Waterborne platooning by smart vessels for smart shipping

Semi-automated vessel train configurations of inland and short sea could bring considerable efficiency benefits, research conducted by Delft University of Technology has found

Authors

Ali Haseltalab, **Linying Chen**, **Alina Colling**, **Luke Borst**, **Vittorio Garofano**, **Robert Hekkenberg**, and **Rudy R. Negenborn**
Department of Maritime and Transport Technology, Delft University of Technology, Delft, the Netherlands

Economic development is currently putting an enormous pressure on transport systems. The demand for freight transport is likely to grow over the next few decades [1]. If roads and railways are the major means of transport to handle the growth, they will face frequent congestion. In densely populated regions, like cities, road networks are already confronted with congestion and capacity problems.

Meanwhile, inland waterways still have plenty of capacity to transport more goods [2, 3]. Waterborne transport could offer an environment-friendly alternative in terms of both energy consumption and noise emissions [4]. To meet the transportation demand and maintain sustainable development, promoting waterborne transport has gained increasing attention.

Like many other technology domains, there is a shift taking place in the maritime industry towards the adoption of smart technologies for transport over water. In this regard, one of the main objectives is to use the current infrastructure in a more efficient way to handle the ever-increasing problems with congestion, delivery delay, emissions, and transport costs.

Advanced technologies are being applied from different aspects to different domains of shipping. While novel cooperative approaches are being used for solving real-time logistics challenges [17,19], the power and propulsion system (PPS) of ships face revolutionary improvements as fully electric and hybrid PPS configurations are being implemented to reduce emissions and increase fuel efficiency [12—16].

Recently, researchers have started investigating the possibility and efficiency of moving vessels in formation, inspired by similar works in robotics and vehicular technology domains, to increase the efficiency of transport with ships. With regard to inland waterways and port areas, platooning, in which multiple vessels follow each other with a certain distance and form a vessel train, has been conceived as the most suitable formation.

This potential futuristic business case can lead to reduced crew and operational cost, improved accessibility of urban areas, and increased logistics flexibility. As a result, more effective transportation over water can be achieved. Smart ships with advanced PPS can even further increase the efficiency and flexibility of vessel platoons if they adopt novel methodologies for forming and controlling the platoons.

In this article, after elaborating on the advantages and disadvantages of platooning over water from the business point of view, it is explained how novel control approaches combined with advanced PPSes can lead to highly effective, flexible, and fuel-efficient vessel platoons. Furthermore, optimal placement of vessels in a train formation is discussed, which can lead to increased fuel efficiency and minimised water resistance.

The contents of this article are based on the results of research carried out at the Department of Maritime and Transport Technology of Delft University of Technology in the Netherlands. The article provides insight and solutions towards enabling a revolutionary transportation scheme that can address the interests of different transportation parties.

Platooning: pros and cons

Waterborne platooning can be achieved without the need for fully autonomous vessels. In one of the operating modes, which is known as leader-follower, it is sufficient for the follower vessels (FVs) to be equipped with technology that allows them to track the platoon leader and keep a safe distance to the vessel in front of them. Such a transport solution is currently being investigated by the NOVIMAR project [5], in which it is assumed that the leader vessel (LV) is fully manned and in charge of navigation of all FVs whilst they are in the train.

The automation of the navigational tasks on the FVs is expected to bring them an economic benefit by reducing the operating costs and thereby improving the competitiveness of waterborne transportation. The way in which these cost savings are achieved differ depending on the sector the platoon operates: In the sea going sector, up to 42% of the vessels' operating cost comes from crewing [6]. The automation of navigational tasks thus requires less crew members onboard for the same operational activities and it has been shown that up to three crew members can be taken off board by automation of the navigational tasks alone [7].

For the inland sector, advantages are expected to be gained in a different manner. Inland vessels have smaller crew sizes than short sea vessels. Their crew size ranges between two and five members [8] yet crewing for smaller inland vessels makes up 56% of the vessels fixed cost [9].

