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Waterborne platooning in the short sea shipping sector

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ABSTRACT

The potential to implement the concept of waterborne platooning in the European short sea transportation system is currently being explored. In the concept, a platoon is referred to as a "Vessel Train" (VT). A VT is composed of a fully manned lead vessel and a number of follower vessels. The lead vessel takes over the navigational and situational awareness responsibilities for the follower vessels (FVs). This enables automation of the navigational tasks on these follower vessels, which in turn leads to a potential reduction in crew size and associated cost.

This paper describes the economic viability of the VT concept. It is applied to a short sea case study in which a fully matured system and an early implementation stage are mimicked. The assessment shows that viability is strongly influenced by the number of crew members removed from the FVs and the departure intervals of consecutive trains. It concludes that while economically viable cases can indeed be identified, the benefits created by this VT implementation are present but not very large. This is making it questionable if a successful application of the concept can be achieved given the risk and uncertainty surrounding the individual parameters.

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 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.

This article studies the implementation of a particular waterborne platoon referred to as a Vessel Train (VT). This VT consists of a fully manned lead vessel (LV) that is digitally linked to a number of follower vessels, for which it assumes navigational control. The main advantage of this solution, shown in Fig. 1, is that the follower vessels (FVs) can operate with a smaller crew since they no longer have to provide situational awareness or navigate the ship. This leads to a reduction in crew cost and thereby potentially improves the competitive position of these vessels. Simultaneously, the reduction in the crew can help manage the predicted shortage of almost 150,000 officers by 2025 (BIMCO, 2015). Since the hiring and firing of crew members cannot be done on very short notice, a follower's decision to join the VT system is not a trip-by-trip decision but a long term commitment, not unlike a mobility service subscription as described by Kamargianni et al. (2016), paid by the followers to the VT operator. The train analogy is also expressed in the operational scheme: to provide a reliable, predictable service the VT operates on a fixed schedule on a fixed route and allows the users to join and leave the train at a port of their choosing.

The goal of this paper is to perform a cost/benefit assessment that makes it possible to determine the economic viability of the VT service in the European short sea shipping (SSS) sector. Additionally, the challenges that must be considered for the implementation of

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the concept are also addressed.

Thus far, only a limited amount of research has been done on waterborne platooning. Chen et al. (2018) modelled the behaviour of autonomous vessels in complex navigational situations with regards to path following, aggregations and collision avoidance. Chen et al. (2019a,b) also address the potential for fuel-saving when placing all-electric autonomous ships in a train with the purpose of cargo relocation within ports. Levants (2006) studied the requirements that a control system for swarming vessels would have. This work particularly emphasized the vessels' abilities to stay near each other at uniform speeds yet still avoiding collisions. Economic assessment of the concept has thus far been limited to Meersman et al. (2020) who focus on the application of the concept in the inland sector and Colling and Hekkenberg (2019) who discuss the choices of different types of LVs used in the concept.

In recent years, more effort has been spent on platooning concepts with trucks. The most considerable perceived benefits of truck platooning are the reduction in manning cost and an improvement in productivity (van Ark et al., 2017). There are also other benefits including a reduction in fuel consumption and emissions due to the reduced drag that occurs when driving closely behind each other (Calvert et al., 2019; Tsugawa et al., 2011). Furthermore, decreasing the space between trucks increases the overall capacity of the road. Simultaneously, the enhancement of the technology may improve traffic safety. Another perceived positive consequence of platooning is that it modernizes the transport sector as it enhances the use of data sharing technologies and allows better communication between different transport units. The emergency breaking, line keeping and truck platooning technologies are potentially able to reduce vehicle accidents by close to 18% (van Ark et al., 2017), as false reactions caused by human judgments are replaced by formed and calculated decision. However, an error in the truck platooning technology would increase the severity of an accident as all units of the platoon would be involved in the accident. A further negative aspect of the integration of platoons into daily traffic is that it will cause unpredictable behaviour from other road users when trying to weave through the platoons (van Ark et al., 2017) and can even cause accelerated pavement damage if not implemented with caution (Gungor and Al-Qadi, 2020). The combination of positive and negative aspects of platooning has been assessed, and successful value cases were identified (van Ark et al., 2017). While truck platooning has reached a development stage in which physical road trials are being conducted (Aarts and Feddes, 2016), the platooning research for the waterborne sector is not nearly as developed.

From the above, it can be concluded that although significant attention has been paid to the technical and safety-related aspects of platooning, some attention has been paid to the determination of the economic viability of such concepts in truck platooning but not for the waterborne platooning application. In this article, we address this gap.

This article explores the influence of crucial variables such as sailing distance, operating speed and waiting times on the net benefit and cost of joining the VT for various short sea shipping vessel types. Based on this cost/benefit analysis, conclusions are drawn regarding which combinations of these variables lead to viable business cases, i.e. cases where the VT operator at least breaks even and the cost per tons nautical mile of transport performance for the follower vessels is equal to or lower than the cost of an identical vessel that does not use the VT concept.

The paper is structured in the following manner: firstly, Section 2 describes the cost model set up as well as the application case for which the cost model is applied in this paper. Section 3 then describes the input data for the different cost calculations of the various types of studied vessels. Section 4 presents the results for different scenarios for the VT application and discusses whether these results lead to a plausible viability of the concept. The paper finishes with a summary of the conclusions and recommendations for further research.

2. Method

The method section first describes the assessment method and the cost calculation for the VT. This is followed by the introduction of an application case for which the assessment method is applied in this paper.

2.1. Model setup

The economic viability of the VT concept is explored using a cost model that calculates the cost of the lead vessel (i.e. the VT operator) and the follower vessels. The viability of the VT is achieved if A) the cost per transported ton of cargo for the follower vessels

Fig. 1. The Vessel Train concept (Vessel Train, 2018).

is equal to or lower than that of a reference ship, i.e. the savings achieved by sailing in the train compensate for the productivity loss and the fee to be paid to the VT operator, and B) the combined subscription fees from the followers at least cover the costs of the VT operator.

