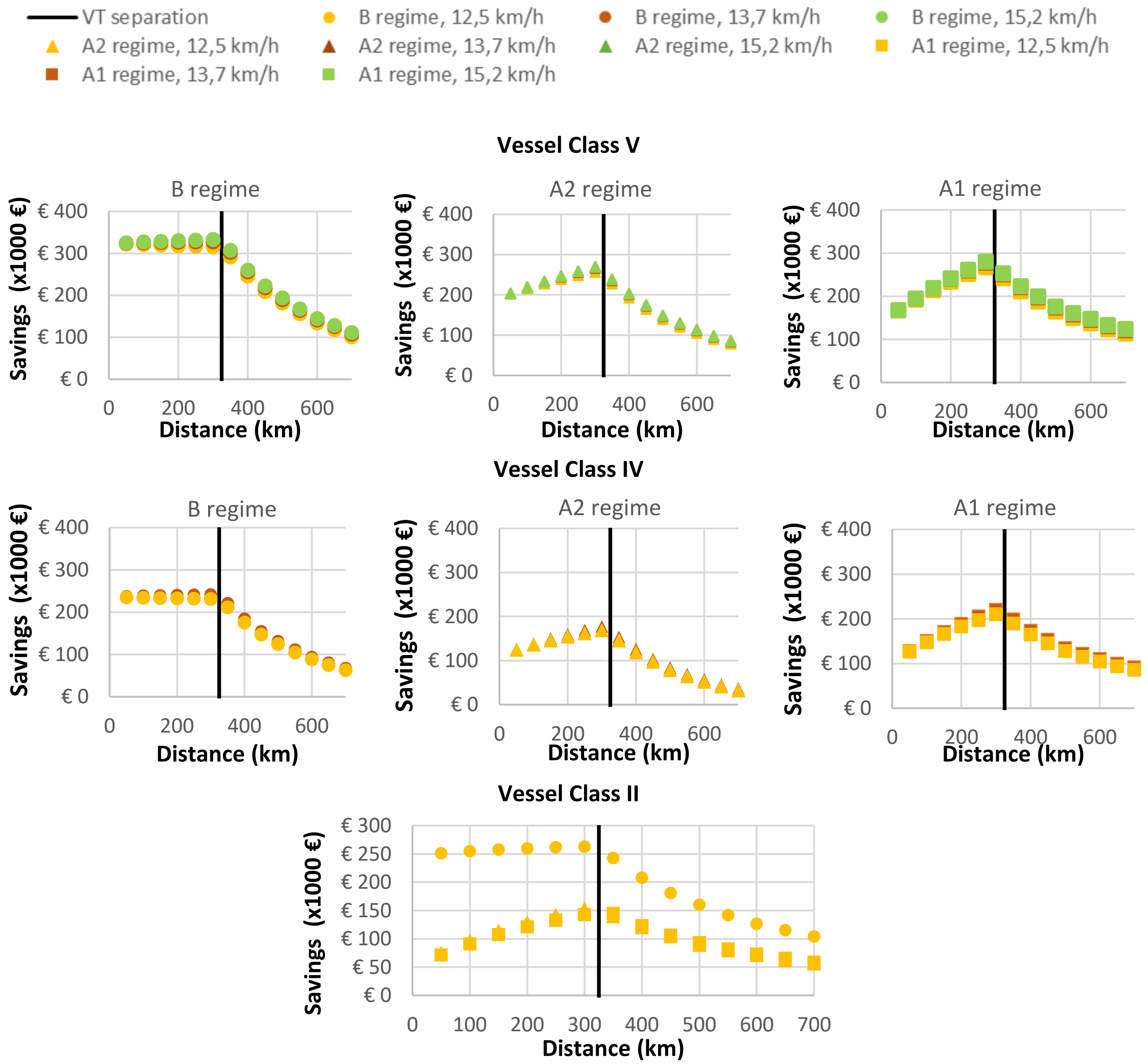


Figure 44: VT Cost Savings for the Base Case

Transition Stage Case

The TSC causes total cost saving variations between € 55.000 to € 105.000. Seeing that this can make up close to a third of the total cost savings, the changes in departure intervals in an important influence factor. Yet, it needs to be acknowledged that in all conditions sailing within the VT journey distance, positive cost savings are indeed achieved. It is only the class II vessel that, compared to an A1 operating regime that the vessel needs to ensure to spend 70 % of its annual operating distance as part of the VT to at least break even with current operating cost.

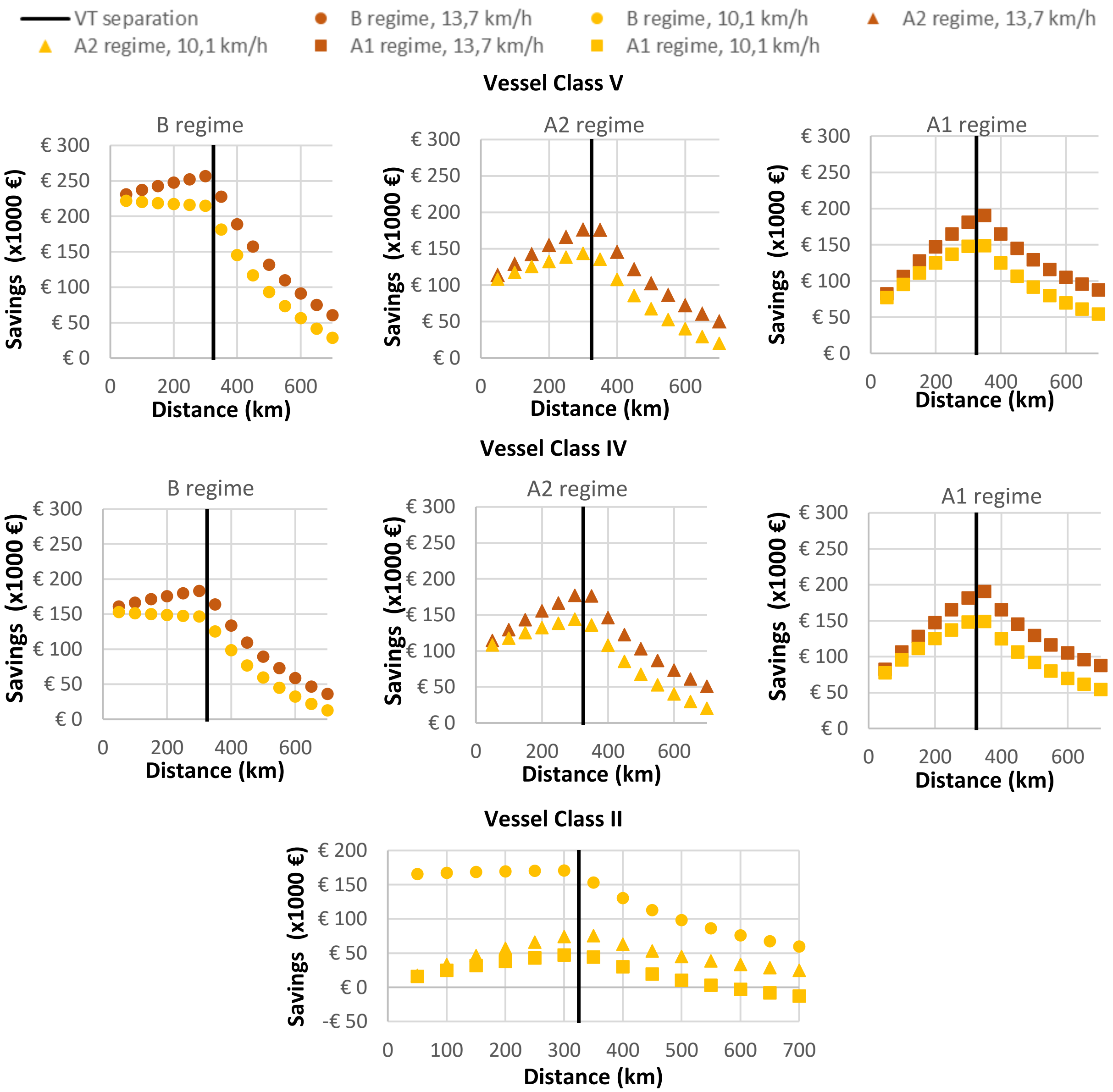


Figure 45: VT Cost Savings for the Transition Stage Case

Cost per tkm

When translating the total saving into cost per tkm, the compensation cost for the single company or the platform-based model becomes more relevant in the inland case application than they have been for the short sea application. For the TSC this results in larger VT length requirements.

The BC and the TSC provide the results that allow a comparison of the savings of the compensation costs, the resulting VT lengths and the total cost reduction achieved by the VT compared to different reference vessel operating conditions.

Base Case

The translation of the cost savings into a cost per tkm in Figure 46 shows the savings to be sufficiently large compared to all operating conditions to compensate for the cost of both the more Rhine appropriate single company model and the platform-based model. The vessel class II results show that that the cost savings for the smaller vessel compared to a B regime can be significantly larger than what is achieved by the other two vessel types.

It is thus concluded that for all vessel types, while the vessel sails in the VT, a single FV is sufficient to ensure economic viability for the VT operator. However, for vessel types IV and II, this minimum VT length increases once the FV decides to sail outside of the VT for more than 175 km and 100 km, respectively to vessel type IV and II.

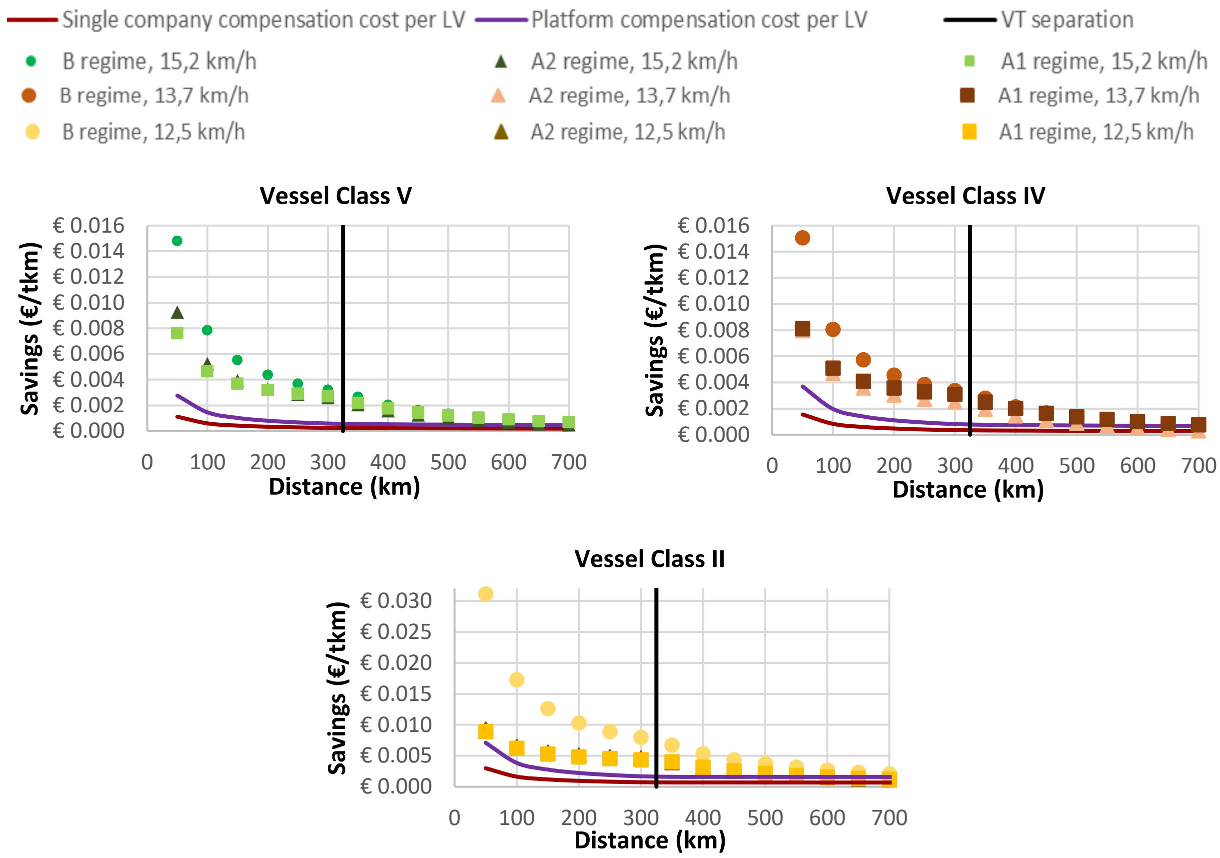


Figure 46: Comparing IWT Cost Savings to Business Model Compensation Requirements for the Base Case

Finally, the study of the cost savings has established that the variation in VT operating speed has little influence on the VT cost savings. Instead of comparing the varying effect of the VT operating speed as it was done for the short sea case, Figure 47 compares the reduced FV cost, i.e. including the cost savings, to the reference vessel transport cost at the three potential operating conditions.

The minimum and maximum percentage cost reduction achieved while sailing in the VT that can be observed from Figure 47 are summarized in Table 26. The maximum cost reduction for the reference vessel operating at B regime is taken at the shortest distance (50 km) as that is least productivity decrease ocurs, whereas that of the reference vessel operating at A1 or A2 regime is at the maximum VT trip distance (325 km) as that is where the FV experiences the greates productvity increase.

Table 26: Maximum Transport Cost Reduction Achieved by the VT Implementation for the Base Case

Operating regime	Vessel Class V		Vessel Class IV		Vessel Class II	
FV journey distance	50 km	325 km	50 km	325 km	50 km	325 km
B	39 %	34 %	37 %	34 %	50 %	47 %
A1	25 %	30 %	24 %	27 %	23 %	35 %
A2	25 %	31 %	24 %	32 %	23 %	34 %

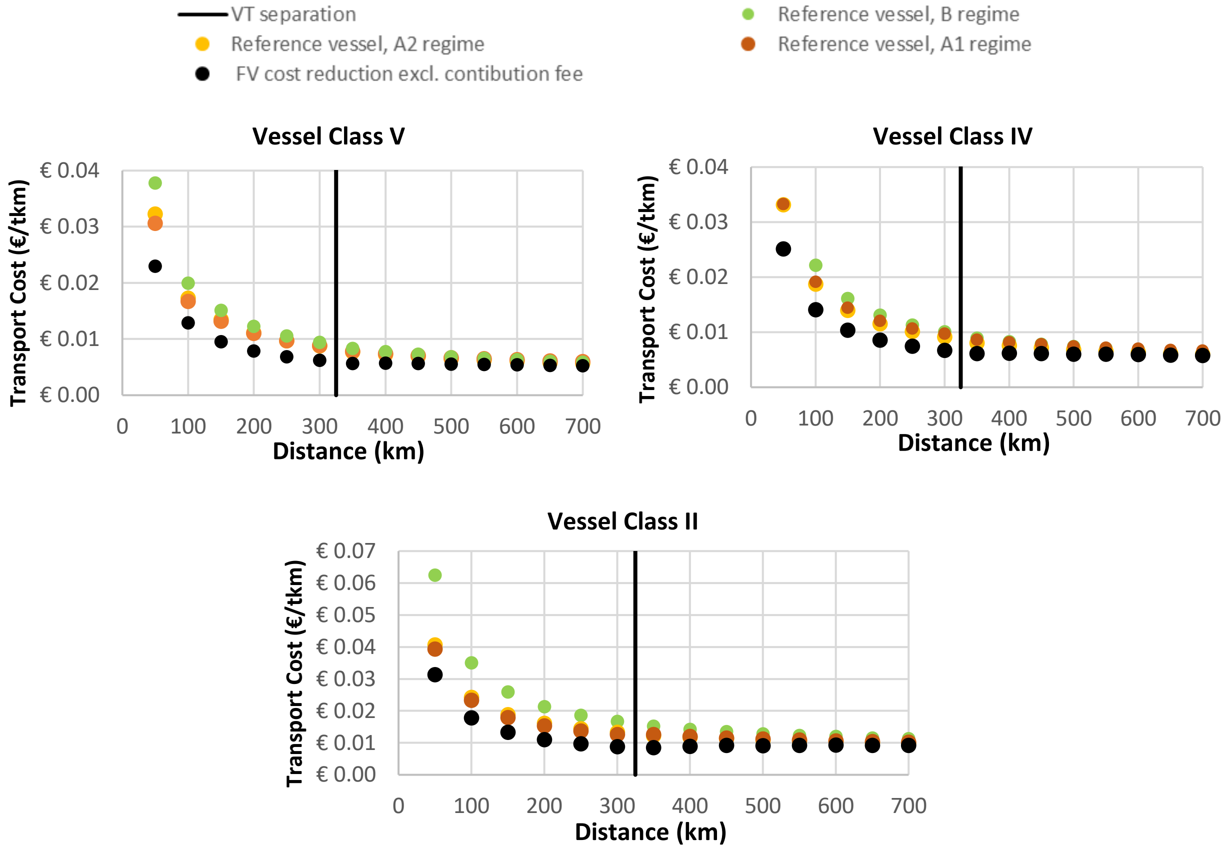


Figure 47: Comparison of the Reference Vessel Cost and Reduced FV Cost at Base Case

Transition Stage Case

The smaller cost saving achieved by the TSC brings more importance to the single company and platform-based compensation cost. Figure 48 shows that the FV savings for all conditions, but the class V B regime conditions, is smaller than the single company compensation cost requirements. The respective minimum FV requirements are plotted in Figure 49.

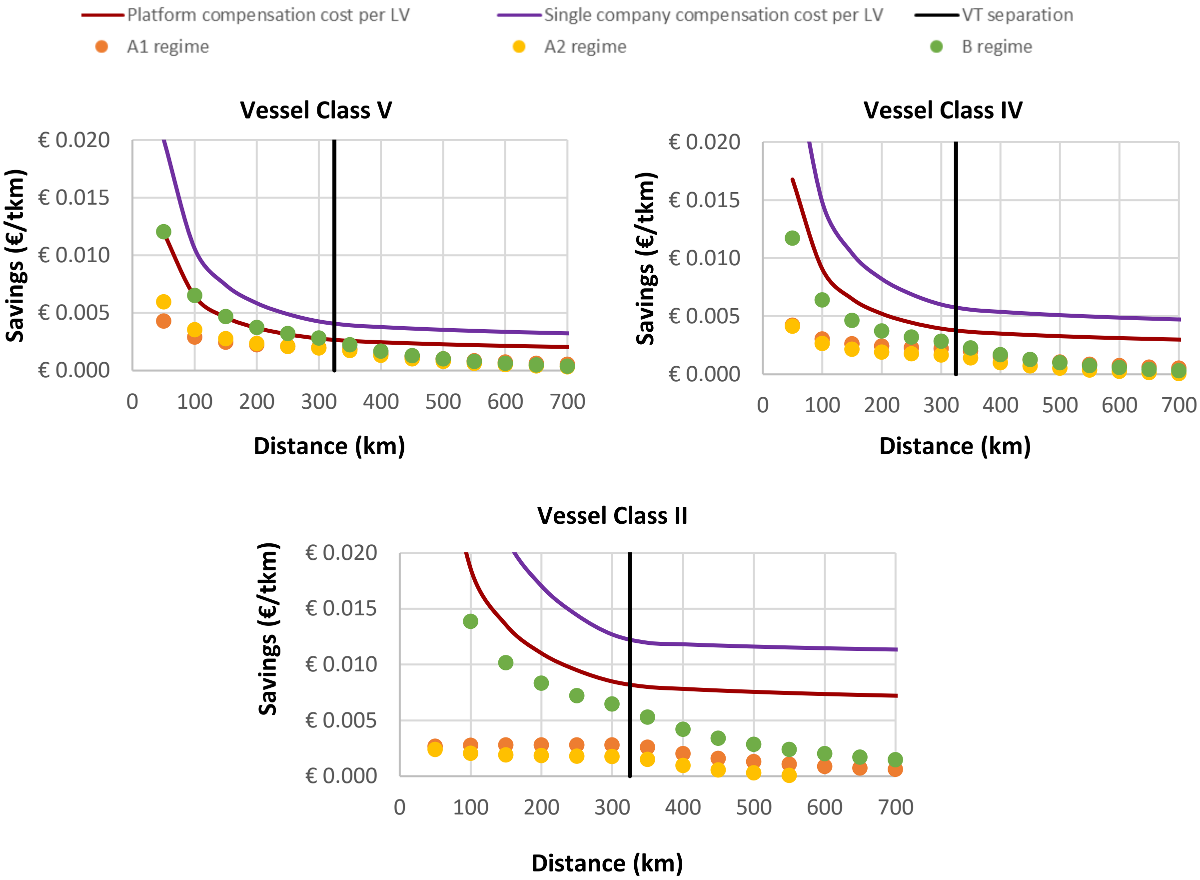
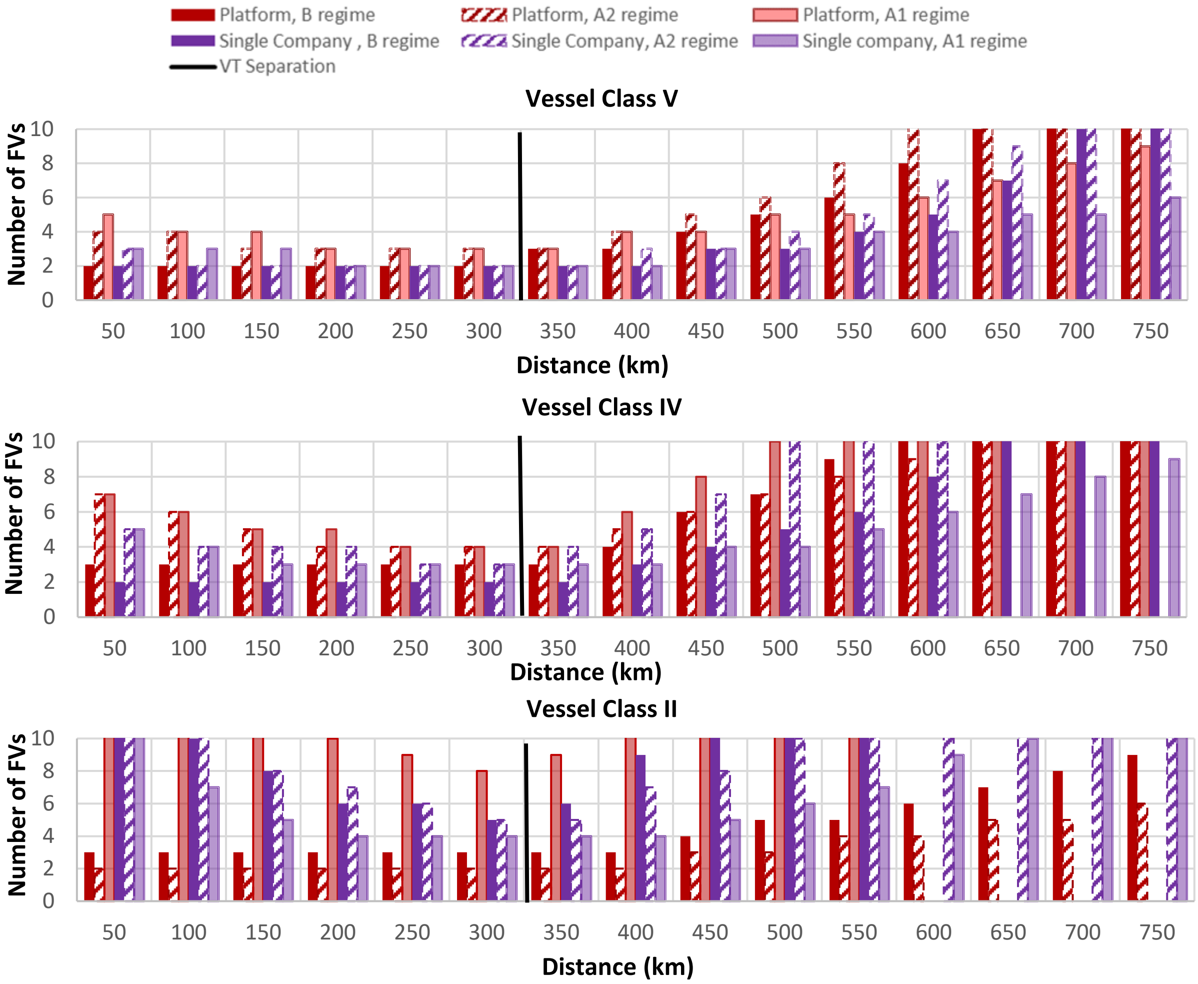


Figure 48: Comparing IWT Cost Savings to Business Model Compensation Requirements for the Transition Stage Case

If we recall the maximum technical VT length of five and use it as guide values for the plots in Figure 49, the TSC is not able to achieve viable conditions for all vessel types. The white spaces, in particular, visible for the class II vessels from an FV distance of 600 km onwards show conditions in which no costs savings are achieved anymore.

