Stability assessment of the river-sea Vessel Train

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ABSTRACT

Vessel Train is a novel waterborne transport concept which implies several digitally connected vessels sailing in a convoy. Vessel Train is consisted of a “lead vessel” and one or more “following vessels”. The lead vessel is fully manned, while the following vessels are remotely controlled from the lead vessel via a control system. This could allow the following vessels to sail either with a reduced crew or with a crew off-duty. This paper addresses the stability assessment of the Vessel Train consisted of the river-sea ships, which are subject to operational limitations when sailing in maritime environment. Using the Second Generation Intact Stability Criteria framework, it is investigated how sailing in the Vessel Train would affect the operational limitations of the river-sea ships depending on their design and operational features.

Keywords: *Second Generation Intact Stability Criteria, river-sea ships, operational limitations, autonomous ships, Vessel Train, NOVIMAR*

1. INTRODUCTION

Project NOVIMAR (NOVel Inland waterway and MARitime transport concepts) examines the possibilities for introduction of a specific waterborne platooning concept (the so-called Vessel Train) in short-sea shipping, sea-river, and inland navigation. Vessel Train (VT) represents a convoy of several digitally connected vessels, whereby only the first vessel in the convoy (the so-called lead vessel, LV) is fully manned, while the rest of the vessels (the so-called following vessels, FV), being remotely controlled from the LV via a control system, operate either with a reduced crew (in partially unmanned regime of sailing) or with a crew off-duty (in periodically unmanned regime of sailing).

This paper aims to conceptualize the stability assessment of the VT used in the river-sea shipping. Namely, considering that the river-sea ships could be inland vessels employed in limited, but regular maritime navigation in coastal zones, and that the sailing in a VT implies a certain degree of ship autonomy, the concept of a river-sea VT would comprise several non-conventional features. Since an international safety regulations framework for river-sea ships does not exist, and the autonomous ships are still out of scope of the present maritime regulatory framework, it seems appropriate to address the intact stability with a state-of-the-art methodology based on first principles rather than on semi-empirical models. Consequently, this paper explores the possibilities for stability assessment of the river-sea vessel trains in maritime navigation using the

Second Generation Intact Stability Criteria (SGISC) framework.

Being intended for inland waterways, inland vessels are not designed in compliance with the intact stability regulations for seagoing ships. It is thus obvious that the river-sea ships may only have a restricted access to maritime environment, limited by weather conditions. Various forms of operational limitations are already being used in river-sea navigation throughout the world, most notably in Belgium, Russia, China, India, etc. (see Bačkalov, 2019). Rudaković (2021), however, proposed a common framework for calculation of operational limitations for river-sea ships based on the SGISC. Thus, the approach employed in this paper is based on the calculations of operational limitations for river-sea ships as described in Rudaković (2021) and Rudaković & Bačkalov (2019).

It is foreseen that the vessel trains may consist of ships of different sizes and design features. Thus, it may be expected that the vessels participating in the VT have substantially different intact stability properties too. The goal is, therefore, to investigate how the limited access to maritime navigation of individual vessels participating in the VT would affect the operation of the vessel train as whole.

2. SAMPLE VESSELS

The analysis was conducted on vessel trains consisted of typical European inland container vessels and tankers of different sizes, ranging from L = 66 m up to the largest self-propelled ships on Western European inland waterways with overall length of 135 m. In total, six different vessels (three containerships and three tankers) were used to form the vessel trains. The principal data of the vessels used in this analysis are given in Table 1. The letter and the number in the vessel name designate the type and the CEMT class of the vessel (see CEMT, 1992), respectively. Body plans of the vessels are given in Appendix to this paper.

A comprehensive analysis of intact stability features of river-sea ships (see Rudaković, 2021) showed that the typical European inland vessels in maritime navigation could be vulnerable to dead ship condition and excessive lateral accelerations, whereby the dead ship condition was normally the dominant stability failure mode. It was found that the river-sea ships, due to their specific hull geometry and the characteristic range of speeds, are generally not vulnerable to pure loss of stability, parametric roll resonance, and surf-riding. These conclusions apply to the sample vessels used in this study too.

Table 1. Main particulars of the sample vessels (all symbols are in compliance with IMO, 2019)

Vessel	c-6	c-5	c-3	t-6	t-5	t-3
L_{WL} [m]	135.2	108.3	66.83	135.2	109.6	66.83
B [m]	11.4	11.4	10.5	11.4	11.35	10.5
d [m]	3.5	2.46	3.45	3.2	3	3.45
C_B [-]	0.9156	0.8683	0.8099	0.9124	0.881	0.8099
C_M [-]	0.9981	0.9964	0.9959	0.9978	0.9986	0.9959
A_L [m^2]	718.4	647.25	132.56	263.16	163.34	132.56
Z [m]	5.486	4.558	2.841	2.945	2.651	2.841
φ_f [°]	13.1	21.3	32	35.3	35.3	32
h_m [m]	13.8	12.6	7.6	10.4	7.9	7.6
l_{bk} [m]	52	42	24.8	52	42	24.8
b_{bk} [m]	0.15	0.175	0.15	0.15	0.136	0.15

3. METHODOLOGY

Stability assessment of the vessels in the vessel trains was performed according to the Vulnerability level 2 of the SGISC for the dead ship condition and excessive accelerations stability failure modes, see IMO (2019). However, certain amendments were made to adapt the SGISC framework to the specific features of the river-sea ships.