To determine these conditions, annual cost are calculated by adding CAPEX (depreciation, interest, insurance), and OPEX (crew, fuel, maintenance and administration) of the vessels cost. The CAPEX, as well as administration cost, are all calculated as a function of the newbuilding price of the Vessel, as is commonly done for such analyses, e.g. by Kretschmann et al., 2015; Grønsedt, 2014; Lyridis et al., 2005; van Hassel, 2011; Verberght, 2019. The newbuild cost, as well as the maintenance cost, are estimated from the generic formula established by Martinez-Lopez et al. (2013). The former is estimated based on the gross tonnage of the vessels while the latter is determined based on the age of the vessel, where the average vessel age of 8 years is used (Moore Stephens, 2015).

In the VT concept, the crucial variables are crew cost, cost of the VT control system, the productivity of the ships and fuel cost, each of which is briefly discussed here.

A reduction in crew cost is the main benefit of the VT system since the navigation tasks on all followers are taken over by the control system on the LV. A study by Kooij and Hekkenberg (2019) developed an algorithm that uses the skills of the crew members and the tasks that need to be performed to determine the cheapest crew composition for a given situation. It has shown that the removal of all navigation tasks on a typical short sea ship allows removal of a second officer and two deck boys. Since the captain is still on board, the remaining crew can still sail the ship in and out of port to a VT-joining location, but cannot navigate it for extended periods of time.

To allow the removal of the mentioned crew members, a control system is required. This system is developed within the NOVIMAR project, and the developers estimate its cost at € 80,000, which includes the installation of the VT track pilot software and hardware (such as antenna or distance sensors) on board of the vessels (Argonics Gmbh, 2017), so this value is also used, assuming depreciation in 5 years.

Since the use of the VT implies that ships can no longer leave port whenever port operations are complete but will have to wait for the next train to leave, additional waiting times are incurred, which reduces the productivity of the followers. Productivity is further affected by having to comply with the speed of the VT rather than being free to choose one's own speed. Productivity of reference (R) vessels sailing outside the train and FVs are calculated as follows:

$$P_{R\ or\ FV} = \frac{T}{\frac{d}{v_R} + t_p + w} V \tag{1}$$

Where:				
	w :	VT waiting time (h)	V:	Cargo volume (TEU)
	P_{RorFV}:	Productivity of reference or follower vessel (TEU/year)	T:	Operating hours (h/year)
	v_R:	Service speed of reference follower vessel (kn)	t_p :	Time spent in port (h)
	d:	Trip distance (nm)		

These two productivities used to determine the maximum FV cost by using equation (2). This equation determines the FV such that the at least equal cost conditions to the reference vessels are met.

$$C_{FV} = \frac{P_{FV}}{P_R} C_R \tag{2}$$

Where: C_{FV}: FV cost (€/year) C_R: Reference vessel cost (€/year).

For the LV, which does not wait and determines the speed of the train, no productivity loss is assumed. Equation (3) is used to determine the operating speed of the LV, hence the speed of the VT. It is set such that the VT operating speeds are as close as possible to the operating speed of the reference vessels.

$$v_{VT} = \frac{2d}{n_{LV} I - 2t_p} \tag{3}$$

Where:

I:	Departure interval of the LVs (h)	n_{LV}:	Number of LV in the transport system
v_{VT}:	Operating speed of VT (kn)		

Following the conclusions of a previous study on this topic (Colling and Hekkenberg, 2019), only cargo-carrying lead vessels are explored, since the cost of a dedicated LV without cargo proved to be unjustifiably high. Dependent on the case studies, the LV cost (see equation (4)) can either be solely composed of the VT control system cost or also of monitoring crew cost, which are added to reflect the case where the VT system control is not fully autonomous yet. No other LV cost are relevant for this assessment as the LV is a cargo-carrying ship, and all other non-VT related cost are covered by the revenue of cargo transportation.

$$C_{LV} = C_{VT} + C_M \tag{4}$$

Where:

C_{LV} :	LV cost (€/year)	C_M :	Monitoring crew cost (€/year)
C_{VT}:	VT control system cost (€/year)		

The final important variable in the method is the fuel consumption of the ships. Although slowing down to match the speed of the VT has a negative effect on productivity, it has a positive effect on fuel consumption. Since fuel consumption is roughly proportionate to the square of the speed (sailing twice as fast roughly quadruples fuel consumption), slowing down saves fuel costs. Fuel cost is calculated by the commonly used powering model of Holtrop and Mennen (1982). The specific fuel consumption is determined as a function of engine loading, as defined by MAK M25E (MaK, 2003), which sets the specific fuel consumption, at 85% MCR, to 185 g/kWh and provides the added fuel consumptions at different engine loads.

Using the method described above, the change in annual cost and productivity of individual vessels can be used to determine the change in the cost of any follower vessel and the maximum contribution a FV can pay to the VT operator to cover the VT-related cost of the LV.

$$C_{fee} = net\ \ savings = C_{FV} - C_R + \Delta_{crew} + \Delta_{fuel} - C_{VT} \tag{5}$$

Where:

Δ_{crew}:	Change in crew cost (€/year)	Δ_{fuel}:	Change in fuel cost (€/year)
C_{FV} :	Reference vessel cost (€/year)	C_{fee}:	VT contribution fee cost (€/year)

With this information, it can be calculated how much a follower can pay to the VT operator without having higher cost than when not sailing in the VT, thus providing a viable business case for the follower. Since the cost of the VT system are known, a straightforward calculation allows determination of the minimum required number of followers to cover these costs (see equations (6) and (7)), thus showing how many followers are required to provide a viable business case for the VT operator.

