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A Viability Study of Waterborne Platooning on the Lower Rhine

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To achieve a modal shift towards waterborne transport and to deal with the shortage of crewmembers, a platooning concept called the "Vessel Train" is explored for the inland navigation sector. A Vessel Train consists of a lead and various follower vessels. The lead vessel is fully manned and takes over the navigational and situational awareness responsibilities for the follower vessels. This leading action benefits the followers through increasing the vessels' productivity and enabling crew cost savings.

This article investigates the viability of the concept for the lower Rhine region, by presenting a cost model that compares the Vessel Train conditions to the current sailing conditions. This model is used to assess a case study where lead vessels operate on a liner service between Antwerp and Duisburg. Economically viable cases for the concepts' early-stage application and fully matured implementation are identified, and boundary conditions are presented. The viable conditions vary depending on the vessel type and the operating regime of the reference vessel. A fully matured VT implementation requires a minimum of 26 participants, whereas an early-stage implementation requires 40 participants. The early-stage implementation additionally includes a minimum distance of 200 km to be spent sailing in the VT and the distance sailed in the VT has to amount to a minimum of 50% of the entire trip.

Keywords: *waterborne platooning, inland navigation, Vessel Train, reduced crew cost, sailing regime.*

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1. Introduction

The original meaning of the word ‘platoon’ refers to a subdivision of soldiers that forms a tactical unit (English Oxford Living Dictionaries, 2018). This definition has been adopted by the transport sector to describe a formation of transport units to reduce the operating cost the participants. In the past decade, the concept of platooning transport units has been studied to help improve the effectiveness of current transport systems. This has been done for road-based transport via truck platooning. Bhoopalam et al. (2018) provide a comprehensive overview of the research done for the truck platoons. The European Automobile Manufacturers Association expects multi-brand platoons to be able to drive across Europe’s motorways by 2023 (Lockwood, 2016).

The study of waterborne platoons, is less advanced; its implementation using refit existing vessels is researched by the NOVIMAR project[4]. There, the platoon of vessels is referred to as a Vessel Train (VT). The VT concept uses one fully manned Lead Vessel (LV), which is equipped with navigation and control systems, allowing it to take over situational awareness and navigation responsibility for the Follower Vessels (FV), while they sail in the platoon, as seen in Figure 1. This permits the FVs to sail with a smaller crew and thus reduce the crew cost. The crew cost can be up to 70% of the annual cost of an inland vessel (Beelen, 2011). While the FVs benefit from achieving crew cost savings, the LV receives an extra source of income, aside from the transport of its cargo, as it provides the leading service to the FVs. The cost savings achieved aim to increase the modal shift towards waterborne transport and enhance navigation into smaller waterways. Simultaneously, the VT implementation helps to deal with the predicted shortage of qualified crew in the inland sector (Danube Commission, 2018; de Leeuw van Weenen et al., 2013) and enables modernization through refitting the fleet.

The NOVIMAR project investigates the technical aspects of the VT in terms of the development of a semi-autonomous navigation control system, from a regulatory, safety and human factor perspective by identifying achievable crew size reductions and from an economic perspective by developing business models and using the output from the other topics to perform a cost-benefit analysis. This latter point of performing an economic feasibility study is the research presented in this article.

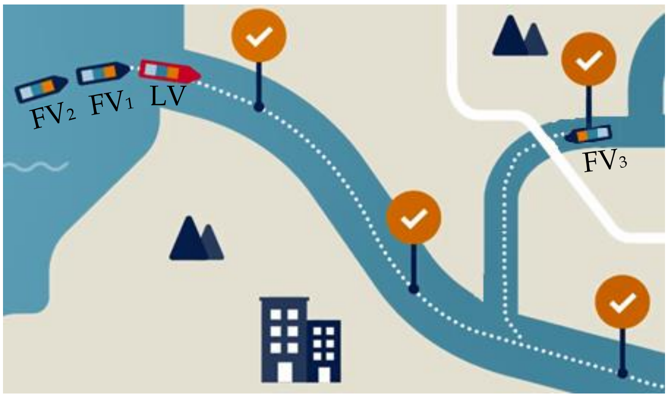

Figure 1. The Vessel Train Concept (Vessel Train, 2018)

The “Train” analogy found in the concept’s name, allows a comparison to be drawn for a reliable and predictable service. In this article, these operational needs are achieved by setting a fixed schedule on a specific route for the VT operations and allowing the users to join and leave the train at a port of their choice. The LVs are cargo carrying, are set to operate on a liner service between two ports and depart when they are ready. These departure intervals and adjustments to the operating speed of the VT, cause waiting times for the FVs. It has to be ensured that the cost created by the VT control technology and transport system does not outweigh the benefits it creates.

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[4] NOVel Inland water transport and MARitime transport concepts, https://novimar.eu/

The payment scheme in which the followers pay the VT operators for their services is comparable to the mobility service subscription as described by Kamargianni et al. (2016). This FV subscription fee needs to cover the LV and other VT operating cost. The VT concept can be compared to a shipping pool (Haralambides, 1996) that shares the LV expenses with all participants and simultaneously improve their own productivity.

This article focuses on the application of the VT in the inland sector, specifically the lower Rhine, which reaches from the north sea estuary to Bonn, Germany, as seen in Figure 2. The implementation of the VT concept in the inland sector allows for benefits to be achieved through an improvement in vessel productivity, even by vessels where the crew size cannot be reduced, according to existing operating restrictions. Inland vessels fall under one of three sailing regimes; A1, A2 or B, which allow for 14h, 18h or continuous operation of the vessel, respectively. The operating regime of a vessel depends on the number and the skillset of the crew members on board. The LVs 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 independent sailing operations. The additional crew members needed to allow for these added operating times are navigating the LV. The crew members on board of the FVs can rest while they are part of the train. Under specific sailing regimes, the FVs can thus benefit from an increase in productivity as well.

The research question this article answers is:

What are the VT boundary conditions and properties that enable an economically viable implementation of the VT concept on the lower Rhine?

The research discusses the requirements for a successful application of a VT transport system for the supply side, hence focusing on the VT and vessel operators. A cost-benefit assessment is performed to demonstrate the economic viability of the concept. It addresses waiting times caused by departure intervals of the VT, the combination of different vessels in the same train through varying operating speeds and identifies the number of required participants in the transport system. Boundary conditions for viable business cases are marked, i.e. cases where the VT operator at least breaks even and the cost per ton-kilometre of transport performance for the FVs is equal to or lower than the cost of an identical vessel that does not use the VT concept. Safety aspects such as achieving timely reactions on the FVs in case of emergencies or the addition of navigational regulations for safe operations with and around a VT are an important aspect of the VT implementation. However, both the safety and regulatory aspect are considered out of scope for this research.

The article starts by providing a background in *Literature Review*. This is followed by the *Methodology* section describing the calculation of the cost-benefit analysis. The *Case Study* presents the route and elaborates on the input data. Here the different vessel types, cost information and two sub-cases are described that aim to mimic different stages of the concepts' implementation. The R*esults* present the VTs effect on the vessels productivity and the cost contribution of an FV as its trip length increases, sailing both in and outside of the VT. This gives an indication of the expected amount of time an FV needs to spend in a VT and the number of vessels needed in the transport system to make the cases economically viable. The *Discussion* section addresses the uncertainties around crew cost before the C*onclusion,* summarises the main observations and provide recommendations for further research.

2. Literature review

A variety of different literature sources can be found that are of relevance to the VT concept. This section presents both comparable waterborne transport projects and prior research on inland navigation cost models upon which the assessment in this paper is based.

The research projects DSSITP (Macharis et al. 2011), BARG TRUCK (2010) and INLANAV (Van Hassel 2011) focusing on small barge convoy systems. The projects aimed to optimize cargo transport usage for small inland waterways and address the shortage of crew members in the inland sector. The WATERTRUCK+ project is the pilot implementation of a small barge system composed of 18 barges that resulted from the mentioned projects (Watertruck+, 2019). These literature examples show that the problems that barges face are similar to the ones the VT concept needs to address as well. The VT differs mainly in its focus on self-propelled cargo vessels and the emphasis on implementing a semi-autonomous navigation system on board of the FVs.

A core part of the VT concept assessment is the development of the cost model. Sample studies such as Lyridis et al., (2005) look at the effect of automating navigational tasks on an ice breaker, whereas Verberght (2019) has made an appraisal of the use of fully autonomous inland vessels fueled by LNG instead of diesel. Other prior research on cost modelling specifically for inland vessels was performed by Beelen (2011), which focuses on understanding the structure and modelling of existing inland shipping operations and Hekkenberg (2013) that looked at ways of reducing cost on inland vessels by altering vessel dimensions. These sources have developed cost models, from which elements are integrated into the assessment of the VT model. The common aspect of these cost models is that they calculate the cost of current operations and compare that to a new scenario involving their strategy of waterborne transportation improvement. The same approach is used in this paper.

The literature on waterborne platooning applications is limited. Other than Chen et al.'s (2018, 2019a; 2019b) work that is written from a system control perspective for the application on autonomous ships, only the NOVIMAR project researches, among other aspects, the economic viability of waterborne platoons. Relevant publications from this project include Meersman et al., (2020) and Colling and Hekkenberg (2019, 2020). Meersman et al., (2020) present an extensive overview of direct and societal cost for a variety of different scenarios in which the vessels could choose to join the VT for individual trips. This paper adds to this research by addressing the waiting times created through the implementation of the VT, and by taking operating regimes into consideration. It also identifies how such a concept could be integrated from the transport systems perspective with a subscription payment by the VT users. Colling and Hekkenberg (2019) describe the benefits and drawbacks of a cargo-carrying versus a dedicated LV and Colling and Hekkenberg (2020) research the viability of the VT concept for a short sea application.