3.1 Idiosyncrasies of safety of VT operations

For the purpose of safety assessment within the NOVIMAR project, the VT has been regarded as a single nautical unit. This means that VT should at least attain the safety level of the conventional vessels. In addition, it also means that the other participants in the waterborne transport should take into account presence of a convoy consisted of multiple vessels sailing in a coordinated manner.

On the other hand, the concept presumes that in case of emergency on one of the followers, the affected FV would be able either to solve the problem without the assistance of other vessels in the VT, or to leave the VT and continue to operate independently, without interrupting the schedule of the remainder of the train. This assumption stems from the specific feature of the VT concept which foresees that the followers are periodically or partially unmanned, i.e. the crew is on board but it is taking rest, or that the ship operates with a reduced crew. Hence, it is expected that the human operators could be summoned in case of an emergency on an FV. When considering sailing of VT along inland waterways, the described approach could be justified from the point of view of the concept efficiency, but also from the safety of navigation perspective, as several vessels at zero speed may impede the traffic on the fairway. However, it is reasonable to assume that a seagoing VT would be subject to international maritime safety regulations; therefore, the master of the leading vessel would be obliged to assist the FV in distress as per SOLAS regulations on obligations in distress situations (see SOLAS Chapter V, Regulation 33).

In case of a failure on the LV, the river-sea VT would have to be disassembled and, after providing the assistance to the ship in distress, the vessels would continue their respective journeys in a conventional manner, if they sailed with the full crew off-duty at the time of the accident. However, if some of the followers sailed in partially unmanned regime at the time of the accident, it is possible that they would not be able to safely continue the voyage on their own. Therefore, it could be argued that the acceptable probability of an accident for the LV should be lower than for the followers in some scenarios since the loss of the LV would have more severe overall consequences. In context of stability assessment, this could be translated into a requirement for more stringent standards for the LV when leading a VT comprised of the followers which sail with reduced crew.

From the point of view of stability assessment, the treatment of VT as a single nautical unit implies that the VT as a whole should attain (at least) the same standards for dead ship condition and excessive accelerations as individual vessels would. Furthermore, the presence or absence of the crew may have different implications for stability assessment depending on the analyzed ship stability failure. In case of the dead ship condition, the actions of human operators should have no influence on stability assessment as the ship should not capsize despite the crew's inability to intervene. Hence, the vessels should attain the same standard of stability in dead ship condition, despite the level of manning. Conversely, in case that the ship is exposed to excessive accelerations, the absence of human operators from the spaces positioned furthermost from the rolling axis (e.g. the wheelhouse) would render the ship not vulnerable to excessive accelerations by default. Therefore, in context of the VT operations, it may be possible to check the vulnerability to excessive accelerations of the LV only.

3.2 Modifications The SGISC framework for application to river-sea ships

River-sea ships may considerably differ from seagoing ships with respect to hull geometry. It is thus questionable whether the methods used for calculation of forces and moments acting on a vessel, which were developed for conventional seagoing ships, could be applied to river-sea ships too. The application of the SGISC framework to the stability assessment of river-sea ships was a subject of an extensive research presented in Rudaković (2021). In brief, the following modifications of the SGISC framework were proposed:

- The simplified Ikeda's method for estimation of roll damping coefficients has been modified to take properly into account the full hull form of the river-sea ships, see Rudaković and Bačkalov (2017).
- Effective wave slope coefficient was calculated by applying the "reduced 3DOF method" on river-sea ships (see Rudaković et al, 2019).
- Instead of the "referent environmental conditions" corresponding to the North Atlantic, it was proposed to use the wind and wave climate parameters – the appropriate mean wind speed and significant wave height relation, and the wave scatter table corresponding to the area where the river-sea ships are supposed to operate.

4. OPERATIONAL LIMITATIONS OF THE VESSEL TRAIN

The stability assessment of the river-sea vessel trains is conducted using the standards for dead ship condition R_{DS0} and excessive accelerations R_{EA2} given in Tables 2 and 3. In accordance with the considerations given in Section 3.1, different values of standards were adopted for the lead vessel (with respect to the dead ship condition and excessive accelerations), and for the following vessel (with respect to the excessive accelerations) depending on the following vessel sailing regime. More stringent standards applicable to the LV leading partially unmanned VT were deliberately increased by an order of magnitude (i.e. the values of R_{DS0} and R_{EA2} were decreased).