Vessel class V is viable for the entire length of the VT route, yet it surpasses the requirements of five FVs for the platform-based model, if it sails under its own navigation control for more than 175 km (54 % of the trip length). For the single company model, this is delayed to a distance of 250 km (77 % of the trip length). Class IV reach viable operating restrictions under a platform-based model and restricted reference vessel operations. There the vessel needs to at least spend 150 km in the VT and can only sail 75 km outside of the train without surpassing the technical feasibility length of five FV. The largest variation in FV requirement is experienced by vessel class II. When comparing to a B regime, the FV requirements stay consistent throughout the VT trip length. However, class II vessels are not likely to currently be operating at B operating regimes. More detailed information concerning the operation of smaller vessels, as well as smaller waterway operating restrictions, are discussed in chapter 6. Instead, in A1/ A2 regimes, the platform-based model combined are either not or exactly follow the five FV guidance for the entire route length.



Vessel Class V

Vessel Class IV

Vessel Class II

Figure 49: Minimum FV Requirement for the Transition Stage Case

The results show that the TSC does not allow stable economically viable conditions for class II vessels throughout the VT route length as both the VT and the FV operator are dependent on other participants to allow breakeven points to be achieved. This suggests that for the early-stage implementation, subsidies would be needed to make the concept attractive for a variety of users and thus ensure a sufficient number of participants.

Yet, even though the required number of FVs may cause the viability of the TSC to be questioned for the VT operator, the individual vessels are still able to achieve a transport cost reduction, as seen from Figure 50. Table 27 summarises the percentage cost reduction achieved by the TSC. The slower VT operating speed for the class II vessels caus the higher cost savings of vessel class II to diminish compared to the values presented in Table 26.

Table 27: Maximum Transport Cost Reduction Achieved by the VT for the Transition Stage Case

Operating regime	Vessel Class V		Vessel Class IV		Vessel Class II	
FV journey distance	50 km	325 km	50 km	325 km	50 km	325 km
B	33 %	32 %	30 %	30 %	41 %	40 %
A1	20 %	24 %	13 %	20 %	12 %	17 %
A2	15 %	25 %	13 %	25 %	12 %	17 %

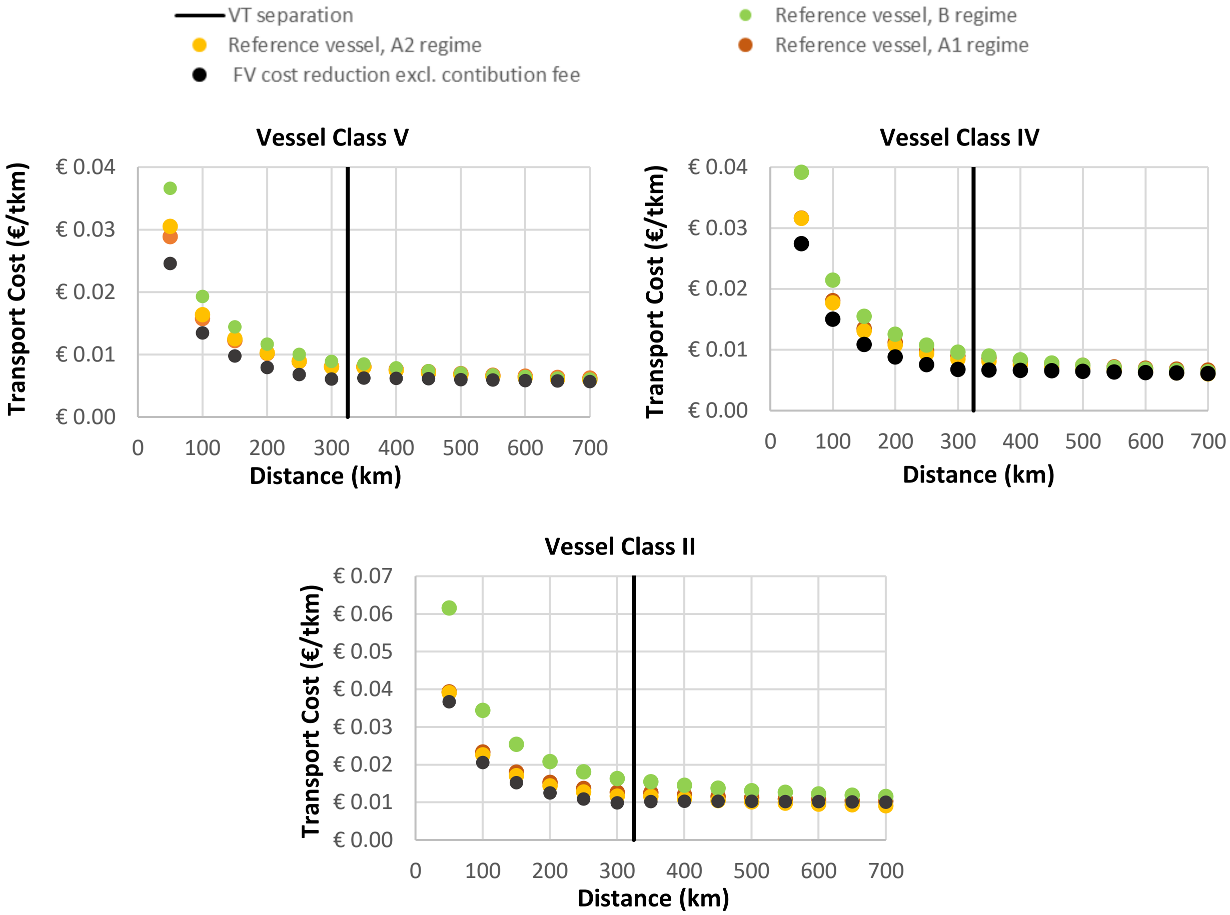


Figure 50: Comparison of the Reference Vessel Cost and Reduced FV Cost at Transition Stage Case

VT Requirements

The results discussed throughout this inland case study makes it possible to conclude a set of VT requirements that indicate the operational needs of the VT transport system. Table 28 structures the VT requirements in the same way in which it was presented in the short sea case study. The main difference lies in the fact that fewer markets are considered as the main vessel types for inland operations are dry bulk and tankers. Additionally, the VT lengths indicate in Table 28 are not restricted by the technical feasibility length of the current technological development of the VT. This means the VT lengths surpass five FVs. That way, the effects on the number of participants can be established in the worst-case scenarios.

Fleet Share Requirements

The market and fleet share estimations are based on the CCNR estimate that state it being 1.433 tankers out of which 1.111 target dangerous cargo sailing in the Rhine region. It also states that the Rhine fleet is currently composed of 6.011 dry bulk vessels, out of which 1.200 are push barges and are hence not self–propelled. This creates a total estimate of 6.344 self-propelled vessels and 5.133 if the dangerous goods carrying ones are not included [179], [180]. The information available about different vessel sizes even allows the dry bulk vessel market estimate to be calculated based on the available vessels of the given size category. This is the reason for which the dry bulk market share appears to be larger than all other market shares with up to 4,3 % of class IV vessels. Overall the fleet share requirements for a VT system between Antwerp and Duisburg requires less than 1 % of the fleet share.

As was previously discussed in the short sea case, the fleet share requirement of less than 1 % is realistic in terms of minimum required participants from the market share. However, a viable VT along the route between Antwerp and Duisburg needs to aim for a much larger market share, to truly be able to achieve a significant modal shift towards waterborne transport. Seeing the cost reductions achieved on the FVs the margins for the VT operators can become significant as long as more vessels participate than required per required fleet share.

Table 28: VT Requirements for Inland Applications

VT requirement	Stage	Vessel Class V		Vessel Class IV		Vessel Class II	
		Best	Worst	Best	Worst	Best	Worst
Distance spent in VT	TSC	NA	NA	NA	150 km	NA	300 km
Percentage time required to be spent in VT	TSC	NA	46 %	30 %	57 %	57 %	100 %
VT length	BC	1	NA	1	NA	1	NA
	TSC	2	5	2	7	2	8
Number of participants in VT transport system	BC	26	NA	26	NA	26	NA
	TSC	12	24	12	32	12	36
market share **Dry bulk***	BC	0,9 %	NA	3,5 %	NA	2,1 %	NA
	TSC	0,4 %	0,9 %	1,6 %	4,3 %	1,0 %	2,9 %
Tankers excl. dangerous goods	BC	8 %	NA	8 %	NA	8 %	NA
	TSC	4 %	7 %	4 %	10 %	4 %	11 %
Total fleet share	BC	0,4 %	NA	0,4 %	NA	0,4 %	NA
	TSC	0,2 %	0,4 %	0,2 %	0,5 %	0,2 %	0,6 %
Total fleet share (excl. dangerous goods)	BC	0,5 %	NA	0,5 %	NA	0,5 %	NA
	TSC	0,2 %	0,5 %	0,2 %	0,6 %	0,2 %	0,7 %

* market share indicated based on vessel size

5.3.4. Sensitivity Analysis of VT Influence Factors

Just like it was done for the short sea application case, the sensitivity analysis can help develop an understanding of the robustness or fragility of the identified viable operating conditions.

The difference between the BC and the TSC presented within the results is already a sensitivity analysis that varies the departure interval change and additional VT operator cost. The variation in departure intervals is explicitly studied within this sensitivity analysis to see the effect of increasing the waiting time purely. Therefore, to recapitulate observations made from the results presented, the VT operator cost increase of € 200.000 per LV is the estimated difference between a fully matured VT control system and the added monitoring crew needed for an early-stage implementation. This VT operator cost variation may also be related to an increase in VT technology cost if the current expert estimates are underestimates. The BC only requires a single FV per LV. Thereby the monitoring crew cost is to be compensated by this single FV as well, which will cause a 30 % decrease in the FV savings. Looking at the total savings of the BC that surpass € 300.000, there is a large enough savings buffer, so as not to affect the required number of participants for a single company model.

The four factors whose variation potential is analysed in this sensitivity analysis are the same as the ones varied for the short sea case: crew cost, waiting time, route length and fuel price.

Crew Cost

The crew cost variation is the most important impact factor for the inland application case. Crew cost variations can have two main reasons: Wage variations due to the role taken from board and wage variation due to geo-economic reasons. This section briefly discusses the reasons for wage variations in the Rhine case study as well as geographical variations and provides an example of the savings reductions that caused the reduction in crew cost.

The wage of a crew member is dependent on their role, amount of experience and age. The role of a boat master/captain on an inland vessel can vary by 15 %, while the lowest role of a deckman can vary up to 65 %, dependent on the age of the crew member [178]. This means that the crew cost savings vary depending on the type of person employed. When crews consist of a captain-owner and his family members, then the crew wages are usually reduced wages. In those cases, the combined labour cost of the husband-wife crew gets to be as low as € 30.000 annually [42]. This is less than half the annual crew cost assumed for two-man crews at A1 regimes. Small cost savings results in individual FVs paying a smaller contribution fee to the VT operator.

In general, it can be said that the net wages for workers employed in western Europe are relatively similar between countries [177]. This is not the case for workers in other parts of Europe. For instance, Czech inland crew members earn about 15 % less than his/her western European counterpart, whereas crew wages obtained from Serbian vessel owners suggest differences of up to 80 %. More details are provided in the geographical area assessment of chapter 6.

Knowing this variation range, the sensitivity analysis looks at the effect of a crew cost that is 20 %, 50 % and 70 % of the crew cost used in the Rhine case study. Compared to a B reference vessel regime, the savings reduce by € 112.000 (33 %), € 185.000 (55 %) and € 294.000 (88 %) respective to the three cost variations. Purely the crew cost reduction can thus thin the buffer of savings that is created in the original Rhine crew cost, down to about € 40.000. While this is still sufficient to cover the single company compensation cost, for a platform based cost, the required number of FVs per LV surpass the guide value of five.

The comparison to the A1 reference vessel regime is influenced very differently. This is due to the absence of crew cost savings. Here the crew cost is mainly used as part of the operating cost of the reference vessel to determine the maximum allowed FV cost. Since in those conditions, the main benefit is achieved by the productivity increase, the saving reduction caused by an 80 % crew cost reduction is € 25.000 (10 %).

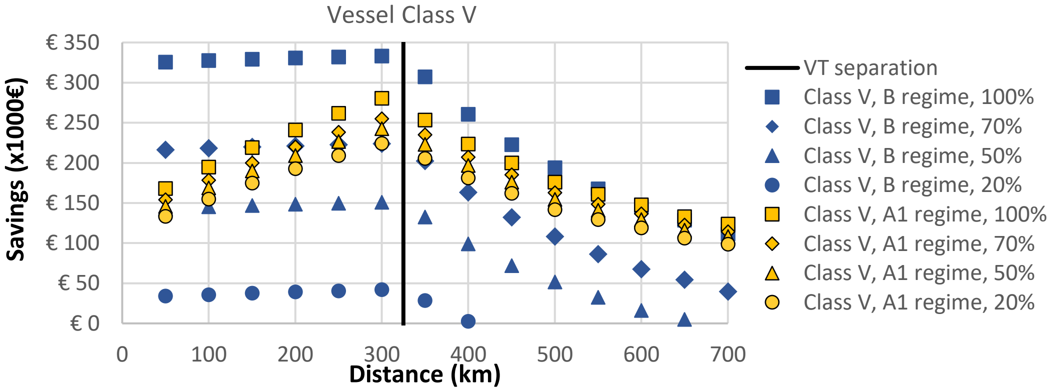


Figure 51: Effects of Crew Cost Variation on a Class V Vessel

Waiting Time

Even though the variation of departure interval and thus waiting time has already been performed in the results by setting the BC and the TSC, Figure 52 provides additional insight into the sensitivity. It demonstrates an operation window of 10 h between 47 h waiting time and 57 h waiting time in which, dependent on the amount of time the FV sails in the train the FV viability can diminish. As a point of comparison, this window is five times greater than the two-hour time frame between the plot values of 100 km 500 km in the short sea case of Figure 31.

The maximum waiting time of 50 h reflects a huge productivity loss in particular for the shortest distances, where the journey time is ten times faster than the waiting time. However, given the large crew cost savings that make up close to 60 % of the reference vessel cost, such a productivity loss can theoretically be outweighed by the savings. This does not vary between the distances; compared to the B reference regime the savings achieved no matter what distance is sailed. That being said, practically, it is highly unlikely that an FV operator would wait for 50 h long for a train to depart; additionally, if the logistics cost that are added, this maximum allowed waiting time also shortens.

If the LV compensation cost for the platform-based business model and the VT length of five FVs is taken into consideration this waiting time reduces from 47 h to 34 h for the B regime at 100 km. The compensation cost per LV risen with increasing waiting times until it plateaus, as fewer LVs are needed in the liner service. Ultimately a single LV can service the route, which means all the shore-based cost needs to be compensated through this one vessel. The 500 km result is an operating condition in which the FV sails independently outside of the VT for 175 km. This explains why the maximum waiting time is below that of the short distance of 100 km in the VT. The more time the FVs are sailing under their own navigational control, the shorted the viable waiting time becomes.

If these waiting times are compared to a reference condition that operates at an A1 regime, the maximum waiting time reduces down to 30 h for the 100 km distance as the crew cost savings drop from € 389.100 to € 99.700 for the class V vessel. If the compensation cost and VT length of five are considered, the waiting time reduces down to 22 h, which is the TSC departure interval assessed as part of the case study. The 500 km distance still achieves more savings than the 100 km, even though the vessel spends part of its time sailing outside of the train on its own. It is to be expected that the maximum allowed waiting time for the class IV and II vessels are much lower than the waiting time identified for the class V vessel.

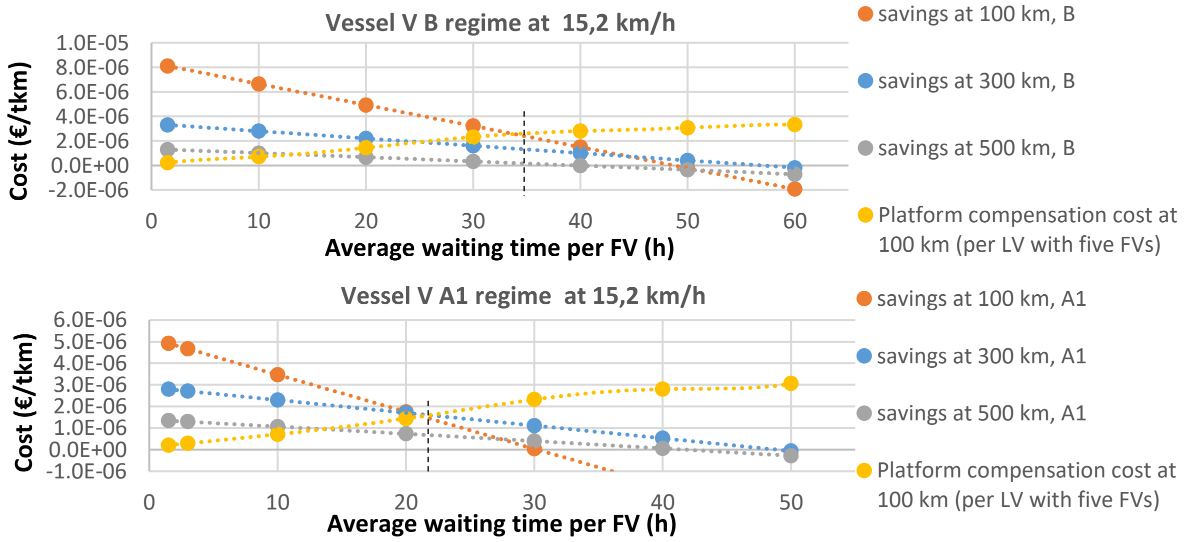


Figure 52: Waiting Time Variation for Vessel Class V

Route Length

Increasing the VT route length to 707 km allows he LVs to operate at 15,2 km/h without created additional waiting times for the LVs around the liner round trip. Figure 53 shows that the variation in route length does not have an effect on the conditions compared to the B regime. The savings achieved at the end of the lengthened route reach equivalent savings to conditions that compare to the continuously operating reference vessel. This means that while up to ~700 km it is favourable for the reference vessel to have operated in a B operating regime. Past a trip length of 700 km the productivity improvements become the predominant benefit in creating savings. If a comparison on a cost per tkm basis is made, this increase in VT route length compared to a reference vessel operating at an A1 operating regime allows the FV to achieve an additional 16 % savings. Translating the values of the increase in length to a cost per tkm results in an increased savings of 9 % compare compared to a B regime and 35 % compared to the A1 regime.

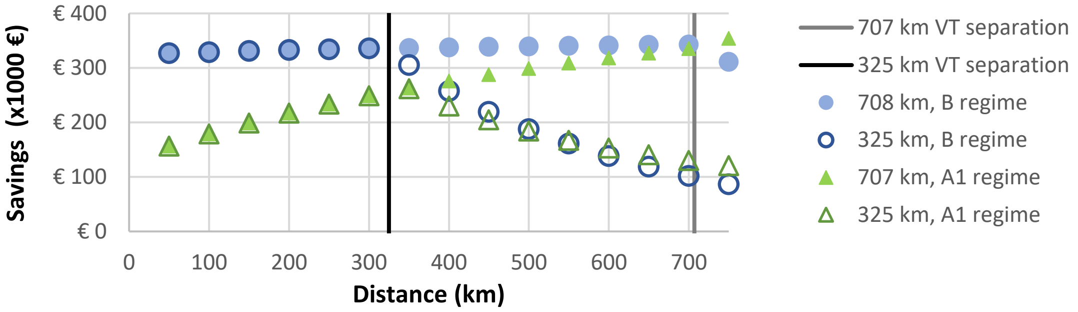


Figure 53: VT Route Length Variation Vessel Class V

Fuel Price

As seen in Figure 40 of the sensitivity analysis of the short sea case study, the fuel cost and thus the fuel price plays a vital role in the viability of the VT. To illustrate the difference between the two application sectors this same parameter assessment is also performed for the IWT case. Figure 54 illustrates the effects of fuel price fluctuations compared to a vessel operating under B and A1 regimes. The fuel cost reduction causes the B regime to suffer a savings decrease the longer the FV stays part of the VT. This is caused by the fuel cost savings created by the slower VT operating speeds. Compared to the B regime a 12 % increase in fuel price causes 0,5 % increase in savings, while the 60% decrease in fuel price causes a savings decrease of 2,6 %. The A1 regime influences the saving changes by 0,6 % and 2,1 %, respectively to the increase and decrease of fuel price.