$$\mathbf{n}_{FV} = \frac{C_{LV}}{C_{fee}} \tag{6}$$

$$\mathbf{n}_{Total} = n_{FV} n_{LV} + n_{LV} \tag{7}$$

Where:

n_{LV}:	Number of LV per transport system	$\mathbf{n}_{FV}$:	Number of FVs required per LV
n_{Total}:	Number of vessels per transport system		

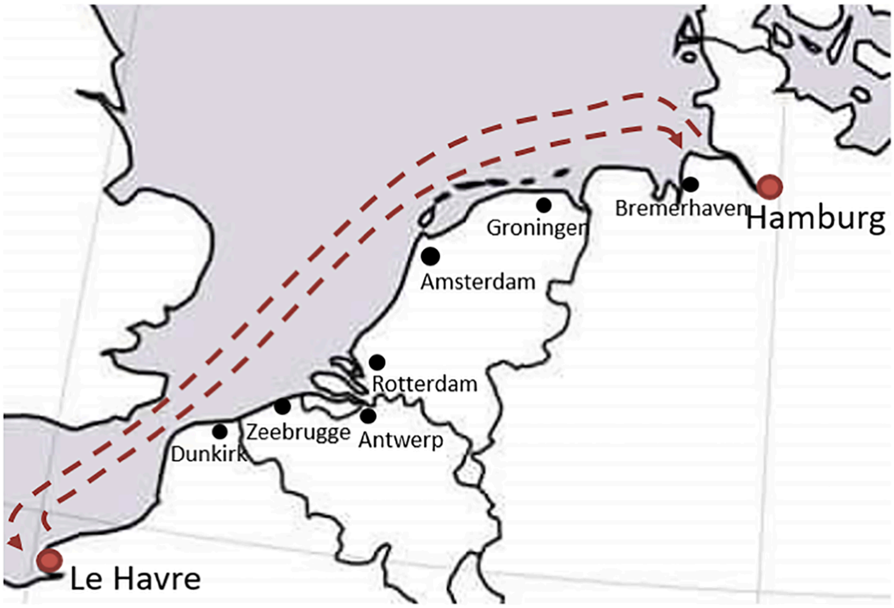

Fig. 2. Case study operating area.

2.2. Application case

The VT transport system assessed in this paper sets LVs to sail on a liner service that operates continuously all year round between Hamburg and Le Havre (see Fig. 2), 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 (Hermans, 2017) shows around 10,500 ship passages annually in front of the Dutch coast. This vessel train route passes by the largest European ports and, therefore, provides opportunities for a large number of vessels to join the train.

The chosen route passes in front of a number of large ports allowing the FVs to reach the port without trouble. The FVs can join the VT at any port along the route.

The assessment performed in this paper determines the FV cost for a number of ship sizes,speeds and for a variety of distances up to the entire route length of 500 nm. It is assumed that FVs operate on a fixed sub-section of the trip all year round since this enables the drawing of clearer conclusions and easier extrapolation of results than if a more diverse sailing pattern is followed. The results are presented for a range of distances at 50 nm intervals. The distance between Antwerp and Amsterdam, which has a length of 180 nm, is used for the sample calculations in the results.

Finally, the assessment also considers two sub-cases, the Base Case and the Transition Stage Case, which assume different stages of development of the VT concept. This is done in order to demonstrate the potential of the VT concept and to identify potential challenges arising on the road to full implementation.

3. Case study

This section provides the input data for the application case. First, the main parameters of the ships are presented together with the crew cost, followed by a brief explanation of the VT control system cost. Next, the conditions for the Base and the Transition Stage Case are elaborated.

The last part of this section benchmarks the current operating conditions of the ships. It compares the productivities and cost breakdown of the ships in the current situation and in the VT, to show how the implementation of the VT affects the different vessel type.

3.1. FV main parameters

The dimensions and properties of the four FV types that are assessed in this article are based on actual vessels and presented in Table 1. Each vessel is intended to be a sample of one market segment. Further data requirements for the calculations of the FV cost are provided in Table 2.

The port time estimate is taken as a standard turnaround time from the review of maritime transport (United Nations, 2019). There the average time in port for all ship types is stated to be 23.5 h. 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. These port times are also a function of the vessels size.

The number and composition of the original crew provided in Table 3 are taken from Kooij and Hekkenberg (2019). They base their study on a 134 m vessel with 750 TEU capacity operated by a Dutch shipping company sailing in Western Europe. To check if the provided data is representative of the sector, it is compared to Ghaderi (2019) for a crew with similar western earnings. The average difference between the cost used in this article and the cost stated by Ghaderi (2019) is 3% across the crew roles. Thus, it is deemed a positive validation of the cost data.

The two larger vessels have the same number of crew members and composition as the vessel used by Kooij and Hekkenberg (2019), while the smaller vessels have one less deck boy on board. Furthermore, two crews operate the vessel annually to allow the vessel to be productive throughout the year.

Table 3 presents the annual crew cost for the different vessel types, which all sum up to slightly more than €1 million per year.

The crew reduction due to the automation of the navigation on board of the FVs is estimated by Kooij and Hekkenberg (2019) to be three crew members: the second officer and two deck boys. Knowing that there are two crews required to operate the ship for an entire year, using the wages presented in Table 3, this creates a crew cost savings of €156,400 annually.

Table 1
Input data for four sample vessel types.

Reference **Market segment**	**I** **Fast and large**	**II** **Fast and small**	**III** **Slow and large**	**IV** **Small and slow**
Vessel type	Feeder	General cargo	General cargo	General cargo
Length (m)	153	100	137	89
Beam (m)	21.5	20	21	13.6
Gross tonnage (t)*	9100	6500	8950	2850
Installed power (kW)*	8000	7800	4350	1800
Capacity (TEU)*	900	650	1000	150
Operating speed (kn)	18	16.5	13	11.5

* Rounded to the nearest 50.

Table 2
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/trip)	23.5

Table 3
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.

3.2. VT control system cost

The annual VT cost is composed of five cost elements and based on the € 80,000 investment cost of the VT control system presented in Section 2.1. Table 4 presents the breakdown, and some of the VT control systems cost elements.