3. Methodology

The method section describes the cost calculations and introduces the two sub-cases that represent different levels of maturity of the concept.

3.1 Modelling approach

This article identifies the economic viability of the VT to be achieved when:

1. the transport cost of the VT user is equal or lower than that of the currently sailing reference vessels;
2. when the combined subscription fees of the FVs at least cover the costs of the VT operator created by providing the leading service.

This definition implies that savings achieved by an FV sailing in the train compensate for the productivity loss, defined as the tonnes of cargo transported per year, for the vessel operator due to waiting time before departure and the fee to be paid to the VT operator. It also assumes that there is a direct correlation between the time savings or losses and the amount of cargo moved annually. Additionally, it is assumed that all VT participants split the cost compensation for the VT operator equally between themselves through the subscription fees.

A cost model has been set up, to determine economically viable VT conditions. It includes depreciation, interest and insurance as a fixed capital cost; crew, maintenance and administration cost as running cost and the fuel cost as voyage cost. Most of these cost elements, except for the maintenance and fuel cost, are calculated as a function of the new building price of the vessel. This is a common approach that was adopted by for example, Kretschmann et al. (2015), Grønsedt (2014), Lyridis et al. (2005), van Hassel (2011), Verberght (2019). The cost estimation method to calculate the new built price and the maintenance of an inland vessel are taken from Hekkenberg (2013). It estimates the maintenance cost based on the installed power on board.

There are four main variables that influence the implementation of the VT concept. These are the fuel cost changes due to the difference between a vessel's normal operating speed and the speed imposed by the VT, the cost of the VT control system, the crew cost and the productivity of the ships. The fuel cost is determined using Holtrop and Mennen (1982) resistance prediction method. This standard method has been slightly adapted to take shallow water effects into account by replacing the form factor calculation with the RhineShip86 method as described by Zeng et al., (2019). The specific fuel consumption is determined as a function of engine loading, as defined by Caterpillar 3406E (Caterpillar, 2001).

The cost of the VT control system is estimated as part of the NOVIMAR project. The installation of the VT track pilot software and hardware (i.e. antenna or distance sensors) on board of the vessels are estimated by Argonics Gmbh (2017) to be € 80,000. The depreciation time of this technology is set to be five years. The VT control system cost is the only VT related cost for the FVs. The LV cost is dependent on the level of development of the control system. If it is not fully matured to an autonomous system, monitoring crew members need to be considered as part of the cost to provide the leading services. In this model, no other LV cost are relevant, as the LV is a cargo-carrying ship. The revenue of cargo transportation covers all other non-VT related cost (Colling and Hekkenberg, 2019). Apart from the VT control system cost, the VT operator also needs to consider the platform cost that allows the coordination of the VT participants. This cost includes software cost, but also shore-based staff and offices and are presented as part of the input data in the case study.

A reduction in crew cost is one of the main benefits the VT system offers since the navigation tasks on all followers are taken over by the control system on the LV. The minimum required crew for the different sailing regimes and per vessel are provided by CCNR guidelines (CCNR, 2016). These guidelines are split into three categories, dependent on the ship length. Table 1 summarises the minimum crew requirements per sailing regimes and indicates the number of crew members saved by the change from the original sailing regime of the reference vessel to an A1 regime. For example, a Class V vessel of 110 m with a B original sailing regime achieves a crew size reduction of two crew members per crew. There are two crew rotations splitting their time onboard to allow a vessel to operate continuously under a B regime. Hence, four crew members can be saved. The four members are the maximum number of crew members that can be saved in any conditions. The difference in minimum crewing requirements for A2 scenarios of medium or smaller vessels only achieve small cost savings by replacing a more expensive crew member with a cheaper one. The A1 conditions do not achieve any crew cost savings as those are the defined minimum crew left on board of the FVs.

Table 1. Minimum Crew Requirements

	L > 86 m			70 m < L ≤ 86 m			L ≤ 70 m		
	A1	A2	B	A1	A2	B	A1	A2	B
Total	3	4	5	3	3	4	2	2	4
Annual Reduction in Crew Size on FVs	0	2	4	0	0*	2	0	0*	4

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

The productivity of vessels is influenced by various factors. Port times (including time spend on actions such as (un)loading, berthing, bunkering) also influence a vessels' productivity but are not specific to VT operations. These port times are adjusted depending on the size of the vessel. FVs are further affected since they have to comply with the speed of the VT rather than being free to choose their own speed. As we are dealing with inland navigation, the vessel speeds are influenced by currents experienced on the river. The vessels are set to operate along the same route length all year. Hence, the length of this route, as well as the amount of time spent sailing and resting per day are also factors of influence.

Equation 1 describes the calculation of the trip time (t_t). The first term is representative of the sailing time of the vessel during the return trip, the second term of the resting times and the third term describes the additional trip times such as waiting times in port. This way of calculating the trip time is slightly adapted in the denominator of all productivity (P) Equations 2 and 3, yet the three terms are still representative for the parts of the trip. The productivity equations are adapted to be representative for the reference vessels conditions (R) at their original sailing regime *i* and the FV conditions. The latter is provided for both approaches in which the FVs only operate within the VT and approaches in which the FV also sails part of the trip under its own navigational control. The operating hours of a vessel operating both in and out of the VT (T_{B+A1}) is given by Equation 3. Each of these equations are used later in the article.

The final component of Equation 3 that is yet to be identified, is the VT operating speed (v_{VT}), expressed by Equation 5. The departure interval of the train is set with the assessment scenario, as is described in later section 4.5. 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.

$$v_{VT} = \frac{d}{I*n_{LV}-2t_p} + \sqrt{\frac{d^2}{\left(I*n_{LV}-2t_p\right)^2} + v_c^2} \tag{5}$$

Where: I: departure interval of the LVs (h) n_{LV}: required number of LVs in the transport system

$$t_t = \frac{2dv}{v^2-v_c^2} + \frac{\frac{2dv}{v^2-v_c^2}}{t_{s_i}} t_{ri} + 2t_p \tag{1}$$

$$P_{Ri} = \frac{T_i}{\frac{2dv}{v_R^2-v_c^2}+\frac{\frac{2dv}{v_R^2-v_c^2}}{t_{s_i}}t_{ri}+2t_p} 2V \tag{2}$$

$$P_{FV} = \begin{cases} \dfrac{T_B}{\left[\frac{2dv}{v_{VT}^2-v_c^2}+\frac{\frac{2dv}{v_{VT}^2-v_c^2}}{t_{s_B}}t_{rB}+2(t_p+t_w)\right]} 2V\,, & if\ \ d_{FV} <= d_{LV} \\ \dfrac{T_{B+A1}}{\left[\frac{2d_{in}v_{VT}}{v_{VT}^2-v_c^2}+\frac{2d_{out}v_R}{v_R^2-v_c^2}+\frac{\frac{2d_{out}v_R}{v_R^2-v_c^2}}{t_{s_{A1}}}t_{rA1}+2(t_p+t_w)\right]} 2V, & otherwise \end{cases} \tag{3}$$

$$T_{B+A1} = \left(\frac{d_{in}}{d_{FV}} * D_B + \frac{d_{out}}{d_{FV}} * D_{A1}\right) 24 \tag{4}$$

Where:

A1: Operating regime that allows 14 h operations
B: Operating regime that allows 24 h operations
d: VT trip distance (km)
d_{in}: distance of the FV spent in the VT (km)
i: original sailing regime of the reference vessel
P_R: annual productivity of the reference vessel (t/year)
T_{B+A1}: Annual operating days of the FV in/outside of the VT (h/year)
t_p: time spent in port (h)
t_s: sailing time (h)
t_w: VT waiting time due to VT departure (h)
v_c: speed of river current (km/h)
v_{VT}: operating speed of VT (km/h)

A2: Operating regime that allows 18 h operations
D: annual number of operating days
d_{FV}: FV distance (km) i.e. $d_{out} + d_{in}$
d_{out}: distance the FV spends sailing on its own (km)
P_{FV}: annual productivity of the FV (t/year)
T_B: annual operating hours at operating regime B (h/year)
T_i: total annual operating hours at operating regime i (h)
t_r: time spent resting (h)
t_t: trip time (h)
v: operating speed of the vessel (km/h)
v_R: operating speed of the reference vessel (km/h)

As the FV productivity is influenced by the VT operating speed, some more emphasis has to be placed on how the FV waiting times are determined. 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 is assumed, which makes the average waiting time to be half the departure interval.

The productivities of the reference and the FV, together with the cost of the reference vessel (C_R) can provide an FV cost using Equation 6. This FV cost is the maximum allowed cost that ensures FVs to perform with at least equal transport conditions as conventional vessels.

$$C_{FV} = \frac{P_{FV}}{P_R} C_R \tag{6}$$

Where: C_R: annual reference vessel cost (€)
C_{FV}: annual follower vessel cost (€/year)

By subtracting VT cost and adding VT benefits to the maximum FV cost, the net savings for the FV can be determined. These can also be viewed as the maximum contribution fee an FV can pay to participate in the VT. Equation 7 provides the calculation for this contribution fee. A positive contribution fee indicates economically viable conditions for the FV operators.

$$C_{fee} = \ net\ savings = C_{FV} - C_R + \Delta_{crew} + \Delta_{fuel} - C_{VT} \tag{7}$$

Where: C_{VT}: annual VT technology cost (€)
Δ_{crew}: change in annual crew cost (€)
Δ_{fuel}: change in annual fuel cost (€)

To ensure the VT conditions are also economically viable for the VT operator, the revenue from the FV operators has to outweigh the cost created by the LV through providing the leading services. This means a minimum number of FV participants are required. Equation 8 provides the mean of calculating these for all different operating conditions.

$$\mathrm{n}_{FV} = \frac{C_{LV}}{C_{fee}} \tag{8}$$

Where: C_{fee}: annual VT technology cost (€)
C_{LV}: annual LV cost created by providing the leading service (€)
n_{FV}: required number of FVs per LV

The developers of the VT technology in NOVIMAR identified a technically viable maximum VT lengths that allow for a line of sight between the LV and the last FV. On the Rhine, this means the VT can have a maximum VT length of 1 km. This is estimated to be a composition of five FVs. This is dependent on the safety distance identified between vessels as well as the current hardware used that requires line of sight. When using an alternative communication method, this length may be improved; hence the five FVs can provide a guideline for a general understanding but does not make the concept technical unfeasible if the vessels surpass this length.

