
CHAPTER 9

Development of a system for assessing navigational and energy safety on inland waterways

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Abstract

An approach to the development of an integrated system for assessing navigational and energy safety on the inland waterways of Ukraine is considered, taking into account current challenges and sustainable development trends. Special attention is given to energy efficiency as a key criterion in the planning, monitoring, and management of navigation. A system architecture is proposed, based on the use of sensor networks, analytical models, river information services (RIS), and digital navigation tools. The main system components are defined, which ensure the reduction of energy consumption, the enhancement of vessel traffic safety, and the optimization of logistical processes. The results of an analysis of the current state of infrastructure are presented, and the necessity of creating a unified information environment to support real-time decision-making is substantiated. Conclusions are drawn regarding the feasibility of implementing such a system as an element in the transition to environmentally safe and energy-efficient waterborne transport.

The developed assessment system for navigational safety enables an increased level of safety on the inland waterways of Ukraine through the integration of modern monitoring technologies and data analysis tools. The implementation of this system will contribute to more effective risk management in navigation and improved economic efficiency of water transport.

The proposed strategies and directions have proven to be essential for improving the efficiency and safety of navigation. The research confirms the need to integrate modern technologies, cooperate with river information services, account for environmental aspects, and ensure active participation of all stakeholders to achieve continuity and safety on inland waterways. The final conclusions support the necessity of creating and implementing comprehensive strategies aimed at optimizing port areas to achieve sustainable development and improve the competitiveness of inland water transport routes.

Keywords

Digital technologies, inland waterways, navigational safety, energy efficiency of navigation, information and navigation systems, river information services.

9.1 Introduction

In the context of current environmental challenges and the urgent need to reduce fuel and energy resource consumption, the development of energy-efficient navigation management systems for inland waterways is becoming increasingly relevant. Shipping, being one of the most energy-intensive modes of transport, has significant potential for improving efficiency through route optimization, speed regulation, vessel operation modes, and enhanced navigational support.

On inland waterways (IWW), where infrastructural constraints, shallow waters, variable hydrological conditions, and high traffic density create additional challenges, ensuring navigational safety must be combined with achieving a high level of energy efficiency. Traditional approaches to navigation safety have primarily focused on collision risks, accidents, or traffic stoppages. However, in the transition toward a climate-neutral economy, it is essential to integrate an energy component into the safety assessment system – one that considers fuel consumption, energy expenditure for maneuvering, schedule efficiency, and the impact of external factors.

The development of an integrated system for assessing navigational and energy safety on inland waterways involves the creation of a methodology that enables objective and dynamic analysis of the water route condition and vessel energy consumption in real time. This system should be based on modern digital technologies, including satellite navigation, AIS, RIS systems, and algorithms for intelligent data analysis and risk forecasting.

In the current conditions of increasing traffic load on Ukraine's inland waterways, the issue of improving the efficiency of navigational information support becomes particularly important. Fairways, as the main arteries of inland water transport, require constant monitoring and timely notification to navigators about changes in the navigational situation, hydrological conditions, and potential hazards. The effective operation of navigational information services is not only the foundation of safe navigation but also a key factor in improving vessel energy efficiency.

The implementation of intelligent monitoring systems, digital data exchange platforms, and automated visualization and analysis processes using AIS, Inland ECDIS, IoT sensors, and satellite navigation significantly reduces fuel consumption,

minimizes delays, and optimizes routes. This contributes not only to safety but also to the reduction of harmful emissions – an essential part of the "green transport" policy and sustainable development agenda.

9.2 Peculiarities of developing a navigation safety assessment system for inland waterways

Navigation safety on Ukraine's inland waterways is critically important not only for the preservation of human life and environmental protection but also as a foundation for ensuring efficient, reliable, and energy-saving navigation. In the context of post-war reconstruction of Ukraine's transport infrastructure, it is necessary to improve navigation safety assessment systems to prevent accidents and reduce risks to navigation.