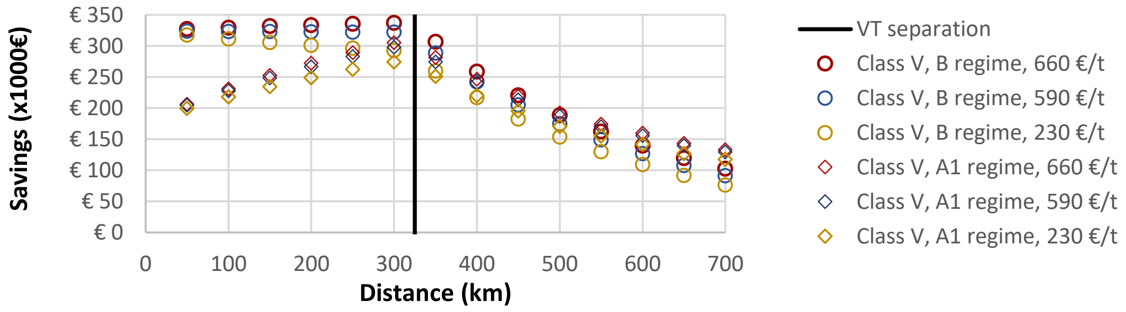


Figure 54: Effect of Fuel Price Variation on Class V Vessel

Summary

In order to compare the effects of individual parameter changes, Table 29 summarizes each variation compared to the BC condition. This means, for instance, the 18 h increase in departure interval from 6 h to 24 h, is a 300 % increase in time variation. Knowing the effect of the percentage variation on the savings, the percentage saving change per 1 % parameter variation can be deduced. This summary of the sensitivity analysis concludes that compared to a reference vessel at a B regime, the crew cost is by far the most important influence factor. This is followed by operating speed, the departure interval and the VT operator compensation cost, that dependent on the maturity of the VT technology or the business model applies. The fuel price is in fourth place, just before the route length that have a small effect on the end savings.

This order of parameter relevance changes when considering a reference vessel that operates at an A1 regime. As in these conditions, the benefit is on the productivity increase achieved, it is also not surprising that the route length becomes the most influential factor. The crew cost the second most important factor, followed by the VT operator cost. The departure interval is at fourth place and once again the fuel price fluctuations has the least effect.

Table 29: Comparison of Sensitivity Analysis Results for the Inland Application Case

Parameters	**Variation**	**Effect on Vessel Class V savings (€/tkm)**		**Savings changes per 1 % variation**	
	from BC	**B**	**A1**	**B**	**A1**
Crew cost	- 50 %	- 55 %	- 8 %	- 1,10 %	-0,16 %
Departure interval	300 %	- 30 %	- 26 %	- 0,10 %	- 0,09 %
Route length	117 %	0,04 %	35 %	<0,01 %	0,30 %
Fuel price	- 60 %	- 2,6 %	- 2,1 %	- 0,04 %	- 0,03 %
VT operator cost	407 %	30 %	48 %	0,07 %	0,12 %

5.3.5. Integrating Other Stakeholders

This section adds the perspectives of the society and the cargo owner on the VT implementation. It serves as an indicator to gauge whether third party perspectives would be willing to accept the VT concept implementation.

Society – Emissions

The sample IWT emission cost presented in Figure 55 show the same trend as was previously seen in Figure 36 the main difference being that the reference vessel emission cost for the short sea vessel I is 52 % higher than that of the IWT vessel. Additionally, the short sea vessel I FVs achieve up to 67 % emission cost reduction compared to the reference vessels while the IWT that have a smaller decrease in operating speed only achieve up to 38 % emission cost reduction.

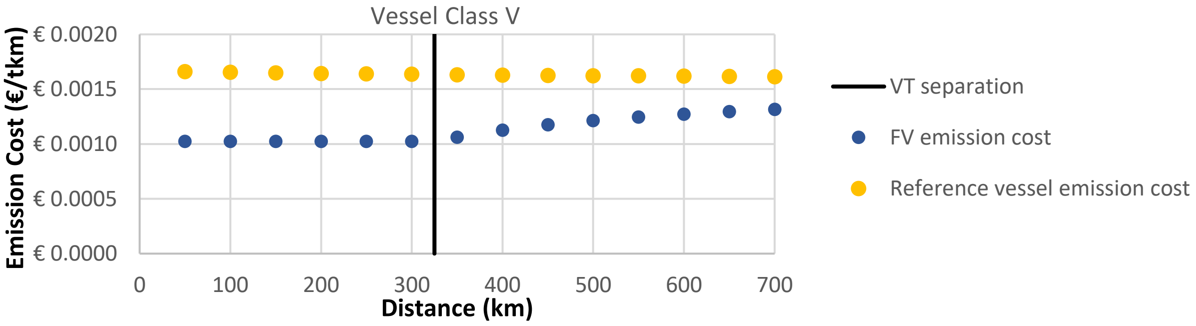


Figure 55: Example Emission Cost for Class V Vessel

Figure 56 visualizes how the internalization of emission cost increases the transport cost. Here the internalization only minimally adds to the cost savings created by the VT. A class V vessel achieves an additional 1 % savings, a class IV vessel <1% and a class II vessel up to 2 %. These additions are created by the small speed decreases in the VT operations that ensure the LVs do not experience waiting times. Therefore, the impact to reduce societal cost through the implementation of the VT in the inland sector is minimal.

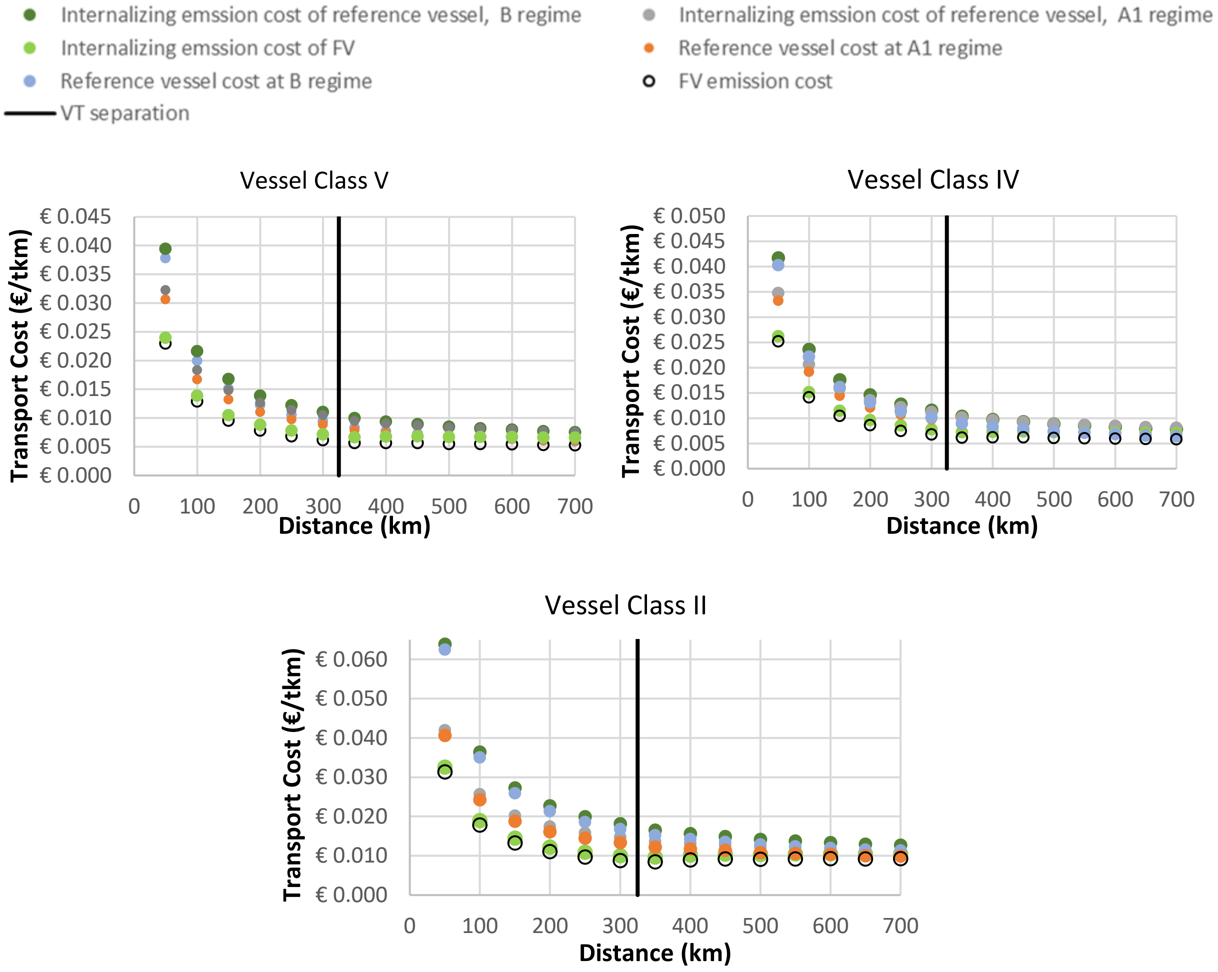


Figure 56: Internalising Emission Cost

Cargo Owners - Considering Stock in Transit and Safety Stock

The final step in the inland case study assessment is to now also look at the changes in cargo-related cost created by the VT. Figure 57 incorporates both the additional cargo-related cost created by the VT operations on the primary left x-axis, as well as its relative increase in cargo cost on the secondary axis. This plot is only provided for vessel V as it represents the general trend for all three of the vessel classes. Instead, Table 30 summarizes the FV cost reduction, including the VT related logistics cost. Compared to a reference vessel sailing at a B regime the cargo cost increases as seen in the light blue dots while for the A1 regime the percentage cargo cost decreases compared to the reference vessel by up to 6 %. Another noticeable difference here in comparison to the short sea case is that there are still clear cost benefits visible even after including the logistics cost.

The comparison of the FV and the reference vessel cost, including cargo-related cost show that even under a B regime that suffers a loss in productivity, a clear total logistics cost reduction can be identified for the FVs. Even considering the cargo cost the differences are as high as 0,015 €/tkm (25 %), 0,014 €/tkm (25 %) and 0,030 €/tkm (40 %) for vessel classes V, IV and II at the shortest distances. These are 20 %, 14 %

and 26 % lower than the maximum cost reductions identified in Table 26. The transport cost difference including cargo cost lowers down to 0,003 €/tkm (22 %), 0,002 €/tkm (22 %) and 0,006 €/tkm (39 %) if the FV stays part of the VT for the entire journey length.

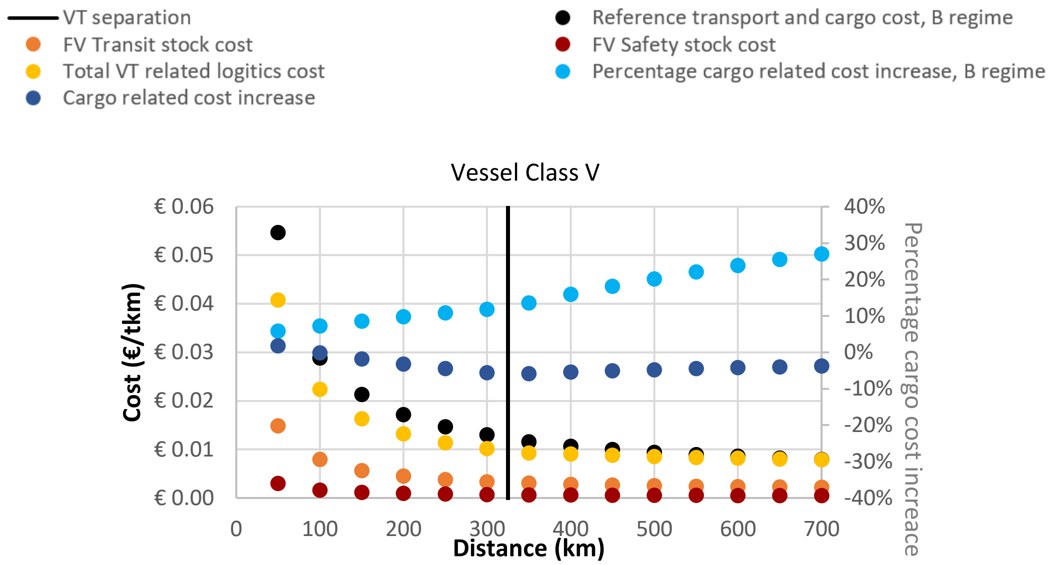


Figure 57: Effect of the VT Operations on Cargo-Related Cost

Table 30: FV cost reduction incl. VT related logistics cost

Ref. vessel sailing regime	B regime		A1 regime	
Journey distance	50 km	325 km	50 km	345 km
Vessel V	25 %	22 %	15 %	23 %
Vessel IV	25 %	22 %	15 %	24 %
Vessel II	40 %	39 %	17 %	31 %

5.3.6. Discussion on the Viability of IWT Application

This case study has shown a much more reliable application case for the inland sector than it has for the short sea sector. In the inland case either the crew cost reduction can make a significant impact or the increase in productivity of the vessels does. In either case, no matter what the reference vessel operating regime, economically viable conditions are achieved by all vessel types. Even the required number of vessel participants to ensure viable operations for both the VT user and the VT operator makes up <1 % of the total Rhine fleet share. If only specific markets are considered up to 10 % of for instance, the tanker market excluding dangerous goods would be required. That being said if larger vessel size are combined with smaller ones this market share would also reduce.

The comparison to the early-stage transition scenario (TSC) did show a reduction in achievable savings. However, contrary to what was observed in the short sea case study, the savings always outweigh the cost of the VT operations. The smaller savings of FVs in the TSC does favour that the single company business model. This is, in particular, the case for class II vessels whose viability may be jeopardised by the fact that the minimum VT length could become longer than technically desired by the VT operation. Therefore, in the early stage of the VT implementation, it should be considered to encourage smaller vessel operators to use the VT by providing subsidies until the VT technology is fully matured and no longer requires a monitoring crew on board.

The sensitivity analysis has also shown that depending on how the main benefit is created, by a cost reduction or a productivity improvement, the effect of influence factors changes, thus answering the sub-question 4 formulated in chapter 1, from the perspective of the inland navigation sector. When the main benefit is achieved by the crew size reduction compared to a B regime, the crew cost is clearly, the most important factor. On the other hand, if the benefit is created by an increase of productivity compared to an A1 or A2 regime the most important factor to consider becomes the route length. This answers the sub-question 4 presented in chapter 1 that sought to identify how the variations of VT properties influence its performance for the inland application.

It is not possible to make an accurate estimate of the number of vessels that will achieve different cost reductions based on their current operating regime, as there is no publically available data that indicates the current operating regimes of vessels. However, given that the majority of vessel operators along the Rhine are small captain-owned companies, there is a high chance that along the Rhine, the productivity-related impact factors play a more important role.

Adding the perspectives of society and cargo owners have both shown additional benefits created by the VT. The smaller operating difference between conventional and VT operations mean that there is close to no societal benefit created by the adjustment of operations alone. While in the short sea sector the emission cost reduction can be as high as 0,0026 €/tkm for the large and fast vessel, the inland sector the smaller VT operation variations cause at most a societal benefit of $1{,}59 \times 10^{-4}$ €/tkm, which is a cost savings improvement of at most 2 % achieved by a class II vessel.

The improvement in productivity created for current operators at an A1/2 regime provides cargo owners with logistics cost savings of up to 0,04 €/tkm for a class II vessel, while compared to a B regime the cargo owners the logistics cost will increase by up to 0,001 €/tkm for a class V vessel. The achievable cost savings including logistics cost reach between 15 % - 25 % for a class V & IV vessel and 17 % - 40 % for a class II vessel. These results lead to conclude that along the lower Rhine, which not only has high traffic densities but also high wages, the VT can indeed create economically viable conditions for both the VT user and operator. Even under conditions where additional monitoring crew is needed the economically viable operations are identified for the majority of the 325 km route. It is only for smaller class II vessels that the economically viable VT length requires more then 1 km length.

This chapter has majorly contributed to the overall research question as it has identified viable operating conditions in the short sea and inland sector in Europe. The next chapter emphasizes how a variation in geographical location influences several different factors simultaneously and can change the inland application case compare to the positive case that is concluded from this case looking at the lower Rhine corridor.

CHAPTER 6:
IMPACT OF THE GEOGRAPHICAL AND SPATIAL CONTEXT ON THE VT VIABILITY

The sensitivity analysis of chapter 5 has provided an understanding how several important factors affect the viability of the VT for a short sea application and an inland shipping application, both of which are set in western Europe. It is, however, important to study the effects of a changing geographical environment on the viability of the VT concept in order to judge the broader applicability of the concept. This section is devoted to studying the geographical and spatial context in which the VT are operating and through it answers sub-questions 4 and 5 introduced in chapter 1. The focus in this section is only placed on the IWT sector, as that has shown in chapter 5 to have the most promising business solution and application potential. For the short sea case, it was shown that even in favourable conditions, viability is hard to achieve.

This chapter is split into three main focus points to study different aspects of the spatial context. First, to provide a detailed overview of the impact factors that change when implementing the VT in different geographical areas, a comparison is made between the Rhine application case that was studied in chapter 5 and the Danube corridor. It also identifies the changes in boundary conditions needed to ensure a viable VT application in these different environments. Second, one of the VT's aims is to improve the attractiveness of smaller inland vessels. To do so, it needs to be ensured that the VT can be implemented in urban areas and on smaller waterways. Therefore, this chapter describes a case that studies the benefits and needs that occur when the VT needs to pass bridges that have to be opened, which will happen commonly for VTs that need to penetrate urban areas. The final point of focus is placed on commenting on the global application potential of the VT concept by providing an overview of the inland navigation sector.

The structure of the chapter follows the three main focal points. Section 6.1 presents the comparison between geographical conditions on the basis of a detailed case study analysis of the Danube corridor. Section 6.2 addresses the penetration of urban areas with the VT with a particular focus on smaller CEMT class II vessels. Section 6.3 is a literature overview that demonstrates the global VT suitability of different IWT sectors. The section finishes with a summary of the main application area conclusions in section 6.4.

6.1. Comparing the Danube and the Rhine Corridor

Research performed since the end of the Cold War has identified the rift that the era has caused the development of the transportation sector, such as discussed by Hall [181]. A clear difference between wages in Rhine and Danube countries can still be identified today in both the inland waterway cruise sector [182], and in the freight transport sector [177]. Furthermore, historical differences have caused the business structure and types of vessels used for waterborne freight transport to develop differently in the South-eastern European inland corridors and the Central European which is also reflected in varying traffic densities and cargo volumes.
Figure 58 maps out where the Danube and the Rhine corridor are located. The research focus in this section is to demonstrate to what extent the VT's implementation needs can be met in different geographical areas. It follows upon the results presented in the inland case study of chapter 5, by adding environmental factors and emphasizing geo-economic condition adaptations for the VT concept. This section starts by examining the geographical and geo-economic impact factors affecting the implementation of the VT by creating a direct comparison of these factors between the Rhine and Danube navigation corridors. Then the method presented in chapter 4 is applied to a Danube case study to illustrate the difference in viability requirements of the VT implementation in these changed conditions.

Figure 58: Map of the Rhine and Danube Corridors

6.1.1. Corridor Differences

This section describes geographical influence factor differences between the Danube and Rhine corridor that are relevant for the viability of the VT. The effects of some of these factors have already been studied in chapter 5. However, by creating a detailed comparison between the two corridors the magnitude of the possible application area differences for the factors is studied. This gives a better understanding on the extent of the savings achieved even when several influence factors are changes simultaneously.

Crew Requirements and Wages

Crew requirements and wages have already been mentioned as an important factor at numerous points throughout this thesis. With regards to crew numbers, no minimum crewing differences are identified between the self-propelled vessel guidelines of the UNECE Resolution No. 61 [183] used by the Danube countries and the CCNR guidelines [104] used by the Rhine countries.

An important crew-related difference that the two regions present is the type of employee. On small family-owned vessels on the Rhine, most of the employees are family members. At times, an external crew member is hired to allow operation at an enhanced operating regime. On the Danube, the employees tend to be mobile workers, whose stay on the vessel is temporary. In either case, there currently is a shortage of skilled workers on inland vessels [184]. On the Rhine, the average age of qualified captains is rising, causing a lack of young, highly skilled boat masters that could take over small family businesses [185]. While on the Danube, the mobile workforce increasingly leaves for employment in the Rhine region to obtain higher wages [177].

There are no official numbers available to indicate the number of vessels operating at any of the respective sailing regimes. However, based on the business structure, the following assumptions are made:

1) Large companies on the Danube are likely to operate their larger class vessels continuously, as that would make most effective use of their vessels.
2) Smaller family-owned vessels (up to class IV) are likely to operate at A1 or A2 regime as that would allow a couple to operate the vessel on their own (class I & II) or with their children (class III & IV).
3) Larger family-owned Rhine vessels are expected to hire mobile workers and hence operate at a B regime.

Figure 59 illustrates the difference in wages between the Rhine and Danube countries. The personnel costs from the Danube countries are approximately 80 % lower than what can be found along the Rhine. It was acquired from an interview with the representative for water transport in Serbia's Center for traffic accidents investigation that personnel in those low-income countries usually do receive additional income through additional payments such as € 25 per day for international travel. The annual cost per person that are provided here are averages across all roles. The crew cost can vary significantly between roles, which has an effect on the VT savings. Given this data, it is expected that the benefits achieved by the VT in the Danube corridor are significantly smaller. This means that more participants will be required per VT than on the Rhine in order to cover the costs of the lead vessel.