Table 2. Standards for dead ship condition R_{DS0} applied to river-sea VT.

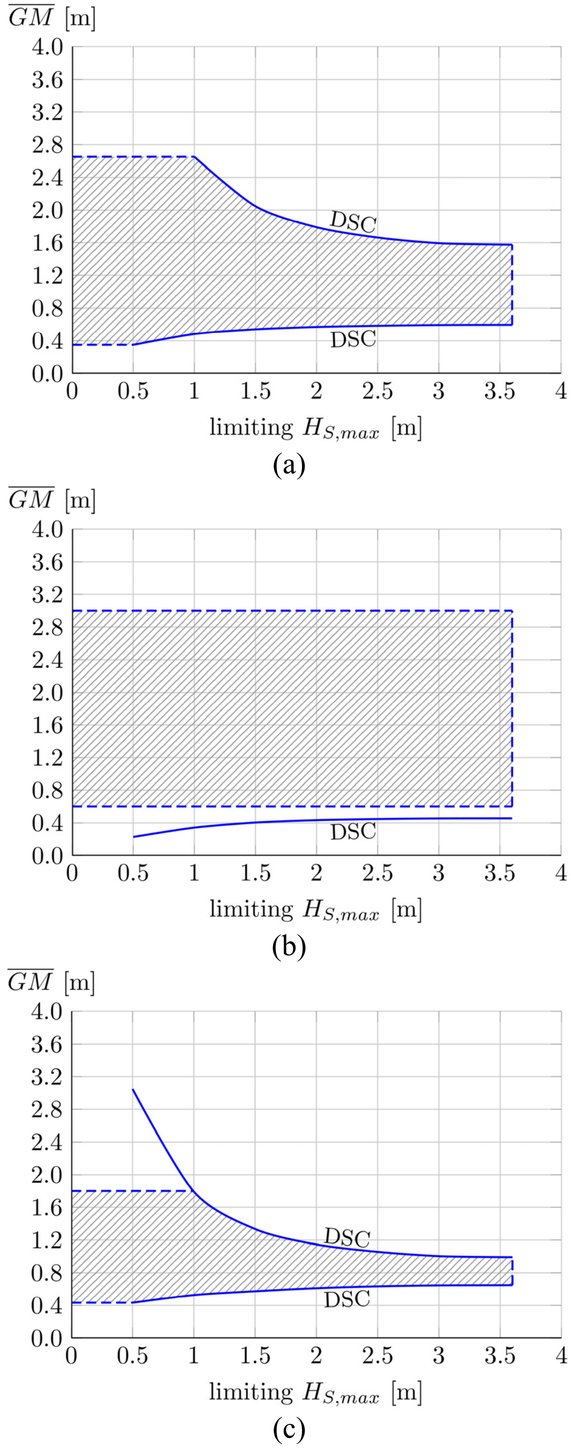
	FV sailing regime	
	partially unmanned	periodically unmanned
LV	0.006	0.06
FV	0.06	0.06

Table 3. Standards for excessive accelerations R_{EA2} applied to river-sea VT.

	FV sailing regime	
	partially unmanned	periodically unmanned
LV	$3.9 \cdot 10^{-5}$	$3.9 \cdot 10^{-4}$
FV	/	/

The calculations were carried out for vessels sailing at their respective design draughts. It was assumed that the river-sea VT would operate in the Southern North Sea coastal zone, so the corresponding environmental conditions (see Rudaković & Bačkalov, 2019) were adopted for the purpose of the calculations. The maximal significant wave height in the designated navigation area is $H_{s,max} = 3.6$ m.

Following the previously described procedure, the operational limitations of examined vessels were calculated, assuming that each of the ships could operate both as an LV and as an FV. The calculated operational limitations are given in Figures 1 ÷ 4. The hatched areas in the Figures represent the range of realistic metacentric heights (for which the adopted stability standards are attained) plotted as a function of $H_{s,max}$. It was found that, in all cases considered, the OL stemming from the ship vulnerability to the dead ship condition stability failure mode were more stringent than the OL resulting from vulnerability to the excessive accelerations.



(a)

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Figure 1. Operational limitations of the examined containerships if the dead ship condition and excessive accelerations stability failure standards are $R_{DS0} = 0.06$ and $R_{EA2} = 3.9\cdot10^{-4}$: a) c-6, b) c-5, c) c-3.