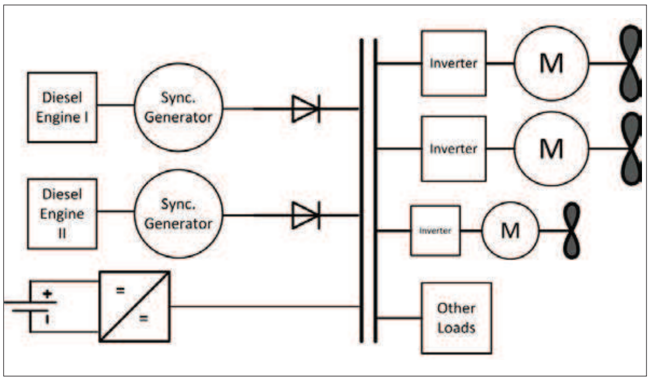


Figure 1: An all-electric architecture with diesel-generators and a battery as energy sources

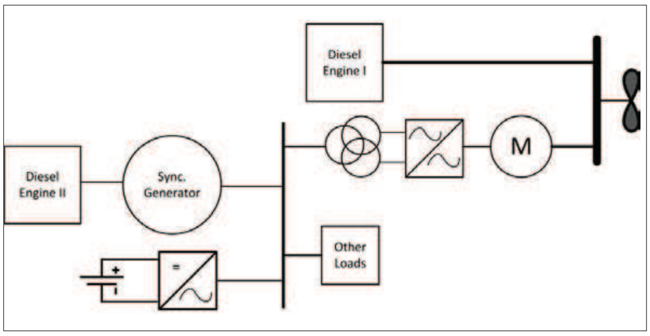


Figure 2: A hybrid architecture with diesel engines and a battery

Inland vessels follow sailing regimes of 14, 18 or 24 hours, which determines the minimum crew requirement onboard. Vessels that currently operate at 24h sailing regimes could make use of the vessel train to keep operating on a 24h schedule but with the crew of an 18h regime. Simultaneously, vessels with smaller crews, operating at 14h sailing regimes, may be able to keep their crew as is but sail on a 24h regime. They would be making use of resting time for their crew and the take-over of navigational responsibility by the leader vessel to raise the productivity of the vessel.

The enhancement in operating time of the platoon provides a further increase relevant for the inland sector if the European Commission starts to keep a closer eye on the exact shift time each crew member spends working, as they do in the trucking industry with the tachograph [10].

Enhancing the level of technology on vessels can take a great amount of convincing and time for ship owners, since enabling waterborne platooning requires large investments and a culture change in the traditional maritime sector. Technological enhancement of full automation also faces liability challenges similarly to other industries. Platooning with crewed vessels can thus be seen as a stepping stone to enhance the automation level onboard without having to deal with several challenges of autonomy.

Providing platooning services creates some business case difficulties. Aspects such as waiting times at gathering places of vessel trains or at bridge/lock passages can cause increases in the trip time. Such waiting times will decrease the benefits the FVs can make within the train. A possible manner to minimise such waiting times could be to create platooning services that operate with high departure frequencies.

Furthermore, the interaction between locks/bridges and the platoon operators can be optimised. This however could only be done on routes with large cargo flows and would require a large number of LVs. The LV services in turn can also be provided in different business models that will affect the economics of the entire vessel train. A dedicated LV will allow greater flexibility in destination but will be more expensive as a service, whilst a multipurpose cargo vessel with the capabilities to lead a train will be cheaper concerning contribution costs but more restricted in its departure and destination [11].

As can be seen from these few examples, the development of an economically viable business model for waterborne platooning involves finding the balance between many different aspects and challenges. Operating in a vessel train does, however, hold the potential to become a solution towards a modernisation in the shipping industry.