3.3. Sub-Cases

The input data of the two sub-cases, the Base Case (BC) and the Transition Stage Case (TSC), are presented next.

3.3.1. Base Case

The Base Case represents the conditions in which the VT is well-established in the future maritime transport system. This 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. In this case study, a VT departure interval of 6 h is used. The transition stage case also explores longer intervals, and in the discussion section, the effects of shortening the intervals are elaborated.

We conservatively assume 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, as time spent at a terminal depends on numerous factors such as the type and amount of cargo (un)loaded and the capacity of the terminal equipment, the time it takes to get from the VT drop-off point to the terminal or waiting time required for bunkering. Therefore, a uniformly distributed arrival pattern is assumed. This means the average waiting time is half the departure interval, i.e. 3 h for the Base Case.

As discussed before, 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 shown in Table 5, ranging from 18 to 24 LVs. With those two values, the VT operating speed for the Base Case can be deduced using equation (2).

3.3.2. Transition Stage Case

The Transition Stage Case is more challenging than the Base Case since the early stages of the VT implementation will not have the need for as many participants. It not only assumes longer departure intervals but also assumes the need for monitoring crews on the LVs

Table 4
Cost breakdown of the annual VT control system 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	€ 4000	€ 600	€ 1600	€ 2000	**€ 24,200**

Table 5
VT Speeds and LV requirements under Base Case.

LV return trip time (h)	144	126	114	108
Speed (kn)	10.3	12.7	14.9	16.4
Number of LV's	24	21	19	18

that ensure safe VT control system operation. Two additional crew members are thus put on board of the lead vessel. Similar to the assumption of the rest of the crew, two crews are expected to rotate to allow the full annual operation of the VT. These monitoring crew members are expected to cost € 45,000 per year (see table 4), which is similar to a second officer. It is expected that the navigational skillset of a second officer is similar to what is expected of the monitoring crew. This sums up to an estimated VT monitoring crew cost of €180,000 per year. A departure interval of 21 h is used. This departure interval increases the waiting time conditions to 10.5 h, thus allowing assessment of the impact of large waiting times on the viability of the VT.

The decrease in departure frequency causes fewer LVs to be needed over the same distance as in the Base Case. In this case, only three speeds (see Table 6) are studied since more or fewer LV's in the system will cause the overall VT operating speed to deviate too much from the current operating speeds of the vessels. The Transition Stage Case drops the required number of LVs to five to seven LVs.

3.4. Benchmark of the standard operating conditions

This section provides the values of the reference vessels which are used in the VT. The benchmarking identifies the differences between the vessel types. At first, the reference vessel annual productivity is quantified, and after that, a cost breakdown is presented.

3.4.1. The productivity of reference vessels

Fig. 3 provides the productivity of the reference vessels assuming 100% loaded. The vessels are expected to be continuously operating on the same distance throughout the year. The longer the trip, the less cargo is moved, since the vessel spends more time sailing and achieved fewer trips.

3.4.2. Cost breakdown

A detailed cost breakdown for each vessel type, composed of the cost elements discussed in Section 2.1, is illustrated by the pie charts in Fig. 4. These pie charts are set for the reference vessels at conditions with the same sample route between Antwerp and Amsterdam and at the operating speeds of each respective Vessel. When comparing the shares of the pie charts, the changes in the crew and the fuel cost become most noticeable. While the crew cost makes up the largest share for the slowest vessel with 48%, the fastest vessel only has a crew cost share of 18%. The fastest vessel has the highest fuel cost, with 43% of its total cost, while the slowest vessels' fuel cost only makes up 23% 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.

4. Results

This section presents the number of return trips, percentage of productivity drop, maximum FV cost, the maximum VT contribution fee and the resulting number of FVs required to make the business case viable for each of the two sub-cases. It also provides a cost breakdown comparison between the reference vessel and the FV.

4.1. Base case

Before demonstrating the results for all FVs, a sample case is described to clarify how each of the features were calculated. These sample calculations are performed for vessel II at its operating speed of 10.3 kn over the sample voyage between Antwerp and Amsterdam.

First, the number of return trips for the FV are calculated. This adds the waiting time to the return trip time of the original condition and results in the annual number of trips, as presented in Table 7.

Table 6
VT speeds and LV requirements under the Transition Stage Case.

LV return trip time (h)	147	126	105
Speed (kn)	10	12.7	17.2
Number of LV's	7	6	5

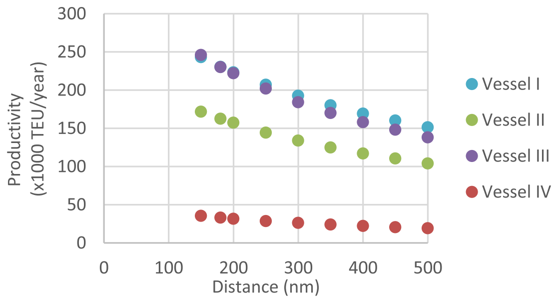

Fig. 3. Productivity of reference vessels.