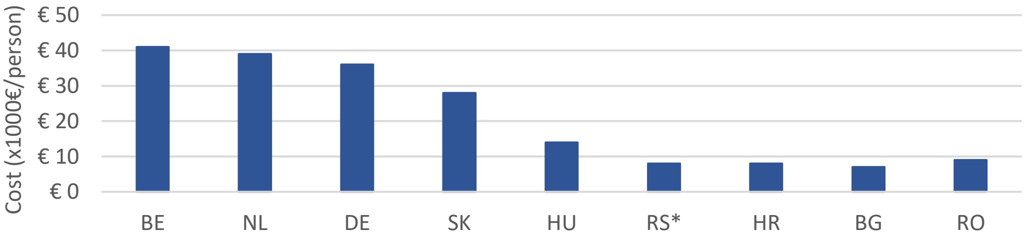


Figure 59: Average Annual Personnel Cost per Person (2016)

Source: 1) [173] 2) *[240] statistical Office of the Republic of Serbia 2019

Cargo Volume and Fleet Composition

Two other closely related influence factors, which have so far directly been addressed by the business model described in chapter 3 and indirectly been touched upon via the fleet share calculations in chapter 5, are the cargo volume and the fleet composition. The Rhine has by far the largest cargo volume transported along its length with about 186 million tons in 2017. Only about 10 % of the European inland waterway transport, 39 million tons (2017), goes via the Danube [185].

The flows of goods on the Rhine are both regional and international. On the Danube, however, most of the goods are moved internationally up the river. As can be seen from Table 31, only Romania makes significant use of the river to move goods nationally.

As explained in chapter 3, the development of the VT concept currently targets only self-propelled vessels, even though a significant number of inland vessels are barge convoys. The active fleet size on a corridor can be estimated using the records of numbers of ships entering ports and locks [185]. The Danube fleet is estimated to be composed of approximately 2.700 vessels and barges [186]. In contrast, the Rhine fleet is composed of about 8.200 vessels and barges [8]. Figure 60 shows the distribution of the different types of vessels used. The large operators on the Danube mainly ship dry bulk on long-term contracts and often make use of barge convoys. Smaller companies are left serving the niche markets and short-term contracts [187]. Only around 480 vessels, 18% of the fleet, are self-propelled. This share gradually increases as the barges get decommissioned and are replaced by second-hand self-propelled Rhine vessels [105].

The Rhine fleet composition contrasts that of the Danube, as there about 78 % of the vessels are self-propelled, 6.344 vessels or 5.133 when excluding dangerous goods vessels [179], [180]. Additionally, the liquid cargo market is significantly larger. The 17 million tons of container goods moved in 2017 make up a fairly small segment of the market, however one that holds a lot of potentials to be able to compete with other modes of transport [173].

The cargo volume and fleet composition are on the one hand, used to determine the required fleet share as was already deduced in chapter 5. Comparing the fleet composition to the cargo volume transported can also provide an indication of the number of vessel passages. These vessel passages can be used to determine whether the transport volume supplied by the VT along a specific route fits realistically and does not surpass the demand. While the research performed in this thesis does not use a transport cargo flow model, it is important to acknowledge that these cargo flows are vital to identify a realistic implementation of the concept [188].

Table 31: Quantity of Goods Transported (x1.000 t)

Source : [241]

Countries	Import/Export	National
RO	10.399	14.697
BG	2.876	1.695
RS	6.128	862
HR	453	0
HU	2.072	200
SK	1.879	36
AT	6.276	609

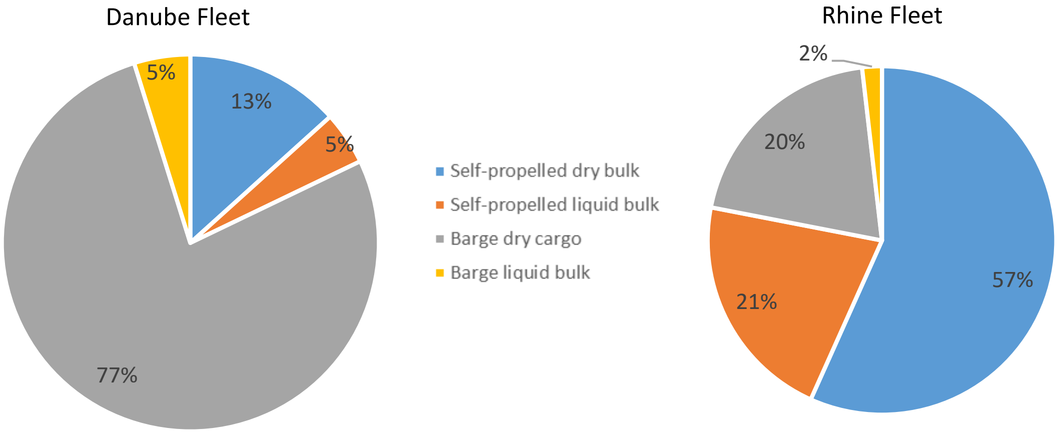


Figure 60: Fleet Composition of Self-Propelled Vessels and Barges

Source: 1) Danube fleet: [186] 2) Rhine fleet: [8]

Geographical and Environmental Factor

Differences in nautical standards in the respective corridors have had an effect on waterborne transportation efficiency. The Rhine has been a regulated waterway for a long time, ensuring it meets the needs of the IWT sector. It has only been in recent years that investment has been pushed into the Danube region so that it can comply with 2013 regulations on aspects such as waterway dimensions, minimum draught and bridge height requirements. This compliance is not expected to be met until 2030 [189].

River Dimensions and Tributaries

The Danube has 2415 km of navigable length and it is 2,7 times longer than the navigable stretch of the Rhine that spans over 885 km. As was mentioned in chapter 3, the mean transport distance of goods on the Danube is 600 km, whereas that on the Rhine is only about 200 km [106]. The Rhine has many river tributaries, such as the Aare, the Main or the Mosel (Figure 58) and its estuary spreads through the entirety of the Netherlands, linking to a great number of canals. All these waterways run through a densely populated (average 250 people/km^2) and a very well developed region of Europe. These conditions make it possible for cargo to reach economically relevant locations and even facilitate door-to-door delivery for some industrial plants in Belgium and the Netherlands [190]. This causes both regional and international waterway transport to thrive.

The situation on the Danube differs; while the main river arm transports large quantities of goods, there are only a few tributaries of the river. The river arms that do exist such as the Sava, the Tisa or the Prut can only accommodate smaller vessel classes. The average population density around the Danube lies at 140 people/km^2 [190]. The relatively low population density compared to the Rhine means that the cargo destinations are more spread out and not necessarily located near the river; therefore confining the transport access to specific regional areas and relying on extensive pre and end-haulage by road to get goods to a variety of locations [106]. This makes it challenging to compete with other modes of transport regionally and causes the main cargo movement to be international over longer distances.

Even though Danube has favourable VT conditions due to its length, the high population density around the Rhine and its tributaries create a greater amount of waterborne traffic density, which can help to create better VT implementation conditions.

Locks

Locks are an essential infrastructure to allow navigation on the upper stretches of the rivers, but also a means to keep an overview of the fleet size and cargo volumes via the lock records. The Danube has 16 locks in the stretch up to Györ, Hungary. Most of them have standard European dimensions of 230 m by 24 m, even though there are a few smaller ones upriver in Germany. On the central Danube, there are the power plant Iron Gate locks, between Serbia and Romania with dimensions of 310 m by 34 m, after which the river flows freely into the Black Sea. Lastly, to reach the port of Constanta, ships have to take the Danube-Black Sea Canal, which has two larger locks with larger dimensions.

Seeing the cargo flows provided in Table 38, it can be expected that the VT route passes by at least the Iron Gates locks, with a capacity of four class V or six class IV vessels, since this allows the VT service to operate in the most traffic dense section of the Danube.

On the Rhine, there are only ten locks with the last downstream lock located just after Strasbourg [191]. The lock chambers of new German locks are designed for large self-propelled vessels with a width of 12,5m [105], making them smaller than the ones that can be found on the central or lower Danube. The locks along the tributaries and canals in the delta are even smaller and limit the capacity of vessel passage. This means VT passage on the main river Rhine and its tributaries can cause longer delays than is expected on the Danube lock passages, as more lock cycles are required to allow all the entire VT to pass.

Environmental Conditions

At times of too high water, ice or strong winds, the navigation on rivers can be suspended. Historical data shows that the average days of navigation suspension are around 5 % to 6 % of the annual days on both rivers [106], [173]. Low water will cause vessels to have restrictions in the draft and thus increase the cost per transport unit, as well as increasing the risk of ship-related accidents due to grounding. There are no official guidelines for ship operators on how to deal with low water situations; it is thus dependent on the individual vessel operators to decide whether to keep operations running in these situations [192]. As a minimum water depth of 2,5 m along the length of the Danube is not guaranteed, low water periods can cause major navigational bottlenecks, whereas the Rhine often has a depth of 3,5 m which helps improve the conditions [193].

Even though the days of navigation suspension affect all vessels no matter if they decide to operate in the VT or independently, a larger number of navigation suspension days reduces the potential productivity gain the VT can achieve, which is why it is taken into consideration in the assessment of the Danube case. The water depth is taken into consideration when calculating the vessel resistances and power requirements. Additionally, shallower waters will cause the operating speed to be slower, which has an effect on the productivity of vessels operating on the Danube compared to those operating on the Rhine.

Geo-Economic Conditions

Business Structure

The business structure on the Danube allows for multiple VT business models to be considered. The inland case study of chapter 5 has already established that on the Rhine, a large part of the fleet is composed of small family businesses. In contrast, on the Danube, most vessels are owned by fairly big, formerly state-owned companies [135]. Figure 61 quantifies the extent of this difference for the available Eurostat data between 2003 and 2012 [194], [195]. While in Belgium, the Netherlands and Germany, companies that own more than ten vessels make-up at most 25 % of the fleet, in most Danube countries, such companies own 60 % to 100 % of the fleet. The only Danube country that has similar vessel ownership to what can be found on the Rhine, is Serbia.

Given the fleet size, these percentages in Figure 61 translate to an estimate of 4.300, 2.300 and 1.600 vessels on the Rhine and 140, 270 and 2.290 vessels on the Danube operated by single ship owners, 2-9 ships owners and > 10 ships operators, respectively. On the Danube, individual companies or alliances of only a few partners can consider setting up the VT for their own operations. On the Rhine, however, the business model is mainly limited to a platform-based model where many individual businesses join the services of a third-party organizer.

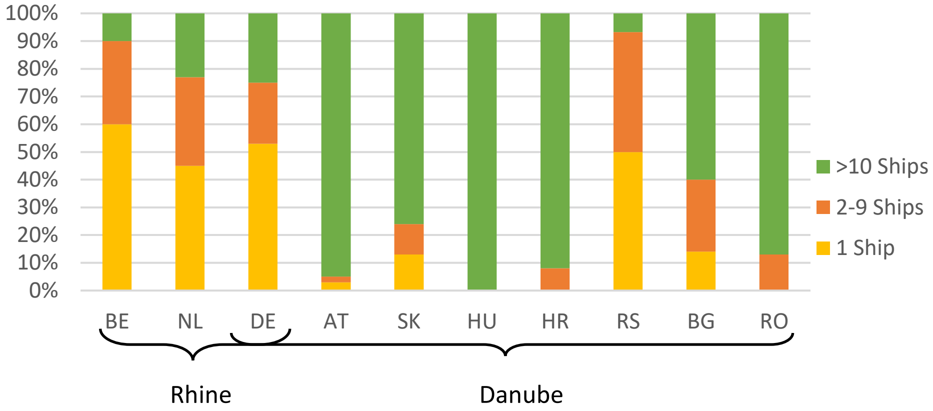


Figure 61: Inland Ship Owners Expressed by the Number of Ships Owned

Source: Authors adaptation of [194], [195], [240]

Vessel Types

Chapter 3 has already touched upon the importance of different vessel types. European vessels are classified by CEMT classes. The self-propelled vessel sizes sailing on a regional level are typically CEMT class I-III, whereas internationally operating vessels are typically classes IV and above. On the Rhine, the most common vessels are equivalent to the dimensions of CEMT class IV and V [187].

There are many barge convoys of CEMT class VI and VII sailing on the lower Danube. Self-propelled vessels are of similar size to their most popular counterparts on the Rhine as some of the larger ones are former Rhine vessels that have been repurposed for use on the Danube [106], even though they are not the most effective vessel designs for the shallower water conditions on the Danube [196]. The shallower waters on the Danube lead to lower speeds.

Ports and Transshipment Equipment

On the Danube, most ports are well equipped for transhipment, with 40 inland E-ports, which are ports of international significance. The average distance between these ports is 60 km, while the E-Ports on the Rhine are on average only 20 km apart [197].

An investigation from PINE 2004 estimated the Rhine ports to be 2.5 times more effective than the Danube ones, even though the crane density is higher on the Danube [190]. While no official figure is available, interviews with a Danube ship operator revealed that the waiting times on the Danube are comparable to those experienced on the Rhine. The causes for port waiting times on the Danube and the Rhine to differ, yet the absolute port times for individual vessels are similar; hence, they are set to be equivalent to the port times set in the inland case of chapter 5. The smaller average port distance on the Rhine makes it less likely that all FVs are destined for the same port and hence reduces the likelihood of congestions at a specific port due to a clustered arrival of vessels.

6.1.2. Danube Corridor Application Cases

This section studies the boundary requirements needed for the VT to become viable on the Danube corridor. It starts by explaining the input data, and pointing out the differences to the Rhine case. Then the assessment results are presented, which show the difficulties in achieving economically viable VT operations on the Danube. Based on these results, the input data are varied individually such that more solid viability can be attained. Hence, the case study identifies boundary condition requirements that need to change to allow for an implementation of the VT concept to be possible.

Input Data

Table 32 summarizes the main input parameter differences between the Danube and the Rhine case. The parameters that form the Rhine route have already extensively been studied in section **Error! Reference source not found.**. The parameters listed in Table 32 serve mainly as a reminder and source of comparison. Any parameters that are not explicitly listed in this table are equivalent to the input data provided in the inland case of chapter 5. The following four subsections describe the motivation behind the parameter changes of Table 32, which have not yet been established explicitly in the Rhine and Danube comparison.

Route Length

With the Danube having a mean transport distance that is three times as large as that on the Rhine, it is deemed most representative for the respective corridors to operate the VT over a shorter route along the Rhine than along the Danube. The Danube case LV route length of 878 km is comparable to a distance between Belgrade and Cernavoda, which is the point at which the Danube-Black sea canal begins (see Figure 58). This distance reflects the length of the lower Danube that has the least number of bottlenecks along the way. The 325 km route length on the Rhine is the one that was used in the inland case study of chapter 5 between Antwerp and Duisburg.

Table 32: Input Data for Corridor Cases

Parameters	Danube	Rhine
LV routes length	878 km	325km
Number of locks	2	0
VT operator	Single company	Third-party (platform-based)
VT user	Single company	Small-family businesses
Water depth	3,5 m	5 m
Reference vessel operating regime	B	A1/ A2 or B
Crew cost savings	€ 75.500 (Class V) and € 65.000 (Class IV)	€ 389.100 (Class V) and € 293.600 (Class IV)
Fleet size	480	6400
Departure interval	24 h	6 h
Number of LVs	6	10
VT operating speed of VT	15,5 km/h	15,2 km/h

Crew Cost

Crew cost are difficult to come by, but for the Rhine navigation, acceptable cost estimates can be made through guiding wage tables; to the best of the authors' knowledge, these do not exist in the Danube countries. The Dutch crew cost are compared to the Serbian wages Table 33. Interviews with Serbian ship operators allowed rough estimates to be set. A captain’s salary can range between € 700 and € 870 per month, whilst the lowest-paid sailor onboard is estimated to earn about € 280 per month, while an apprentice is estimated to be paid about € 220 per month. The roles ranked in between are estimated according to these two extremes. The conversion of these monthly wages into the annual cost presented in Table 33 assumes an indirect crew cost and employment-related cost 30 % [12] for both the Dutch and the Serbian crew cost. These costs include company recruitment cost or flag state regulation for indirect crew cost and factors such as social dues, sick pay, and/or port expenses for the employment-related cost. In Serbia, the crew receives additional bonuses such as € 25 per day for international travel, which are added to the base salary. This can make up a substantial part of the salary considering that if the vessel spends a third of its time abroad, the crew member each receive about € 2.700 bonus per year. It is assumed that this bonus is paid for one-third of the operating time, given that the Danube route runs two-thirds of its way through Romania and given that the vessel operates under a B regime, thereby requiring two crews to rotate.

The wage differences (Table 33) differ on average 74 % between the two regions. The total crew cost savings achieved through the VT implementations are presented in Table 32, which are deduced from the minimum crewing requirements and their wages in Table 33.

Table 33: Annual Wage of Inland Crew per Role

Role	Boat master			Helmsman	Boatman	Apprentice
	>86m	70-85m	<70m			
Dutch	€ 56.300	€ 55.100	€ 54.100	€ 46.000	€ 31.800	€ 40.300
Serbian	€ 17.600	€ 16.200	€ 14.800	€ 9.500	€ 8.800	€ 7.500

Departure Interval

Given the longer route, the smaller fleet size and cargo volume on the Danube, this departure interval needs to be increased. Hence, a departure interval of once per day is deemed appropriate for the Danube case to meet realistic fleet share requirements of approximately 10 %.

Assessment results

Figure 62 provides the annual cost savings changes for the Danube corridor. The results stand in stark contrast with the Rhine case results presented in chapter 5, where all operating conditions, even those of small Class II vessels, were able to achieve viability via at least small cost savings. As a reminder, a class V vessel achieved a total cost savings between € 231.000 and € 256.000, while a class IV achieves savings between € 160.000 to € 183.000. These savings are from the TSC, where the departure intervals are closest to the Danube case.

With the limiting operating conditions, the Danube case only shows to be viable if a class V FV stays part of the VT for more than 500 km. A maximum of € 10.000 cost savings can be achieved by a class V vessel. Even if the class IV and class V savings are combined, assuming a single company operation, the VT cannot provide benefits, as the class V vessel benefits cannot outweigh the € 20.000 cost for a class IV vessel. The long departure interval combined with the small crew cost-benefit and the reduction in productivity compared to the B reference vessel regime is in most cases not able to create sufficient benefits to outweigh the VT system cost. Measures need to be taken to identify viable conditions for the Danube corridor based on the results that are presented in the sensitivity analysis. This checks whether the concept is beneficial for all types of self-propelled Danube vessels.

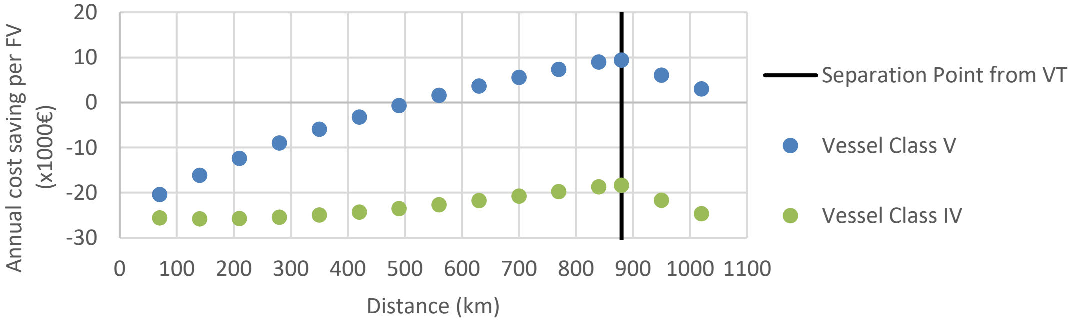


Figure 62: Annual Cost Savings per FV for the Danube Vessel Class IV and V

Sensitivity Analysis

The sensitivity analysis of section 5.3.4 already covered the effects of variations in crew cost, route length and departure interval which are all three factors of the geographical application differences. Section 6.1.1 listed many more geographical differences between the two corridors. Even though it is not possible to quantify the effects, such as the impact of port distances, without detailed port information and assessing the overall transport network performance, some of the geographical differences such as water depth, days of navigation suspension or the number of lock passages can be assessed from a single vessels' perspective. Hence, there are the three influence factors added in this sensitivity study. The results of this sensitivity analysis are expressed in terms of percentage change of the annual cost savings compared to the Rhine base case per vessel. For all but the lock passage variation, the changes are provided at the point of maximum savings, when the FV spends the entire trip as part of the train i.e. at 325 km. The results are summarized in Table 34.

The water depth variation is varied from 5 m to 3,5 m as that is the difference between the Rhine and the Danube average depth. The navigation day suspension is varied from 18 to 22 days as that is the average difference between the two corridors. There is also a larger variation made, including 60 days of navigation day suspensions, which are the expected navigation day suspension reached annually on the Rhine within this century due to climate change [198]. Lastly, the variation from 0 to 2 locks is representative of the difference between the Rhine and the Danube route presented in Table 32. This is also increased to 8 locks to demonstrate the effects of shifting the operations further upriver.

Looking at the results of all parameter variations of Table 34, the variation of the water depth and the days of navigation suspension have a negative effect on the FV savings achieved per tkm. Even though the 1,5 m decrease of water depth causes 2.3 % decrease in savings, due to higher fuel consumption, this depth variation is not going to decrease much more as then vessels can no longer navigate on the river. This is why the navigation day suspension has a lot more potential to reduce the productivity and FV savings of vessels than purely shallower waters does. It needs to be considered that the unreliability these two factors create, has a negative effect on cargo owners willingness to choose waterborne transport. If the waterborne conditions become too unreliable, the customers are likely to change their choice of transport mode and will not return. Hence, while the results in Table 34 show a small effect, these long term and demand-side effects are not reflected in these results.

The lock passage sensitivity analysis results need to be viewed similarly. The Rhine case has shown that a VT can be composed of as little as one FV. This would mean the entire VT fits into a single lock cycle. For such short trains the only difference between the VT and current operating conditions are the VT waiting times. The sensitivity analysis for the 2 and 8 lock passages allows to conclude that every added lock reduces the FV savings per tkm by 3,1 %. Apart from the additional number of lock cycles that could be required if the VT becomes too long, the VT is also affected by locks that are located in close proximity to each other. The VT aims to reduce the workload of the crew on the FVs; yet if every few hours the crew is called onto the bridge to take over a lock manoeuvre the benefit for the VT user diminishes. This negative effect is not taken into consideration in this quantitative savings reduction, which means lock passages will have an even larger impact on the FVs. Therefore the VT operators should choose routes that have either very clustered or very few widely spread locks along the route.

Table 34: Average Change in Cost Savings due to the Variation of Influence Parameters

Influence factors	Water depth (m)	Days of navigation suspension		Lock passage	
Variations	3,5	22	60	2	8
Change in savings	-2,3 %	-1,1 %	- 3,1 %	-6,2 %	-24,7 %

Adapting Danube VT Operating Conditions

The Danube application results given in Figure 62 have shown that the case study set in Table 32 does not provide viable conditions. This section, therefore, identifies the combination of parameter variations that allow for viable conditions to be achieved.