To enable waterborne platooning and turn it into an advantageous transport scheme for different waterborne transportation sectors, several technological challenges should be addressed. These challenges range from control and artificial intelligence challenges to design and efficiency issues. In the remainder of this article, several solutions for some of these challenges are discussed.

In the following, it is also explained that platooning can be a quite flexible transport approach in which all the vessels can decide on the vessel train specifications (such as speed and number of operating vessels) and does not only happen under the leader-follower protocol, where the leader decides on all the features of the vessel train. This makes platooning a fruitful waterborne transport scheme for all the parties involved.

In the next section, the role of innovative power and propulsion system architectures for having fuel-efficient vessel trains is discussed.

Advanced power and propulsion system configurations

Alongside increased autonomy, and mainly due to environmental restrictions from international maritime authorities, there is a shift towards more efficient Power and Propulsion System (PPS) architectures as a replacement for direct-diesel propulsion configurations. Based on the agreements made in the International Maritime Organization (IMO), the shipping industry agreed to reduce its carbon emissions by 50% from 2008 levels by 2050. To address this, alternative energy sources are combined with innovative – and mainly – electric PPSes as the first step. Alongside fuel efficiency and reduction of emissions, innovative PPS can also increase the adaptability of ships to different operating profiles.

The complexity of innovative onboard PPS architectures is increasing due to the addition of several components

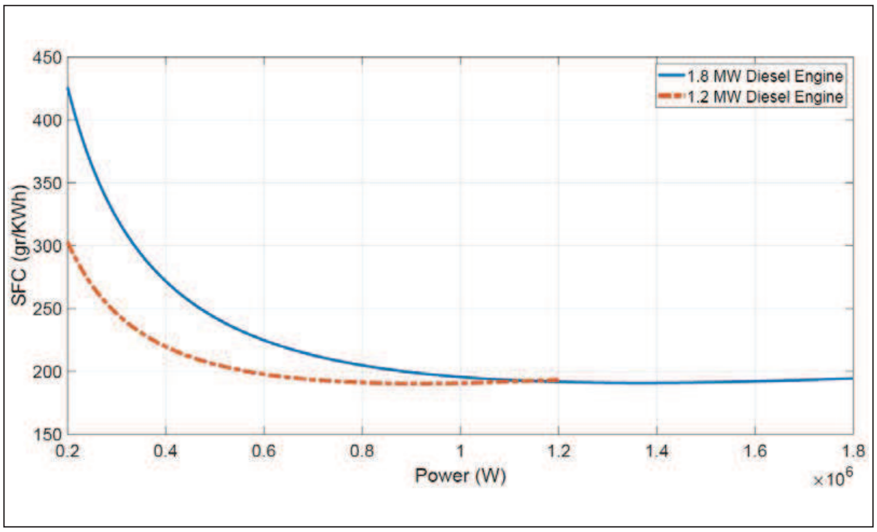


Figure 3: SFC curve of two diesel engines with different power ratings

such as synchronous generators, induction motors, and power conversion modules. The innovative architectures can be divided into two different types: all-electric architectures in which this relationship is formed only through an electrical grid (Figure 1) and hybrid architectures in which the relationship between diesel engine and propellers is established both directly and through electrical machinery (Figure 2). It has been shown that such advanced architectures cannot be as efficient as expected unless advanced control and energy management algorithms are adopted. There has been considerable research increasing the fuel efficiency of ships with these architectures. For more information regarding this work see [12] and references therein.

Ships with advanced PPS architecture are more adaptive to different types of operating profile as they can use diverse types of energy sources for carrying out their operations. Moreover, this diversity provides flexibility in reaching a fuel consumption-based optimal split between the different energy sources' share of generating power. In a vessel train where different types of vessels with different PPS specifications meet to sail at a similar voyage speed, this flexibility and adaptiveness can help to improve efficiency.