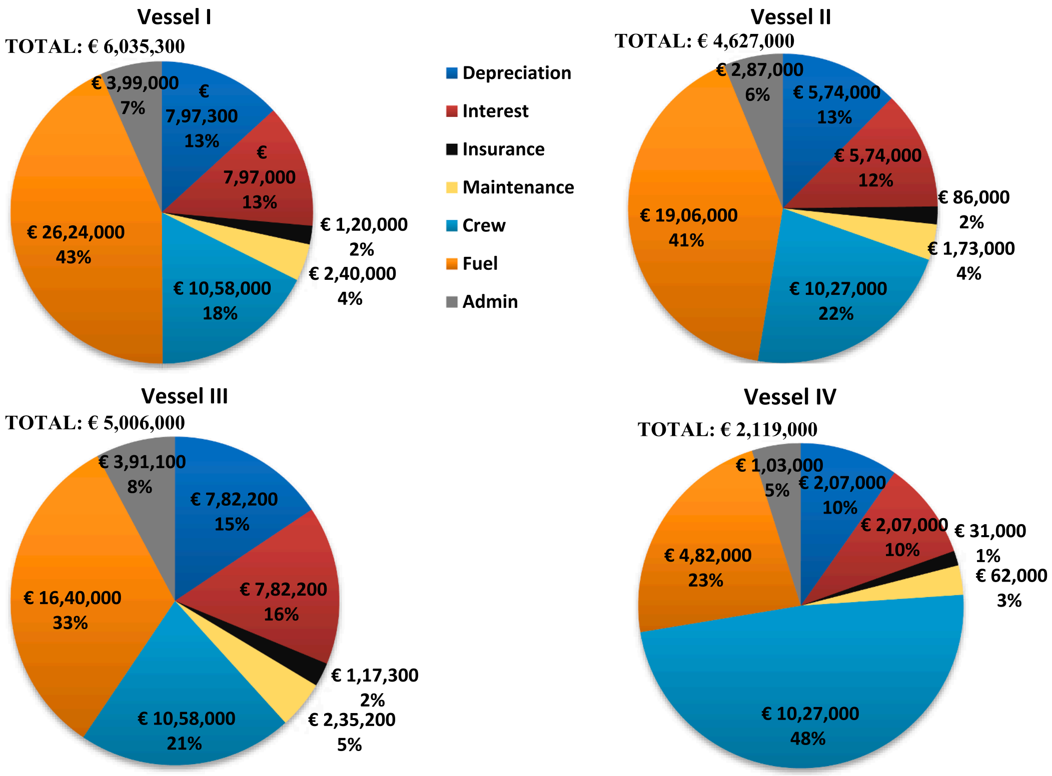

Fig. 4. Cost breakdown for all vessel types.

Table 7
Number of return trips for Base Case.

Speed (kn)	**10.3**	**12.7**	**14.9**	**16.4**
Return trips	98	106	112	115

Step 1 $$\textbf{\textit{Number of return trips}} = \frac{360\ \textbf{\textit{days}}*24\ \textbf{\textit{h}}}{2*\left(\frac{180\ \textbf{\textit{nm}}}{10.3\ \textbf{\textit{kn}}} + 23.5\ \textbf{\textit{h}} + 3\ \textbf{\textit{h}}\right)} = 98$$

Step 2 describes the calculation of the percentage productivity drop created by fewer trips being sailed in the VT. For the sample case, this is 22%, as the operating speed of the VT is 6.2 kn slower than its reference operating speed but port times, excluding waiting times, are unaffected.

Step 2 $$\%\textbf{\textit{Productivity Drop}} = \frac{162{,}500\frac{\mathrm{TEU}}{\mathrm{Year}} - 98*650\ \ \mathit{TEU}*2}{162{,}500\frac{\mathrm{TEU}}{\mathit{Year}}}*100 = 22\%$$

As shown in Fig. 5, the productivity of the various vessel types changes. The initial productivity drops at the shorter distances are

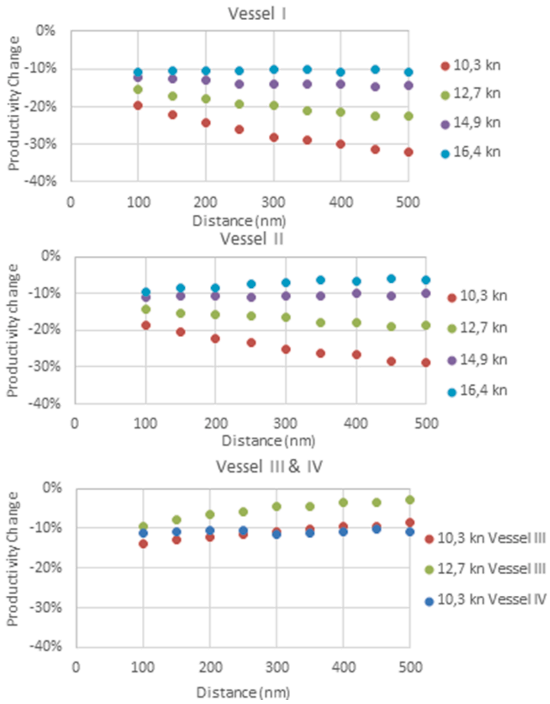

Fig. 5. Effect of VT implementation on vessel productivity for the base case.

mainly influenced by the additional VT waiting times. The productivity drop due to these waiting times reduces with lengthening trips, as the vessels spend more time sailing and a smaller number of trips are sailed. However, this can only be seen for conditions that are close to the original operating speed of the reference vessels, where no significant productivity losses are obtained through slowing down. The productivity loss for vessels I and II at 10,3 kn and 12,7 kn, increases as the route lengthens since the reduction in VT waiting times is largely outweighed by the increase in sailing time due to slowing down.

The smallest productivity decreases of less than 5% are achieved by vessel III where under VT conditions the vessel only operates

