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DESIGN AND OPERATIONAL INNOVATIONS IN ADAPTING THE EXISTING MERCHANT RIVER FLEET TO COST-EFFECTIVE SHIPPING

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ABSTRACT

Modernisation of the existing river fleet adapted for the local conditions of the Middle and Lower Vistula can be considered as a solution to slow down the progressive decrease of river transport in this area. The implementation of technical improvements, smart technologies and enhancement of transport performance may partially solve the problem of growing demand for multimodal transport of containers and oversized loads in a shorter perspective than the expected period of planned revitalisation of the river. The paper presents investigations on the modernisation of river convoys adapted to the current navigational conditions of the Lower Vistula. The different options have been discussed by the authors with river fleet operators and the best recognised solution was agreed to be the use of river convoys combining modernised motor barges and the pushed barges previously used in this area. Improvement of the transport profitability, reduction of fuel consumption, air pollution and noise can be achieved at minimum costs by modernisation of the main power-propulsion systems of outdated motor barges and the implementation of innovative steering systems on pushed barges. The demand for power-propulsion and manoeuvring performance of modernised convoys is discussed in the paper.

Keywords: river convoy capacity; integrated steering system; smart river unit

INTRODUCTION

The ten-year perspective of inland waterways modernisation in Poland anticipated in the assumptions made by the Ministry of the Maritime Economy and Inland Navigation [6] is the economic justification for the modernisation of the existing means of transport before the expected navigational requirements are satisfied.

The technological and economical study presented here aimed to determine technical assumptions for inland waterborne transport units intended for navigation on the Lower Vistula, currently used mainly for the individual transport of bulk and oversized loads.

The growing demand for container transport via inland waterways is the reason for the development of technical solutions related to ecological river training, planning river ports with logistic centres and transport means adapted to the local conditions within the framework of European programmes [3, 10], as well as feasibility studies commissioned by the Polish government. The systemic approach to waterborne inland transport development should include comprehensive logistic planning [7].

The ship-owners currently operating river vessels have recognised the construction of a new river fleet for current river conditions as non-negotiable. However, modernisation of the existing fleet adapted for local conditions should be considered and should slow down the further decrease of river transport. The developments should be based on the types of barges currently being used.

The latest study on the implementation of smart ships in waterborne transportation [21] presents the view that the first fully autonomous ships will be put into service in less than five years, so new designs and developments of existing waterborne transport units should take into account the rapid introduction of smart technologies in river transport.

The wide implementation of ICT technologies will increase the flexibility and efficiency of operations and enable areas previously not available for manned vessels to be used for safe and efficient transport [21].

DEVELOPMENT OF SMART RIVER TRANSPORT IN EUROPE

The main tendencies in modern waterborne transport development are the implementation of smart technologies and economies of scale.

SMART TECHNOLOGY APPLICATIONS

There are six basic levels of ship autonomy [21]: level 0, which means manual operation; level 1 – automatic control over the set route; level 2 on which the calculated route can be updated by an external system; level 3 on which the decisions on navigation and ship operation are calculated by the system and controlled by the operator in case of uncertainty; level 4 on which the decisions worked out by the system should be approved by a human operator; level 5 on which the monitored autonomy needs a human response only in situations that are uncertain for the system; and level 6 – full autonomy based on artificial intelligence.

Remote control of operations requires the automation of all the main systems on board, and their integration into a single communication channel [11, 12]. The transition from level zero to level one of autonomy means, as a first step, the integrated control of steering and propulsion devices.

DNVGL class guidelines regarding autonomous and remotely operated ships, introduced in September 2018, recommend that onboard "systems and components supporting the propulsion function shall be arranged with redundancy and capacity sufficient to ensure that the vessel can maintain a navigable speed in case of potential failures of single systems and components" [9].

The conditions of smart inland waterborne transport development should be included in the design assumptions for both the new builds and modernised units.

ECONOMY OF SCALE OF RIVER TRANSPORT UNITS

The well-known development of economies of scale with respect to maritime transport cannot be simply transferred to the inland waterborne transport environment. However, in the last ten years the tendency of a growing tonnage of transport units has been observed within the main inland fleets in Western Europe.

Inland waterway transport is energy-efficient, as an inland vessel is able to transport one tonne of cargo almost four times further than a truck using the same consumption of energy (370 km as against 300 km by rail and 100 km by truck). The transport cost is competitive and the unit cost decreases over long distances.