The adoption of advanced approaches for the control of the PPS and energy management can lead to a significant increase in fuel efficiency and reduced emissions [13—16]. Furthermore, when it comes to multi-vessel operations, if an intelligent cooperative approach is developed for vessels to collaborate with each other towards the goals of their mission by considering each other's limitations, efficiency and performance can even be further improved.

As an example, in a vessel train, consider two vessels with different engine specifications. The specific fuel consumption (SFC) curves of these vessel are shown in Figure 3. The question then is what speed is best for a platoon that includes these two vessels so that the overall fuel efficiency is maximised? And how can this speed be reached? In the next section, using advanced approaches, a cooperative protocol whereby collaboration between vessels is enabled with the aim of decreasing fuel consumption is introduced.

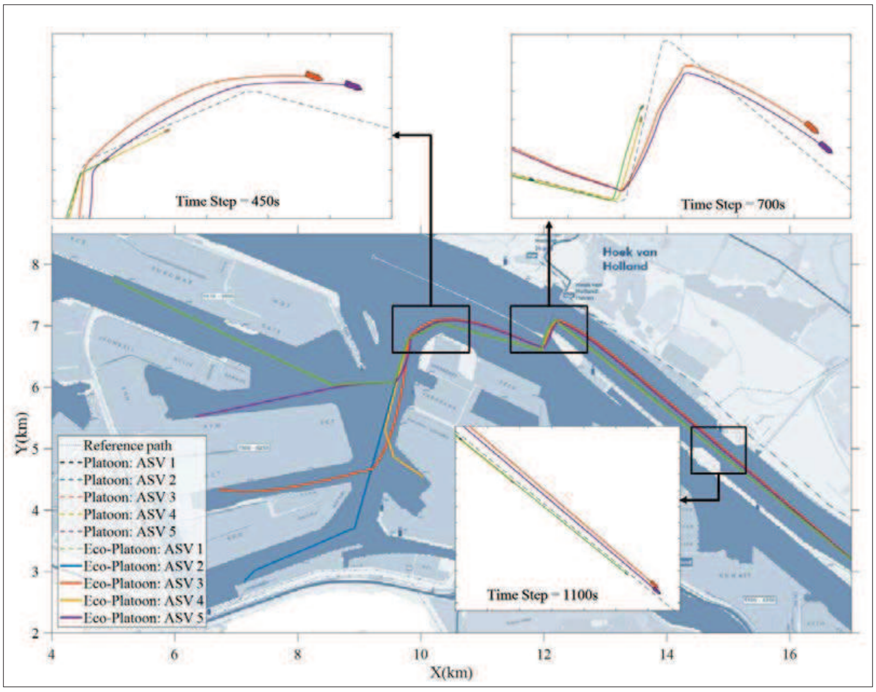
Eco-Platooning for Smart Ships

Ships usually have predetermined origins, destinations and paths, to sail in groups ships should reach consensus on the speed of the platoon. At the same time, ships should avoid collisions with nearby vessels. Thus, in the platoon of vessels, the following needs to be considered at the same time:

1) Trajectory following: attempt to follow the predetermined paths
2) Speed consensus: attempt to keep the same speed with nearby ships
3) Collision avoidance: avoid collisions with nearby ships

In the platooning problem, a vessel controller per vessel makes decisions based on the information provided by sensors and the information it receives from other vessels. An agreement is achieved when the actions of the controller are chosen