The sensitivity analysis identified that the route length and the departure interval are two controllable parameters that can improve the VT operations. Additionally, crew cost also plays an important role for the

viability performance of the VT. Hence, only there three parameters are focused upon for the adaptation. The first parameter adjusted is the crew cost. It is only controllable to an extent as the cost still have to meet reasonable regional employment levels. Therefore it was assumed that an increase of crew cost by 20 % is within reason, given the uncertainties surrounding the crew cost per company.
Figure 63 plots the changes that each of the three adaptations creates for a class IV vessel and the benefits all three combined for a class V vessel.

If the route length is increased by 475 km up to Budapest, which does not cross any additional locks on the way, makes the trip 1400 km long. This brings the class IV vessels € 10.000 closer to beneficial conditions. If this distance is combined with the reduced VT waiting time of 6 h, then class IV vessels are close to breaking even at the full VT journey length. All three adaptations combined are able to provide VT cost savings of about € 10.000 no matter how long the FVs stays sailing in the VT. Class V vessels are able to achieve benefits of up to € 50.000 per FV. The class IV and V vessel savings can make up between 2 % - 7 % of the reference vessel operating cost.

It is noticeable that a reduction in waiting times causes the class IV plot to take on a slight bathtub shape. This is caused by the shorter port times of class IV vessels. At short distances, the productivity of the class IV vessels improves due to the port time savings outweighing additional fuel cost, when the vessel is able to operate on more trips. However, the longer journeys the more additional fuel cost are created. At short distances, the VT waiting times hides this curvature, as the added waiting times are more influential the more VTs are used. Yet, when the waiting times are reduced the curvature becomes more apparent. In a cost per tkm comparison to the reference vessels these values result in a cost-saving of up to 3 % for the class IV vessel and up to 7 % for the class V vessel.

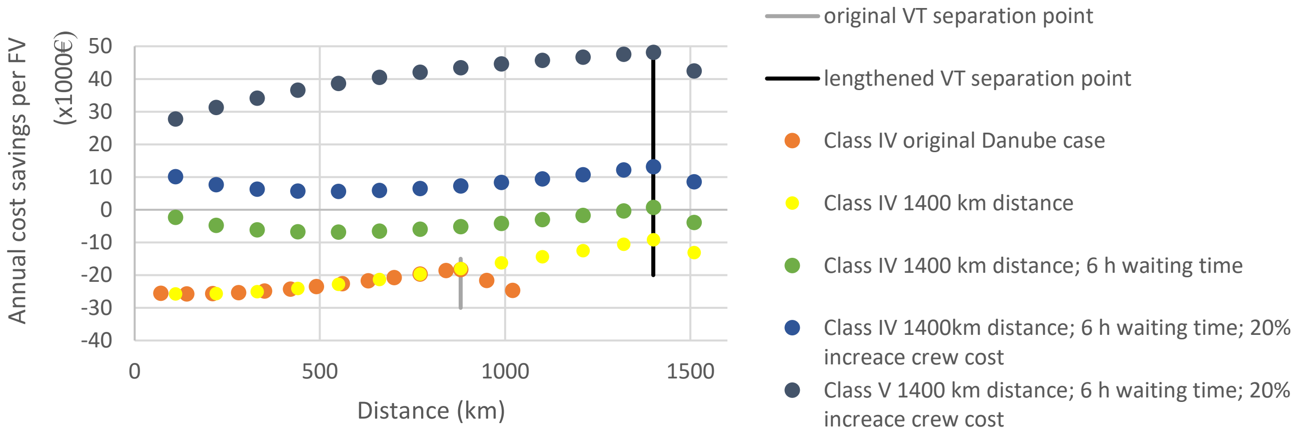


Figure 63: Danube Case Condition Alteration for Class IV and V Vessels

Feasibility Checks

The feasibility checks identify the minimum distance an FV has to stay in the VT, the minimum number of FVs per LV, the number of participants required in the transport system and the market share required of the existing self-propelled fleet. All but the minimum distance feasibility checks are provided at the VT trip length, so assuming the FV stays sailing in for the entire trip. The feasibility checks of the adjusted Danube case results are summarized in Table 35.

On the Danube, the VT operating cost are a lot lower than on the Rhine, but the required fleet share rises to 11 % of the self-propelled vessel fleet. This is significantly higher than the < 1 % fleet share identified in Table 28 of the Rhine case. While the Danube fleet share appears high this can still be feasible since it can represent one large company or an alliance of a few operators working together to improve their productivities.

Seeing that the departure intervals make such a large difference, one could consider that further benefits can be achieved if the business model is changed to a departure on-demand basis. As mentioned in chapter 3, adapting such a service concept would require detailed knowledge of all departures and destinations as well as excellent coordination of vessels.

Table 35: Feasibility Checks for the Rhine and the Danube Cases

Vessel Type	Number of FV per VT	Number of participants	Fleet share
V	1	36	8 %
IV	2	54	11%
Combined	1	36	8 %

6.1.3. Conclusion and Discussion on the Danube Case

This chapter subsection presents a comparison of the geographical and geo-economic features of the Rhine and the Danube inland navigation corridors in light of the potentials for the introduction of the VT concept. It describes impact factors that have an effect on the VT concept implementation and assesses the viability for both operating corridors. While the Danube has the advantageous conditions that it is long and has larger cooperation running the waterborne transportation sector corridors, the Rhine provides favourable conditions in terms of crew income levels and waterborne traffic density. These latter two are the main influence factors for the VT implementation.

While the Rhine case presented in chapter 5 was able to demonstrate viability under the existing conditions, the Danube case requires careful consideration of the VT operating conditions. It needs a long route of about 1400 km as well as a maximum average waiting time of 6 hours to make the VT viable for a liner service departure.

Even with a financial benefit created with the adapted Danube conditions, achieved through a raise in crew income, the traffic density on the Danube, is not high enough to implement the concept. A way in which the traffic density can be increased is by adding push convoys into the train, as they are more numerous on the Danube than self-propelled vessels. For this to be possible, it needs to be investigated if it is possible and desirable to include barge convoys in the VT system. Barge convoys are wider and longer than self-propelled vessels. Thereby changing the way they react to environmental factors or special manoeuvres such as overtaking. Due to the larger size of push convoys, they also tend to be slower, which means VT users would have to accept even longer delays compared to conventional operations if both self-propelled vessels and push barges are included in the same VT. On the other hand, it may also be likely that VT would only be composed of push barges. Convoys usually have longer transport distances with more crew members working in shifts, which means there may also be potential for crew savings. Yet, the larger amount of cargo they transport also reduces the effects on the savings per ton-km, as the cost savings of a single crew member are spread over a larger amount of cargo. All in all, including barge convoys to enhance the traffic density is needed to allow one of the two main influence factors for the VT implementation to be met.

6.2. Penetrating Urban Area With the VT

The study of the application area does not only concern the adaptation in different geo-economic environments as discussed in section 6.1.1, it also concerns the adaptation of the VT concept to deal with different infrastructural conditions, such as sailing in small waterways that interacting with urban traffic.

The introduction in chapter 1 touched upon the aim of the VT concept to help improve the competitive attractiveness of smaller vessels, that are suffering from a steadily diminishing fleet size as no new vessels are being built. This decrease in the proportion of smaller vessels in the fleet is attributed to four primary causes [10]: 1) Hard competitive decision; 2) lack of economies of scale; 3) Unwillingness of banks to invest and new ship-owners to operate; 4) Entry and exit barriers. While the VT concept cannot help address all of these reasons it is able to help improve the competitiveness of the smaller vessels by reducing the transport cost. The viability study in chapter 5 included a detailed look at the cost reduction potential for smaller CEMT II vessels that fall into the category of vessels that perform regional operations and have the potential to operate in urban areas. This section takes a closer look at the challenges and opportunities created when penetrating urban areas, in particular considering the VT interaction with bridge opening operations that influence land-based transportation operations. The challenge in the bridge interactions lie in determining whether the entire VT can pass in one bridge opening. The information presented within this section has been published in a conference paper co-authored by the author of this thesis and several BSc students [199].

The research presented in this sub-section is structured as follows. First, a brief overview of prior research with regards to obstacle passage on waterways is portrayed in section 6.2.1. Then section 6.2.2 identifies the most influential factors regarding VT-bridge operation interactions and calculates the effects they have on the length of the VT, i.e. the number of FVs possible, in urban areas. These factors are related to the infrastructure of a bridge, the impact on land traffic and bridge operation regulations. In order to assess the effects of these factors on the VT implementation viability, a model was been developed that determine both the requirements for the road and the waterborne traffic. The methodology of this model is explained in section 6.2.3. This model is applied to a case study in the Dutch province of Noord-Holland where vessels sail along urban area into the metropolitan area and ends in the port of Amsterdam in section 6.2.4. Section 6.2.5 follows by providing some of the more general guidelines this case study allows to deduce on the penetration of urban areas with the VT related to the maximum road traffic density and bridge distances for an implementation. The section finishes with a summary of the main conclusions that suggest that the main business incentive of the VT should not be focused on the penetration of urban areas.

6.2.1. Background Research on Obstacle Passage on Waterways

Numerous studies exist on the topic of bridge passage. In the early 1990s [200] suggested bridge designs to avoid collisions on densely used waterways. More recently, the topic has gained importance with regard to obstacle avoidance of autonomous navigation systems. Other research makes use of navigational systems such as laser detection and ranging (lidar) to help avoid collisions with bridges [201] and [202] elaborate on the difficulties of bridge passage that cause a temporal block of communication signals.

Procedural optimization of "obstacle" passage has mainly been dealing with lock passage, as locks are one of the main capacity limiting factors for waterways [203], [204]. Research on the procedural optimization of bridge passages has been limited to the Dutch province of Noord-Holland setting up the *Blauwe Golf* [205]. The *Blauwe Golf* (Blue wave) uses bridge management systems that give bridge operators an opening advice using input from emergency services. This optimizes the traffic flow near bridges to improve the conditions for the road and waterborne users by reducing the number of bridge openings. The research presented in this section adds to the developments of the *Blauwe Golf* by identifying how the VT - bridge interaction can help cluster vessel passages.

6.2.2. Vessel Train Potential and Challenges in Urban Areas

The historical data gathered by the province of Noord-Holland in 2018-19 shows that on average, 97 % of bridge openings happen for a single vessel passage [206]. Bridges are usually not open for longer than 10 minutes, where 3,5 minutes are needed to actually open and close the bridge, [207]. Given the fact that some bridges open up to 6.000 times per year, one can deduce that clustering vessels in fewer bridge passages has the potential to save days' worth of road traffic waiting times along an entire route that leads into urban areas.

Benefits

The benefits of The VT implementation of the productivity improvement for smaller vessels have already elaborately been discussed in prior chapters within this thesis. Chapter 5 also addressed the emission cost savings that a modal shift can achieve. The benefit that can be created specifically with regards to urban area penetration is a societal congestion time reduction for road users, due to clustering of vessels when using the VT. The clustering requiring fewer bridge openings.

Challenges

There are also factors that make the clustered passage of vessels in a VT challenging. These factors concern traffic density, regulations and infrastructure.

Traffic Density

The traffic density on a waterway is a crucial factor when considering the deployment of a VT. The implementation area needs to ensure sufficiently large cargo flows to have enough vessels joining the VT. An additional influential factor that can pose a challenge to the VT navigation is the presence of a large number of recreational or non-cargo vessels that complicate the autonomous navigation of the FVs.

Regulations

The urban penetration of the VT may be hindered by regulatory restrictions regarding the maximum number of simultaneous adjacent bridge openings. Interviews with bridge operators and Province of Noord-Holland representatives concluded that, bridges located in the vicinity of emergency services may at a moment's notice need to close to allow emergency services to reach their destination within a reasonable timeframe. For the same reason, the province aims to, dependent on the traffic conditions, have no more than two adjacent bridges open simultaneously. Additionally, some bridges do not accommodate openings during rush hours, in order to minimize the traffic jams created [207]. Furthermore, some bridges in urban areas do not operate at night (between 23:00h - 05:00h) unless special permission is granted. This emphasizes the need for careful planning. While this is not a VT specific problem, it can prevent the VT users from reaping the VT's greatest benefit of an improvement in productivity by operating continuously with a smaller crew. The bridge operating hours may change if the demand requires it, yet the restrictions of adjacent bridge openings and rush hour openings are likely to stay in place even with a greater use of the waterways.

Infrastructural Limitations

One infrastructural factor is the size of the waterway, which influences the maximum size of vessels. Smaller vessels of CEMT class I-III are more likely to reach into urban areas than larger vessels, since waterways leading into urban areas are typically small. Another infrastructural aspect is the distance between bridges. As the number of simultaneous adjacent bridge openings is limited to two, the distance between these bridges plays a decisive role in determining the maximum possible VT length and safety distances between vessels that are required to sail on a given route.

Finally, the number of bridges along the route influences the VT operations. Every bridge passage requires the VT to reduce its sailing speed. This lower speed needs to be kept until every vessel has passed the open bridge, as the speed limits on the urban waterways do not allow FVs to catch up with a LV, if they were to speed up after passing the bridge themselves. Thereby, every bridge passage and vessel in the train will add additional time to the trip compared to the operations of a conventional vessel would experience. In order to quantify the effects of these influence factors on the viability of urban penetration with the VT, the factors are incorporated in a model and a case study that applies the model.

6.2.3. Methodology to Assesses the VT Urban Area Penetration

To identify the circumstances needed for a viable penetration of the VT, a model has been developed that compared the road based to the waterborne traffic conditions. A viable urban access is defined by ensuring: 1) economically viable VT length 2) that regional regulatory limitations are met and 3) that at least equivalent congestion situation to the current situation is achieved. Attaining additional congestion benefits is desirable to gain political support for the implementation of the VT concept.

The calculations presented in this methodology are targeted to quantify three aspects of the VT-bridge interaction:

1. The maximum bridge opening time from a road-based perspective
2. The maximum required bridge openings from a waterborne perspective
3. The reduction in road-based waiting time that clustering of vessels can achieve

The maximum bridge opening time determines whether the road conditions allow for economically viable VT operations to take place, while the number of required simultaneous bridge openings, defines if the waterborne infrastructure allows viable operations. The reduction in road traffic waiting time due to the clustering of vessels is needed to calculate the societal congestion cost-benefit. Savings in congestion cost can help sway the municipalities to loosen regulatory restrictions, which can help the implementation of the VT. Looking ahead to a longer term, the congestion cost savings can also potentially improve the viability of the overall concept if the political decision were to be made to internalize external cost.

Figure 64 provides a visual representation of the type of data (in the cylinders) used to determine the model results (in the rectangles). Two viability checks have been created (in the hexagons) to ensure the road and waterborne infrastructure conditions allow for economically viable operations of the VT. The first viability check compares the performance of the road condition with the minimum opening required for the VTs to pass. The second, checks whether the spacing between the bridges allows for the VT to pass without opening more than two bridges simultaneously. Lastly, a large congestion cost benefits could help argue the adaptation of regulatory limitations for the VT operations or potentially reduce the required number of FVs through the internalization of external cost. This is represented by the dotted lines in Figure 64.

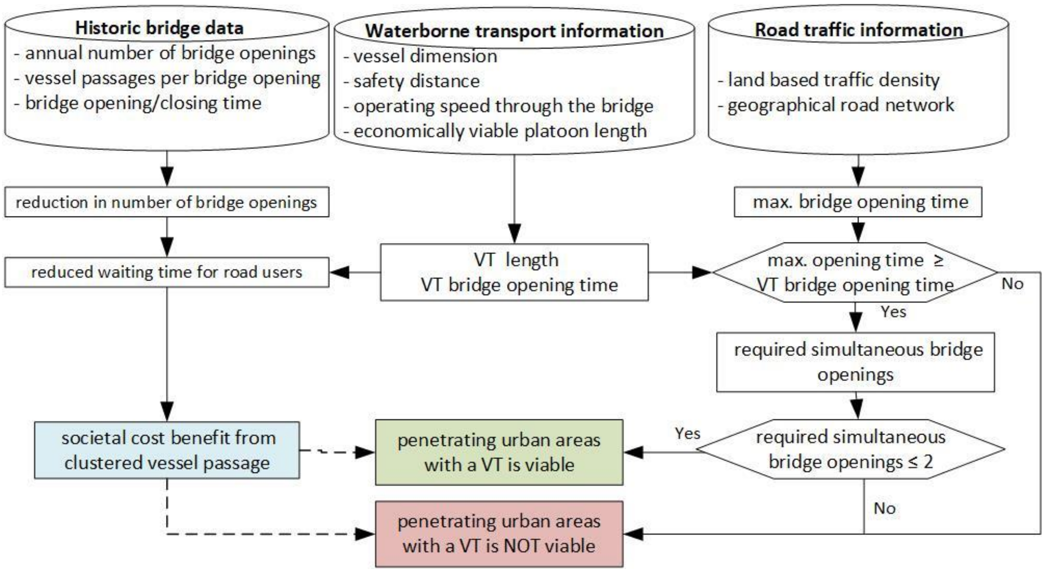


Figure 64: Methodology Structure to Assesses the VT Urban Area Penetration

Maximum Bridge Opening Time

The maximum bridge opening times are calculated based on the assumption that the bridge opening is only allowed to cause standstill traffic jams in the immediate roads leading to/away from the bridge. This sets the maximum allowed traffic jam length equal to the distance to the closest road intersection.

The maximum opening time of a bridge is hence dependent on the formation and dissipation of the traffic jams. The length of a traffic jam is calculated with the traffic jam theorem [208], in which the opening of a bridge can be compared to the modelling of a traffic incident or a red traffic light. The theorem uses traffic intensity in vehicles per hour and traffic density in vehicles per km information to determine the amount of time and length it takes for the congestion to dissipate. Equation 34 calculates the queue build-up rate, which is the number of km with which the traffic jam grows per hour (km/h).

$$\mathbf{u_1} = \frac{\mathbf{q_2} - \boldsymbol{q_1}}{\boldsymbol{k_2} - \boldsymbol{k_1}} = \frac{\mathbf{0} - \boldsymbol{q_1}}{\boldsymbol{k_j} - \boldsymbol{k_1}} \qquad \text{Equ. 34}$$

u_1: queue build-up rate (km/h)
k_2: incident density (vehicles/km)
q_1: pre-incident flow rate (vehicles/h)
k_1: pre-incident density (vehicles/km)
k_j: jam (incident) density (vehicles/km)
q_2: incident flow rate (vehicles/h)

For stationary traffic, the number of vehicles per hour of the outbound traffic is equal to 0. When the bridge is down, all the vehicles can drive again. The queue dissipation rate, once the traffic is rolling again can be determined using Equation 35. Once the bridge closes there is no traffic in front of the first car. Therefore the capacity flow rate is equal to the maximum flow rate. This means that the traffic is in a state of 'free flow'; the maximum rate of cars can dissipate the traffic jam. This is also the reason why the incident flow rate is set to 0.

The maximum allowed jam distance up to the closest intersection is known. Hence, the queue dissipation time can be calculated. Once the dissipation time is known, Equation 37 can be inserted into Equation 36 to solve for the incident time, which is the maximum allowed opening time of the bridge.

$$\mathbf{u_2} = \frac{\mathbf{q_3} - q_2}{k_3 - k_2} = \frac{q_{max} - 0}{k_c - k_j} \qquad \text{Equ. 35}$$

$$t_2 = \frac{Q}{u_2 - u_1} \qquad \text{Equ. 36}$$

$$Q = t_1 u_1 \qquad \text{Equ. 37}$$

k_c: capacity (dissipation) density (vehicles/km)
q_{max}: maximum flow rate (vehicle/h)
t_1: incident duration (h)
t_2: queue dissipation time (h)
q_3: capacity flow rate (= q_{max}) (vehicle/h)
Q: maximum allowed queue length until next crossing (km)
u_2: queue dissipation rate (km/h)

VT Length

The VT length depends on the length of the vessels in the VT, the safety distance between the vessels and the space before/after the train, at which the bridge starts to open or close. It is expressed by equation 38.

$$L_{VT} = d_{aft} + d_{front} + L_{LV} + \sum_{i=1}^{n} (L_i + d_{sw} L_i) \qquad \text{Equ. 38}$$

d_{aft}: spacing between VT aft and bridge at closing initiation (m)
d_{sw}: safety distance factor between vessels
L_{LV}: LV length (m)
d_{front}: spacing in front of VT when the bridge should already be fully opened (m)
L_i: length of FV i
n: number of follower vessels in VT

VT Bridge Opening Time

The VT length determined in section 3.2. is used in Equation 39 to determine the bridge opening time due to the passage of the VT.

$$t_{VT} = \frac{\frac{L_{VT}}{1000}}{v_{lim}} + t_{o\&c} \qquad \text{Equ. 39}$$

$t_{o\&c}$: opening and closing time of the bridge (h)
t_{VT}: opening time for the VT bridge passage (h)
v_{lim}: limited operating speed of VT at bridge passage (km/h)

Required Number of Simultaneous Bridge Openings

The maximum required number of simultaneous bridge openings along the length of a given route is calculated by Equation 40. This is based on identifying the space available at each section between bridges and is compared to the length of the VT in Equation 41.

$$b_o = \max(\mathrm{o_x}) \qquad \text{Equ. 40}$$

$$\mathrm{o}_x = \min_{o \le b_r} \sum\nolimits_{j=\mathrm{x}}^{o} s_j \geq L_{VT} \text{ where } \mathrm{x} = 1 \dots \mathrm{b}_r \qquad \text{Equ. 41}$$

b_o: maximum required bridge opening along the route
o_x: number of open bridges at a specific section x along the route
b_r: number of bridges on the route
s: length of the section between bridges

Reduction in the Number of Bridge Openings

The expected reduction of bridge openings is deduced from an estimate of the required number of FVs that are needed to create economically viable operations for the VT organizers. The calculation of these values as well as an estimate for the expected market share are taken from the inland case study results of chapter 5. The number of single-vessel bridge passages is based on the historical data and is inserted into Equation 42.

$$s_{bo} = p_s m - \frac{p_s m}{n_{min}} \qquad \text{Equ. 42}$$

m: market share of VT implementation (%)
o_x: number of open bridges at a specific section x along the route
s_{bo}: number of saved bridge openings per year
p_s: number of annual single vessel passages
n_{min}: number of FVs in VT to make it economically viable

Reduction in Waiting Times for Road Users

While scheduling benefits may be created by having longer opening times, these benefits are not quantified within this research. For there to be a congestion benefit, the time it takes for all follower vessels to pass shall not surpass the bridge opening time for a single vessel. Equation 44 expresses this basic condition that needs to be met for a congestion cost-benefit to be achieved. The reduction of waiting time is the difference between the reduced number of bridge openings and the added time per bridge passage for the additional vessel times, which is taken for all bridges along the route.

$$t_{p_s} = \frac{\frac{d_{aft} + d_{front} + L_{LV}}{1000}}{v_{lim}} + t_{o\&c} \qquad \text{Equ. 43}$$

$$\frac{\frac{\sum_{i=1}^{n}(L_i + d_{sw}L_i)}{1000}}{v_{lim}} \leq t_{p_s} \qquad \text{Equ. 44}$$

$$s_w = \sum_{j=x}^{b_r} \left(\frac{p_s m}{n_{min}} (t_{VT} - t_{p_s}) - s_{bo} t_{o\&c} \right)_j \qquad \text{Equ. 45}$$

t_{p_s}: time for a single vessel passage (h)
s_w: waiting time savings for road users (h)

Congestion Cost-Benefit

Congestion is very complex to model. This calculation has the aim to provide a rough estimate of the cost benefit and thus identifies the congestion in a simplified manner based on the reduction in waiting time at bridges. It assumes the same type of vehicles and vehicle spacing on the roads.