The modelling approach is applied in different cases to allow an all-rounded conclusion to be drawn from the VT assessment. First, a reference case is set that is used as a benchmark of existing operations. Then the VT concept is assessed based on two scenarios: the Base Case and the Transition Stage Case. These cases assume different development stages of the concept and help identify potential challenges arising on the way to full implementation.

The Base Case (BC) represents the conditions in which the VT is fully established in the future waterborne transport system. This assumes that the technology is sufficiently developed not to need any monitoring crew on board the LVs. A fully established transport system also implies that a large number of participants are likely to be involved with the concept. Thus, assuming a sufficient number of vessels are involved in accommodating shorter departure interval. The reasoning behind calling this situation the Base Case is that it is the scenario with the ideal conditions and thereby forms the base of the viability assessment. If the viability cannot be shown for this case, then any worse conditions will also not be implementable.

The Transition Stage Case (TSC), mimics the early stages of the VT implementation. It assumes more challenges with a lower number of participants (both LV and FVs) and a less-developed VT control system. The VT control system is therefore assumed to require supervision in the form of monitoring crew on board of the LVs, to ensure the safety of the FVs. The smaller number of participants means that the departure interval for the TSC is longer.

4. Case Study

This section serves to present all necessary input data for the application case. First, the route is described, then the main vessels types, together with their main parameters and respective crew cost are introduced. Then a brief section concerning the VT technology cost is provided, followed by a discussion about the reference case, which benchmarks values and illustrates the cost breakdown of the reference vessel cost. The last two sections give the input data differences for the BC and TSC.

4.1 Route

The transport system assessed in this case study is a liner service of inland lead vessels, to which the FV can sign up via a digital platform. The service 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 2. 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 (DuisPort, 2020).

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 (viaDonau, 2016) which lies within the operating distance of the VT. Under normal water conditions, the current on the Rhine is 4 km/h (Schweighofer *et al.*, 2018). Even though this can vary significantly throughout the year, for this specific application case, no further environmental factors are considered.

Figure 2. Operating Area of the Case Study

4.2 Vessel Types

Table 1 in the method section, identified three main vessel length categories for which the CCNR guidelines vary. Hence, three vessel types fitting each of these categories have been chosen for this assessment. 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 2. The fuel consumption slightly differs between each vessel class and is set at an 80% maximum continuous rating of the engine. The added fuel consumptions at different engine loads are modelled on the properties of the Caterpillar 3406E (Caterpillar, 2001). The fuel price is set to 800 euro per tonne. The cargo capacity of the vessels is indicated in tonnes, as that is the cargo unit of dry bulk vessels that make up a large fraction of the Rhine fleet. The vessels could also be container vessel, in which case the capacity would be indicated in TEU, where 1 TEU weighs approximately 14 tonnes.

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 (Malchow, 2010). 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 (Staadsblad van het Koninkrijk der Nederlanden, 2011). The average of these values are used as the port times for the different vessel classes in Table 2. Even though these port times are not VT specific, in combination with the waiting times created by the VT departure intervals, successful application conditions may be impacted by larger port times.

Table 2. 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)	1071	435	376
SFC (g/kWh)	210	218	230
Capacity (t)*	2200	1500	600
Operating speed (km/h)	16	15	13
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 and FVs. Table 3 provides the annual percentages that make up the capital and administration cost based on the building cost estimates.

Table 3. 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)	360

4.3 *Crew Cost*

Crew cost are dependent on the number of crew required on board, see Table 1. Simultaneously, they are also highly influenced by the wage of different roles. There are no established workers agreement for wages. In this article, the crew wages are taken from a Dutch wage table (QUOVADIS, 2018). This wage table does not include employment-related cost (e.g. rotations, travel arrangement, supplies) or indirect crew cost (e.g. sick pay, social dues, agency fees). In order to estimate these extra cost, the crew cost model of Ghaderi (2018) is used. Ghaderi identifies the extra cost to make up to 30% of the total crew cost. The annual crew cost under different sailing regimes and the corresponding annual crew savings are provided in Table 4 and are based on Table 1. When comparing these savings, it becomes apparent that the savings diminish for vessels IV and II that currently operate at an A2 regime.

Table 4. Annual Crew Cost and Saving for the Different Operating Regimes

Vessel Class	Annual Cost			Annual Crew Cost Savings	
	B	A2	A1	From B	From A2
V	€ 488.800	€ 134.800	€ 99.700	€ 389.100	€ 35.100
IV	€ 392.000	€ 105.100	€ 98.400	€ 293.600	€ 6.700
II	€ 377.600	€ 75.600	€ 69.600	€ 308.000	€ 6.000

Source: Based on QUOVADIS (2018)*, adjusted by the authors, rounded to the nearest € 100 and corrected for inflation*

4.4 *VT Cost*

The VT cost is split into the VT control system cost that each vessel participating in the VT has to consider based on the VT control system investment and the platform cost needed to coordinate the independent parties.

There are five cost elements that are based on the investment cost € 80.000 for the VT control system presented in section 3.1. Table 5 presents the breakdown of each of these elements and results in the annual VT control system cost of € 24.200 per vessel.

Table 5. Cost Breakdown of the Annual VT Technology Cost

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

In addition to the VT control system, that each LVs needs to be compensated for, a platform cost for the coordination of the vessels needs to be accounted for in the subscription model transport system. This platform cost is evenly distributed over the number of LVs in the transport system and will therefore be paid as part of the FV contribution fee.

Rental of office spaces and software licences, updates and other overheads are estimated to be € 50.000, where € 10.000 is the expected annual fee for offices and screens in the remote control centre of the port of Antwerp. The coordination and maintenance of the platform 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 organizer also operates the LVs and has a profit margin of 20%

on the total cost. In case the VT operator is an independent agent from the LV operators, additional margins need to be added. However, these are dependent on the VT companies pricing strategies, which will not be considered at this stage of the development of the concept.

4.5 Reference Case

The reference case serves as a means to benchmark the current operating conditions. This section identifies the differences between the vessel types by taking a look at the cost breakdown and provides a sample of the reference vessel data to which the VT conditions are later compared.
Table 6 presents the scenario-specific values upon which the reference cost calculations are based. These are calculated using equation 1. The values presented are representative of the LV trip length of 325 km and at the reference vessel operating speed, as presented in Table 2.

Table 6. Time and Productivity Information of Reference Vessels

Item	Sailing Regime and Vessel Type								
	B			A2			A1		
	V	IV	II	V	IV	II	V	IV	II
Return trip time (h)	158	155	135	173	170	154	189	188	175
Annual number of return trips	55	56	64	35	36	39	32	32	35
Annual productivity (t)	202400	168000	76800	154000	108000	46800	140800	96000	42000

Cost Breakdown

The pie charts in Figure 3 illustrate the importance of the crew cost of a continuously operating vessel. This crew cost is more significant with decreasing ship size, making up to 65% of the total cost on class II vessels, as seen in Table 7. The second most significant cost contributor is the capital cost (deprecation, interest and insurance cost) followed by the fuel cost. When looking at the cost breakdown changes of the two most extreme sailing regimes in Table 7 it is clear that these changes cause dramatic shifts. Under an A1 sailing regime, the most crucial cost factors become the capital cost followed by the fuel cost for the larger vessels. In contrast, for vessel classes IV and II, the crew cost is still the second most important cost contributor.

Seeing this cost breakdown also emphasizes that the investment cost to refit the vessels with the VT technology is small compared to other cost elements. It is, therefore, not expected that a cost variation in the technology cost presented in section 4.1. will have an impact on the results.