Transporting goods on inland waterways is advantageous, as convoys of pushed barges can transport more goods per distance unit (tkm) than any other type of land transport and could help to reduce road traffic. In the first quarter of 2018, the transport performance on European inland waterways reached 34.9 billion tkm [5].

The observed tendencies of changes in the size of river units towards greater tonnages since 2005 are presented in Fig. 1 [15].

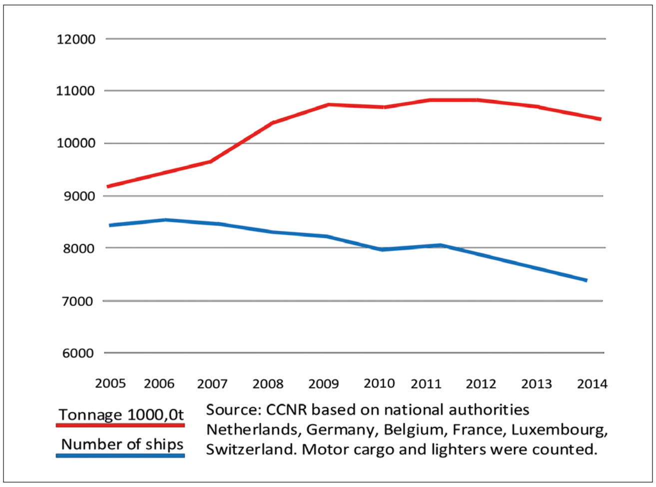

Fig. 1. Growing tendencies in decrease of the number of river units and increase of their tonnage in Western Europe since 2005 [15]

The waterborne inland transport of dry goods in Western Europe is dominated by Dutch vessels. These account for 49% of West European vessels and 56% of their tonnage. There are around 10000 inland vessels operating on the Rhine and more than 3000 vessels operating on the Danube. 75% of the waterborne transport means on the Rhine are dry cargo self-propelled units or dumb barges, while 15% are tanker vessels. Push and tug boats account for 13%. 7% of the total number of inland vessels in the Danube countries are tankers, while push and tug boats account for 18% of the total vessels [5].

The transport performance on European inland waters presented an increase of 4% in the first quarter of 2018 compared to the first quarter of 2017. In the same period, the waterborne inland transport performance in Poland presented a 27% decrease.

Waterborne inland transport in Poland in the period 2000–2017 decreased from 0.8% to 0.3% [8].

POSSIBILITIES OF COST-EFFECTIVE CARGO TRANSPORT ON LOWER VISTULA

The number of transport units operated by Polish ship-owners has not changed much in recent years. The number of barges BP-500 was 509 and decreased by 7 units. The fleet of pushers and tug boats was 219 units and increased by 5 units in 2017. The total number of barges BM-500 was 89, a decrease of 2 units from 2017 [8].

The main Polish ship-owners: OT Logistics Group [24] including: OT Logistic SA, Deutsche Binnenreederei and Rentrans Cargo, Navigar [23], Zegluga Szczecinska [25] and Fabico [22], operate their fleets in Western Europe, in Poland mainly on the Oder Waterway and the Lower Vistula in small amounts.

PERSPECTIVES OF DEVELOPMENT OF RIVER NAVIGATION

The Polish Ministry of Maritime Economy and Inland Navigation has carried out several feasibility studies related to the modernisation of Polish rivers. The detailed scope of investment in the short-term perspective includes the following tasks: the building of a new dam below Wloclawek, a feasibility study and investment documentation of Lower Vistula cascades [6].

The Kujawsko-Pomorskie Voivodeship together with the City of Bydgoszcz carried out, within the EMMA European Project, a location study for the construction of a multimodal platform: a river port and logistics centre in the area between Bydgoszcz and Solec Kujawski [10].

The inland waterway of the Vistula River, planned within the II priority of Assumptions for the plans of inland waterways development in Poland in 2016/2020, with the perspective to 2030 [6], and the proposed location of a new river port and logistics terminal in Otorowo [10] are presented in Fig. 2.