The number of vehicle-kilometers saved is the product of the saved waiting time, the traffic intensity and the length of each vehicle (including the safety distances between vehicles). The saved number of vehicles together with the generalized societal congestion cost values provided for different road users, determine the total societal cost savings due to a reduction in congestion.

$$s_{con} = q_1 \, s_w \frac{L_v(1 + d_r)}{1000} c_{con} \qquad \text{Equ. 46}$$

c_{con}: cost of road congestion (€/v-km)
s_{con}: savings due to congestion reduction (€)
d_r: distance between road vehicles (% vehicle length)

6.2.4. Application Case De Kaag - Amsterdam

This section is an application case of the methodology that was just presented. It starts by introducing the route of the case study, which passes through the Dutch province of Noord-Holland and ends in Amsterdam. The input data for this route is listed provided. Lastly, the case study results and concludes whether it is viable to penetrate the urban area leading into Amsterdam with the VT are explained.

The Route

The route for the case study was picked based on waterborne and road traffic density, the waterway size, bridge distances as well as the data availability from the bridge management systems of the province Noord–Holland. The route starts on the western side of the Haarlemmermeer polder Ringvaart and runs between the Kaag and the IJ, in the centre of the port of Amsterdam (see Figure 65). It is the most intensively used urban waterway in the province of North-Holland and has short bridge spacing in the metropolitan area of Amsterdam. It is a segment of the inland waterway connecting the port of Rotterdam and the port of Amsterdam. Table 36 provides an overview of the operations along this route. Based on the dimensions of a CEMT class II vessel with an air draught of 4,7 m, 14 of the 19 bridges that are crossed along the way have to open. As the VT is targeted for cargo vessels, only the average number of bridge openings for cargo vessels are considered and not a large number of recreational vessel passages. The average number of bridge passages is by about 97 % composed of single vessel passages. Finally, the map in Figure 65 also indicates the location of emergency services that may cause bridges to immediate close or may limit the number of adjacent bridge openings.

Figure 65: Urban Penetration Case Study

Source: [242]

Table 36: Route Features

Operating between	De Kaag <-> Port of Amsterdam
Route Length	25,6 km
Number of bridges	19*
Number of bridges with available data	5*
Average distance between bridges	1,3 km
Average number of openings (cargo vessels)	1.660/ year*
Bridge opening times	5:00 h - 23:00 h*
Waterway size	Up to CEMT III

* Source: [209]

Input Data

Not all 19 bridges have complete data available for the waterborne side in terms of the annual number of bridge openings, not for the roadside in terms of the average vehicle length, traffic intensity, maximum traffic jam length and the average operating speed of the vehicles. The data that is available is provided in the appendix. Where the data is not available, the average of all other available data points is used instead. These averages are presented in Table 37. The road traffic is modelled for average day and rush hour conditions.

The case study is applied for a varying number of FVs in the train. Dependent on the development stage of the VT technology, the results of chapter 5 have identified a minimum number of FVs to create an economically viable case for CEMT class II vessels. A fully matured control system only requires one FV. In the early stages of the implementation, additional monitoring crew is needed on the LVs; hence the required number of FVs rises to **three FVs**, in case the originally sailing condition of the reference vessel is continuous, and **six FVs**, if the reference vessel only operated for 18 h per day. Based on this data, the vessel type chosen for this case study is also a CEMT class II.

The congestion benefits are calculated by using the metropolitan area cost for 8 of the bridges. The remaining 6 of the bridges are considered to be located in an urban environment. The market shares of the VT for these results will be varied from 1 % to 100 %.

Table 37: Input Data for Case Study

Input data	Value	Unit	Source
Waterborne Traffic			
Vessel Length (CEMT 2)	85,0	m	[210]
Operating speed	8	km/h	[211]
Limited operating speed at bridges	6	km/h	
Distance before LV and after last FV	0,13	km	1 min at 8 km/h [207]
Bridge opening and closing time	0,058	h	[209]
Safety factor between vessels	1,5	Ship lengths	[48]
Road Traffic			
Vehicle length (average day; rush hour)	4,6; 4,2	m	[212]
Vehicle speed (average day; rush hour)	83; 70	km/h	[212]
Intensity	746; 1253	veh/h	[212]
Max Intensity	2500	veh/h	[213]
Max jam length	1200	m	[212]
Distance between road vehicles	10	%	
Congestion Benefit			
Metropolitan area, car	242,6	€ct/vkm	[144]
Metropolitan area, truck	460,9	€ct/vkm	[144]
Urban area, car	75	€ct/vkm	[144]
Urban area, truck	144	€ct/vkm	[144]

Urban Penetration Viability Assessment Results

Maximum bridge opening time

The maximum opening time for the available bridge data is presented in Figure 66. Each set of bars is representative of a bridge along the route. The blue bars present the time a bridge can be open in normal traffic conditions for an average day in 2018. The red bars show the bridge opening times for the same bridges during rush hour. The faintly coloured bars show bridges, where only indicative data was available since the data quality was insufficient. In close proximity to Amsterdam, which are the two sets of bars on the right-hand side of Figure 66, the bridge opening times are significantly shortened because the intersections are very close to one another.

The required bridge opening times for the VT of one, three and six FVs require 8,5 min, 12,7 min and 19,1 min, respectively, with a safety distance of 1,5 ship lengths between vessels. If this safety distance were to be reduced to 0,5 ship lengths, the required bridge opening time diminish to 7,6 min, 10,2 and 14 min. In either case, the feasibility check with the maximum opening times concludes that only the VT with a single FV, taking 7,6 min, would be able to pass most bridges in the indicated bridge times of Figure 66, outside of rush hours away from Amsterdam. With the failure of this feasibility check, the case route is not viable for the VT penetration into urban areas. For this to become viable, the route would have to be cut short and the VT would have to separate for the final bridges.

Interviews with bridge operators revealed that most of the municipalities in the Netherlands pursue a policy that has a maximum of ten minutes bridge opening time per passage [207]. This means there may be room to extend these passages slightly. With this extended time and a reduction in safety distance, a VT length of at most three FVs becomes possible.

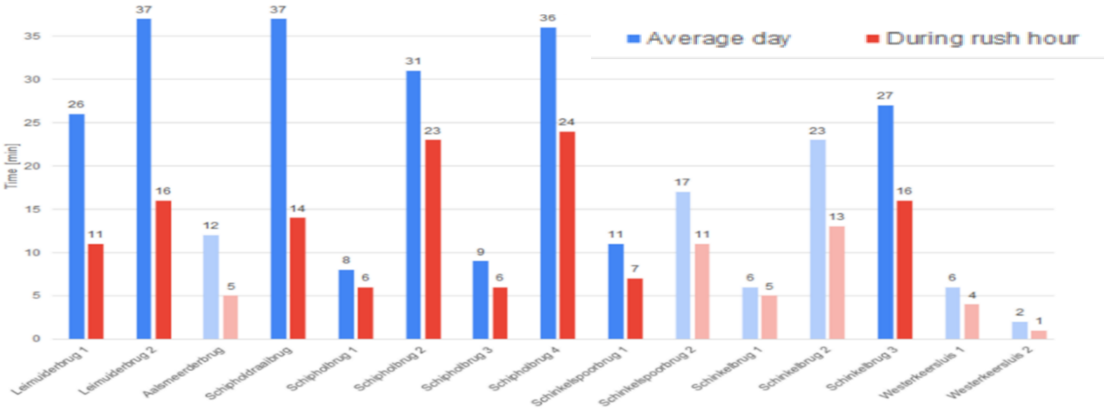


Figure 66: Maximum Bridge Opening Times on an Average Day and at Rush Hour

Maximum Number of Bridges Simultaneously Open

Figure 65 showed that the bridges with opening limitations due to emergency services are 2, 3, 7, 8, 11, 12 and 13. Table 38 indicates the number of simultaneous bridge openings required per bridge section. When considering only a single FV, bridge sections seven and eight are the limiting factors, as the VT may not be able to pass in case of an emergency situation on the road. Longer VTs increase the number of bridges that open simultaneously up to five in the urban area of Amsterdam. Hence, the case study leading into Amsterdam is thereby also not passing the second feasibility check. This means that the FV crews will need to stay alert between bridge sections seven and eight to potentially decouple from the train, if the emergency road traffic causes the VT to get separated by the bridge.

Table 38: Open Bridges Required per Route Section

Viable VT lengths	length (km)	Bridge sections																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 FV	0,62	1	1	1	1	2	1	3	2	1	2	2	1	1	1	2	2	3	3
3 FV	1,04	1	1	1	3	2	1	3	2	1	3	2	2	2	2	3	4	4	3
6 FV	1,67	1	1	1	3	2	1	4	3	2	4	3	3	3	4	5	5	4	3

Congestion Improvement

One of the goals of this research is to identify how much congestion cost-benefit the VT would be able to achieve. Even though the feasibility checks, that would ensure seamless VT-bridge passage, were not met, it is still worth gauging the magnitude of the potential congestion cost savings, as it can still be indicative for other routes with more appropriate bridge spacing's. It is hence useful to obtain an understanding of how large potential congestion cost savings could be. Before, presenting the congestion cost savings, the maximum VT length that is able to achieve these savings is shown in Table 39. This is calculated based on Equation 46 while solving for n. This length is determined for a variety of safety distances. It shows that all the economically viable VT lengths presented in the case study section can be accommodated. However, for this to be possible, the safety distance between the vessels needs to be 10 % or less of the vessel length.

Table 39: Maximum Number of FVs in VT Based on Safety Distance Between Vessels

Safety distance	0,1	0,5	1	1,5
Max VT Length (LV + FVs)	7	6	5	4

The total annual hours of bridge opening time saved over the length of the route can vary from as high as 219 h with 3 FVs or 106 h with 1 FVs at 100 % market share, to as little as 1 h saved with 3 FVs or 48 min with 1 FVs at 1 % market share. Figure 67 translates these savings into monetary values for a range of different market shares. The bottom line represents the conditions in which all road traffic participants would be cars and the top line assumes all participants to be trucks. The maximum social congestion benefit has a range that lies in the green shaded area dependent on the composition of the road traffic. The maximum cost saving achieved for this route, in the best case savings scenario that all waiting traffic are trucks would be close to € 0,8 million. Any results where the VT has a market share smaller than 25 % are negligible. Given the fact that even VT implementation of 25 % of the market share can be considered large, a realistic implementation of the concept with about 10 % of the market share is not able to improve the VT case viability to penetrate urban areas. This demonstrates the importance of the point made in section 5.2.2 that only a large fleet share adopting the VT will create a societal benefit.

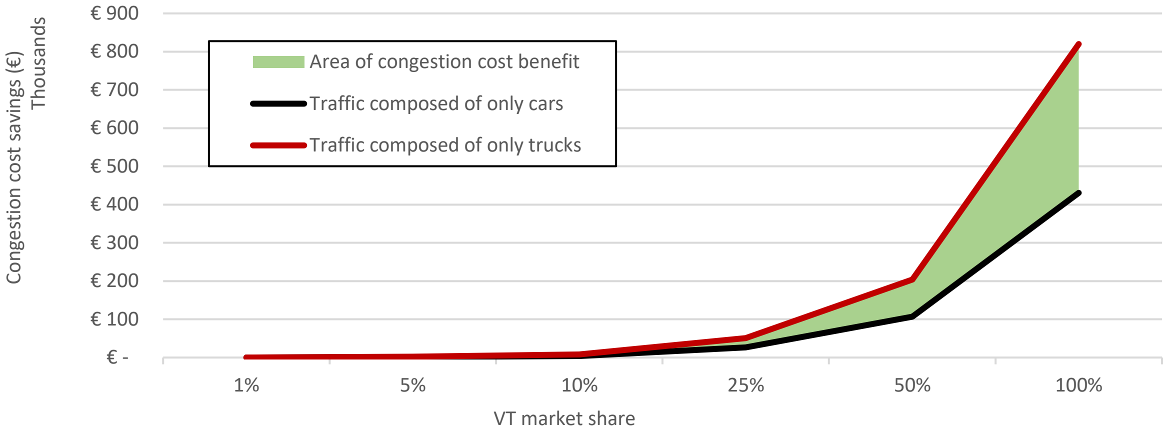


Figure 67: Congestion Cost-Benefit for Different VT Market Shares

It should be noted that based on the required number of participants and the return trips for the VT liner service given in chapter 5, around 4.000 passages are needed. These are more passages than the recorded annual cargo vessel passages for the route (see Table 37). If the other type of vessels are counted, including recreational vessels, the demand for the required number of vessel passages can be met, with the total passages reaching around 6.000. This means that the theoretical market share of 66 % of all participants, cargo and recreational vessel, would be needed to ensure economically viable VT operations to be achieved.

This final observation lets us conclude that the route can only be considered as an addition to the VT operations and not as its main service, as that would mean the cargo flows on these smaller waterways need to be larger. Alternatively, the business model of the VT operator would also have to be adjusted such that other types of waterway users can take advantage of the VT services as well.

6.2.5. General Guidelines for Implementation of VTs in Urban Areas

The case study application showed that the metropolitan area of Amsterdam is a challenging target for the VT implementation. This is mainly due to the road traffic intensity and short road distances to intersections. However, this case study is not representative of all urban areas. It could be viewed as a worst-case scenario.

Routes with less road traffic density would likely not fail at the bridge opening times feasibility check, but rather more likely at the number of simultaneous bridge openings.

The plots in Figure 68 are generic lookup keys that can provide guidelines to determine if a specific route can fit the requirements to pass the feasibility tests. The data accompanying these plots are provided in the appendix at the end of this chapter. The left plot provides bridge opening times based on various traffic conditions that can be crosschecked with the passage time of the desired VT length. This value can then be used in the right plot to determine if the bridge spacing along the route meets the minimum lengths. The right-hand key was explicitly set to accommodate vessel lengths of CEMT I-III, which are the vessel types sailing on smaller waterways in urban areas.

The minimum viable conditions from the lookup tables conclude that with an allowed traffic jam length of as short as 400 m, the maximum traffic intensity cannot surpass 550 vehicles per hour to ensure that at least a VT with one FV can pass. VTs composed of Class II vessels need a minimum bridge spacing of 400 m to ensure the passage of a VT with at least one FV.

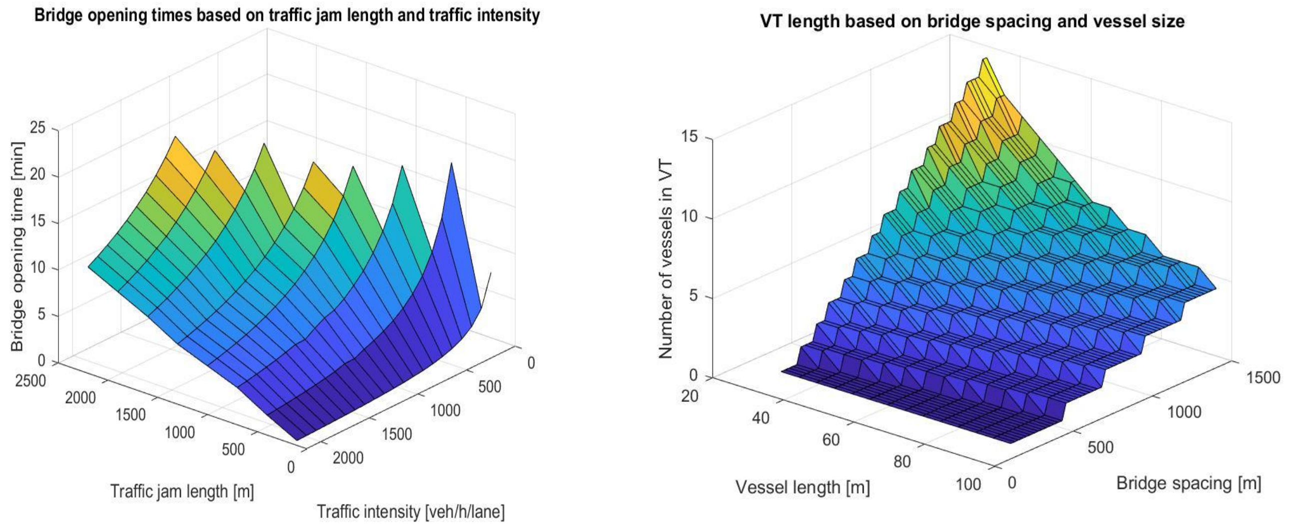


Figure 68: Generic Lookup Keys for VT Penetration of Urban Areas

6.2.6. Conclusion of Penetrating Urban Areas with a VT

This sub-section of the application case chapter presented the opportunities and challenges of applying the VT concept in urban areas. The model compares the road to the water traffic conditions and determines whether a given route is viable for the VT concept implementation. To demonstrate the application viability a route in the Dutch province of Noord- Holland is studied.

The main influence factors of urban penetration are: 1) Bridge opening time 2) Maximum number of simultaneous adjacent bridge openings. The number of adjacent bridge openings is highly dependent on road-based emergency traffic that needs to reach its destinations without significant delays. Yet, a rule of thumb is that no more than two adjacent bridges should be opened simultaneously. The viability of the VT operations fitting into the distance between these bridge openings is dependent on the geographical spacing of the bridges as well as the safety distances between vessels. Additionally, the VT operations would have to be targeted such that they fall outside of rush hours, yet still within the opening times of the bridges.

The case study has shown to be a challenging route for the seamless VT implementation and does not achieve viability for the entire route. In the metropolitan area of Amsterdam, the traffic on the road, even outside of rush hour, does not allow the bridges to be open for long enough to let a minimum VT of one FV pass together with the LV. It is expected that other urban areas may indeed achieve viability. This can be confirmed by cross-checking the general guidelines provided in this paper. The assessment of the congestion benefit showed that a maximum of € 0.8 million could be achieved over this single route when clustering all cargo vessels to pass with at least one other vessel. The VT would at least require a participation of 25 % of all cargo vessels passing for a noticeable congestion cost reduction to be achieved. Such a required fleet share is high for a target implementation of the VT concept.

The number of passages a viable VT liner service creates requires more vessel passages than the cargo vessels passages recorded along the route. This suggests that either the route can only be considered as an addition to the VT operations and not as the VTs main service route or other vessel types, potentially including recreational vessels, would have to be joining the train.

6.3. The Global Application Potential for the VT

The study of the application areas has compared the geographical application differences between the Danube and the Rhine region as well as the challenges of penetrating urban areas on smaller waterways, with its main focus on the European inland waterway network. The focus is justifiable given that the Rhine corridor is one of the two most advanced inland waterway transport corridors in the world, together with the Yangtze River in China [214]. The global potential for short sea shipping sector is not studied within this section as the results of chapter 5 have not been able to identify a robust application case for this sector. The focus is hence placed on the inland sector.

This section intends to contribute to the identification of the global VT application potential by providing a literature overview of the activities on inland waterways worldwide. Globally more than 650.000 km of inland waterways are used for commercial and recreational navigation. The inland navigation network in Asia is the largest that spans ~ 370.000 km, followed by the South American with ~ 130.000 km, the African with ~ 53.000 km, the European with ~ 52.000 km, the North American with ~ 42.000 km and the Australian with 2000 km of waterways [215]. The map in Figure 69 illustrates the largest of these waterways and makes it clear that the Rhine is one of the shortest rivers. Nevertheless, the majority of the river transportation is limited to the Rhine-Danube, Yangtze and the Mississippi river [216].

Based on the viability assessments performed in this chapter as well as chapter 5, the key geographically related VT success factors have been identified to be the route length, the crew cost and the traffic density, which can be reflected in the cargo volume and the fleet size. The fleet size aspect includes the fact that a large part of the fleet has to be composed of self-propelled vessels. Aside from these three main success factors, the implementation of the VT technology requires a certain standard of technological development within the inland navigation sector, which makes this an additional criterion to evaluate the implementation potential. Finally, the early-stage implementation of the concept also requires an environment of governmental support. Even though it has been shown that IWT might develop differently in different regions even if they make similar policies decisions [217], an indicator of funding availability for private companies and infer a potential success of the concepts' implementation. These five criteria are focused upon in the global comparison of the different inland navigation regions. Each of these criteria is presented in Table 40 and visually represented by the bars in Figure 69 where the geographical potential, the fleet size and cargo volume, the conditions of technological development, the government support/incentive creation and the average wage in the region indicative for the crew cost are illustrated per region.

It should be noted that the average income in Table 40 take into consideration the average income per country/region in which the rivers run. While these cost do not reflect the corporate cost of the employment, compared to the European crew cost information provided in Figure 59, it can be seen that these general averages are higher than the expected inland transport wages. Nevertheless, these average incomes provide a general awareness of the magnitude of the potential crew cost savings.