Table 7. Cost Breakdown of the Three Sample Vessels at their Original Service Speed for a 325 km Trip

Cost Elements Operating regime	Vessel Type					
	V		IV		II	
	B	A1	B	A1	B	A1
Depreciation	12 %	22 %	12 %	21 %	9 %	22 %
Interest	12 %	22 %	12 %	21 %	9 %	22 %
Insurance	2 %	3 %	2 %	3 %	1 %	3 %
Maintenance	2 %	3 %	2 %	3 %	1 %	2 %
Crew	47 %	18 %	51 %	23 %	65 %	28 %
Fuel	19 %	21 %	16 %	17 %	9 %	12 %
Admin	6 %	11 %	6 %	11 %	5 %	11 %
Total	**€ 1.031.000**	**€ 560.000**	**€ 766.000**	**€ 420.000**	**€ 581.000**	**€ 250.000**

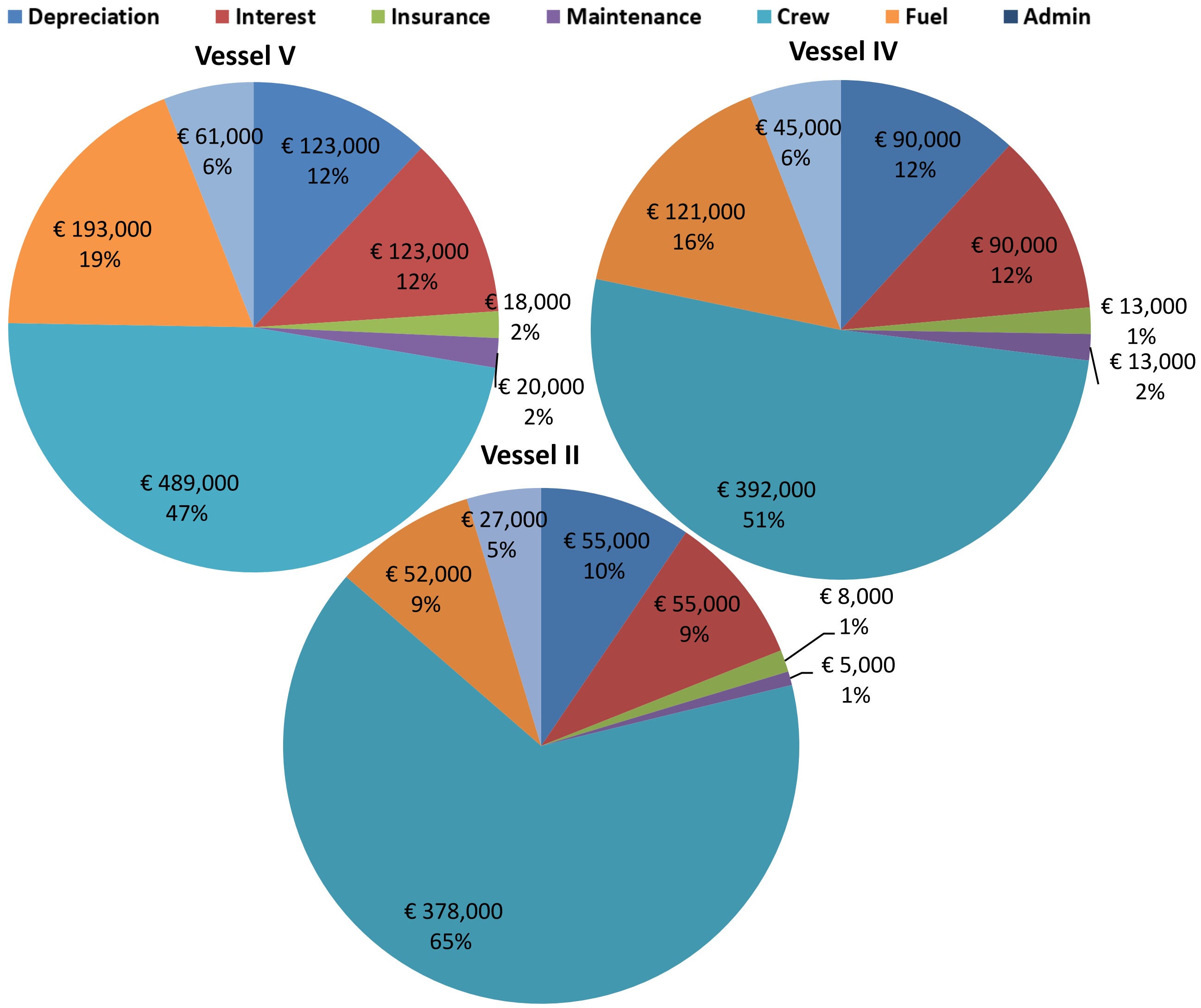

Figure 3: Cost Breakdown under B Operating Regime

4.6 Base Case

The larger number of participants assumed in the BC allow a departure of an LV every 6 h. This departure interval influences the time it takes to complete a journey since it creates waiting times for FVs. The average waiting time is half the departure interval, i.e., 3 h for the BC.

The LV is assumed to operate in a normal liner schedule with predetermined time slots in ports, which strongly reduces waiting times that are usually seen for inland vessels. An LV port time of 10 h is set, which is sufficient time to (un)load even a class V vessel. The VT operating speeds for the BC are determined using Equation 4 and gathered in Table 8.

The number of LVs also influences the VT operator cost, which needs to be compensated for by the FVs. Based on the input data provided in section 4.1. the compensation per LV is calculated, see in Table 8, vary by € 4.500 per LV.

Table 8. **VT Speeds and LV Requirements under the Base Case**

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

4.7 Transition Stage Case

The early-stage implementation of the TSC assumes a departure interval to be one LV per day, meaning that an FV waiting time of 12 h is created. The monitoring crew is assumed to be composed of two crew members dedicated to keeping the FVs safe. These are in addition to the standard crew operating the LV. As the LVs are rotating two crews to operate continuously annually, a total of four extra crew members have to be added to the cost. The cost of each of these crew members are assumed to be similar to that of a helmsman. A crew member of this skillset costs the vessel operator € 50.000 per year. The LVs have to be compensated an additional € 200.000 on top of the VT technology cost from Table 5. This adds up to an annual LV cost of € 224.200. The platform cost and profit margin are distributed over the number of LVs. The compensation cost are provided in Table 9 and vary by nearly € 30.000 per LVs.

The larger departure intervals limit the VT operating speeds that can be assessed without adding any waiting times to the LV. For the TSC only two slower speeds can be achieved, as seen in Table 9. The longer departure interval requires fewer LVs over the 650 km distance.

Table 9. VT speeds and LV Requirements under the Transition Stage Case

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

5. Results

The results of the assessment are given for each vessel type compared to all three sailing regimes of their currently operating counterparts. First, the results from the BC are shown. This BC also includes sample calculations to illustrate the working of the model. After that, the results of the transition stage case are presented.

5.1 Base Case

The first step of the sample calculations the percentage of productivity change based on equations 2 and 3. The sample conditions are for a class V vessel, over the full 325 km in which the VT sails at 12,5 km/h and compared to a reference B sailing regime. The full range of results showing the changes in productivity are given in Figure 4 and Figure 5.

Step 1 $\%\ Productivity\ change = -11\%$

Figure 4 and Figure 5 illustrate the productivity change of the vessels as a function of the distance travelled for each of the three sailing regimes. The black vertical lines on the plots indicate the point of separation of the VT. Any FV sailing for longer distances will need to sail part of the distance under its own navigational responsibility with its A1 crew requirement. 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. This restriction explains the more notable drops every ~100 km, where the trip length does not fit into the A1 operating hours and additional resting times are needed.

The B regime conditions show negative productivity as the added waiting time and the reduced speed forcibly causes longer trips than the reference vessel that operates continuously. Longer trips mean fewer trips annually, hence the number of transported tonnes per year decrease too. When comparing the negative productivity changes of the different vessel types at their B regime, the productivity of the class II vessel suffers the least. This is due to its shorter port times, which allows the smaller vessels to make up more round trips than the larger ones.

The productivity changes significantly as soon as scenarios are considered that allow the FVs to sail through their resting times while being part of the train. The productivity changes of the A2 regimes are smaller than those of the A1 regime. This is due to the additional 4 h operating time gain of the A1 regime. 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 is caused by different port times.