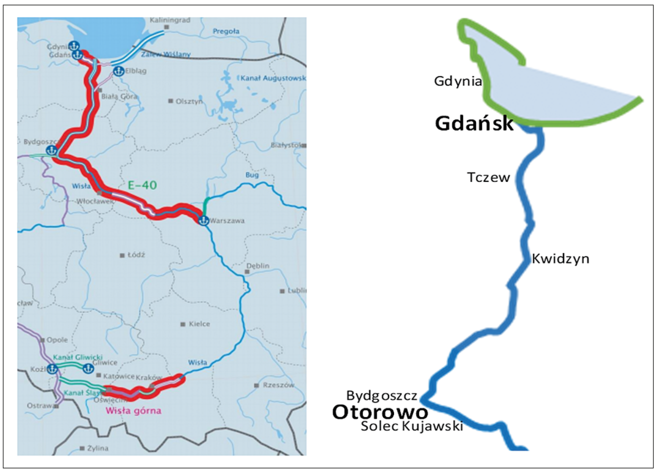

Fig. 2. Planned inland waterway of Vistula River and proposed location of a river port and logistics terminal in Otorowo [6, 10]

The main navigational limits on the Gdansk–Otorowo section are related to the water depth and air draft. The transit depth is 1.8 m, so the maximum mean draft of vessels is 1.5 m. The maximum lengths and breadths of convoys are limited by the dimensions of the lock at Przegalina: 188.37 m length and 11.91 m breadth.

Transport units

The river convoys operated on the Middle and Lower Vistula are different combinations of pushing and towing trains [18]. There are BP type barges: pushed barges BP-1000, BP-500, BP-400, self-propelled motor barge BM-500, and Galar-1 and Galar-2 barges adapted to the local conditions.

The main parameters of the barges BP-500 and BM-500 are presented in Table 1.

Tab. 1. Main particulars of the barges BP-500 and BM-500 operated on the Lower Vistula River

Main particulars	BP-500	BM-500
Length [m]	45	56.5
Breadth [m]	9.5	7.5
Draft [m]	1.6	1.7

The fleet characteristics influencing transport costs are the fleet age and operational parameters, including the power-propulsion performance. The development of river navigation on the basis of modernisation of the existing fleet, including self-propelled barges BM-500 and pushed barges BP-500, has been discussed with river fleet operators as a best possible solution in the 10–15 year period of the planned river revitalisation.

The improvement of transport units' profitability can be achieved at minimum costs by modernising the outdated main power-propulsion and steering systems to reduce fuel consumption, air pollution and noise.

The hybrid diesel electric propulsion and integrated steering system, including the bow hydrodynamic rotors and dynamic coupling of barges, have been considered.

The new river pushed train proposed for operation on the Lower Vistula combines modernised barges: barge BM-500 and one or two barges BP-500 will have a greater transportation capacity and efficiency than a pushed train combining a pusher and barges. The available power of the modernised motor barge power-propulsion system should be not less than the power of the pusher [13].

The convoy of a motor barge BM-500 and pushed barges BP-500 with dynamic coupling and a bow steering system on the pushed barge has already been tested with respect to resistance and manoeuvrability using the physical scale model and CFD simulations [1].

TRANSPORT CAPACITY OF RIVER CONVOYS BASED ON MODERNISED BP-500 AND BM-500 BARGES

The presented analysis of possible transport units and convoys for the Lower Vistula has been carried out on the basis of previous experience of river fleet operators. It has been assumed that the analysed convoys operate during a navigational season of 250 days on not less than II class waterways. The port operations time was assumed to be 24 hours with 12 working hours a day. For the considered Gdansk–Otorowo section of the Lower Vistula, 198 km in length, the corresponding maximum air draft has been limited to two layers of containers.

RIVER CONVOYS CONFIGURATIONS

The single BP-500 motor barge and three configurations of river convoys were selected to compare the transport capacity:
- single motor barge BP-500,
- pusher with two pushed barges: pusher Bizon and 2 BP-500 barges,
- motor barge BM-500 pushing one pushed barge BP-500,
- motor barge BM-500 pushing two pushed barges BP-500.

The operational parameters of motor barge BM-500 are presented in Table 2.

Tab. 2. Operational parameters of BM-500 motor barge

Parameter	Voyage up the river	Voyage down the river
Loading capacity (tonnes)	380	380
Loading capacity (TEU)	20	20
Average speed of the loaded barge (km/h)	7.1	12.6
Average time of the voyage (h)	28	16

The main operational parameters of the convoys are presented in Tables 3–5.