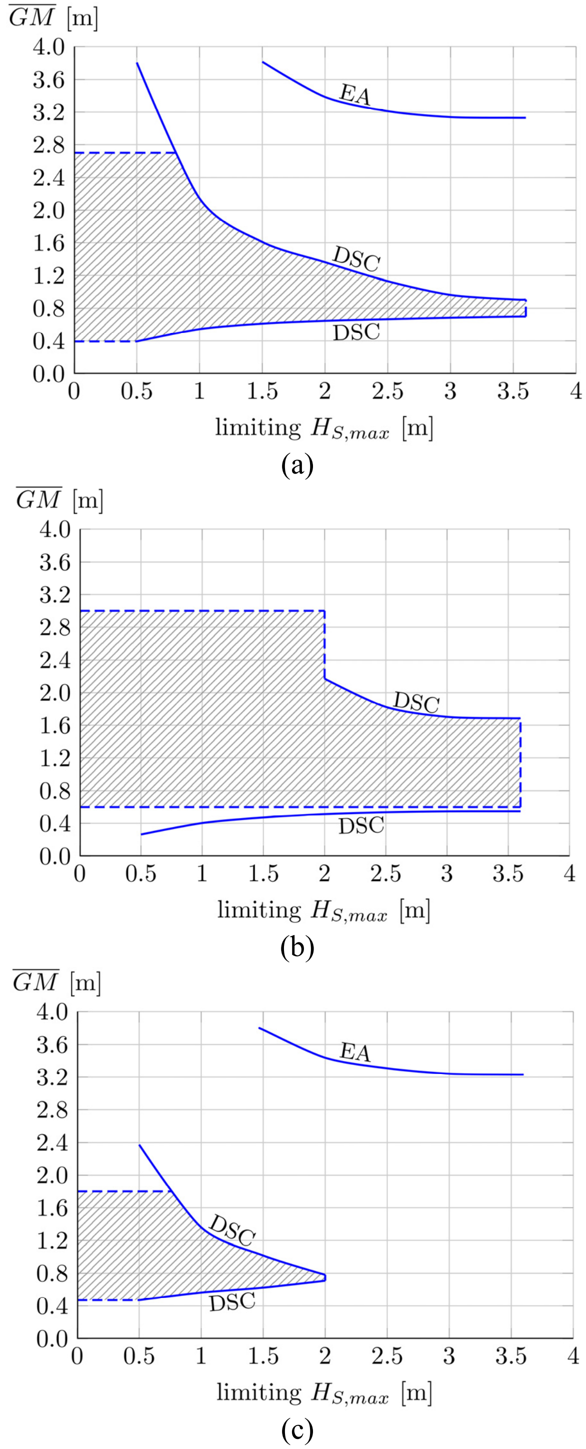

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Figure 2. Operational limitations of the examined containerships if the dead ship condition and excessive accelerations stability failure standards is $R_{DS0} = 0.006$ and $R_{EA2} = 3.9\cdot10^{-5}$: a) c-6, b) c-5, c) c-3.