Ukraine's inland waterways have significant development potential, but the low level of navigation safety limits their use. The main risk factors include outdated infrastructure [1], insufficient navigational equipment on vessels [2], and the absence of an integrated monitoring system [3]. Therefore, developing a modern architecture for a navigation safety assessment system is an urgent need [4], which will contribute to more effective navigation management.

In the current context of energy instability, rising fuel and energy costs, and ecological challenges, it is important not only to ensure safe vessel movement but also to evaluate the efficiency of that movement in terms of energy consumption, environmental impact, and time expenditure. Excessive maneuvering, port delays, route inconsistencies, and a lack of energy-optimal planning increase fuel consumption and harmful emissions. This creates an objective need for the development of an integrated system for assessing both navigational and energy safety, which will reduce risks and simultaneously improve the energy efficiency of all components of the navigation process.

The relevance of this study is driven by the continuous growth of freight traffic on waterways, the need to ensure uninterrupted and safe vessel movement in ports, and the necessity to reduce the environmental impact on inland water resources. This makes the study and implementation of modern strategies and technologies for optimizing water areas and ensuring sustainable navigation development especially important.

The developed architecture and identification of the key components of a navigation and energy safety assessment system for Ukraine's inland waterways should serve as a decision-making tool for operators, dispatchers, and governing bodies.

It will help enhance navigational safety, ensure stable energy consumption, optimize logistics chains, and minimize environmental impact.

To achieve this goal, the following tasks must be addressed:

1. Analysis of existing navigation safety assessment systems and identification of their shortcomings.
2. Development of the architecture for an integrated navigation safety assessment system.
3. Identification of the system's key components, including sensor networks, data processing tools, analytical algorithms, and visualization means.
4. Testing of the system prototype under real operating conditions.

The architecture of the proposed navigation and energy safety assessment system (Fig. 9.1) is based on the principles of digital transformation of transport infrastructure, integration with traffic management platforms, analytical mechanisms for evaluating energy consumption and risk, and adaptive response to changes in the navigation environment. The system is intended to provide a comprehensive approach to inland waterway management, simultaneously accounting for technical safety indicators and the energy efficiency of navigational decisions.

An innovative architecture for the navigation safety assessment system has been developed to enhance the accuracy of monitoring the navigational environment, automate the processing of information on potential risks, and provide timely notifications to operators and vessel pilots.

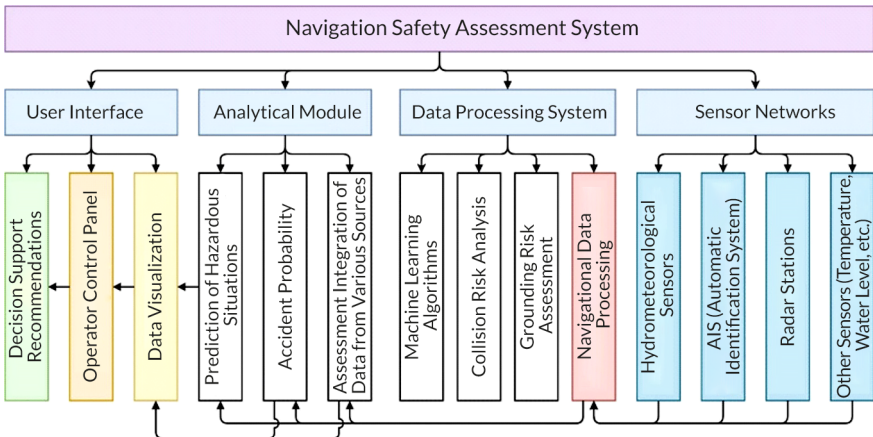


Fig. 9.1 Architecture of the navigation and energy safety assessment system for inland waterways

The system is built on the principles of integrated data collection, analysis, and visualization, utilizing artificial intelligence technologies and modern sensor solutions. It is capable of adapting to real-time changes in the navigation situation, considering both safety and energy efficiency parameters of vessel movement. The main components of the architecture have been defined:

1. Sensor networks.

The sensor network is the primary source of input information for the system. It includes:

- hydrometeorological sensors that record wind speed and direction, air and water temperature, atmospheric pressure, water level, currents, and waves. These data allow forecasting changes in hydrological conditions, which is especially important for safe navigation in shallow or unstable bottom terrain conditions;
- AIS (automatic identification system) stations that provide automatic tracking of vessel movement parameters (course, speed, location), enabling the creation of an accurate traffic picture in the fairway;
- radar and hydroacoustic systems, including coastal radars and echo sounders, which provide obstacle detection, identification of non-AIS objects, and monitoring of fairway depth.