Tab. 3. Operational parameters of convoy: pusher and 2 BP-500 barges

Parameter	Voyage up the river	Voyage down the river
Loading capacity (tons)	880	880
Loading capacity (TEU)	48	48
Average speed of the loaded barge (km/h)	4.4	10.4
Average time of the voyage (h)	45	20

The configuration of the convoy of barges BM-500 and BP-500 is presented in Fig. 3.

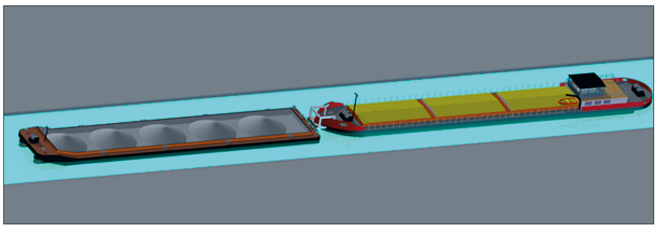

Fig. 3. Convoy of BM-500 and BP-500 barges

The proposed configuration of the convoy of BM-500 and 2 BP-500 barges is presented in Fig. 4.

Tab. 4. Operational parameters of the convoy: BM-500 and BP-500 barges

Parameter	Voyage up the river	Voyage down the river
Loading capacity (tons)	820	820
Loading capacity (TEU)	44	44
Average speed of the loaded barge (km/h)	5.7	10.4
Average time of the voyage (h)	34	20

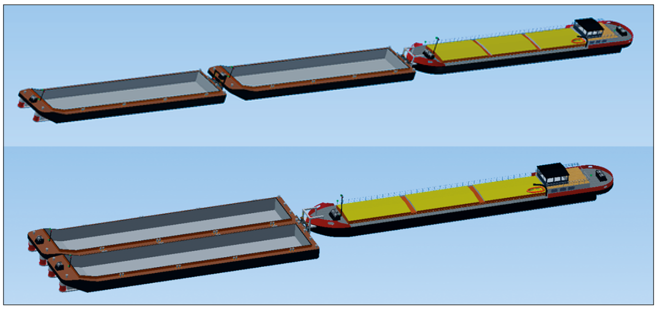

Fig. 4. Convoy of BM-500 and 2 BP-500 barges: up-river configurations (upper drawing) and down-river configurations (bottom drawing)

Tab. 5. Operational parameters of the convoy: BM-500 and 2 BP-500 barges

Parameter	Voyage up the river	Voyage down the river
Loading capacity (tons)	1260	1260
Loading capacity (TEU)	68	68
Average speed of the loaded barge (km/h)	5.7	10.4
Average time of the voyage (h)	34	20

ECONOMICALLY EFFECTIVE TRANSPORT CAPACITY OF RIVER CONVOYS

Transport capacities in the navigational season in relation to operations between Gdansk and Otorowo estimated for the considered convoys are presented in Table 6. The assumed numbers of round voyages were as follows: 32 for a BM-500 barge, 20 for the pusher with 2 BP-500 barges, 31 for a BM-500 pushing a BP-500 barge, 31 for a BM-500 pushing 2 BP-500 barges.

The unit costs of transport and time of a round voyage without time of port operations and night breaks are presented in Table 7. The costs include fuel costs, personnel costs, depreciation costs, maintenance costs and overheads due to conducting business – assumed as 35%.

The unit cost of transport of the convoy of a modernised BM-500 and two BP-500 barges is estimated to be less than the unit cost for a pusher and two pushed barges. It is about 26 PLN/t for bulk cargo and 490 PLN/TEU for containers. The difference is 10% for bulk cargo and 7% for containers; however, it is dependent on the operational cost of the modernised barges.

Tab. 6. Transport capacities for different configurations of pushed convoys

Convoy configuration	Transport capacity	
	tons	TEU
BM-500	24320	1280
Pusher (Bizon) 2 BP-500	35200	1920
BM-500 BP-500	50840	2728
BM-500 2 BP-500	59520	3200

Tab. 7. Unit transport costs for different configurations of pushed convoys

Convoy configuration	Time of the round voyage	Transport capacity	
	days	PLN/t	PLN/TEU
BM-500	1.83	36	700
Pusher (Bizon) 2 BP-500	2.71	29	531
BM-500 BP-500	2.25	31	577

The number of round cruises in the average navigational period of 250 days may be increased due to a decrease of port operations time.