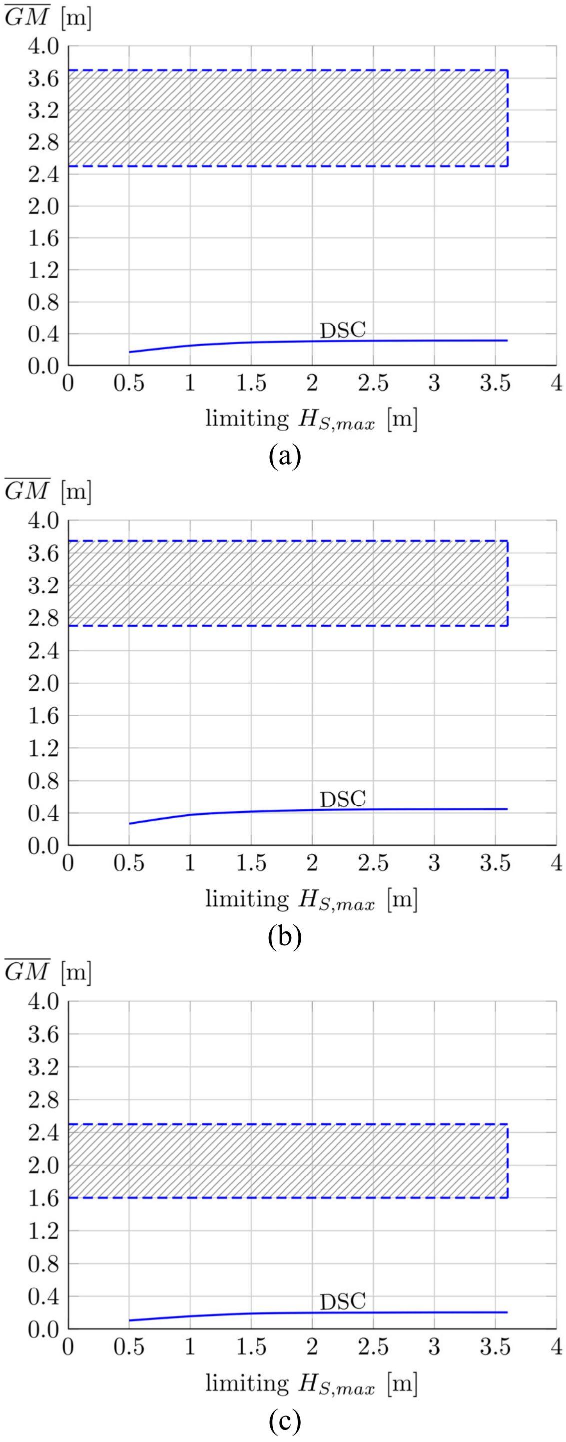

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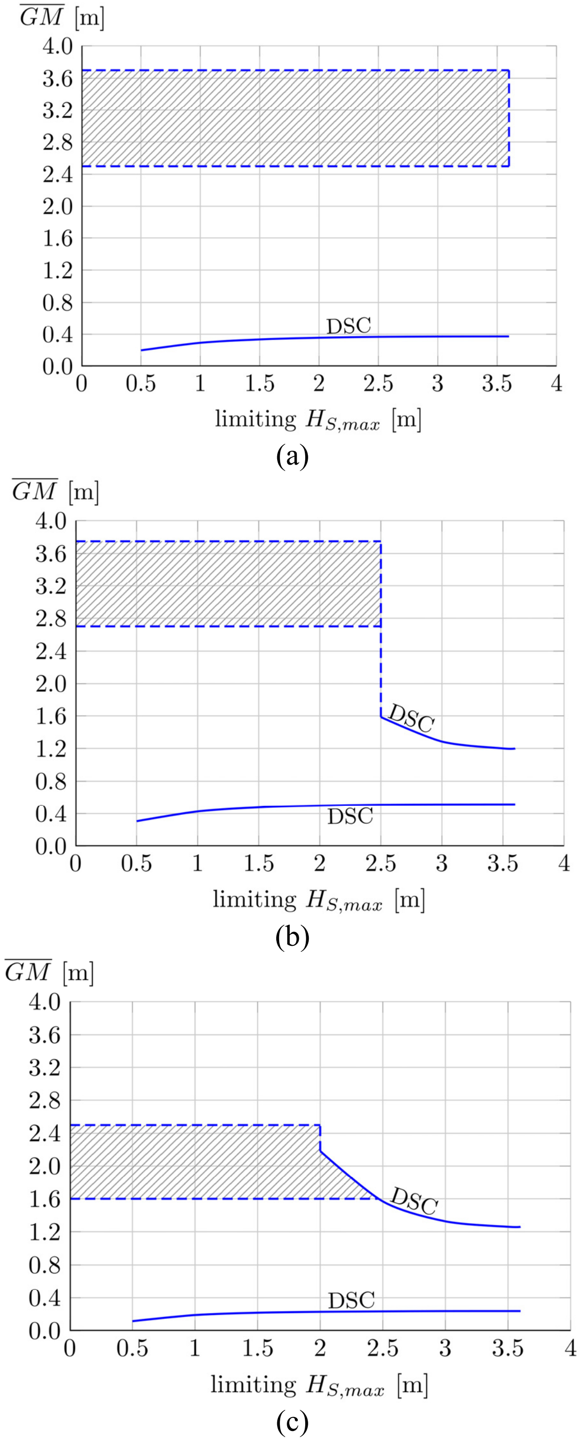
Figure 3. Operational limitations of the examined tankers if the dead ship condition and excessive accelerations stability failure standards are $R_{DS0} = 0.06$ and $R_{EA2} = 3.9 \cdot 10^{-4}$: a) t-6, b) t-5, c) t-3.



(a)

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Figure 4. Operational limitations of the examined tankers if the dead ship condition and excessive accelerations stability failure standards is $R_{DS0} = 0.006$ and $R_{EA2} = 3.9 \cdot 10^{-5}$: a) t-6, b) t-5, c) t-3.

To quantify the impact of design and operational measures on operational limitations, Rudaković & Bačkalov (2019) introduced the indicators of operational limitations *OLI* and $\overline{x}_C$. *OLI* is defined as the ratio of the calculated operational limitations (the hatched areas in Figs. 1–4) and the theoretical maximum of operational limitations (gray rectangular area bordered by the range of possible metacentric heights and the range of significant wave heights that occur in the navigation area, Fig. 5). $\overline{x}_C$ is obtained by normalizing the position of the centroid x_C of the hatched area with respect to the abscissa of the OL chart, with the half of the maximal significant wave height in the wave scatter table (in this case, $H_{s,max}$ = 3.6 m). Consequently, in case of unrestricted navigation, it would be $OLI = 1$ and $\overline{x}_C = 1$.

