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Abstract

A waterborne platooning concept, i.e. a Vessel Train (VT) it is composed of a fully manned lead vessel that takes over navigational responsibility for the followers. Joining a VT helps improve the competitiveness of smaller vessels and increase their use, as it allows a vessel to sail continuously with a small crew. This paper identifies the challenges created when penetrating urban areas and models the viability of the VT. The influence factors of the implementation hinge on the maximum opening times and on the simultaneous opening of adjacent bridges. The results provide guidelines for a successful integration of the semi-autonomous platooning system in urban areas.

1. Introduction

The rising ownership and use of private and commercial road vehicles cause a worsening of the congestion situations across Europe, *ACEA (2019)*. In the Netherlands, the average driver spends 37 h per year in traffic jams, *Jorritsma et al. (2020)*. One way to reduce these road traffic delays is to move cargo from the road to the waterways. In countries that have extensive waterway networks such as Belgium and the Netherlands, this may lead to more congestions due to bridge opening in urban areas or even leading into metropolitan areas. Using waterborne platooning can help cluster the vessel passages and reduce the number of bridge openings. This paper studies the implications and implementation requirements of a waterborne platoon in urban areas.

The NOVIMAR project (https://novimar.eu/concept/) is developing a waterborne platooning concept referred to as the Vessel Train (VT), that aims to improve the competitiveness and service level of waterborne transport. Its intention is to bring waterborne transport into urban areas, through enhanced use of smaller vessels. The Vessel Train concept consists of a fully manned lead vessel (LV) that is digitally linked to a number of follower vessels (FV), for which it assumes navigational control. Moving the navigational tasks to the LV allows the FVs to either reduce the size of their crew and the associated crew cost or improve the productivity of the vessels. The productivity gain is achieved since inland vessels can choose to only operate 14 or 18 hours per day with a smaller crew (i.e. two or three crew members). If the navigation-related tasks are taken over by the LV, the FV can keep sailing while the crew is resting, thus allowing 24-hour operations with a crew for 14 or 18 hours. The FV crew left on board is still able to navigate the vessel on its own outside of the VT. Hence, the operating flexibility of the followers is ensured.

1.1. Prior research

1.1.1. Waterborne platooning

Most literature studying the application of the waterborne platooning concept for inland navigation originates from the NOVIMAR project. It researches, among other aspects, the economic viability of the Vessel Train. 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 different viable scenarios in which the vessels could choose to join the VT that serves existing cargo flows. *Colling et al. (2020)* identify a minimum VT length and a required number of participants for a VT liner service with different inland vessel types. This paper builds on the latter research by identifying the additional requirements that urban areas create to allow a successful implementation of the Vessel Train concept.

1.1.2. Obstacle passage

Numerous studies exist on the topic of bridge passage. In the early 1990s *Larsen (1993)* suggested bridge designs to avoid collisions on densely used waterways. More recently, the topic has gained importance with regards to obstacle avoidance of autonomous navigation systems. *Ramón et al.'s (2009)* research the use of navigational systems such as laser detection and ranging (lidar) to help avoid collisions with bridges. Others like *Heßelbarth et al. (2020)* elaborate on the difficulties of bridge passage that cause a temporal block of communication signals.

Procedural optimisation of "obstacle" passage has mainly been dealing with lock passage, as locks are one of the main capacity limiting factors for waterways, *Backalic and Bukurov (2011), Uchacz (2013)*. Research on the procedural optimisation of bridge passages has been limited to the Dutch province of Noord-Holland setting up the *Blauwe Golf (2020).* The *Blauwe Golf* (Blue wave) uses bridge management systems that give bridge operators an opening advise using input from emergency services. This optimises the traffic flow near bridges to improve the conditions for the road and waterborne users by reducing the number of bridge openings. The research presented in this paper adds to the developments of the *Blauwe Golf* by identifying how the VT - bridge interaction can help cluster vessel passages.

1.2. Research Focus

The research questions addressed in this paper are:

1. What are the factors that influence the VT- bridge interaction when penetrating urban areas?
2. Under what conditions is the VT penetration into urban areas viable?
3. What market share does the VT need to achieve to provide congestion benefits to the road traffic?