REQUIREMENTS WITH RESPECT TO MANOEUVRABILITY OF A RIVER CONVOY

The pushed convoy of a BM-500 and BP-500 has worse manoeuvring characteristics than the convoy consisting of a pusher and barge BP-500 [1, 13]. The analysis of new solutions of river convoys based on a motor barge and pushed barges for coal transport on the Oder Waterway was presented in 2012 by Kulczyk [13]. Due to the manoeuvrability required, the authors proposed a Schottel pump jet as a bow rudder. The Schottel pump jet is an azimuth thruster that can be operated in shallow water conditions – with 0.3 m under-keel clearance. The pump jet used as an auxiliary propulsion unit greatly increases the possibility of convoy control, but it is expensive, limits the cargo space in the bow hold and generates thrust streams that influence the river environment [16].

The innovative solution of the bow steering system presented in [1], installed on the bow of the pushed barge, and flexible coupling between the motor barge and pushed barge, can significantly improve the manoeuvrability of the convoy.

With respect to the Polish Register of Shipping rules [17], the push train manoeuvring characteristics should satisfy the criteria for pushed convoys based on trials performed in deep water conditions and shallow water conditions with the water depth to draft ratio in the range of 0.5–1.2 (Table 8).

Tab. 8. Manoeuvrability criteria for river convoys [17]

Obligatory test	Criteria
Minimum speed through the water	Should be not less than 13 km/h
Stopping distance over the ground in shallow water for convoys having length equal to or less than 110 m and beam equal to or less than 11.45 m.	- Shall be no greater than 480 m in flowing water with current velocity of 1.5 m/s in direction of flow, until speed over ground is 0 m/s, - Shall be no greater than 305 m in standing water.
Evasive action test: zig-zag trials: - 20°/20° - 45°/45° both performed to port and starboard.	Turning speed (Fig. 5) r_1=r_2 should be: 20°/min in 20°/20° trial, 40°/min in 45°/45° trial. Time t4 should be: - 150 s for h/T<2, - 110 s in deep water.
Turning test	Is not considered for convoys longer than 86 m.

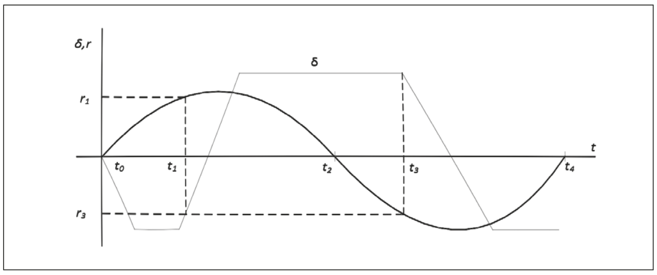

Fig. 5. Diagram of the evasive manoeuvre, σ– rudder angle [°], t_i- time to reach turning speed r_i [17]

For practical ship design for operation and for safety, the local environmental conditions should be taken into account – especially the possible widening of the safe manoeuvring area due to strong wind [14]. This is important for convoys with big windage areas carrying oversized goods or containers.

The results of model tests presented in Fig. 6 [1, 2] allowed the estimation of the turning ability of a motor barge and pushed barge convoy of 100 m length equipped with bow rotors and dynamic coupling.

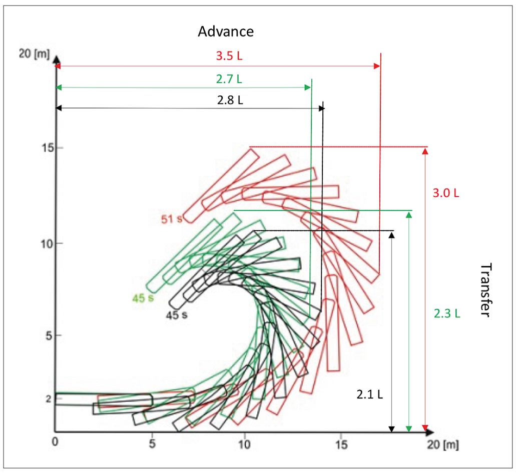

Fig. 6. Turning manoeuvre of the push train using bow rotors (red), stern rudders and bow rotors (green), stern rudders, bow rotors and dynamical coupling system (black)

The parameters of the turning trial performed using different combinations of steering devices are presented in Table 9.