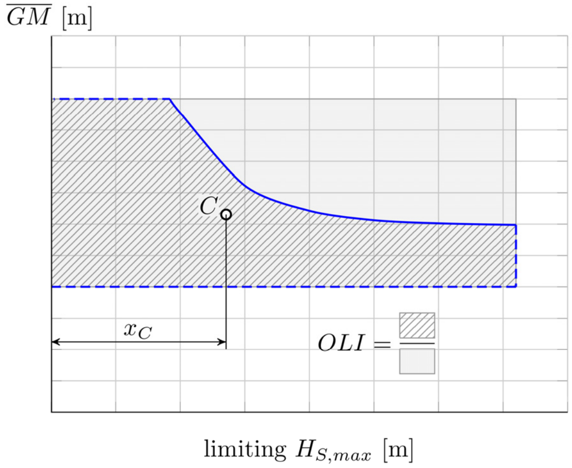

Figure 5. The definition of indicators of operational limitations *OLI* and $\overline{x}_C$.

Table 4. Indicators of operational limitations and the maximal allowable significant wave height of the sample ships.

Vessel	*OLI*	$\overline{x}_C$	$H_{s,max}$
c-6	0.60	0.81	3.6 m
c-5	1	1	3.6 m
c-3	0.49	0.71	3.6 m
t-6	1	1	3.6 m
t-5	1	1	3.6 m
t-3	1	1	3.6 m

The indicators of operational limitations of the sample vessels when they sail outside of the VT are given in Table 4, along with the maximal significant wave height up to which the vessels may operate in maritime environment. It may be noticed that the navigation of all examined tankers is practically unrestricted in the designated area. This is also valid for the CEMT class Va containership.

However, when a vessel joins the VT, her operational limitations may be additionally constrained. In general, this may happen in one of the following scenarios:

- The vessel should be the lead vessel in a VT comprising the followers which sail in partially unmanned regime.
- The vessel should be the lead vessel in a VT comprising at least one following vessel whose OL are restricted to a lower limiting significant wave height $H_{s,max}$ than the OL of the rest of the vessels.
- The vessel should be the following vessel in a VT comprising at least one following vessel or the lead vessel whose OL are restricted to a lower limiting significant wave height $H_{s,max}$ than the OL of the rest of the vessels.

It follows that the operational limitations of a river-sea VT correspond to the operational limitations of its, stability-wise, “weakest” member in the given loading condition.

The OL of most of the vessels would significantly change if the vessels should lead the VT consisted of followers with the reduced crew, since in such case the LV would be the subject to a more stringent standard of stability in dead ship condition (R_{DS0} = 0.006). Indicators of operational limitations of the sample vessels and their reduction relative to the “base case” (Table 4) are given in Table 5. The reduction of indicators of operational limitations is particularly pronounced for the vessels c-3, t-5, and t-3 since the maximal significant wave height up to which these vessels could safely operate (with respect to intact stability) is considerably reduced too. The only vessel whose OL would not change in this case is the largest tanker, t-6.

If the following vessels in the VT would sail in periodically unmanned regime, then the OL of the lead vessel would not be affected. Namely, all vessels examined in this study, when fully loaded, would be allowed to sail in the significant wave heights up to 3.6 m (see Fig. 1 and Fig. 3). However, if the followers sail in partially unmanned regime, then their operational limitations may be substantially affected by the operational limitations of the lead vessel, see Tables 6 ÷ 9. More precisely, if the VT composed of followers sailing with a reduced crew is led by the c-3, t-5 or t-3, then the OL of the following vessels and thus the operational OL of the complete VT would be considerably constrained. As it was already pointed out, this is a consequence of the adoption of a more stringent dead ship condition standard ($R_{DS0} = 0.006$), which results in limiting the maritime navigation of the c-3, t-5 and t-3, to $H_{s,max} = 2$ m, $H_{s,max} = 2.5$ m, and $H_{s,max} = 2.47$ m, respectively (see Fig. 2, Fig. 4 and Table 5).

Table 5. Indicators of operational limitations and the maximal allowable significant wave height of the sample ships when they lead a VT where the followers sail in partially unmanned regime.

Vessel	OLI	$\overline{x}_C$	δOLI [%]	$\delta \overline{x}_C$ [%]	$H_{s,max}$
c-6	0.42	0.60	30	26	3.6 m
c-5	0.78	0.83	22	17	3.6 m
c-3	0.29	0.38	41	46	2 m
t-6	1	1	0	0	3.6 m
t-5	0.63	0.63	38	38	2.5 m
t-3	0.76	0.60	24	40	2.47 m

Table 6. OLI of the following vessels sailing in a partially unmanned regime in a VT led by a particular lead vessel (LV).