Figure 69: Worldwide Waterways and Most Relevant Rivers for Inland Navigation with VT Implementation Potential Indicators [218]

The Chinese inland waterway transport has by far longer than any European river and has the largest traffic with 4,9 billion tons of cargo moved per year. It is also the fastest-growing inland navigation sector worldwide having more than quadrupled since the year 2000 [216]. The vast majority of the cargo is moved on the Yangtze River (80 %) [219]. In 2011 the fleet was composed of about 110.000 self-propelled cargo vessels. About 50 % of vessels are less than 50 m in length, are operated by small captain owned businesses. Only 6,5% of the waterways can accommodate vessels larger than 1000 tons [219], when are then usually owned by larger shipping companies. All vessels are required to have AIS and VHF on board, but only the more modern and often larger vessels operating on these waterways with dense waterborne traffic, are meeting higher technological development standards, including electronic chart display and Information systems (ECDIS) and GNSS. The mix of new and old vessels means that the navigation technology standard on the Yangtze are in general, slightly lower than what can be found on the Rhine.

The Chinese inland navigation authorities allow 24 h operations [218], however, the manning requirements indicate that additional crew members are needed if more than 16 h of sailing operation time are surpassed for larger vessels. Smaller vessels require additional crew if they exceed 10 h of sailing operations [220]. Thereby the regulations do not specify operating regimes in the way that the European regulations identify them, yet limitations in operations do exist which means an improvement of productivities of the vessels can also be expected on Chinese waterways. While the VT benefit through the improvement of productivity can be achieved at least with equal if not better results in China, the benefits through the crew cost savings are much smaller. Even the lower Eastern European income identified along the Danube, is still higher than the average Chinese income. This means that the VT benefits are going to be much smaller. The higher departure frequency that can be accommodated due to the greater traffic density can compensate for part of the benefit reduction, but the

overall cost benefits are still very small. It could therefore be said that the inland navigation along the Yangtze fit in between the Rhine and the Danube corridor operations in terms of business structure, vessel type and technology.
The Chinese government has the strategic objective to heavily expand the waterway system to allow larger vessels to sail on longer stretches of the river these projects are mainly focused on infrastructural investment [216]. Simultaneously, it aims to develop the IWT into a market-based economy [221]. Given the progression speed, it is hence questionable if the step of automating the navigational tasks, that VT concept takes, is large enough to achieve sufficient market traction and governmental recognition for subsidy given the relatively small savings potential it holds with the crew size reduction on low wages.

The US inland navigation sector is with an annual cargo volume of 0,6 billion tons over a commercially relevant distance of 16.000 km, the second most traffic dense inland waterway region. The average transport distance is with 750 km the particularly advantageous for the VT operations [219]. This long-distance, however, also caused push barges to be the most widely used waterborne transport mode. Additionally, the transport system is mainly composed of about a dozen large transport companies [222]. Hence from a business structure and vessel type resembles the Danube case study. The VT would therefore have to be usable by the 4000 self-propelled vessels [223]. To avoid accidents on such a high traffic dense waterway, the technological development of the vessels also have comparable standards to the vessels in Europe, where for instance, AIS and Inland Electronic Navigation Charts (IENC) are widely used. The main business potential for the VT implementation in the US is their higher income per person. As seen from Table 40 it is on average higher than in Europe.
The funding of the waterway maintenance is half raised through private means and the other half is publically funded by the federal government and the U.S. Army Corps of Engineers [216]. A sales expert within maritime automation technology expects that the US market will wait for technologies to have proven themselves with the help of subsidies in the European or Asian markets, before American vessel operators are going to be willing to invest into technological development for their vessels [224].

The summary of the success factors of all other regions in Table 40 shows to be insufficient for a VT implementation in the short or medium term. This is the case even though in some regions the waterborne transport mode is of vital importance since it forms the means to access to certain parts of the population during floods or in areas with badly accessible terrain [225][226]. This means the need for inland waterway development there has an additional importance to the improved good transfer and traffic jam reduction is achieved in Europe.

On the Asian waterways such as along the Mekong the navigation conditions allow continuous operations [227], the river conditions in South America or Africa often only allow daytime operations [225]. Navigation technology systems such as AIS and ECDIS start to be introduced in South America [225], Asia [228] but also along the Nile [229]. However, these current onboard technologies of vessels are far from being a standard, which means there is no application case for the VT concept. A final noteworthy point is that the traffic density in Asia is larger than for the other two regions. The vessels used within these regions are, however, usually small and not comparable to the inland vessel standard used for the VT. For example, the 50.000 registered cargo vessels that the Vietnamese fleet is composed of is mainly formed of vessels with smaller than 50 m in length [230].

Table 40: Overview of the Worldwide Inland Navigation Potential

Regions	Main commercial rivers	Geographical potential	Current fleet size and cargo volumes	Conditions of navigation technology	Government support and incentive creation	Average annual income [231]	Ref.
USA	Mississippi, Ohio River	* 41.000 km of which 16.000 km commercially significant * 750 km average transport distance	* Cargo volume: 0,6 billion tons * Fleet size : 4.000 self-propelled vessels and 25.000 barges	High standard of technological development, IENC, AIS, GNSS and VHF are standard.	Waterway maintenance is 1/2 funded by the federal government & the U.S. Army Corps of Engineers and 1/2 by private users.	$ 65.850	[216] [219] [223]
China	Yangtze	* 110.000 km of which 24.000 km commercially significant * 630 km average transport distance	* Cargo volume: 4,9 billion tons * Fleet size: 108.733 cargo vessels	All inland vessels are required to have AIS and VHF. Some of the more modern vessels in particular larger ones on the lower Yangtze also have ECDIS and GNSS.	The government has a tendency to intervene into the market to initiate an appropriate allocation of resources. It tries to improve the conditions in the River region by developing a market-based economy.	$ 10.400	[219] [232] [233] [221]
Europe	Rhine, Danube	* 3.500 km navigable waterway * Average transport distance 290 km, (Rhine 200km, Danube 600 km)	* Cargo volume: 0,5 billion tons * Fleet size : 12.894 self-propelled vessels and barges	High standard of technological development, IENC, AIS and GNSS and VHF are standard.	To support technological development, the EU or local governments provide support funds.	$ 53.000 – $ 12.620	[219] [106]
Africa	Nile, Niger, Congo	* Navigable river length Niger (10.800 km), Congo (17.000 km), Nile (800 km)	* Cargo volume: Nile 3 million tons; Niger 450.000 tons * Fleet size: Nile 1.358 cargo vessels; Niger 139 cargo vessels	Nile: Some barges do not even have communication facilities onboard, however IENCs and GNSS coverage are in development.	There are insufficient funds or support capabilities by the federal governments to ensure appropriate waterway accessibility.	$ 2.900 - $ 590	[219] [234] [235] [236] [226] [229]
Asia	Volga, Ganga, Mekong	* Navigable river: Russia 102.000 km Vietnam 17.700 km India 14.500 km	* Cargo volume: Russia 118, 6 million tons; India 70 million tons; Mekong 3 million ton * Fleet size: Vietnam 50.000 registered cargo vessels < 1.050 t; Cambodia 506 cargo vessels	In most Mekong countries, AIS, GPS and ECDIS are voluntary. VTS is not available. Only in Vietnam vessels of more than 999 tons need compulsory AIS and GPS. There ECDIS become available.	IWT is acknowledged to bring economic prosperity to the region, but its implementation is constrained by the lack of appropriate governance mechanisms between authorities in different countries.	$ 11.260 - $ 2.120	[218] [227] [228] [230] [237] [238] [221]
South America	Amazon, Parana	* 13.000 km of Amazonian waterways are commercially used	* Amazon 5 million tons (expected 2023)	Navigation is reliant on the experience of the crew, where charts are at times still drawn by hand.	Some investments are put into the improvement of the waterways via for instance, dredging.	$ 9,100 – $ 5.520	[219] [225] [239]

6.4. Conclusions on the Effect of Application Areas on the VT Implementation Potential

Chapters 2 to 5 have not only developed an understanding of the VT concept and its influence factors but also described the modelling approach that allows the feasibility scenario analysis to be performed. This chapter enhances the work by adding perspective to understand regional and global application area differences that change the input data of the viability assessment. Hence, it reveals the application potential and answers the final sub-question on the effects of the geographical and spatial context on the viability of the VT.

In the first part of this chapter, a detailed comparison between the Rhine and Danube case was made, which shows the application of the single company business model to accommodate the larger company fleets that are present along the Danube. Additionally, with an increase in crew cost of 20 %, that is still in the realm of reasonable uncertainty variation from the Serbian crew cost, which are used as guiding figures, a route of 1400 km and a 6 h departure interval can still achieve economically viable conditions for the VT users. The case studied concluded a fleet share requirement of up to 11 % of the self-propelled Danube fleet. While this is possible to be achieved with the large transport companies along the Danube, the cargo volumes demand that is currently available for the self-propelled vessels is smaller than the VT service would create. Hence, it needs to be determined in what way push barges can be included into the train.

The second section of this chapter identified the challenges and opportunities that urban area penetration in VT formation entail. This is an aspect that mainly concerns the regional waterways in Belgium and the Netherlands. The VT can help cluster bridge openings in urban and metropolitan areas, which can result in a reduction of societal congestion cost. To make fully efficient use of the VT concept, careful scheduling of VT operations and also an adjustment of the opening times of infrastructures (bridges and locks) needs to be possible. The case study allowed to conclude that passing of a VT with at least one FV, without impacting road users, an allowed traffic jam length (distance to the nearest road crossing) of 400 m needs to be available with a traffic density of no more than 550 vehicles per hour. Also, a waterborne bridge spacing of at least 400 m is needed to ensure emergency vehicles can pass swiftly. A look at the waterborne traffic density has also concluded that the current cargo volumes are not large enough to cover the demand created by a regular VT service. It can therefore be concluded that the route of this case study can only be considered as an addition to the VT operations and not as its main service, as that would mean the cargo flows on these smaller waterways need to be larger.

The last section has developed a global outlook of the application potential of the VT concept. It identifies the main success facts to lie within the crew cost and the cargo volume/fleet size. Yet, other aspects involving of the geographical length of worldwide waterways, the development of navigation technologies used on board, as well as governmental support and incentive creations to develop the local IWT, have also been considered as important features for the VT implementation. The main areas of potential for the VT implementation lie within the US and the Chinese IWT markets, as they both have larger traffic densities than in Europe. The focus of the US market operations lie on push barges. It is not to be expected that the US market will be the first adopter of such a concept, even though their potential business benefit from the crew size reduction is expected to be the largest compared to other regions worldwide. In contrast, the Chinese market can be viewed as more appropriate for early-stage implementation given their large number of self-propelled vessels and the governmental support mechanisms for technological implementation. However, the government aims to develop the IWT sector into a market-based economy, which requires business potential. Given the low average income, which is even lower than it was studied along the Danube, the business potential is limited to the improvement of productivity as there are similar operating regimes as seen in Europe.

All other regions in the world may hold geographical potential with large rivers but have simply not far enough developed inland navigation sectors to even consider an application of the concept. It can therefore be concluded that the Rhine corridor is the most appropriate location for the VT implementation with its high wages as well as its current regulatory set-up that ensures for productivity increases to be gained and a governmental incentive to subsidize technological development in the IWT sector.

CHAPTER 7: CONCLUSIONS ON THE VIABILITY OF THE VT

The aim of this thesis is to assess the ways the VT concept can improve the competitiveness of IWT and short sea transport by assessing its viability for a variety of operating scenarios and areas with the main research question being:

What are the conditions for economic viability of the Vessel Train?

It is answered on the basis of the five sub-research questions that were defined in chapter 1.3:

RQ 1: What aspects of the vessel operations are altered when sailing in a platoon?
RQ 2: What are the VT properties influenced by in *the IWT and the Short Sea Sector?*
RQ 3: How can the viability of a VT transport system be assessed?
RQ 4: How do variations of the VT properties influence its performance?
RQ 5: How do geographical and spatial differences influence the possible implementations of the concept and its viability?

This chapter draws conclusions on the VT concept by explicitly answering the research questions with knowledge from: the workings and features of the VT, the input parameter variation and assessment of the concepts' viability and the geographical and spatial influences in section 7.1. It ends by providing an explicit answer to the overall research question on how the VT can improve the competitiveness of the two waterborne transport sectors. Section 7.2. closes by providing topics for further research related to training cost, cargo flow integration and cost-sharing strategies for VT users.

7.1. Conclusions Drawn Regarding the Research Questions

This sub-chapter addresses the answer to each research question presented in chapter 1. Section 7.1.1. answers sub-questions 1 and 2, while sections 7.1.2. through 7.1.4. respectively address sub-questions 3 to 5.

7.1.1. Defining the Altered Vessel Operations in a Platoon and the VT Properties

The most characteristic property of the VT compared to conventional vessels, is that all participants have the VTRadar and ArgoTrackPilot on board. The investment cost of this technology is expected to be small enough to allow small captain-owned businesses to be able to afford it. This VT control system technology, combined with either a dedicated or a cargo-carrying LV, that oversees the autonomous navigation track pilot, allows the FVs to reduce their crew size, and with it, the operating cost. Inland vessels have the added advantage that they can improve their productivity if they are currently sailing in a restricted A1 or A2 operating regime. As part of the train, they can sail during their resting times, which means they are moving for at least an additional six hours. A negative consequence of operating in a VT, is that additional waiting times are created when the participants gather before the departure, which results in productivity losses compared to the current operations. While this is an effect that can be compensated for by the improved productivity of some inland vessels, any continuously operating vessels i.e. short sea and inland vessels operating under a B regime, increase their lead time and decrease their productivity.

Joining the VT transport system is a long term decision: once the crew members have been taken off board, they cannot be rehired on a trip-by-trip basis. This means the current continuously operating vessel become dependent on the LV departure service to be able to perform at an equivalent operational standard. Additionally, if the VT makes use of cargo-carrying LVs, the FV operator also becomes dependent on the final destination and operating area of the LVs. Hence, in particular, short sea vessels that may require longer solo navigation capabilities to reach their final destination, lose flexibility when deciding to join the VT.

All VT participants also need to accept that the train's operating speed is dictated by the slowest member of the train. This means fast vessels suffer an additional increase in lead time and loss in productivity. However, this forced slow steaming creates additional fuel cost savings for the operator and also has a positive impact on polluting emissions. Whilst this is an effect that can result from VT operations, it is not restricted to the VT. Any vessel can choose to adapt its operations to save fuel cost.

An operational aspect that stays comparable to current vessel operation are lock passages. The autonomous navigation system is not able to perform complex special manoeuvres such as lock passages, from the LV supervision only. It is therefore expected that the FV operators take over during such obstacle interactions, just like in conventional vessels operations. Yet, the locks are located geographically too close to each other, calling upon the FV crew frequently, and does not allow them to achieve sufficiently long resting periods. The lock passages can become a showstopper for the overall concept.

7.1.2. Setting-up of the VT Viability Assessment

The viability of the VT transport system is assessed by setting up an assessment model which determines the potential cost savings of the VT implementation. At the core of the assessment lies the VT cost model that is founded on established SCBAs. This calculates the cost based on the dimensions of the vessels, operating regimes, VT liner service departures and environmental factors for both the inland and the short sea sector. The VT cost model enables the current vessel's operations to be compared to the VT operating conditions. The difference between these two operations enables viable VT operating requirements to be identified for both the FV and the VT operators. The model accommodates an analysis for a range of vessel types, operating conditions (i.e. operating speeds, journey length), varying maturities of the technology implementation and business structures for a liner operation of the train between two specific destinations. The outputs of the model include the identification of minimum operating distances, percentage time spent as part of the VT, the required VT length, required number of participants and hence also the required percentage fleet share.

The extensive literature of vessel cost models revealed a large number of different cost elements, which were not all integrated into the VT cost model, as some of them are of limited or no relevance to the VT concept. Additionally, a number of cost elements are either very hard to calculate, or lack data from a waterborne transportation environment. A thorough assessment has been described in chapter 3 that explains the relevance of the shortlisted cost elements, which are integrated into the viability assessment model. To conform with the standards of a complete cost-benefit analysis, third party cost elements such as societal cost due to pollution, but also the benefits due to the slower operations and the created modal shift are included in the assessment. Additionally, the perspective of the cargo owner is considered by calculating the additional safety and transit stock caused by the additional lead times of the FVs.

7.1.3. Understanding the Effect of VT Property Variation on the Performance

Two approaches have been used to obtain a clear indication on the effect of VT property variation on the performance of the concept. On the one hand, different scenarios are set up within the short sea and the IWT case study, i.e. the base case and the transition stage case as well as the Danube case study. Each of these scenarios varies the departure interval, the VT operator cost and the VT operating speed simultaneously, to demonstrate the effects of different implementation maturity levels.

The short sea assessment showed that faster short sea vessels are the main vessel types that benefit from the VT and can achieve economic viability, but this is mainly due to the slow steaming feature of the VT. Slower vessels also achieve economically viable conditions, yet they require minimum operating distances spent in the VT. The transition stage case can no longer achieve economically viable conditions for slower vessels and also requires the faster FVs to sail along in the VT for at least 150 km in order for savings to be made. Here the cost-savings between 3 % to 26 % can be achieved, the higher value are created when speed reduction occurs. A transport system requires between 2 % and 5 % of the European short sea fleet to participate.

A VT applied to the IWT sector manages to achieve a maximum transport cost reduction of between 30 % and 50 % dependent on the vessel type, and an operating regime of the reference vessel conditions with a fully matured control system. In the transition stage, this reduces down to 17 % to 41 %. The smaller class II vessels, manage to achieve the greatest cost reduction potential, as crew cost makes up 61 % of their annual operating cost. In the inland application, the difference between the early-stage and the fully-matured technology implementation, creates a noticeable difference in cost savings. These mainly affect the number of required FVs per LV and participants as part of the transport system. Even though many of the transition stage FV lengths surpass the maximum technical length, the tool of governmental subsidies may be needed to help bridge the time until the technology has fully proven itself and gained trust by VT users. This is because clear societal benefits have been identified with regard to pollution reduction. The part of the assessment that internalizes the societal cost-benefit manages to achieve an additional 10 % to 25 % transport cost reduction dependent on the route length and vessel type.

The second method of assessing the effect on the performance is through sensitivity analysis. The assessment compares the changes in cost savings caused by a 1 % variation in the input parameter. Given the high dependence of the short sea case on the fuel-cost savings, it is not surprising that the most variation is caused by fluctuations in fuel price, followed by the route length, and departure frequency t can tip the scales between viable and unviable conditions within a waiting time frame of 3 h. The smallest effect of the four studied parameters is created by crew cost variation, which demonstrates the secondary importance of crew size reductions compared to slow steaming operations. All parameter variations cause changes in savings between 1,72 % and 0,1 % respectively to the most and least influential parameter. Seeing the uncertainty in the SS input data variation, operations cannot be guaranteed for all types of vessels.

The sensitivity analysis of the inland vessels, currently operating at restricted operations, indicates the route length variation has the greatest effect, followed by the crew cost-saving and the VT operator cost. Seeing that there are longer waiting times for inland operations, it is also not surprising to see that departure intervals are in fourth place, allowing a viable waiting time frame of 10 h, followed by the variation in navigating days. Finally, the low operating speeds mean that the fuel cost has the least impact on cost variation. A 1 % input data variation here causes between 0,3 % to 0,08 % of cost-saving variation. An inland vessel that currently operates continuously, on the other hand, is more reliant on crew cost-saving and on the departure interval as its main benefit is created via the crew cost savings and its main disadvantage is the loss of productivity. A 1 % variation of the VT properties causes between affects the cost-savings between 1,1 % and < 0,01 %.

The assessment of the inland applications VT property variation allows one to conclude a much more robust business case, than the volatile business model identified for the short sea sector. This is due to the fact that the IWT case can achieve benefits due to a productivity increase as well as the crew cost savings, whereas the short sea case is mainly dependent on the fuel cost-savings, with a comparably small addition of the crew cost-savings. While the fuel cost savings are cost benefits, they can be viewed as artificial benefits because they do not allow for better service, nor do they truly improve the pollution emission of the transport mode, since the technology of the prime movers on board of the vessels are not pushed to evolve.

7.1.4. The Effects of Geographical and Spatial Context for the Application Potential of the VT

The main geographically influenced success factors hinge on the route length, the crew cost and the traffic density on the rivers. Lower crew cost savings can be compensated for by long distances and frequent departure intervals, which are as close as possible to an on-demand service. The fairly low Danube crew cost, which only makes up about 20 % of the Rhine crew cost, manages to achieve viable conditions for the larger self-propelled vessels with a trip length of 1400 km and a departure interval of 6 h. The supply of self-propelled vessel transport volumes that would be created by such a transport system is much more than the demand currently requires.

Geographical differences cause diverse evolutions of business structure and fleet compositions. Along the Rhine, a large fraction of the vessels are self-propelled and captain-owned, whereas along the Danube, most transport companies are operating a large number of push barges, and self-propelled vessels only make up a small percentage of the fleet. The variation in fleet size between the Danube and the Rhine operating fleet has an impact on the minimum required fleet share, which makes up to 11 % and less than 1 %, respective to the corridor. This increase in fleet share requirement is not necessarily a problem, as a larger transport company can compose an entire train of its own fleet. However, larger companies are more likely to operate their vessels continuously, which means the Danube adaptation of the VT will not take advantage of the productivity increase achieved along the Rhine.

Spatial limitations like inconveniently spaced locks require the FV crew to take over navigational responsibility every few hours. This would eliminate the navigation benefit created by the VT. The VT operator, therefore, have to operate a service along a journey such that it is not only long, but clusters any possible lock to a specific part of the route. Spatial limitation from bridge passage in urban areas requires road traffic to at least allow a traffic jam creation of 400 m with a maximum traffic intensity of 550 vehicles/h. The waterborne infrastructure should also allow for a minimum bridge spacing of 400 m so that a VT with at least one FV to pass without creating an additional traffic jam.

In a global comparison of waterways, the Rhine is the shortest of the most traffic dense rivers. It is also comparably less affected by the environmental conditions, as it is held at high maintenance standards and is located in an area of the world that does not suffer as much from wet and dry season fluctuations. Aside from the European waterway, only the US and Chinese traffic densities, fleet size, and technological developments would allow for the potential implementation of the VT. It has been concluded that the Rhine corridor is the most appropriate location for the VT implementation with its high wages, current regulatory set-up that ensures for productivity increases to be gained and a governmental incentive to subsidize technological development in the IWT sector.

7.1.5. The Conditions of Economic Viability of the Vessel Train

The VT concept achieves economically viable operations for FVs that join the VT liner service lead by a cargo-carrying LV, between two destinations. The VT is able to reduce the operating cost of a vessel by lowering the crew cost and by increasing the productivity of vessels that currently operate at a restricted operating regime. These improvements come at the expense of additional waiting times and a loss of flexibility.