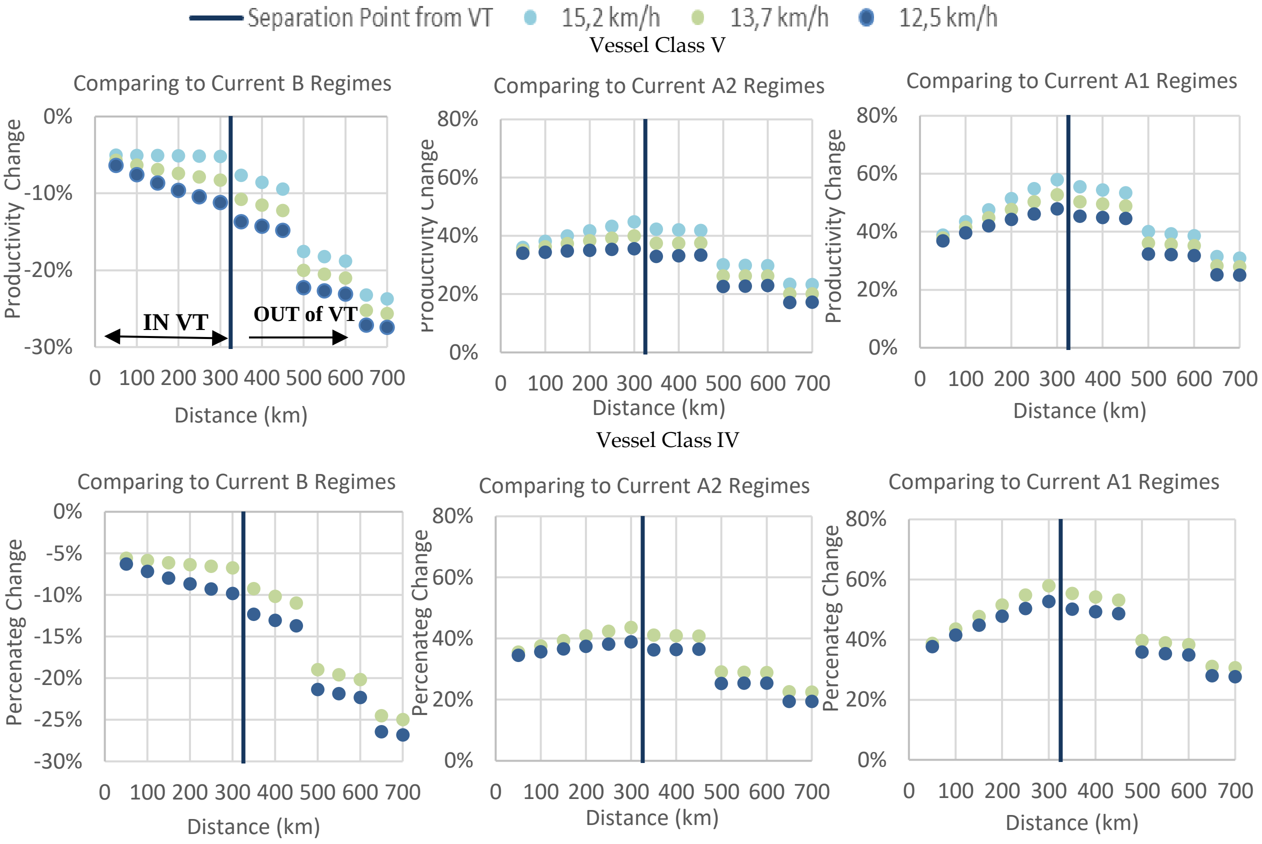

Figure 4: Productivity Change Plots For Vessel Class V and IV

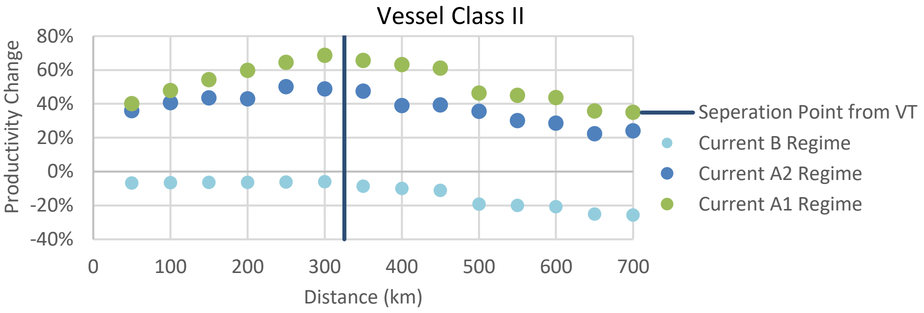

Figure 5: Productivity Change Plot For Vessel Class II

The maximum FV cost is shown via the sample calculation in step 2, which is based on equation 6. This result is then used in the contribution fee calculation shown in step 3, based on equation 7, where € 193.400 is the fuel cost at reference conditions and € 111.700 is the fuel cost at FV conditions.

Step 2 $C_{FV} = \frac{211.200}{237.600} € \, 1.027.000 = € \, 914.000$

Step 3 $C_{fee} = € \, 914.000 - € \, 1.027.000 + € \, 425.100 + (€ \, 193.400 - € \, 111.700) - € \, 24.200 = € \, 369.600$

The results are plotted in Figure 6 and Figure 7. It is noticeable that the operating speed variation affect the VT contribution fee reasonably little, even with the high fuel price that would cause the fuel cost difference to increase. The higher speed increases fuel consumption and eliminates the benefit created by the productivity increase. For instance, in the sample case of the class V vessel compared to a B regime, the difference in maximum FV cost between the 12,5 km/h and the 15,2 km/h is about € 57.000. The fuel cost increase makes up about € 55.000, thereby leaving € 2.000 more savings for the FV operator. This small cost difference is negligible.

The comparison of the three operating regimes shows that both the crew cost savings can be achieved for the B regimes, and the productivity improvements can be demonstrated for the A1/A2 regimes. The lower VT compensation cost 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.

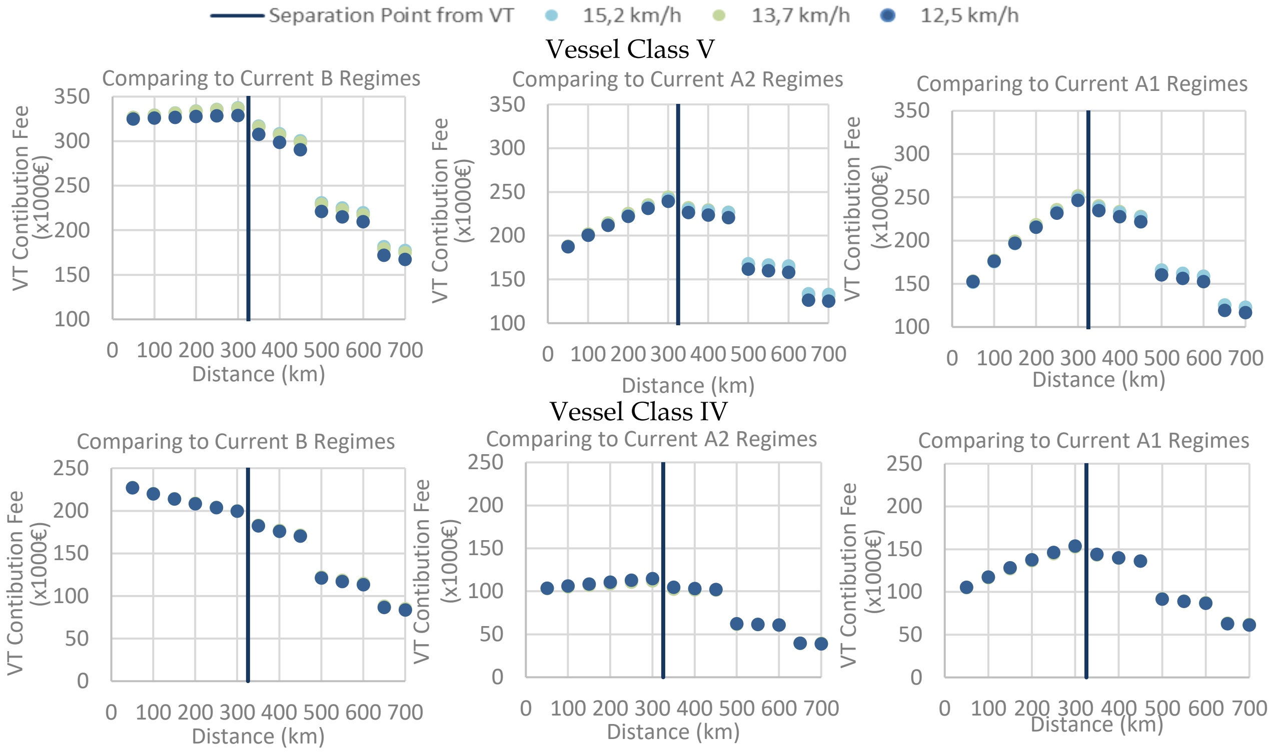

Figure 6: VT Contribution Cost Plots For Vessel Class V and IV

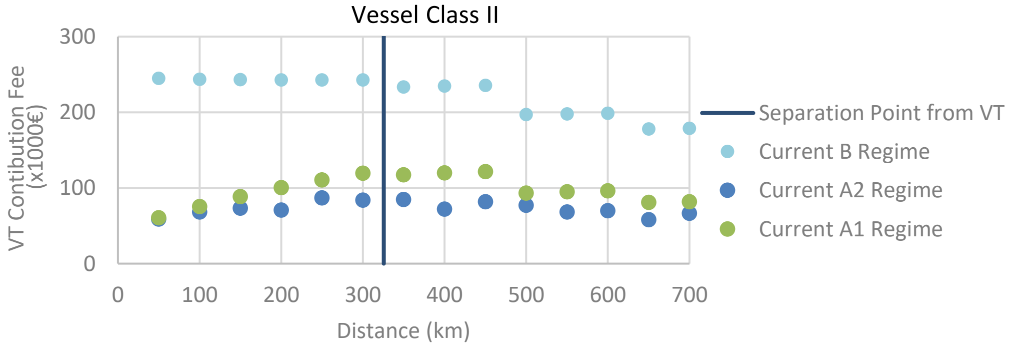

Figure 7: VT Contribution Cost Plots For Vessel Class II

The VT contribution fee, that the FVs can pay to the LV, increases the longer the FV sails in the train and reduces once the FV leaves the train, just like it is seen for the productivity. The comparison of the plots for the three vessel types also show the larger vessels to have steeper slopes once the FVs are under their own navigational control. 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 to diminish faster.

The FV contribution fee is compared to the reference vessel cost in order to demonstrate its possible impact. To allow for an objective comparison, these cost are converted into a cost per ton-km, as shown in Figure 8. The plots are only provided for a comparison to the B operating regime as there is little visible difference for the other two plots since the variations are small (in the order of 10^(-4) €/tkm). The VT's smallest cost improvement per ton-km for respective vessel classes V, IV and II are 2,5 x $10^{-3}€/tkm$ 4 x $10^{-3}€/tkm$ and 1 x $10^{-2}€/tkm$ respectively. The class II vessel achieves the best improvement by sailing in the VT. They manage to cut more than 50 % of the average cost per ton-km, while larger vessels only manage to cut about 30%.

Finally, the LV compensation cost plotted in Figure 8, provides a visual indication of how small this cost is compared to the annual savings. The contribution fee plotted here is the largest of the three speeds. This means that for all conditions in the BC, a single FV suffices to cover the leading expensive, the platform cost and a profit margin for the VT operator. Considering that 11 to 13 LVs are needed in this transport system (see Table 8), it can be concluded that at least 22 and as many as 26 participating vessels are needed to make this system viable. Additionally, given that the VT contribution fee stays positive in all distance variations, it is possible for all vessels to sail more than 50% of its time outside of the VT and still perform better than the reference vessel.