FV LV	c-6	c-5	c-3	t-6	t-5	t-3
c-6	0.60	0.60	0.42	0.60	0.48	0.48
c-5	1	1	0.555	1	0.69	0.69
c-3	0.49	0.49	0.375	0.49	0.42	0.41
t-6	1	1	0.555	1	0.69	0.69
t-5	1	1	0.555	1	0.69	0.69
t-3	1	1	0.555	1	0.69	0.69

Table 7. The relative reduction of OLI (in %) of the following vessels sailing in a partially unmanned regime in a VT led by a particular lead vessel (LV).

FV LV	c-6	c-5	c-3	t-6	t-5	t-3
c-6	0	0	30	0	20	21
c-5	0	0	45	0	31	31
c-3	0	0	23	0	14	15
t-6	0	0	45	0	31	31
t-5	0	0	45	0	31	31
t-3	0	0	45	0	31	31

Table 8. $\overline{x}_C$ of the following vessels sailing in a partially unmanned regime in a VT led by a particular lead vessel (LV).

FV \ LV	c-6	c-5	c-3	t-6	t-5	t-3
c-6	0.81	0.81	0.49	0.81	0.59	0.585
c-5	1	1	0.555	1	0.69	0.69
c-3	0.71	0.71	0.47	0.71	0.55	0.54
t-6	1	1	0.555	1	0.69	0.69
t-5	1	1	0.555	1	0.69	0.69
t-3	1	1	0.555	1	0.69	0.69

Table 9. The relative reduction of $\overline{x}_C$ (in %) of the following vessels sailing in a partially unmanned regime in a VT led by a particular lead vessel (LV).

FV \ LV	c-6	c-5	c-3	t-6	t-5	t-3
c-6	0	0	39	0	27	28
c-5	0	0	45	0	31	31
c-3	0	0	34	0	23	24
t-6	0	0	45	0	31	31
t-5	0	0	45	0	31	31
t-3	0	0	45	0	31	31

5. DISCUSSION

In none of the examined cases, operational limitations of the LV were affected by the operational limitations of the FV. Operational limitations of the individual FV would not be affected by the operational limitations of the LV in case that the followers operate in periodically unmanned regime, that is, with the full crew off-duty. However, the operational limitations of both the FV and LV could be considerably affected in case that the followers operate in partially unmanned regime, that is, with the reduced crew.

Among the examined ships, the "worst leaders" were the small vessels – the tanker and the containership of the CEMT class III (designated as t-3 and c-3, respectively) and the CEMT class Va tanker (designated as c-5). Should these vessels lead a VT composed of the vessels with the reduced crew, their indicators of operational limitations *OLI* and $\overline{x}_C$ would reduce by 24% and 40% respectively (in case of the small tanker), by 41% and 46% (in case of the small containership), and by 38% both (in case of the large tanker), see Table 5. Moreover, the OL of the followers in the partially unmanned vessel trains led by c-5, c-3 or t-3 would significantly constrain as well: *OLI* of the followers would reduce between 14% and 45% (see Table 7), while $\overline{x}_C$ would reduce between 23% and 45% (see Table 9).

The "best leader" would be the largest tanker (t-6) which may navigate in the designated area without restrictions, regardless of the sailing regime of the followers. This also means that the OL of the following vessels led by t-6 would not degrade, regardless the size of the crew onboard.

The second-best option for the LV would be the CEMT class Va containership (c-5) as her indicators of operational limitations *OLI* and $\overline{x}_C$ would reduce by 22% and 17% respectively (see Table 5), in case that the VT comprises the following vessels with the reduced crew.

It was also demonstrated that the OL of an individual vessel (which could affect the OL of the VT) may strongly depend on her specific design features (such as angle of flooding, freeboard, exposed lateral area, etc.) rather than on main dimensions of the vessel. For example, the maritime navigation of the examined CEMT class VI (L_{pp} = 130 m) tanker would be unrestricted in the designated area, which is not the case with the CEMT class VI containership (see Table 4). Contrary to that, the CEMT class Va (L_{pp} = 105 m) containership would be superior as the lead vessel of partially unmanned VT when compared to CEMT class Va tanker (see Table 5). Therefore, the performance of the river-sea ships in terms of operational limitations cannot be simply related to their size and class.

6. CONCLUSIONS

Vessel Train (VT) is a novel waterborne transport concept based on the principle of platooning: the first vessel in the "train" would be fully manned and in control of one or several following vessels which sail either with a reduced crew or the crew off-duty. In this paper, the methodology for stability assessment of the river-sea vessel trains was proposed.

The operational limitations of the river-sea VT were defined by the operational limitations of its "weakest" member in the given loading condition. The principal advantage of the proposed methodology is in the possibility to define the operational limitations of a complete vessel train prior to its departure, using the precomputed operational limitations of each of the VT participants. However, it should be acknowledged that the outcome of the analysis depends on the assumed interdependence and responsibilities of the vessels in the VT in case of a stability failure, and on the adopted values of stability failure standards.