2. Data processing system.

The information collected by sensors is sent to a computing module where it is processed using machine learning algorithms. The system is capable of:

- automatically classifying high-risk situations (e.g., crossing courses, failure to maintain safe distance, approaching shallow areas);
- detecting atypical vessel behavior patterns that may indicate potential threats;
- taking into account weather and hydrological conditions when assessing navigation safety.

3. Analytical module.

This component performs situational analysis and forecasting. Statistical modeling and neural network computing methods are applied to:

- predict hazardous scenarios (collisions, grounding, navigation in low visibility conditions);
- determine the optimal trajectory considering the minimization of water resistance, fuel consumption, and time spent in risky zones;
- support real-time decision-making.

4. User interface.

A centralized control panel displays information in a user-friendly visual format:

- interactive maps visualizing navigation conditions, risks, forecasts, and recommendations;

- alert notifications regarding changes in conditions or threats;
- customizable dashboards for dispatchers, vessel pilots, and analysts;
- reporting modules for further analysis and operational optimization.

During prototype testing in real operational conditions, it was found that the accuracy of navigation situation assessment increased by 35% compared to traditional monitoring systems. This improvement allowed for a reduction in incidents related to risky maneuvers; enhanced proactive traffic management; decreased fuel consumption through the selection of energy-efficient routes; and reduced environmental impact on inland waterways.

Optimization of the creation of operational water areas in ports on inland waterways is a strategically important direction for ensuring uninterrupted, safe, and energy-efficient navigation [5]. In conditions of increasing traffic, the need to reduce fuel consumption, and compliance with environmental standards, the issue of rational planning and management of water areas becomes especially relevant. At the same time, this process cannot be isolated – it requires close integration with RIS, which provide real-time navigational support [6]. Below are the key steps and considerations fundamental to achieving comprehensive optimization:

1. Hydrographic surveys. A primary condition for effective planning of operational water areas is conducting detailed hydrographic surveys, which include:

- high-precision mapping of riverbeds, identification of bottom features, depths, widths, and potential obstacles;
- creation of digital models of the bottom and shoreline used for further 3D modeling of operational zones;
- regular monitoring of changes in bottom morphology, enabling the detection of shoaling, sedimentation, and the need for dredging works.

Such studies form an objective basis for designing efficient working zones, minimizing vessel downtime, and avoiding unnecessary maneuvering, which directly impacts the reduction of fuel consumption.

2. Navigation modeling. It is noted that the use of navigation modeling software to simulate vessel movements and interactions in the water area is a highly advisable measure that defines the scale of the chosen technical solution. The model selection should be based on justified maximum vessel dimensions, for example, the "Dnipro-Max" type [7]. These simulations allow the formation of an energy-efficient configuration of the water area, reducing the number of maneuvers, decreasing vessel dwell time in the port, and optimizing logistical chains.

3. Environmental impact assessment. Any changes to the configuration of port water areas must comply with current environmental standards. The impact of dredging and construction works on the local ecosystem, particularly on biodiversity,

water quality, and bottom sediments, is assessed. The project for modernizing existing or creating new hydraulic structures must convincingly demonstrate compliance with environmental regulations and measures to minimize negative effects. These steps help reduce the ecological footprint of navigation, contributing to the achievement of green transport goals in Ukraine.

4. Stakeholder involvement. It is particularly recognized that engaging all relevant stakeholders, including port authorities, shipping companies, environmental agencies, and local communities, and incorporating their considered input can help shape the optimization plan and ensure it meets the needs of all parties. Involving these stakeholders ensures transparency of the process and the formation of a balanced development model.