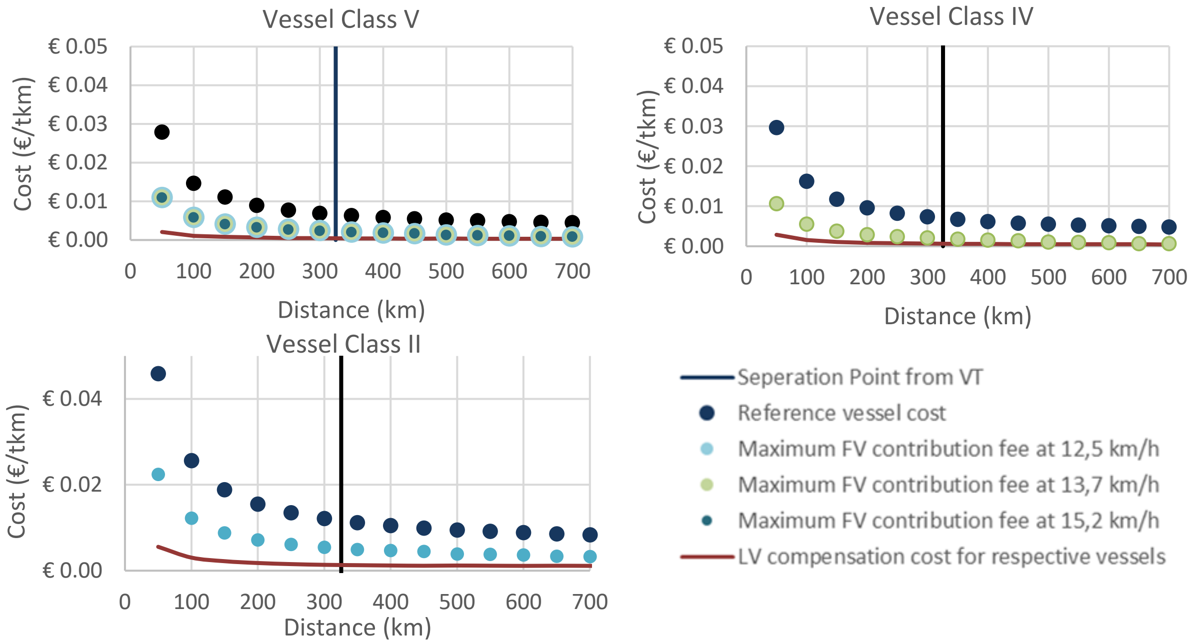

Figure 8: Cost per ton-km Comparison to Reference Vessels and the LV Compensation Cost for a B Operating Regime

5.2 *Transition Stage Case*

The Transition Stage Case results presented in this section can identify the impact that a change in waiting time and additional LV cost makes on the successful implementation of the VT. Here the productivity, VT contribution fee and VT length are determined for the changed conditions. The productivty changes in Figures 9 and Figure 10 are plotted for both the TSC, and as a means of comparison for the BC. The difference between the BC and the TSC makes it appear that the change in VT operating speed has a more significant effect on the vessel productivities in these adapted conditions. When seeing that, 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 the class IV and V TSC compared to the maximum 10% differences for the two speeds at the BC scenarios.

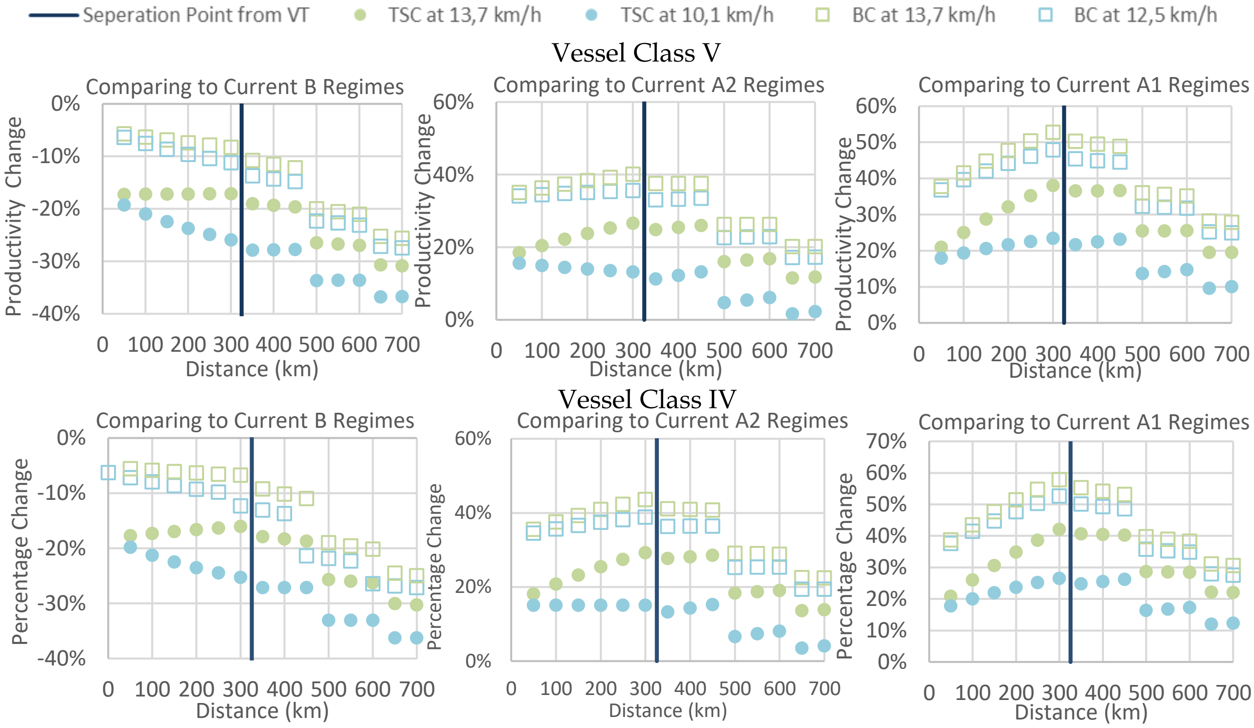

Figure 9: Productivity Change Plots for Vessels V and IV

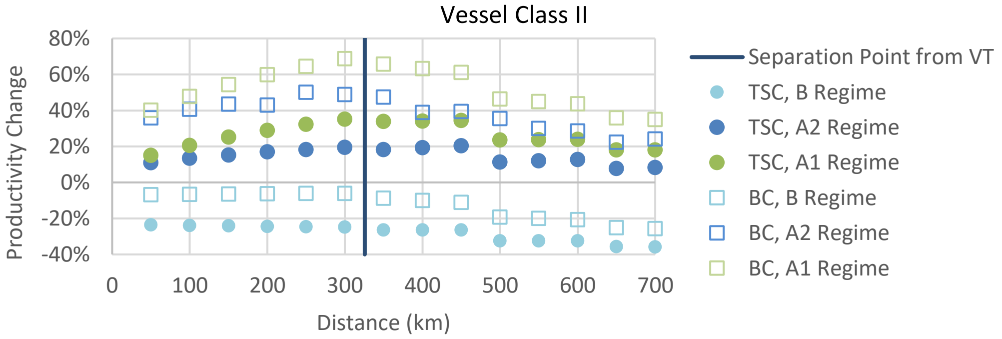

Figure 10: Productivity Change For Vessel Class II

The B regime plots show there to be a general 10% reduction of productivity compared to the BC results. The A1/A2 regimes have an approximately 18% lower productivity than the BC, reaching even up to 30% for the class II A1 peak condition. The TSC results of the contribution fee (Figure 11 and Figure 12) are also reduced accordingly. Compared to the BC values (represented by the squares), this varies by € 50.000 to € 100.000. A point worth noting is that none have a negative contribution fee, which means in all cases, the benefits of joining the VT outweigh the VT control system cost. In some cases, however, these benefits become very small, as seen for vessel class II at an A1 regime.