It was shown that the operational limitations of the participants in the VT may considerably change depending on the composition of the VT and the sailing regime of the following vessels. From the point of view of the intact stability assessment, the efficiency of the vessels involved in the VT would not diminish if the VT would be composed of the followers sailing in periodically unmanned regime (i.e. with the crew off-duty). If the followers, however, are supposed to sail in the partially unmanned regime (i.e. with the reduced crew) then the OL of the VT could be preserved by carefully selecting the lead vessel.

The most efficient VT would be composed of tankers (regardless of their size) and/or CEMT class Va containerships as following vessels sailing in periodically unmanned regime led by some of the vessels of the same types and classes. The efficiency would considerably diminish if the VT would consist of the followers sailing in partially unmanned regime, led by the CEMT class III containership or a tanker of the same class, or by the CEMT class Va tanker. In fact, the most efficient VT could become the least efficient one, if the sailing regime is changed from periodically to partially unmanned, and an appropriate vessel is not available to lead the train.

Considering that the ships of CEMT class Va are regarded as the backbone of inland navigation in Western Europe, it seems particularly important to note that their performance in the VT in terms of operational limitations may substantially vary depending on the type (containership or tanker) and the specific design characteristics of the vessel, as well as on the role of the vessel in the VT (lead vessel or following vessel) and the sailing regime of the followers. Therefore, this aspect of safety should be a subject of a careful consideration in the VT voyage planning phase, which would be feasible with the proposed methodology.

7. ACKNOWLEDGMENTS

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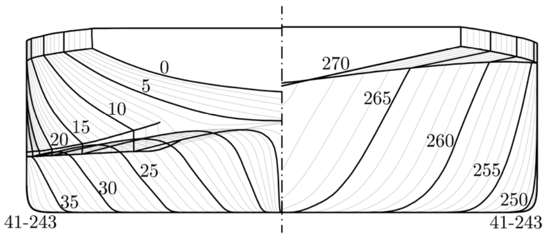
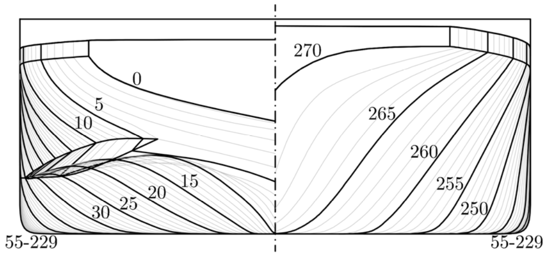
APPENDIX: BODY PLANS OF THE SAMPLE VESSELS

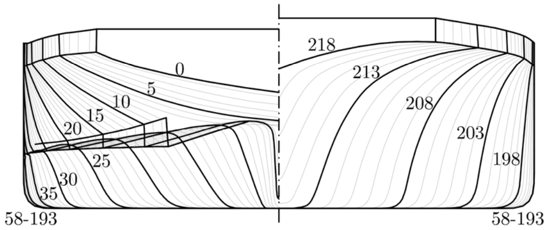
Body plans of the sample vessels are given in the same scale. Cross sections are equally spaced at the distance of 0.5 m and numbered starting from the aftmost position.



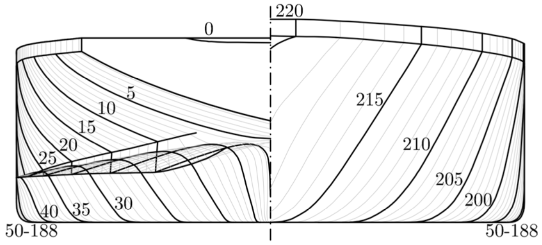
c-6



t-6



c-5



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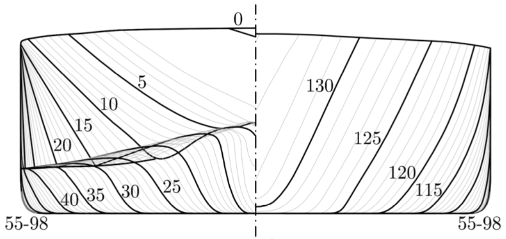
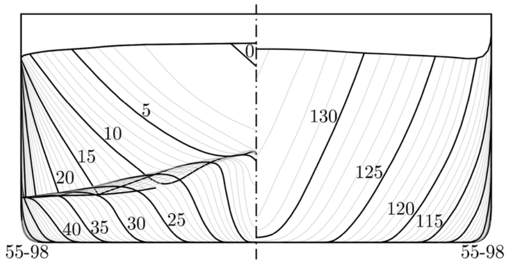


c-3



t-3