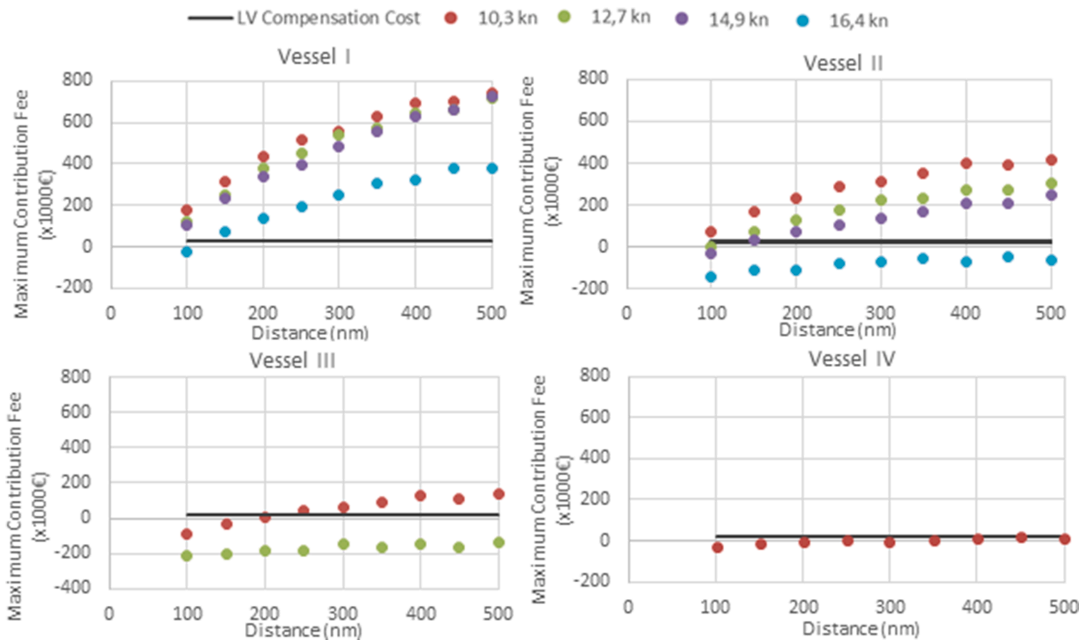

Fig. 6. Maximum contribution fee for vessel under base case conditions.

0.3 kn slower than its normal operating conditions. The largest productivity drop is experienced by vessel I over more than 32%.

To determine how these productivity drops impact the potential for a viable business case, the maximum contribution fee is determined. First, the maximum FV cost is calculated, as shown in Step 3 below, using equation (2). This is then used in Step 4, which applies equation (5) to calculate the maximum contribution cost. The description below the applied equations clarifies how the values are computed. The results for the contribution fee per FV are depicted in Fig. 6.

Step 3 $\boldsymbol{MaximumFVcost} = \frac{98*650TEU*2}{162{,}500\text{TEU/Year}} *€\ 4{,}627{,}000 = €3{,}627{,}568$

Step 4 $Contribution\ cost = €\ 204{,}968 = €\ 3{,}627{,}568 - €\ 4{,}627{,}000 + €\ 154{,}600 - (€\ 832{,}000 - €\ 1{,}906{,}000) - €\ 24{,}200$Where the following variables are implemented from equation (5):

$\Delta_{crew} = €\ 154{,}600 = 2(2*€\ 15{,}460 + €\ 46{,}400)$
(two crews annually of two deck boys and one second officer)
$\boldsymbol{C_R} = €\ 4,627,000$ (view Fig. 4)
$\boldsymbol{C_{fuel_R}} = €\ 1,906,000$ (operating speed of 16.5 kn)
$\boldsymbol{C_{fuel_{FV}}} = €\ 832,000$ (operating speed of 10.3 kn)
$\boldsymbol{C_{VT}} = €\ 24,200$ (view Table 4)

Any negative contribution fee in Fig. 6 indicates that the annual VT control system cost of transport, when the vessel sails in the VT, are larger than for the reference situation. It does, hence not provide any benefit for the VT participants.

While for vessel I all conditions lead to a positive maximum contribution fee, i.e. savings, vessel II does not manage to achieve savings when operating closest to its original operating speed. The shorter routes for vessel III and IV at the lowest speed start by not showing savings, yet past a distance of 200 nm these also achieve a positive contribution fee. When sailing in the 10.3 knot VT, vessel III never achieves savings. Finally, the comparison of the four plots in Fig. 6 shows that the benefits from vessel III and IV are very small in comparison to those of the faster vessels I and II, as there are no additional fuel savings.

Fig. 7 visualizes this point by drawing a direct comparison between the reference vessel cost and FVs cost, excluding any contribution fee. In order to provide an objective comparison between the vessel types, the cost have been expressed in euro per TEU nauticalmile. The plots make it clear that while the viable conditions of the faster vessels show clear cost per TEUnm benefits compared to the reference conditions, the slower vessels end up with very small benefits.

The final step is to determine the required number of FVs needed to compensate for the VT cost created on the LV. This uses the calculated maximum contribution fee and compares it to the LV cost. Fig. 6 includes the €24,200 LV compensation cost as a frame of reference. This LV compensation cost is in most cases so small that the VT only needs a single FV. The only conditions for which this single vessel is not sufficient is between 150 nm and 350 nm distances of vessel IV. The required number of FVs is demonstrated by the sample calculation in Step 5.

Step 5 Required number of FVs $= €\ 24,200/€\ 204,968 = 0.1$ so 1 FV

The Base Case requires up to 24 LVs to allow for a 6 h departure interval, which means if at least one FV per LV is required, a total of