This paper identifies the most influential factors regarding VT-bridge operation interactions and calculates the effects they have on the length of the VT, i.e. the number of FVs possible, in urban areas. These factors are related to the infrastructure of a bridge, the impact on land traffic and bridge operation regulations. In order to assess these factors, a model was developed that assesses both the requirements for the road and the waterborne traffic. This model is applied to a case study in the province Noord-Holland leading along urban area into the metropolitan area and ends in the port of Amsterdam.

2. Vessel Train potential and challenges in urban areas

The historical data gathered by the province of Noord-Holland in 2018-19 shows that on average, 97 % of bridge openings happen for a single vessel passage, *Provincie Noord-Holland (2020)*. Bridges are usually not open for longer than 10 minutes, where 3.5 minutes are needed to actually open and close the bridge, *Backers (2020)*. Given the fact that some bridges open up to 6000 times per year, one can deduce that clustering vessels in fewer bridge passages has the potential to save days' worth of road traffic waiting times along an entire route that leads into urban areas.

2.1. Benefits

The improvement of competitiveness achieved with the VT by the reduction of crew cost or enhancing the productivity can influence a modal shift towards waterborne cargo transported. The improvement of the competitiveness is targeted in particular at the smaller vessels, that can take less advantage of the economies of scale. This is one of the reasons why smaller vessels are continuously diminishing in numbers with no new built vessels joining the fleet, *van Hassel (2011)*. Modal shift from road to water has a positive effect on the environmental impact of transport as inland vessels still have a smaller environmental footprint than road transport, emitting 17% less CO2 and 34% less NOx, *Otten et al. (2016)*. Additionally, the VT implementation leads to clustering of vessels, thereby requiring fewer bridge openings which can create a societal benefit through the reduction of road user waiting times.

2.2. Challenges

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

2.2.1. Traffic density

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

2.2.2. Regulations

The urban penetration of the VT may be hindered by regulatory restrictions regarding the maximum number of simultaneous adjacent bridge openings. Interviews with bridge operators and Province of Noord-Holland representative concluded that, bridge located in the vicinity of emergency services may at a moment's notice need to close to allow emergency services to reach their destination within a reasonable timeframe. For the same reason, the province aims to, dependent the traffic conditions, have no more than two adjacent bridges open simultaneously. Additionally, some bridges do not accommodate openings during rush hours, in order to minimise the traffic jams created, *Backers (2020)*. Furthermore, some bridges in urban areas do not operate at night (between 23:00h-05:00h) unless special permission is granted. This emphasises the need for careful planning. While this is not a VT specific problem, it can prevent the VT users from reaping the VT's greatest benefit of an improvement in productivity by operating continuously with a smaller crew. The bridge operating hours may change if the demand requires it, yet the restrictions of adjacent bridge openings and rush hour openings are likely to stay in place even with a greater use of the waterways.

2.2.3. Infrastructural limitations

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

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

3. Methodology

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

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

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

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

Fig.1 provides a visual representation of the type of data (in the cylinders) used to determine the model results (in the rectangles). Two viability checks have been created (in the hexagons) to ensure the road and waterborne infrastructure conditions allow for economically viable operations of the VT. The first viability check compares the performance of the road condition with the minimum opening required for the VTs to pass. The second, checks whether the spacing between the bridges allows for the VT to pass without opening more than two bridges simultaneously. Lastly, a large congestion cost benefits can help argue the adaptation of regulatory limitations for the VT operations or potentially reduce the required number of FVs through the internalisation of external cost. This is represented by the dotted lines in Fig.1.