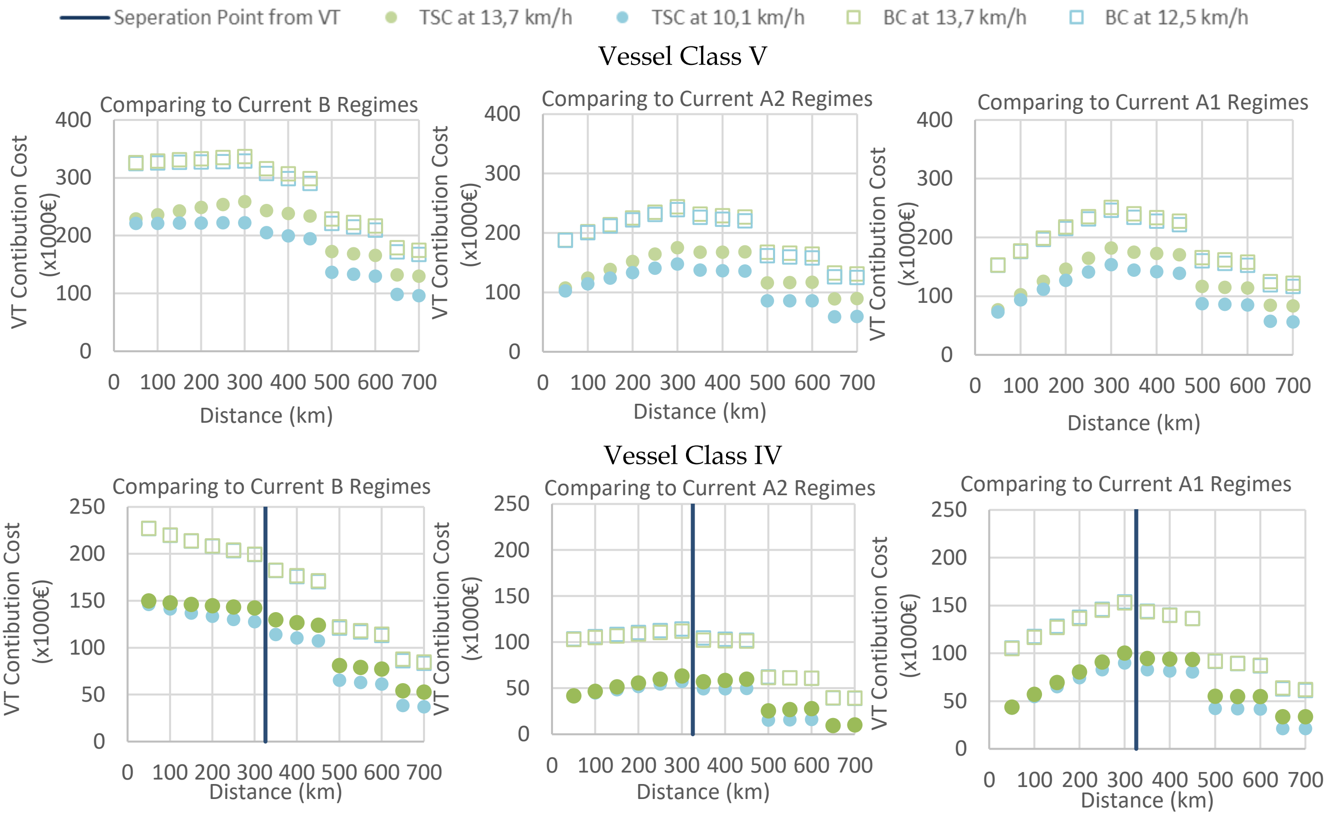

Figure 11: VT Contribution Plots For Vessel Class V and IV

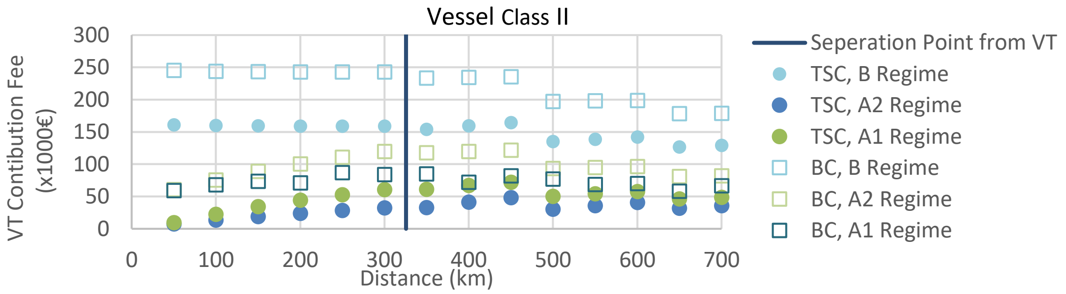

Figure 12: VT Contribution Cost For Vessel Class II

When these values are translated to cost per ton-km, a very different picture is painted for the VT requirements. The LV compensation cost in Figure 13 is representative of the slowest speed conditions, as that would be mimic the worst-case condition. In most cases, the LV compensation cost lies above the cost per ton-km of the FVs contribution. This means more than one FV is required to compensate for a single LV.

The FV contribution cost is dependent on the distance an FV travelled; hence the number of FVs required per LV also changes depending on this distance. Equation 8 is used to determine the values plotted in Figure 15. The three plots in Figure 15 make it clear that most conditions of the TSC require more than five FVs to become economically viable. Class V vessels can meet the FV requirement while sailing in the VT, whereas class IV vessels have a wider spread of FV requirements dependent on their operating conditions, reaching from as low as three to 23 FV per LV. Class II vessels that are currently sailing under B regimes would achieve viable conditions with as little as three FVs no matter the length of the trip spent as part of the VT. Yet, under an A1 regime, the maximum required number of vessels does not drop below six FVs.

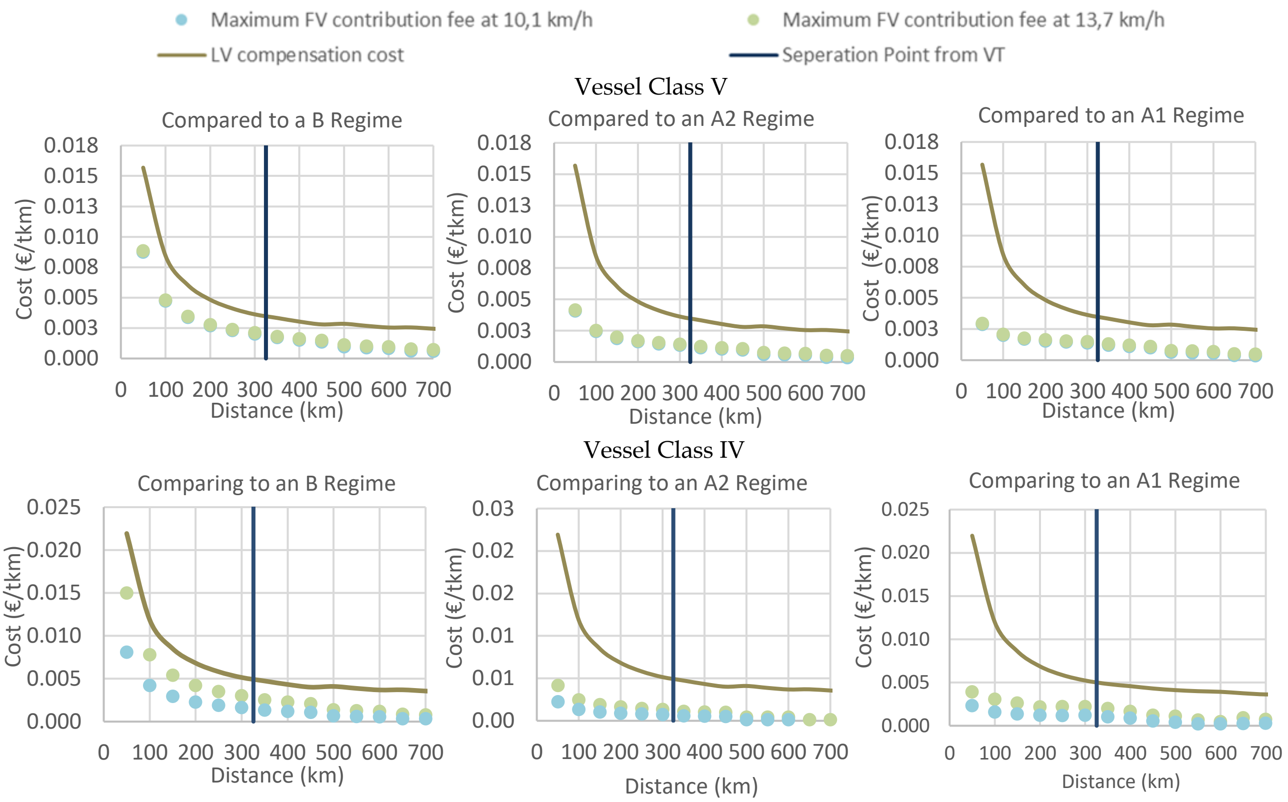

Figure 13: Cost per ton-km Comparison to Reference Vessels and the LV Compensation Cost for Vessel Class V and IV

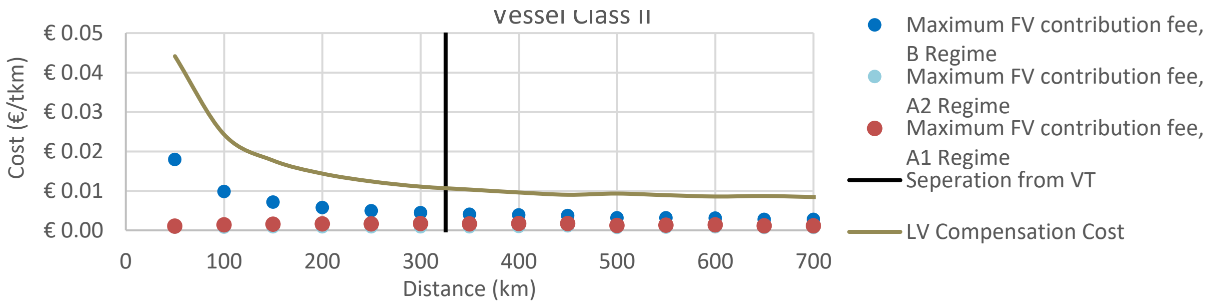

Figure 14: Cost per ton-km Comparison to Reference Vessels and the LV Compensation Cost for Vessel Class II

Vessel class IV and II (A regimes) allow for a minimum sailing distance and all vessel classes allow for a minimum VT trip percentage to be identified. While class V vessels do not have a minimum distance spent sailing in the train, they do require the FVs to spend 50% of their time in the VT before the FV requirements surpass the current technically viable conditions. Using those same guidelines, the class IV vessels need to spend at least 200 km sailing in the VT and at least 72% of its trip as part of the VT, compared to an A1 sailing regime.

The best-case conditions, in which the FV sail in the VT for the entire trip length, show participants requirements range between as little as 12 (incl. LVs), for all vessel types compared to a B regime, to as high as 40 participants. Needing more participants make the implementation more challenging and the likelihood of gathering sufficiently long VT on regular bases becomes a lot smaller.

The results show that the TSC does not allow stable economically viable conditions 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.