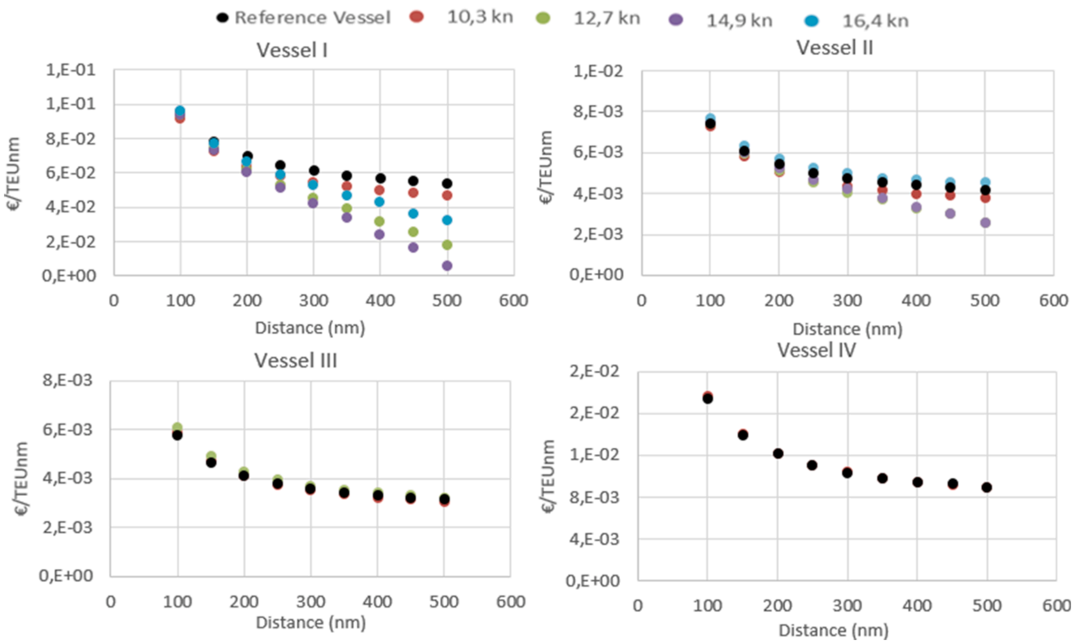

Fig. 7. Comparing reference vessel cost and FV cost without contribution fee.

24 FVs are needed to participate in the transport system. Thus, if 48 vessels are involved, the VT system would have enough participants to become economically viable. The non-viable cases make it clear that slow vessels may not find the VT concept attractive, as their benefits are very small compared to the sacrifice they have to make to join the VT.

4.2. Transition stage case

Due to the larger departure intervals, the Transition Stage Case (TSC) reduces the number of return trips to the values indicated in Table 8.

This change in the number of return trips causes a drop in productivity for the short distances of about 15% compared to the BC, as seen in Fig. 8. When followers spend longer on the train, the productivity drop is reduced, in particular for vessel III and IV. This implementation case, therefore, favours followers that can stay in the VT for most of the LV route.

The maximum contribution fees in the transition stage, see Fig. 9, show to be viable in fewer conditions than what was seen in the base case. Even though the fuel savings still occur, the decrease in productivity means that the cost savings for the FV are not large enough to compensate for the productivity drop. Vessels III and IV do not show any viability. Vessel II only shows viability past 400 nm, while vessel I shows viability for the two slower operating speeds past the distance of 280 nm.

Other than the changes in viability based on the maximum contribution fee, the transition stage also causes changes in the required number of FVs. The LV compensation cost are significantly higher at € 204,200, which is composed of the €180,000 from the crew and the VT control system cost of € 24,200.

Compared to the BC plots in Fig. 6, the TSC plots in Fig. 9 show that the maximum contribution fee is less than half as large. The TSC conditions cause some FVs to have a positive contribution fee, but that cannot compensate for the LV cost on their own. This occurs, for instance, to vessel I in Fig. 9. The distances at which more than one FV is required is shaded in the respective plot. In some cases, such as the 12,7 kn condition for vessel II, the best viable case requires 47 FVs per LV. Even though such a number of FV participants meets the first criterion of viability, i.e. meaning it meets at least the breakeven point for the FV operator, it is questionable whether such a VT length is realistic. A quantitative example showing the infeasibility of such a long train is given by addressing communication and data transfer requirements between the vessels in the train. Allowing sufficient communication data transfer between the LV and the last FV will be a challenge with long trains. Niwa et al. (2015) have performed 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. A length of 47 vessels definitely surpasses this length.

Based on these TSC results, the number of vessels required for a VT composed of vessel I at a distance of more than 400 nm, ranges between 25 and 56 vessels including the LVs. The best conditions for a vessel II that can be achieved, over the full length of the route between Le Havre and Hamburg and at a speed of 12,7 kn, are a need of three FVs per LV. This sums up to a total number of 24 participants in the transport system.

5. Discussion

The comparison between the Base Case and the Transition Stage Case demonstrates that once the technology is established, the concept provides viable application conditions for all four vessel types. The study has shown that the viability of the VT application is dependent upon the waiting times and even small differences in waiting time can make the difference for a viable case.

It should be acknowledged that the crew cost calculations also highly dependent on the flag state of the ship and the nationality of the crew. The cost used in this paper are representative of a shipping company paying competitive western European wages. Silos et al. (2012) present crew cost in their research that has up to 90% lower cost when the flag and crew nationality change from Dutch to Algerian. This makes it clear that the VT concept's applicability are restricted to geographical areas in which seafarers' incomes is relatively high.

The results provide insights into the expectations on how many cargo vessels need to be involved in the overall VT system. The Base Case requires at least 48 vessels (LVs and FVs). The Transition Stage Case, on the other hand, could achieve viability with as little as 12 vessels, however, the transport system would provide less flexibility to the users as longer waiting times are required.

In order to determine if it is plausible that the VT system can achieve the required numbers of participants, these have been crosschecked with an estimate of the total European fleet size. Clarksons World Fleet Register Listing (2018) listed 4500 vessels, in the size range classed as short sea ships, owned by European companies. These European companies are likely to have relatively crew wages, thus making them eligible to join the VT. Looking at the range of vessels required for the VT transport system, this makes up at most 1% of those ships. Such a share is deemed realistic for the implementation of a new transport concept.

Even though changes in crew cost could vary significantly, the results presented in this paper suggest that the cost-benefit created by the removal of the crew is by far not the largest benefit in the VT system. Instead, the act of taking vessels out of their originally intended operations and integrating them into a well set up slow-steaming system creates the most benefits. Effects of such slow steaming operations do not only provide economic benefit through fuel savings, especially with an increasing oil price but is also used as a tool to reduce emission. Psaraftis and Kontovas (2013) expect that slow steaming becomes the norm in the future, as it is a way to meet the environmental regulations. However, such operations are not VT specific. They could be adapted by any vessel operator.