Tab. 9. Parameters of the push barge model turning using different control devices

Parameter	Advance	Transfer
Turning with stern rudders [2]	3.0 L	2.6 L
Turning with bow rudders	3.5 L	3.0 L
Turning with bow and stern rudders	2.7 L	2.3 L
Turning with stern rudders, bow steering system and dynamic coupling	2.8 L	2.1 L

The differences between the performance of the convoy with and without dynamic coupling were 10% in advance and 20% in transfer distances.

The stopping distance over the ground for the push barge should be less than 305 m in standing water. If the turning is used as an anti-collision manoeuvre, the advance for the push barge without bow rotors is equal to 300 m and is only a little less than the stopping distance. The use of bow rotors decreases the advance to 270 m. The difference is equal to one third of the push barge length.

The turning performance of the BM-500 and BP-500 barges convoy is presented in Fig. 7.

Fig. 7. Turning performance of convoy: BM-500 and BP-500, turning control by bow steering system and dynamic coupling

The turning performance of the convoy of a BM-500 and 2 BP-500 barges is presented in Fig. 8. Turning using the bow steering system and dynamic couplings between barges give numerous possibilities of push train handling in winding rivers.

The necessary developments of modernised convoys are hybridisation and electrification of shipboard systems.

The replacement of the conventional drive used on the BM-500 (with main engine power 2 x 88–100 kW) with a hybrid diesel-electric drive with increased power corresponding to the pusher (Bizon: 2 x 118 kW; Koziorozec 2 x 120 kW) should provide the necessary power for the convoy [13].

The power required by the convoy should also take into account changing river depth [19, 20]. It has been confirmed by CFD calculations [1] that the predicted resistance of a 100 m length convoy at 10 km/h speed in deep water is 25.5 kN; the resistance at 15 km/h in 5 m deep water, which means a 0.6 shallow water Froude number, is 70 kN.

Diesel-electric drive and automatic steering accompanied by the integration of all the main on-board control systems [11] introduces the possibility of applying remote operation via a single communication channel.

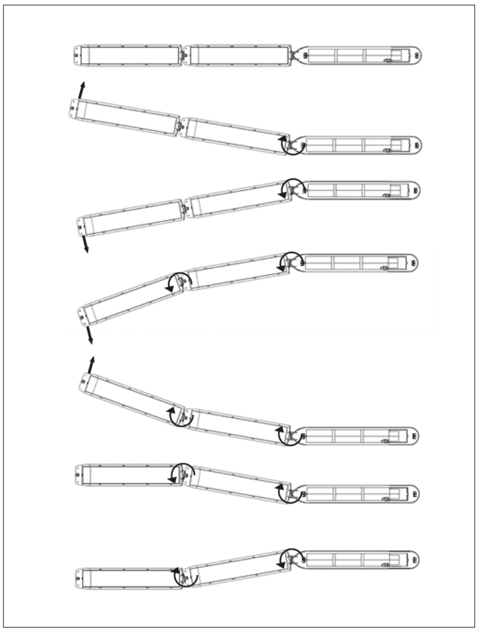

Fig. 8. Turning performance of convoy: BM-500 and 2 BP-500, turning control by bow steering system and dynamic couplings between barges

CONCLUSIONS

The three configurations of river convoys presented in the paper were compared with respect to their transport capacity over the navigational season. The capacity for the pusher Bizon with two pushed barges was estimated to be 31% less than the capacity of the modernised motor barge BM-500 in convoy with a barge BP-500. The capacity of the motor barge BM-500 pushing two BP-500 barges was estimated to be 15% greater than the capacity of the modernised motor barge BM-500 pushing one BP-500 barge.

The design and operational innovations presented in the paper have been proposed for adapting the existing merchant river fleet of BM-500 and BP-500 barges built in the middle of the last century, and operating on the Lower Vistula River, to cost-effective modern shipping.

Improvement of the manoeuvrability and reduction of the required manoeuvring area for the push train can be obtained by installing new steering devices including a dynamic coupling system and bow rotors on the pushed barge. The model tests confirmed the increase of the turning capacity of a modernised BM-500 barge dynamically coupled with a BP-500 barge and equipped with bow rotors. The transfer during convoy turning for the dynamically coupled barges with rotors is 0.9 L less than for the conventional convoy using stern rudders only.

The system should be flexible to allow for different levels of autonomy, depending on location, congestion or emergencies. The integrated control of onboard systems should be a step forward in the implementation of smart technologies – satisfying the requirement that the navigation system should be able to maintain the ship's route, adapt it to the changing river conditions, avoid collisions and operate the ship efficiently.

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