Figure 4: Trajectories of the ships in simulation using eco-platooning



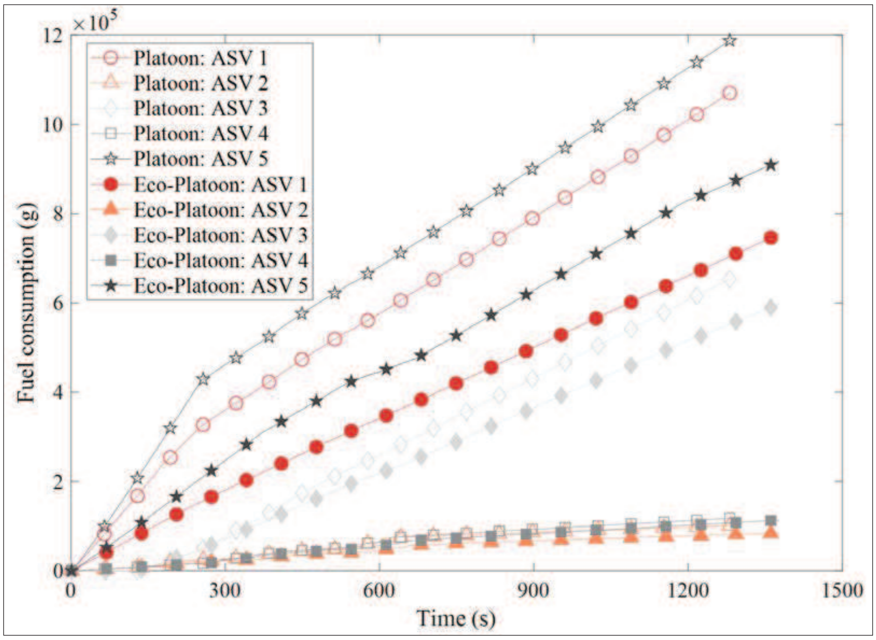


Figure 5: Total fuel consumption of each vessel

based on the information it receives from the controller of other vessels.

In a waterborne platoon, there can be several ships with different specifications regarding ship size, shape, power ratings, etc. As a result, their suitable operating profiles might differ. A fuel-efficient platooning method, eco-platooning, is proposed [17], which involves finding a consensus on the speed for the platoon that is optimal for all the ships subject to their operational objectives and the efficiency specification of their PPS. In eco-platooning, each ship controller proposes a fuel-efficient speed that can make its diesel engine to operate within the efficient region of its SFC curve.

As an example, simulation experiments were carried out for a waterborne platoon consisting of five ships navigating from the different terminals in the Port of Rotterdam to inland waterways. Each ship had different dynamics and engine settings to be considered, and was controlled by an advanced control approach known as model predictive control (MPC) that tries to reach consensus on the platoon speed by negotiating with other vessels through the eco-platooning protocol.

Figure 4 shows the trajectories of the vessels. The ships have similar trajectories in the experiments using eco-platooning protocol and a platooning protocol which does not consider the PPS specifications of the vessels. Total fuel consumption of each ship using two approaches are provided in Figure 5. Table 1 provides the comparison of average speed, average fuel consumption rate (FCR) and total fuel consumption of the experiments using the normal platooning and eco-platooning approaches. The results suggest that a significant amount of fuel saving could be achieved by using eco-platooning. For more information regarding this research work and its results, the reader is referred to [18].

Optimal platooning formations

Another issue in platooning is the positioning of follower vessels in a platoon since the water resistance will be subject to

		ASV 1	ASV 2	ASV 3	ASV 4	ASV 5
National Platooning	Average speed (m/s)	0.42	0.40	0.33	0.37	0.46
	Average FCR (g/s)	152.55	14.37	93.14	16.77	169.28
	Fuel (x10^5 g)	10.71	1.01	6.54	1.18	11.89
Eco-Platooning	Average speed (m/s)	0.34	0.37	0.31	0.35	0.39
	Average FCR (g/s)	100.04	11.22	79.29	15.04	121.67
	Fuel (x10^5 g)	7.55	0.85	5.98	1.13	9.18
Difference[a]	Average speed (m/s)	-0.08	-0.04	-0.03	-0.02	-0.07
	Average FCR (g/s)	-52.51	-3.15	-13.85	-1.73	-47.61
	Fuel (x10^5 g)	-3.17	-0.16	-0.56	-0.04	-2.71
FCR improvement[b]		-34.4%	-21.9%	-14.9%	-10.3%	-28.1%
Fuel improvement[b]		-29.6%	-16.2%	-8.6%	-3.7%	-22.8%

[a] Difference=Eco-Platooning - Normal Platooning; [b] Improvement=Difference/Platooning

Table 1: Comparison of the simulation results

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change due to propulsion and hull effects from the front vessels. As a result, it is vital to find the optimal position for follower vessels where the resistance is minimum. This problem has been investigated at the Maritime and Transport Technology department of Delft University of Technology where different positioning configurations have been tested [18].