Another crucial aspect of VT transport system lies in the departure intervals of the LV. A sample assessment is made, to demonstrate the effects of the variation of the waiting times on the viable conditions for a FV. Fig. 10 plots the maximum contribution fee for three distances with varying waiting times for vessel IV, as that has shown to have both viable and unviable conditions throughout the route. The plot shows that the viability changes within a waiting timeframe of 2 h. This is a short timeframe given the inherent uncertainties

Table 8
Number of Return Trips for the Transition Stage Case.

Speed (kn)	10	12.7	17.2
Return trips	83	89	97

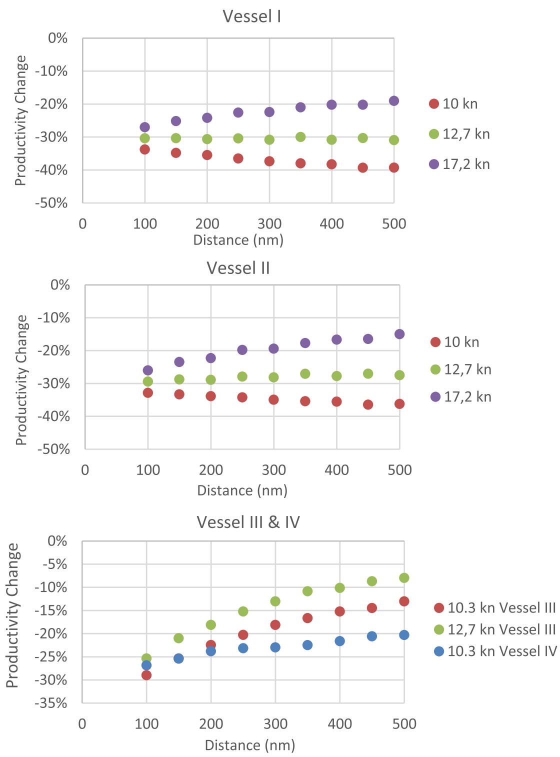

Fig. 8. Effect of VT implementation on vessel productivity for the TSC.

created in waterborne transport.

Conditions of the spot market for general cargo vessels are less represented by the case study described in this paper. Vessels operating on the spot market have continuously varying route lengths and destinations. The route that was chosen for this paper is a highly frequented route. Therefore, it is still possible for vessel that follow a more erratic call pattern to join at any point on this route. However, the operating area and thereby the flexibility of these vessels is then restricted to the area in which LVs operate.

This paper has presented the assessment method that can be used to determine the VT concept's viability. However, the results of the case study and the discussion have shown how easily uncertain parameters can tip the balance to be economically viable. It can therefore be said that the VT benefits from only automating the navigational tasks are not large enough to guarantee a successful application of the VT in the short sea sector.

The application of the VT concept could potentially be investigated for specific applications of vessels that depart at specific intervals, in which the waiting times no longer make a significant difference. An example of such an application could be the supply vessels to offshore energy farms.

6. Conclusions

This article provided an introduction to the VT concept and described a method with which the concepts' viability can be determined for a liner VT transport system. The concept's viability has a large dependency on the waiting times of the FVs before departure, the number of crew members removed on the FVs, the crew wages, the number of participants in the transport system and of fuel savings achieved through the means of slow teaming. The case study was able to identify a number of economically viable conditions in the fully matured, as well as in the early stage implementation stage of the concept. In those cases, the required number of participants is low enough to be plausible for implementation as they would make up less than 1% of the existing European short sea shipping fleet. However, it is questionable if the benefits created by the VT implementation are large enough to guarantee a successful application of the concept given the risk and uncertainty surrounding the individual parameters.

The nature of the SSS sector restricts the benefits of the concept to solely the reduction of crew number and fuel savings, due to

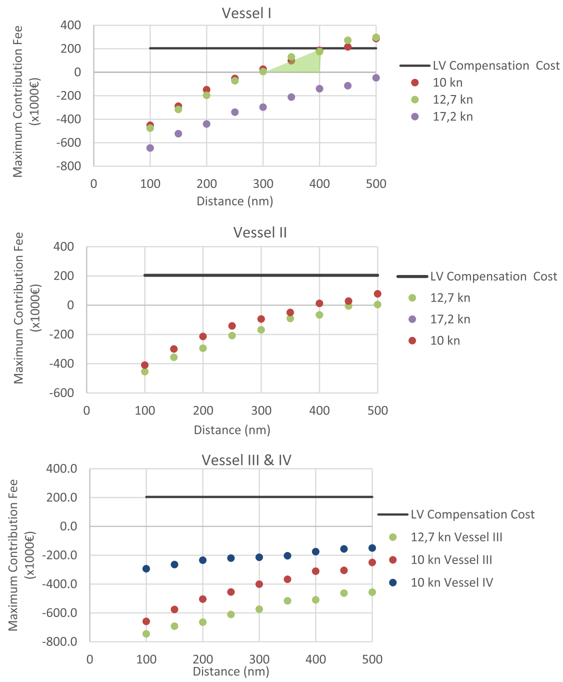

Fig. 9. Maximum contribution fee for vessel under TSC conditions.

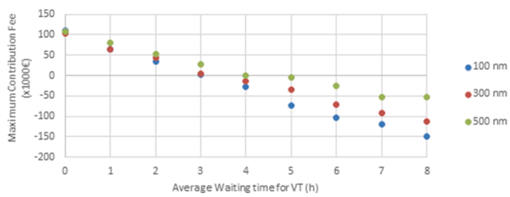

Fig. 10. Influence of variation in waiting time on contribution fee of vessel IV.

forced slow steaming, whereas in the inland sector the VT can also reap additional benefits of an increase in productivity. This increase in productivity is achieved by some inland vessels, that are currently restricted in their daily operations to 14 h or 18 h per day. To sail 24 h per day regulations require a larger crew. When sailing as part of the VT, it is expected that inland FVs which have previously been restricted can operate continuously, without needing a larger crew. For this reason, further research of the VT concepts' application is mainly focus on the application in the inland sector.

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