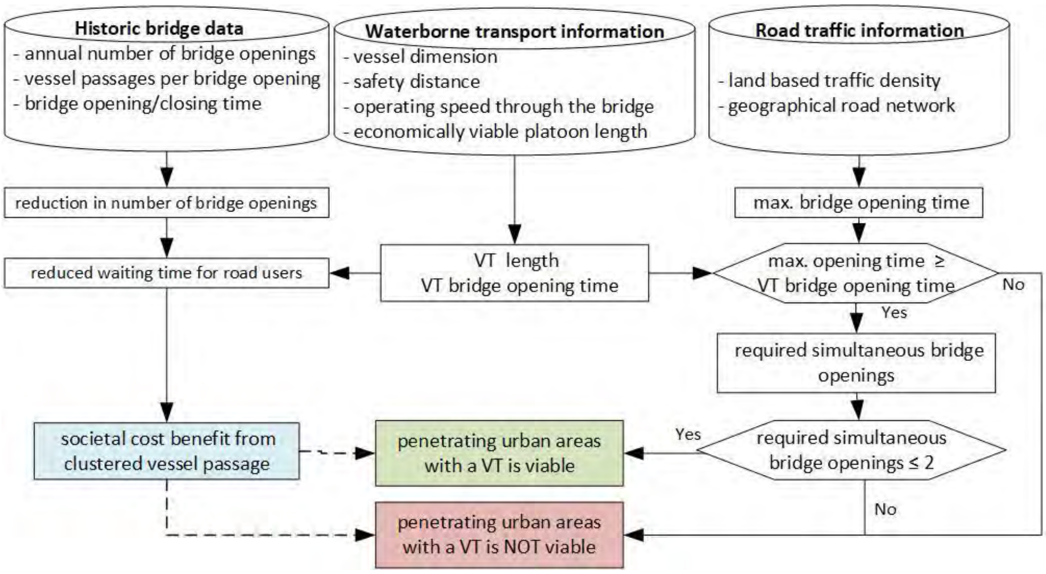

Fig.1: Methodology structure

3.1. Maximum bridge opening time

The maximum bridge opening times are calculated based on the assumption that the bridge opening is only allowed to cause standstill traffic jams in the immediate roads leading to/away from the bridge. This sets the maximum allowed traffic jam length equal to the distance to the closest road intersection. The maximum opening time of a bridge is hence dependent on the formation and dissipation of the traffic jams. The length of a traffic jam is calculated with *Jeihani's (2015)* traffic jam theorem, in which the opening of a bridge can be compared to the modelling of a traffic incident or a red traffic light. The theorem uses traffic intensity in vehicles per hour and traffic density in vehicles per km information to determine the amount of time and length it takes for the congestion to dissipate. Eq.(1) calculates the queue build-up rate, which is the number of km with which the traffic jam grows per hour (km/h).

$$u_1 = \frac{q_2 - q_1}{k_2 - k_1} = \frac{0 - q_1}{k_j - k_1} \tag{1}$$

u_1:	Queue build-up rate (km/h)	k_1:	Pre-incident density (vehicles/km)
k_2:	Incident density (vehicles/km)	k_j:	Jam (incident) density (vehicles/km)
q_1:	Pre-incident flow rate (vehicles/h)	q_2:	Incident flow rate (vehicles/h)

For stationary traffic, the number of vehicles per hour of the outbound traffic is equal to 0. When the bridge is down, all the vehicles can drive again. The queue dissipation rate, once the traffic is rolling again can be determined using Eq.(2). Once the bridge closes there is no traffic in front of the first car. Therefore the capacity flow rate is equal to the maximum flow rate. This means that the traffic is in a state of 'free flow'; the maximum rate of cars can dissipate the traffic jam. This is also the reason why the incident flow rate is set to 0.

The maximum allowed jam distance up to the closest intersection is known. Hence, the queue dissipation time can be calculated. Once the dissipation time is known, Eq.(4) can be inserted into Eq.(3) to solve for the incident time, which is the maximum allowed opening time of the bridge.

$$u_2 = \frac{q_3 - q_2}{k_3 - k_2} = \frac{q_{max} - 0}{k_c - k_j} \tag{2}$$

$$t_2 = \frac{Q}{u_2 - u_1} \tag{3}$$

$$Q = t_1 u_1 \tag{4}$$

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

3.2. VT length

The VT length depends on the length of the vessels in the VT, the safety distance between the vessels and the space before/after the train, at which the bridge starts to open or close. It is expressed by Eq.(5).

$$L_{VT} = d_{aft} + d_{front} + L_{LV} + \sum_{i=1}^{n}(L_i + d_{sw} L_i) \tag{5}$$

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

3.3. VT bridge opening time

The VT length determined in section 3.2. is used in equation 6 to determine the bridge opening time due to the passage of the VT.

$$t_{VT} = \frac{\frac{L_{VT}}{1000}}{v_{lim}} + t_{o\&c} \tag{6}$$

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

3.4. Required number of simultaneous bridge openings

The maximum required number of simultaneous bridge openings along the length of a given route is calculated by Eq.(7). This is based on identifying the space available at each section between bridges and is compared to the length of the VT in Eq,(8).