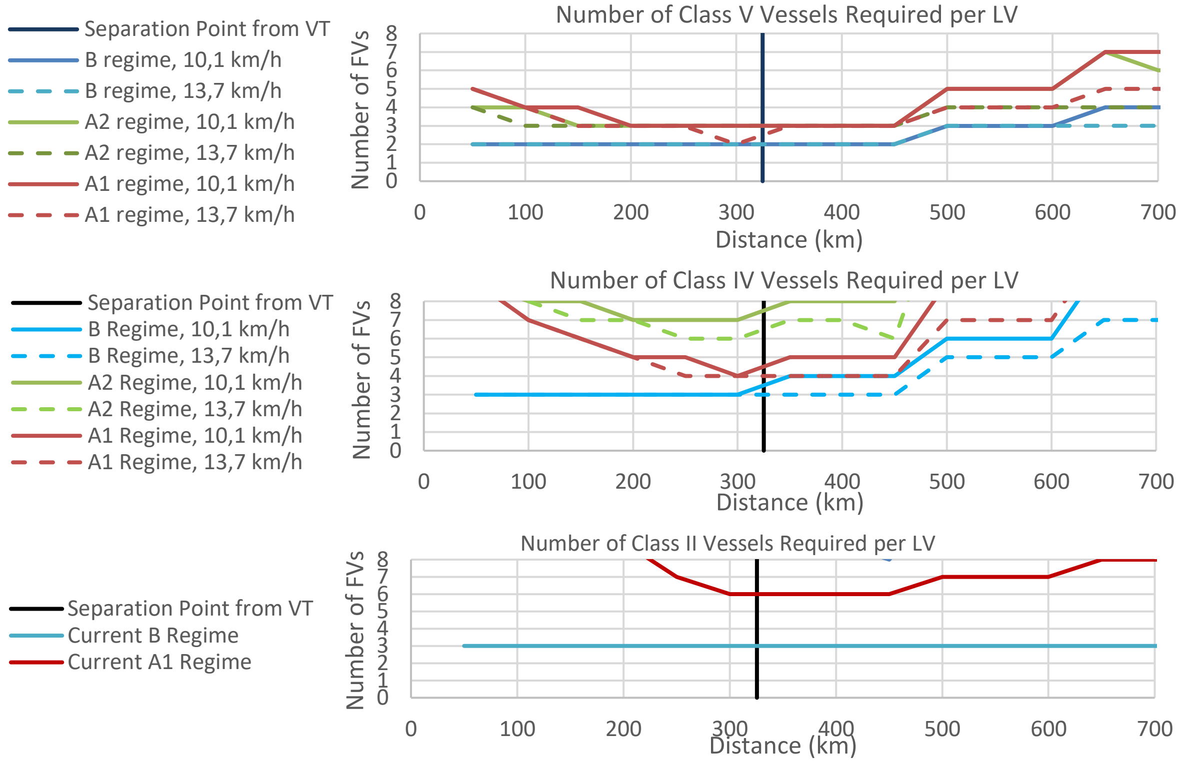

Figure 15: Number of Required Vessels per LV

6. Discussion

The results presented in the last section describe the effects of parameter variation through the assessment of different scenarios. The BC and TSC scenarios vary departure intervals and operating cost, while vessel type, sailing regime and operating speed are varied within the individual plots. This section arranges the results in form of a sensitivity analysis that summarizes the main conclusions drawn from the assessment. The second part of the section addresses the limitations of this study and the application of the VT concept on the Rhine.

6.1 *Sensitivity study*

Following the elaborate discussion of various cases in the previous section, Table 10 summarizes the effect of parameter variation on the FV savings. The percentage changes in this sensitivity analysis are compared to the saving per ton-km calculated for the BC class V vessel scenario. The base scenario of the analysis sets the reference vessel operations at a B regime, a VT operating speed of 13,7 km/h and the operating route length over the full 325 km of the VT.

The difference between the BC and the TSC lies within a departure interval change and additional VT operator cost. The variation in departure intervals of 18 h, from 6 h to 24 h, increase the waiting time of the FVs and thus affects their savings negatively, causing it to reduce by 15%. This reduction is not large enough to impact the required number of participants in the transport system.

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. 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 to not affect the required number of participants.

The reference sailing regime B is compared to a variation for the A1 and A2 regimes. The savings at the A1 regime are purely created by the improvement in productivity. These are 27% fewer savings than the ones created by the crew cost savings achieved in the B regime. The A2 regime does have small crew cost savings and hence has slightly improved savings compared to the A1 regime. Yet, A2 savings are still 25 % smaller than ones achieved in a B regime.

The variations within the operating speed are representative of the BC speed variations from 13,7 km/h to 15,2 km/h and to 12,5 km/h. These speed variations have the smallest effects on the savings, which only change up to 3 %. The sensitivity analysis shows that the increase in speed creates a larger reduction of savings due to higher fuel cost than an improvement due to the increased productivity. This is similar to what was observed for the short sea sector (A. Colling and Hekkenberg, 2020), however, with much smaller effects as in the inland sector vessels are operating at slower speeds.

Table 10. Summary of sensitivity results for different assessment parameters

Parameters	Variation	Effect on savings
Departure interval	+ 18 h	- 15 %
VT operator cost	+ 200.000 €/ LV	- 30 %
Sailing regimes	A1	- 27 %
	A2	- 25%
Operating speed	+ 1,5 km/h	- 3 %
	- 1,2 km/h	+ 1 %

Finally, the results of different vessel classes cannot be compared fairly to those of a class V vessel. The larger the vessels, the greater the effect of the economies of scale. Larger vessels by default have smaller cost per tkm than smaller vessels. The most appropriate way of comparing different vessel types is to look at the percentage savings compared to their maximum FV cost. The VT savings make up 36 %, 52 % and 48 % for class V, IV and II vessels, showing that the class IV vessel benefits most and the class V least from the VT.

6.2 Limitations

Another parameter that has not been studied within the presented results are the crew wages. 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 (QUOVADIS, 2018). 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 (Hekkenberg, 2013). 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 less contribution fee to the VT operator. This means that more participants are needed in the transport system. In the worst case, the savings may be so small that they result in economically unviable conditions where the VT control system's cost on the FV can not be compensated for by the crew savings.

In general, it can be said that the net wages for workers employed in western Europe are relatively similar between countries (de Leeuw van Weenen *et al.*, 2013). This is not the case for workers in other parts of Europe. De Leeuw van Weenen et al. (2013) state that Czech inland crew members earn about 15 % less than their western Europeans counterpart, whereas crew wages obtained from Serbian vessel owners suggest differences of up to 80%. While the application VT concept on the

Rhine corridor has demonstrated viability, this does not mean that it is also an appropriate transport concept for other areas such as the Danube region.

Looking at the required number of participants presented in the results, up to 26 cargo vessels participants are needed once the transport system is fully implemented in order to achieve full viability. This value is highly dependent on the departure frequency of the LVs, shown by the Base and Transition Stage Cases. The Rhine fleet is composed of 7000 dry cargo and 1462 liquid cargo self-propelled vessels (CCNR, 2019). In view of this fleet size and the route running along the main Rhine corridor, the participant requirements for such a transport system is deemed realistically achievable.

Finally, integrating new technology also comes along with the need for training. It is acknowledged that this is an additional cost uncertainty that needs to be considered in the VT concept's implementation; however, the concept development at the time of writing does not allow this cost to be quantified.

7. Conclusions

This article presents the VT concept and describes a cost model which can be used to determine the concepts' viability for a liner transport system. It shows that the application of the concept within the inland sector allows for not only crew cost savings but also an improvement in productivity for some vessels. This is a key factor in achieving economically viable conditions. The benefits attained by VT participants can vary significantly between the size of inland vessels, the current operating conditions of the reference vessel and the maturity of the VT control system.

The Rhine corridor case study provides insight into the identification of boundary conditions. In an early-stage implementation of the TSC these include a minimum distance of 200 km to be spent sailing in the VT for class IV vessels. This distance has to amount to 76% of the trip length for class IV vessels. A class V vessel needs to spend at least 50% of the trip part of the VT, to meet economically viable conditions. The minimum requirement of participants is quantified for each scenario. To the limit, a minimum of 26 participating vessels are needed to allow the fully mature VT transport system to achieve viability. It is also concluded that the early stage of the VT implementation, requiring additional monitoring crew on the LVs and hence increases the participant requirements to 40 vessels. Points for future research needs to introduce the impact of the demand side, i.e, vessel cargo owner, and societal impacts into the assessment.

Acknowledgement

The research leading to these results has been conducted within the NOVIMAR project (NOVel Iwt and MARitime transport concepts) and received funding from the European Union Horizon 2020 Program under grant agreement n° 723009.

Nomenclature

$A1$:	Operating regime that allows 14 h operations	$A2$:	Operating regime that allows 18 operations
B:	Operating regime that allows continuous operations	BC:	Base Case
C_{fee}:	annual VT contribution fee cost (€)	C_{FV}:	annual follower vessel cost (€/year)
C_{LV}:	annual LV cost created by providing the leading service (€)	C_R:	annual reference vessel cost (€)
C_{VT}:	annual VT technology cost (€)	D:	annual number of operating days
d:	VT trip distance (km)	d_{FV}:	FV distance (km) i.e. $d_{out} + d_{in}$
d_{in}:	distance of the FV spent in the VT (km)	d_{out}:	distance the FV spends sailing on its own (km)
FV:	Follower Vessel	I:	departure interval of the LVs (h)
i:	original sailing regime of the reference vessel (A1/A2 B)	LV:	Lead Vessel
n_{FV}:	Required number of FVs per LV	n_{LV}:	number of LV in the transport system
P_{FV}:	annual productivity of the FV (t/year)	P_R:	annual productivity of the reference vessel (t/year)
T_B:	annual operating hours at operating regime B (h/year)	T_{B+A1}:	annual operating days of the FV in/outside of the VT (h/year)
T_i:	annual operating hours at operating regime i (h/ year)	TSC:	Transition Stage Case
t_p:	time spent in port (h)	t_r:	time spent resting (h)
t_s:	time spend sailing (h)	t_t:	trip time (h)
t_w:	VT waiting time due to VT departure (h)	V:	cargo capacity of the vessel (t)
VT:	Vessel Train	v_c:	speed of river current (km/h)
v_R:	operating speed of the reference vessel (km/h)	v_{VT}:	operating speed of VT (km/h)
Δ_{crew}	change in annual crew cost (€)	Δ_{fuel}:	change in annual fuel cost (€)

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