The results of these experiments suggest that for vessels with approximately similar size and circular hull shapes, it is favourable to position the follower vessel at an angle of 30° to 50° behind the front vessel. Moreover, the longitudinal distance with the front vessel changes based on the speed of the platoon. Figure 6 shows the optimal placing of the follower vessel at 3.5 knot. The energy consumption of the follower vessel in different positions relative to the front vessel is compared with the energy consumption of a single sailing vessel in Figure 7.

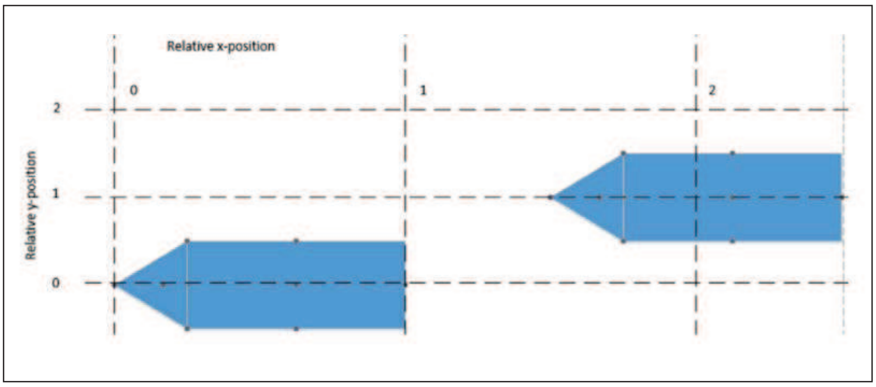

Figure 6: Optimal positioning of the follower vessel at 3.5 knot

Conclusion

In this article, waterborne platooning as an innovative shipping scheme is explained and introduced. Its advantages and disadvantages are mentioned and some solutions are proposed for enabling fuel-efficient vessel trains. Platooning using smart vessels is a novel transport approach which can address several waterborne transport issues. It is in accordance with the concept of autonomous shipping and can lead to increased autonomy and reduced transport costs.

In order to enable waterborne platooning, many issues need to be addressed, which requires extensive considerations by both academic and industrial communities.

Acknowledgment

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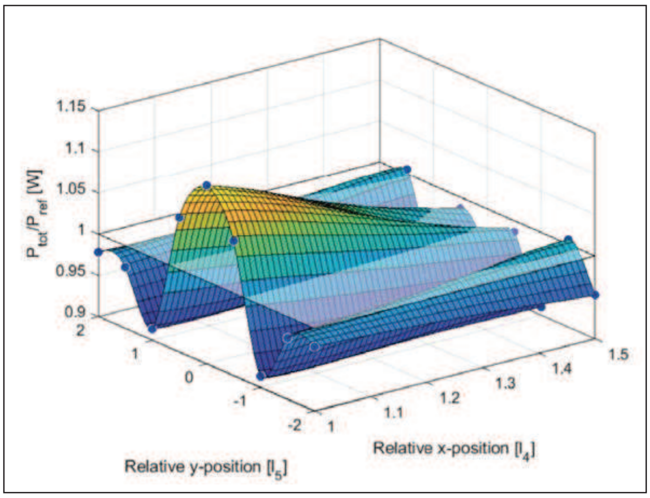

Figure 7: Energy consumption of the follower vessel in different positions relative to the leader vessel and in comparison with a single sailing vessel at 3.5 knot

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