$$b_o = \max(\mathrm{o_x}) \tag{7}$$

$$\mathrm{o}_x = \min_{o \le b_r} \sum_{j=\mathrm{x}}^{o} s_j \ \ge L_{VT} \text{ where } \mathrm{x} = 1 \ldots \mathrm{b}_r \tag{8}$$

b_o: Maximum required bridge opening along the route
o_x: Number of open bridges at a specific section x along the route
b_r: Number of bridges on the route
s: Length of the section between bridges

3.5. Reduction in the number of bridge openings

The expected reduction of bridge openings is deduced from an estimate of the required number of FVs that are needed to create economically viable operations for the VT organisers. The calculation of these values as well as an estimate for the expected market share is taken from the research presented in *Colling et al. (2021)*. The number of single-vessel bridge passages is based on the historical data and is inserted into Eq.(9).

$$s_{bo} = p_s m - \frac{p_s m}{n_{min}} \tag{9}$$

m: Market share of VT implementation (%)
p_s: Number of annual single vessel passages
n_{min}: Number of FVs in VT to make it economically viable
s_{bo}: Number of saved bridge opening per year

3.6. Reduction in waiting times for road users

While scheduling benefits may be created by having longer opening times, these benefits are not quantified within this research. For there to be a congestion benefit, the time it takes for all follower vessels to pass shall not surpass the bridge opening time for a single vessel. Eq.(11) expresses this basic conditions that needs to be met for a congestion cost-benefit to be achieved. The reduction of waiting time is the difference between the reduced number of bridge openings and the added time per bridge passage for the additional vessel times, which is taken for all bridges along the route.

$$t_{p_s} = \frac{\frac{d_{aft}+d_{front}+L_{LV}}{1000}}{v_{lim}} + t_{o\&c} \tag{10}$$

$$\frac{\frac{\sum_{i=1}^{n}(L_i+d_{SW}L_i)}{1000}}{v_{lim}} \le t_{p_s} \tag{11}$$

$$s_W = \sum_{\mathrm{j=x}}^{\mathrm{b}_r} \left(\frac{p_s m}{n_{min}}\left(t_{VT} - t_{p_s}\right) - s_{bo} t_{o\&c}\right)_j \tag{12}$$

t_{p_s}: Time for a single vessel passage (h)
s_W: Waiting time savings for road users (h)

3.7. Congestion cost-benefit

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

$$s_{con} = q_1 \, s_w \frac{L_v(1+d_r)}{1000} c_{con} \tag{13}$$

c_{con}: Cost of road congestion (€/v-km)

d_r: distance between road vehicles (% vehicle length)

s_{con}: Savings due to congestion reduction (€)

4. Case study

This section is an application case of the methodology described in section 3. Section 4.1. introduces the route of the case study, that passes through the Dutch province of Noord-Holland and ends in Amsterdam. The input data for this route is listed in section 4.2. Section 4.3. describes the case study results and concludes whether it is viable to penetrate the urban area leading into Amsterdam with the VT.

4.1. The route

The route for the case study was picked based on waterborne and road traffic density, the waterway size, bridge distances as well as the data availability from the bridge management systems of the province Noord–Holland. The route starts on the western side of the Haarlemmermeer polder Ringvaart and runs between the Kaag and the IJ, in the centre of the port of Amsterdam, Fig.2. It is the most intensively used urban waterway in the province of North-Holland and has short bridge spacing in the metropolitan area of Amsterdam. It is a segment of the inland waterway connecting the port of Rotterdam and the port of Amsterdam. Table I provides an overview of the operations along this route. Based on the dimensions of a CEMT class II vessel with an air draught of 4.7 m, *Rijkswaterstaat (2011)*, 14 of the 19 bridges that are crossed along the way have to open. As the VT is targeted for cargo vessels, only the average number of bridge openings for cargo vessels are considered and not the large number of recreational vessel passages. The average number of bridge passages is to about 97% composed of single vessel passages. Finally, the map in Fig.2 also indicates the location of emergency services that may cause immediate closer of a bridge or may limit the number of adjacent bridge openings.