The short sea sector application managed to identify individually economically viable cases, for large and fast vessels, which are mainly due to the adoption of slow steaming operations of the VT. The crew cost savings achieved on their own, cannot compensate for the loss of productivity created due to the additional waiting time and flexibility loss since the FVs become reliant on the LV. Instead, the FVs need the benefits created by slow steaming, which is not unique to the VT operations. This means that no convincing case could be conclusively made for a wide-scale application across the short sea sector as a minimum level of savings cannot be guaranteed.

The inland sector application demonstrates a more solid application case. The Rhine region case, which has a high income and high traffic density, achieves a savings potential of up to 51 % dependent on the vessel and the reference vessel operating regime. Such a VT liner service would require less than 1 % of the current self-propelled Rhine vessel fleet to be part of the service, making it relatively easy to implement. Nevertheless, the study of the geographical and spatial context has revealed that areas with lower incomes cause the VT concept to suffer a significant reduction in savings potential and thereby make achieving viable operating conditions unlikely. It was shown that in lower-income regions viable conditions can only be achieved with long routes of approximately 1400 km and a frequent departure interval of for instance 6 h. Such a high departure frequency would require a larger number of vessel passages along the waterways than are currently available. The viability can additionally be significantly impaired by inconveniently spaced lock or bridge passages. For viable VT operations, lock passages along the route need to be clustered in a limited timeframe of the trip as they require the FV crew to take over navigational control. Bridge passages in urban areas on the other hand need a minimum bridge spacing of 400 m so as not to require more than two simultaneous adjacent bridge openings.

The study of a route in an urban area with relatively high traffic density compared to other canals in urban areas, has concluded that there is a lack of sufficiently large cargo flows along those waterways which will inhibit the VT to use access to urban areas as part of its main business model. Although the original VT concept was intended to enhance the attractiveness of smaller vessels, it is unlikely that smaller vessels will benefit from a VT penetration into urban areas if it is not a main business model for the VT operators. For it to become the main business model additional building blocks for the waterborne transport chain would be needed, that can improve the waterborne transport sector as a whole and increase the cargo flows along waterways. Such building blocks could for instance include faster cargo handling systems that could help reduce the lead time.

The conditions of economic viability for the four case studies presented in this research are summarized in Table 41.

Table 41: Conditions of VT Economic Viability of Four Case Studies

Short Sea Case	IWT Rhine Case	IWT Danube Case	IWT Urban Areas
• Vessels with fast operating speeds (e.g. ≥ 30 km/h)	• Class II & IV vessels require a fully mature technology to ensure viability operations on shorter routes	• Larger vessels class IV and V	• VT length: 1 - 6 FVs
• Departure intervals: 6 h	• Maximum departure interval every 34 h (B operating regime) and every 22 h (A1 operating regime)	• Current vessel operating at a B regime	• Maximum road traffic intensity of 550 vehicles/h, if traffic waits at most 400 m in front of a closed bridge
• Minimum participants: 10 – 90 (LV & FVs)	• Minimum participants: 12 – 36 (LV & FVs)	• Fully matured control system (no additional monitoring crew)	
• Required fleet share: < 1 % - 3 %	• Required fleet share: < 1%	• Required fleet share: 8 - 11 %	
• Minimum operating distance for FVs: 224 km - 773 km	• Minimum operating distances: none for larger vessels, up to 300 km for Class II vessels	• Requires ~20 % higher crew wages than are officially paid in Serbia	• Minimum bridge spacing of 400 m
• High crew wages (crew savings achieves € 154.000)	• High western European wage levels	• High departure intervals: 6 h	• ~ 4.000 vessel passages are needed by the VT which is 66 % of all currently passing vessels
• Willing to operate slow steaming	• Percentage of time required to be spent in the VT (30 % - 100 % dependent on the vessel type)	• A route with clustered lock passages	
• Willing to be restricted to LV operating area		• Long routes: ~1.400 km	
• High fuel prices		• Single company business model	

The assessment of the worldwide application potential of the VT concludes that the Rhine case is the most suitable early-stage implementation bed for this concept, with another possible alternative being the Yangtze River in China. The Yangtze river has a high traffic density and even though the incomes are low the vessels also operate in restricted operating regimes, which allows them to also achieve a productivity gain.

7.2. Points for Further Research

As was seen in the research contribution in section 1.4, the points for further research can also be split into points for further scientific research and managerial and legal actions that need to be taken in make a VT implementation possible.

7.2.1. Further scientific research

The assessment performed in this research is a simplification of the real-world complexity in order to obtain an overall understanding of the VT potential. To ensure that the VT concept assessment covers more of this real-world complexity, further research should include more detailed cargo flows and research into the logistics capabilities of individual ports. This makes it possible to also apply a wider network assessment, with potentially several routes along which the VT operates. A more detailed assessment of the cargo flows and the transport network will allow the potential for modal shift to be estimated, which can add an additional benefit created by the VT implementation. This would also require studying the competitiveness of the waterborne platoon in comparison to other modes of transport in a multi-modal context.

Another point of real-world challenge integration includes an assessment of the VT concept on port operations, which for instance include the clustered port arrivals. Such an assessment could be done in form of time-domain simulations or using queuing theory, to determine the effects on waiting times. From a VT operator perspective, an important point for further scientific investigation lies in identifying pricing strategies based on a variety of FV types. These strategies would need waiting time cost allocation between FVs, but also fairness strategies from the perspective of the VT operator. The VT operators could, for instance, receive subsidies to help enhance the use of smaller inland vessels, which means they would need to operate in areas favourable for smaller vessel operations.

A further research aspect is related to the fact that LV operators need to be aware of the behaviour of different vessel types in confined waters. The main reason why push convoys have not been included as viable FV options in the VT concept, is their larger size, slower speeds and more limited manoeuvrability, which make it more difficult to judge the convoy’s behaviour in the train. Further research needs to focus on ensuring a better understanding of the roles of push barges in the VT. This can allow a wider range of potential customers, which means a smaller overall fleet share requirement. Allowing a VT adaptation for push barges increases the application area potential of the concept for corridors such as on the Danube or the Mississippi corridors.

7.2.2. Further managerial and legal action for a VT implementation

In order for the implementation of the VT concept to be possible, the legislative challenges need to be tackled by regulatory authorities such as the IMO or the CCNR. These include allowing unmanned bridges, which requires the technology developers to demonstrate an inherently safe design that allows for quick reaction times to be achieved by the FVs crew. Such regulatory challenges need to include the VT as a new transport entity within the navigation regulations.

Once such regulatory aspects are understood by the lawmakers, and it is clear what actions need to be taken, in order to allow regulations to change to accommodate VT, more concrete steps towards implementation can be taken. Here more work needs to be put into concretizing and developing the online platform that is the base for the platform-based VT business model on the Rhine. This not only includes, the physical development of an online platform that allows the booking of the FVs with the VT, but also determining the responsibilities and liabilities between the VT coordinator and the LV operators.

For these regulatory and legal actions to be taken there needs to be a business entity that takes on the challenge of the VT integration. Even though monetary benefits for, in particular the Rhine, have been identified, such positive business cases are not the only requirement for a VT concept implementation. The VT operator would need to have contacts to vessel operators, their trust and their willingness to cooperate with their competitors, in addition to expertise in logistics and platform management as well as knowledge on how to achieve regulatory bodies to approvals for such a business. It needs an entity that is willing to convince the market that such an endeavour is worthwhile and to embrace the change. As by the status of the end of the NOVIMAR project, an entity that has both the willingness and expertise to realize the VT concept has not yet been identified in the market.

This research investigated the automation of the navigation tasks, just one of many sub-systems on board a vessel. It has shown that a business application of incremental development of automation technology onboard vessels can be achieved for specific vessel types in certain regions but cannot be guaranteed for a large scale worldwide application. When reflecting on Figure 3 in chapter 2 that illustrates the incremental vessel type implementation path, to autonomous vessels versus the incremental technology implementation path, it can be said that the path leading towards the future of autonomous vessels is not likely to follow one of the paths. Instead, research on both the incremental vessel type implementation and the incremental technology implementations are needed. This allows technological progress and cultural changes to be adopted on board of the existing fleet, while technological solutions are found that allow for larger business economic impact to be accommodated.

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ANNEX

Table 42: Bridge Input Data

Ref.	*Bridge name*	*Bridge Heights (m)*	*distance to next bridge (km)*	*annual number of average bridge openings for cargo*	*Road data vailability*
1	OudeWeteringbrug	**2,7**	2,24	**1568**	No data
2	Leimuiderbrug	**2,5**	7,32	**2615**	Available
3	Aalsmeerderbrug	**2,5**	5,37	**2125**	Available
4	Bosrandbrug	**1,4**	0,74	**1735**	No data
5	Schipholdraaibrug	**3,4**	0,13	**250**	Available
6	Schipholbrug (brug in A9)	**7,9**	3,28	1659	Available
7	Schinkelspoorbrug	**8,1**	0,03	1659	Available
8	Schinkelbrug (metrobrug)	**8,1**	0,03	1659	No data
9	Schinkelbrug (brug in A10)	**7**	1,6	1659	Available
10	Zeilstraatbrug	**2,7**	0,43	1659	No data
11	Theophile de Bockbrug	**2,5**	0,35	1659	No data
12	Overtoomsebrug	**2,4**	0,82	1659	No data
13	Kinkerbrug	**2,5**	0,7	1659	No data
14	Wiegbrug	**2,5**	0,68	1659	No data
15	Beltbrug	**2,9**	0,45	1659	No data
16	Van Hallbrug	**2,6**	0,47	1659	No data
17	Kattenslootbrug	**2,5**	0,4	1659	No data
18	Willemsbrug	**2,7**	0,1	1659	No data
19	Singelgrachtspoorbruggen	**6**	0,5	1659	Available

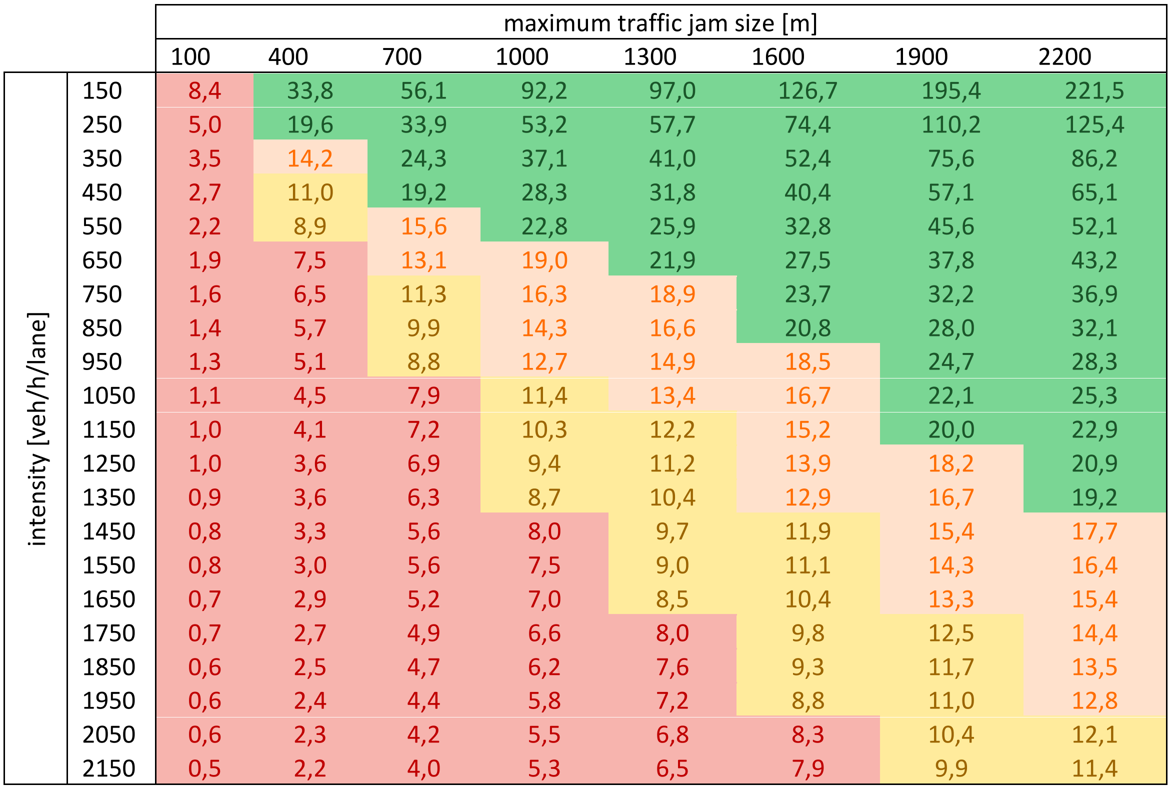
The red values of the bridge heights indicate that the bridge needs to open to let cargo vessels pass. The bold values of the average number of annual bridge openings for cargo vessels based on the available data from the bridge management system. All other values are the average of the available data.

Table 43: Available Road Traffic Data

Ref.	Measurment point	Average day			Rush hour			Max jam length [km]
		Intensity [veh/h/lane]	Speed [km/h]	Vehicle length [m]	Intensity [veh/h/lane]	Speed [km/h]	Vehicle length [m]	
2	Leimuiderbrug, downstream, links	363	88	4,3	869	84	4,2	0,8
2	Leimuiderbrug, upstream, links	328	79	4,5	806	30	4,0	1,0
3	Aalsmeerderbrug, downstream, links	186	84	4,3	508	88	4,0	0,2
5	Schipholdraaibrug, upstream, links	189	74	5,9	643	71	4,6	0,8
6	Schipholbrug, downstream, rechts	798	93	4,6	1223	71	4,2	0,6
6	Schipholbrug, upstream, rechts	1000	95	4,6	1463	85	4,2	2,7
6	Schipholbrug, upstream, links	809	88	4,6	1250	68	4,2	0,6
6	Schipholbrug, downstream, links	875	96	4,6	1360	84	4,2	2,7
7	Schinkelspoorbrug, upstream, links	1132	79	4,6	1798	60	4,2	1,1
7	Schinkelspoorbrug, downstream, rechts	1224	87	4,6	1897	74	4,2	1,8
9	Schinkelbrug, downstream, links	1621	86	4,6	2138	75	4,2	0,9
9	Schinkelbrug, downstream, links	909	92	4,6	1702	78	4,2	1,8
9	Schinkelbrug, upstream, rechts	972	91	4,6	1714	78	4,2	2,3
19	Westerkeersluis, downstream, links	438	59	4,2	772	56	4,3	0,2
19	Westerkeersluis, upstream, links	356	54	4,2	650	52	4,1	0,1
	Average	746,6	83,0	4,6	1253	70,3	4,2	1,2

Assumptions made for this data:

- During the day, all the lanes except for the emergency lanes were used. Only during rush hour, all the lanes, including the emergency lanes, were used for traffic.
- The data only consist of working days, weekends and public holidays were excluded



		maximum traffic jam size [m]							
		100	400	700	1000	1300	1600	1900	2200
intensity [veh/h/lane]	150	8,4	33,8	56,1	92,2	97,0	126,7	195,4	221,5
	250	5,0	19,6	33,9	53,2	57,7	74,4	110,2	125,4
	350	3,5	14,2	24,3	37,1	41,0	52,4	75,6	86,2
	450	2,7	11,0	19,2	28,3	31,8	40,4	57,1	65,1
	550	2,2	8,9	15,6	22,8	25,9	32,8	45,6	52,1
	650	1,9	7,5	13,1	19,0	21,9	27,5	37,8	43,2
	750	1,6	6,5	11,3	16,3	18,9	23,7	32,2	36,9
	850	1,4	5,7	9,9	14,3	16,6	20,8	28,0	32,1
	950	1,3	5,1	8,8	12,7	14,9	18,5	24,7	28,3
	1050	1,1	4,5	7,9	11,4	13,4	16,7	22,1	25,3
	1150	1,0	4,1	7,2	10,3	12,2	15,2	20,0	22,9
	1250	1,0	3,6	6,9	9,4	11,2	13,9	18,2	20,9
	1350	0,9	3,6	6,3	8,7	10,4	12,9	16,7	19,2
	1450	0,8	3,3	5,6	8,0	9,7	11,9	15,4	17,7
	1550	0,8	3,0	5,6	7,5	9,0	11,1	14,3	16,4
	1650	0,7	2,9	5,2	7,0	8,5	10,4	13,3	15,4
	1750	0,7	2,7	4,9	6,6	8,0	9,8	12,5	14,4
	1850	0,6	2,5	4,7	6,2	7,6	9,3	11,7	13,5
	1950	0,6	2,4	4,4	5,8	7,2	8,8	11,0	12,8
	2050	0,6	2,3	4,2	5,5	6,8	8,3	10,4	12,1
	2150	0,5	2,2	4,0	5,3	6,5	7,9	9,9	11,4

Green: allows viability for all VTs; Orange: allows conditions for viable trains with three to six FVs (assuming safety distance of 1,5); Yellow: allows minimum viable conditions of one FV to be met; Red: Not viable

		Average vessel length [m]													
		35	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
Minimum bridge spacing [m]	**100**	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	125	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	175	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	200	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	225	2	1	1	1	1	1	1	1	1	1	1	1	1	1
	250	2	2	1	1	1	1	1	1	1	1	1	1	1	1
	375	2	2	2	2	1	1	1	1	1	1	1	1	1	1
	300	2	2	2	2	2	1	1	1	1	1	1	1	1	1
	325	3	2	2	2	2	2	1	1	1	1	1	1	1	1
	350	3	3	2	2	2	2	2	2	1	1	1	1	1	1
	375	3	3	3	2	2	2	2	2	2	1	1	1	1	1
	400	4	3	3	3	2	2	2	2	2	2	2	1	1	1
	425	4	3	3	3	2	2	2	2	2	2	2	2	1	1
	450	4	4	3	3	3	2	2	2	2	2	2	2	2	2
	475	4	4	3	3	3	3	2	2	2	2	2	2	2	2
	500	5	4	4	3	3	3	3	2	2	2	2	2	2	2
	525	5	4	4	4	3	3	3	3	2	2	2	2	2	2
	550	5	5	4	4	3	3	3	3	3	2	2	2	2	2
	575	6	5	4	4	4	3	3	3	3	2	2	2	2	2
	600	6	5	5	4	4	3	3	3	3	3	2	2	2	2
	625	6	5	5	4	4	4	3	3	3	3	3	2	2	2
	650	6	6	5	5	4	4	3	3	3	3	3	3	2	2
	675	7	6	5	5	4	4	4	3	3	3	3	3	3	2
	700	7	6	5	5	4	4	4	4	3	3	3	3	3	3
	725	7	6	6	5	5	4	4	4	3	3	3	3	3	3
	750	8	7	6	5	5	4	4	4	4	3	3	3	3	3
	775	8	7	6	6	5	5	4	4	4	3	3	3	3	3
	800	8	7	6	6	5	5	4	4	4	4	3	3	3	3
	825	8	7	7	6	5	5	5	4	4	4	4	3	3	3
	850	9	8	7	6	6	5	5	4	4	4	4	3	3	3
	875	9	8	7	6	6	5	5	5	4	4	4	4	3	3
	900	9	8	7	7	6	5	5	5	4	4	4	4	3	3
	925	10	8	7	7	6	6	5	5	5	4	4	4	4	3
	950	10	9	8	7	6	6	5	5	5	4	4	4	4	4
	975	10	9	8	7	6	6	5	5	5	4	4	4	4	4
	1000	10	9	8	7	7	6	6	5	5	5	4	4	4	4
	1025	11	9	8	8	7	6	6	5	5	5	4	4	4	4
	1050	11	10	9	8	7	6	6	6	5	5	5	4	4	4
	1075	11	10	9	8	7	7	6	6	5	5	5	4	4	4
	1100	12	10	9	8	7	7	6	6	5	5	5	5	4	4
	1125	12	10	9	8	8	7	6	6	6	5	5	5	4	4
	1150	12	11	9	9	8	7	7	6	6	5	5	5	5	4
	1175	12	11	10	9	8	7	7	6	6	5	5	5	5	4
	1200	13	11	10	9	8	7	7	6	6	6	5	5	5	5
	1225	13	11	10	9	8	8	7	7	6	6	5	5	5	5
	1250	13	12	10	9	8	8	7	7	6	6	6	5	5	5
	1275	14	12	11	10	9	8	7	7	6	6	6	5	5	5
	1300	14	12	11	10	9	8	7	7	7	6	6	5	5	5
	1325	14	12	11	10	9	8	8	7	7	6	6	6	5	5
	1350	14	13	11	10	9	8	8	7	7	6	6	6	5	5
	1375	15	13	11	10	9	9	8	7	7	6	6	6	5	5
	1400	15	13	12	11	10	9	8	8	7	7	6	6	6	5

Red: not VT viable; Blue: a mature VT economically viable; Dark blue: early state VT economically may be viable depending on the operating regime of the reference vessel; Green: VT is viable for most conditions.

LIST OF CONFERENCE AND JOURNAL PUBLICATIONS

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C. Benson, P. Sumanth & **A.Colling**, (2018). Standing on the Shoulders of Giants: How the Maritime Industry can Leverage Developments in Autonomy from other Domains. 14th INEC.

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ABOUT THE AUTHOR

“Alina Colling was born in Germany, grew up in France, lived and studied in UK and moved to the Netherlands for her masters and subsequently her PhD. Having been through such diverse cultures and ideas made Alina open to fresh ideas, new experiences while being warm, supportive and empathetic with everybody she interacts with. Alina brings a lot of enthusiasm and energy in both professional and personal settings which makes everybody enjoy the journey as much as the destination.

Alina started off her technical education by completing a bachelors, where she developed a keen interest in ships and composites materials. After graduating with Honors in her Bachelors study at Plymouth University, she pursued a masters in Maritime Technology at TU Delft specialising in Ship Design Production and Operation. She spent her master thesis investigating an automated manufacturing solution for custom-made composite components of Superyachts. Alongside her studies, she managed several ISO certifications in Supply Chain Foundation, Risk Management Foundation and Business Continuity Foundation. She was offered a PhD position at TU Delft to support the development of Vessel Train transport and operations. You find the details of her work in this thesis. As the next chapter, Alina is now bringing her skills into the industry as a Global Product Specialist at ABB Marine and Ports in Norway.

In her spare time, Alina is an avid dancer, investor, runner and seems to be eternally enthusiastic for relaxed evenings with board games and wine. Conversations with her have always been insightful, joyous and have opened new avenues!“

Written by friend and colleague: Pranav Sumanth