Fig.2: Case Study Route, https://www.google.com/maps

Table I: Route features

Operating between	De Kaag <-> Port of Amsterdam
Route Length	25,6 km
Number of bridges	19*
Number of bridges with available data	5*
Average distance between bridges	1,3 km
Average number of openings (cargo vessels)	1660/ year*
Bridge opening times	5:00 h - 23:00 h*
Waterway size	Up to CEMT III

* Source: Provincie Noord-Holland (2020)

4.2. Input Data

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

The case study is applied for a varying number of FVs in the train. Dependent on the development stage of the VT technology, *Colling et al. (2021)* have identified a minimum number of FVs to create an economically viable case for CEMT class II vessels. A fully matured control system only requires one FV. In the early stages of the implementation, additional monitoring crew is needed on the LVs; hence the required number of FVs rises to three FVs, in case the originally sailing condition of the reference vessel is continuous, and up to six FVs, if the reference vessel only operated for 14 h per day. Based on this data, the vessel type chosen for this case study is also a CEMT class II.

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

Table II: Input data for case study

Input data	Value	Unit	Source
Waterborne Traffic			
Vessel Length (CEMT 2)	85.0	m	*(Rijkswaterstaat., 2011)*
Operating speed	8	km/h	*(Balduyck, 2013)*
Limited operating speed at bridges	6	km/h	
Distance before LV and after last FV	0.13	km	1 min at 8 km/h (*Backers, 2020)*
Bridge opening and closing time	0.058	h	*(Provincie Noord-Holland 2020)*
Safety factor between vessels	1.5	Ship lengths	*(Hekkenberg & Colling, 2020)*
Road Traffic			
Vehicle length (average day; rush hour)	4.6; 4.2	m	*(NDW, 2020)*
Vehicle speed (average day; rush hour)	83; 70	km/h	*(NDW, 2020)*
Intensity	746; 1253	veh/h	*(NDW, 2020)*
Max Intensity	2500	veh/h	*(Knoop & Hegyi, 2020)*
Max jam length	1200	m	*(NDW, 2020)*
Distance between road vehicles	10	%	
Congestion Benefit			
Metropolitan area, car	242.6	€ct/vkm	*(Korzhenevych et al., 2014)*
Metropolitan area, truck	460.9	€ct/vkm	*(Korzhenevych et al., 2014)*
Urban area, car	75	€ct/vkm	*(Korzhenevych et al., 2014)*
Urban area, truck	144	€ct/vkm	*(Korzhenevych et al., 2014)*

4.3. Results

4.3.1. Maximum bridge opening time

The maximum opening time for the available bridge data is presented in Fig.3. Each set of bars is representative of a bridge along the route. The blue bars present the time a bridge can be open in normal traffic conditions for an average day in 2018. The red bars show the bridge opening times for the same bridges during rush hour. The faintly coloured bars show bridges, where only indicative data was available since the data quality was insufficient. In close proximity to Amsterdam, which are the two sets of bars on the right-hand side of Fig.3, the bridge opening times are significantly shortened because the intersections are very close to one another.

The required bridge opening times for the VT of one, three and six FVs require 8.5 min, 12.7 min and

19.1 min, respectively, with a safety distance of 1.5 ship lengths between vessels. If this safety distance were to be reduced to 0.5 ship lengths, the required bridge opening time diminish to 7.6 min, 10.2 and 14 min. In either case, the feasibility check with the maximum opening times concludes that only the VT with a single FV would be able to pass most bridges outside of rush hours away from Amsterdam. With the failure of this feasibility check, the case route is not viable for the VT penetration into urban areas. For this to become viable, the route would have to cut short and the VT would have to separate for the final bridges.

Interviews with bridge operators revealed that most of the municipalities in the Netherlands pursue a policy that has a maximum of ten minutes bridge opening time per passage, *Backers (2020)*. This means there may be room to extend these passages slightly. With this extended time and a reduction in safety distance, a VT length of at most three FVs becomes possible.

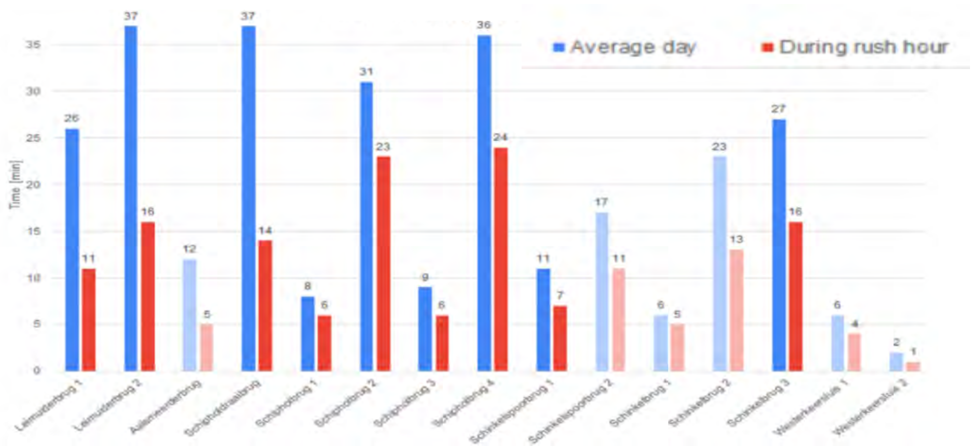

Fig.3: Maximum bridge opening times on an average day and at rush hour

4.3.2. Maximum number of bridges simultaneously open

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

Table III: Open bridges required per route section

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

4.3.3. Congestion improvement

One of the goals of this research is to identify how much congestion cost-benefit the VT would be able to achieve. Even though the feasibility checks, that would ensure seamless VT-bridge passage, were not met, it is still worth gauging the magnitude of the potential congestion cost savings, as it can still be indicative for other routes with more appropriate bridge spacing's. It is hence useful to obtain an understanding of how large potential congestion cost savings could be. Before, presenting the congestion cost savings, the maximum VT length that is able to achieve these savings is shown in table IV. This is calculated based on Eq.(5) while solving for n. This length is determined for a variety of safety distances. It shows that all the economically viable VT lengths presented in the case study section can be accommodated. However, for this to be possible, the safety distance between the vessels needs to be 10% or less of the vessel length.

Table IV: Maximum number of FVs in VT based on safety distance between vessels

Safety distance	0.1	0.5	1	1.5
Max VT Length (LV + FVs)	7	6	5	4

The total annual hours of bridge opening time saved over the length of the route can vary from as high as 219 h with 3 FVs or 106 h with 1 FVs at 100% market share, to as little as 1 h saved with 3 FVs or 48 min with 1 FVs at 1% market share. Fig.4 translates these savings into monetary values for a range of different market shares. The bottom line represents the conditions in which all road traffic participants would be cars and the top line assumes all participants to be trucks. The maximum social congestion benefit has a range that lies in the green shaded area dependent on the composition of the road traffic. The maximum cost saving achieved for this route, in the best case savings scenario that all waiting traffic are trucks would be close to €0.8 million. Any results where the VT has a market share smaller than 25% are negligible. Given the fact that even VT implementation of 25% of the market share can be considered large, a realistic implementation of the concept with about 10% of the market share is not able to improve the VT case viability to penetrate urban areas.

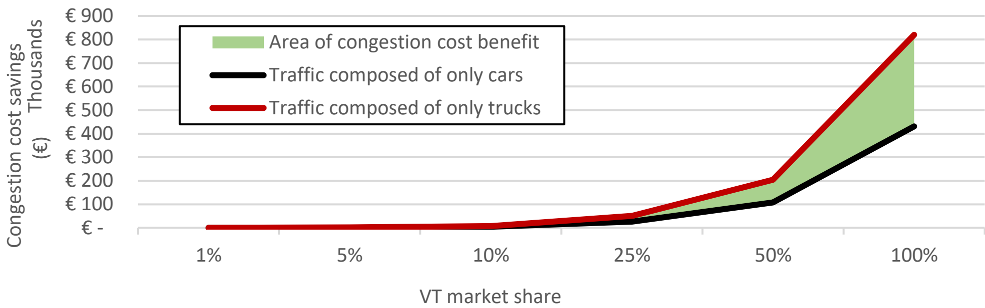

Fig.4: Congestion cost-benefit for different VT market shares

Based on the required number of participants for the VT liner service presented in *Colling et al. (2021)*, around 4000 passages are needed. These are more passages than the recorded annual cargo vessel passages for the route, Table I. However, if the other type of vessel, including recreational vessels are counted, the demand for the required number of vessel passages can be met, with the total passages reaching around 6000. This means that the theoretical market share of 66% of all participants, cargo and recreational vessel, would be needed to ensure economically viable VT operations to be achieved. This final observation lets us conclude that the route can only be considered as an addition to the VT operations and not as its main service, as that would mean the cargo flows on these smaller waterways need to be larger. Alternatively, the business model of the VT operator would also have to be adjusted such that other types of waterway users can take advantage of the VT services as well.

5. General guidelines for successful implementation of VTs in urban areas

The case study application showed that the metropolitan area of Amsterdam is a challenging target for the VT implementation. This is mainly due to the road traffic intensity and short road distances to intersections. However, this case study is not representative of all urban areas. It could actually be viewed as a worst-case scenario. Routes with less road traffic density would likely not fail at the bridge opening times feasibility check, but rather more likely at the number of simultaneous bridge openings.

The plots in Fig.5 are generic lookup keys that can provide guidelines to determine if a specific route can fit the requirements to pass the feasibility tests. The data accompanying these plots are provided in the appendix. The left plot provides bridge opening times based on various traffic conditions that can be crosschecked with the passage time of the desired VT length. This value can then be used in the right plot to determine if the bridge spacing along the route meets the minimum lengths. The right-hand key was explicitly set to accommodate vessel lengths of CEMT I-III, which are the vessel types sailing on smaller waterways in urban areas.

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

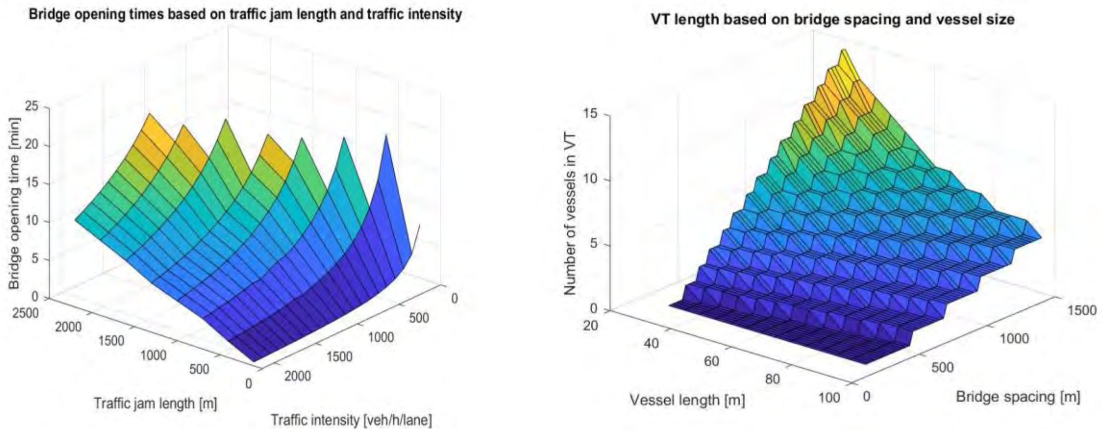

Fig.5: Generic lookup keys for VT penetration of urban areas

6. Conclusion

This paper presented the opportunities and challenges of applying semi-autonomous navigation to penetrate urban waterways with the VT concept. The model compares the road to the water traffic conditions and determines whether a given route is viable for the VT concept implementation. To demonstrate the application viability a route in the Dutch province of Noord- Holland is studied.

The main influence factors of urban penetration are: 1) Bridge opening time 2) Maximum number of simultaneous adjacent bridge openings. The bridge opening times are based on the traffic intensity and the road space to the next crossing in front of the bridge. The number of adjacent bridge openings is highly dependent on road-based emergency traffic that needs to reach its destinations without significant delays. Yet, a rule of thumb is that no more than two adjacent bridges should be opened simultaneously. The viability of the VT operations fitting into the distance between these bridge opernings is dependent on the geographical spacing of the bridges as well as the safety distances between vessels. Additionally, the VT operations would have to be targeted such that they fall outside of rush hours, yet still within the opening times of the bridges. Regulations such as the bridge operating hours or even the maximum individual opening times could be amended with a greater vessel demand, others such as the number of simultaneous bridge openings, are not likely to be changeable.

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

The required number of passages concluded from the viability study by *Colling et al. (2021)* requires more vessel passages than the cargo vessels passages recorded along the route. This suggests that either the route can only be considered as an addition to the VT operations and not as the VTs main service route or other vessel types, potentially including recreational vessels, would have to be joining the train. The model developed within the research is used to provide generic lookup keys that can serve as guidelines to determine if another route could be suitable for the VT application.

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Appendix

Table V: Bridge data input data

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

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

Table VI: Available road traffic data

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

Assumptions made for this data:

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

Table VII: Bridge opening times (min) dependent on road traffic

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

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

Table VIII: Maximum viable VT lengths dependent on vessel sizes and minimum bridge distances

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

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