5. River information services (RIS). A general overview of RIS is provided, emphasizing the importance of integrating hydraulic and hydrographic institutions with RIS systems that deliver real-time information about river conditions, traffic, and weather [8]. This data is critically important for optimizing the use of water areas and ensuring safe navigation. Integrating RIS with the design and operation of water areas enables the implementation of intelligent vessel traffic management systems, which are key to reducing fuel consumption, lowering emissions, and improving navigational safety.

6. Vessel traffic management. One of the key components for ensuring the effective functioning of operational water areas in ports is the implementation of modern vessel traffic management systems. Such systems are designed to optimize traffic both within the port zone and along the entire inland waterway segment. They should be based on the use of data from River Information Services, providing access to hydrographic, meteorological, and navigational information in real time. This may include traffic control, movement monitoring, and automated reporting systems integrated with radar surveillance and Inland ECDIS. Thanks to these systems, it is possible not only to reduce the risks of collisions and delays but also to optimize fuel consumption by minimizing idle time and rationally distributing traffic flows.

7. Dredging and maintenance. Regular dredging operations and maintenance of water areas are integral to maintaining an adequate level of navigational safety. In inland waterways, where water level fluctuations and sediment dynamics can significantly alter depths, these measures must be planned and based on up-to-date hydrographic data [8]. This approach not only enhances safety but also ensures a stable traffic regime, contributing to energy savings by reducing the need for maneuvering and delays.

8. Safety measures. Navigational safety is a priority component in the planning and operation of operational water areas. The main elements of the safety system

should ensure clear vessel orientation in space, especially under challenging weather or night conditions. Such measures include:

- installation of navigational aids – buoys, lateral marks, signal lights, light-houses – which must comply with IMO international standards;
- equipping these objects with sensors and connection to RIS, allowing automatic updates on their status, position, and functionality;
- providing backup power supply and redundant control systems to guarantee the stability of navigational infrastructure in emergency situations;
- integration of these aids into digital navigation systems significantly improves response times and reduces the risk of accidents.

9. Technology integration. Enhancing the efficiency of port water area management is also impossible without the active implementation of innovative digital solutions such as AIS (Automatic Identification System), IoT sensors, and satellite navigation to improve the efficiency and safety of port operations. These technologies can provide real-time data for decision-making. They increase transparency, speed of response to changing conditions, and the overall level of safety and energy efficiency of vessel movements.

10. Emergency response planning. To improve readiness for crisis situations, a clearly developed emergency response system is necessary. The provided sample emergency response plan considers a wide range of potential incidents, including vessel collisions, fuel spills, fires, groundings, and meteorological anomalies. It defines interaction algorithms between port services, RIS, local authorities, emergency rescue teams, medical institutions, and emergency services. The response plan must include operational alerting tools, including digital channels, mobile applications, and automated notifications. Regular drills and system tests should be scheduled to enhance staff preparedness.

Such an integrated approach to safety management not only reduces risks but also strengthens the overall resilience of port infrastructure to extraordinary situations.

11. Compliance with regulatory requirements. One of the fundamental conditions for the successful implementation of optimization measures for operational water areas is ensuring their compliance with current national and international regulatory frameworks. Particular attention is given to the implementation of provisions related to energy efficiency in shipping. Specifically:

- national standards (DSTU, sectoral regulations) should take into account modern requirements for reducing energy consumption during vessel maneuvering within water areas, including through optimization of dimensions, speeds, and operating conditions;

- international norms (e.g., IMO energy efficiency design index (EEDI) and energy efficiency operational indicator (EEOI)) must be incorporated into the criteria for evaluating the efficiency of port infrastructure optimization;
- regulatory environmental compliance implies the integration of solutions that reduce fossil fuel consumption, shorten vessel waiting times, and promote electrification of port facilities.

Thus, compliance with legal requirements is not only a legal necessity but also a foundation for implementing systematically coordinated energy-efficient solutions into navigational infrastructure.

12. Monitoring and evaluation. Sustainable development of inland waterways requires a continuous cycle of monitoring and adaptive optimization of water area functionality. Energy efficiency here acts not only as an outcome but also as a key evaluation criterion. Continuously monitor and assess the performance of optimized water areas and make adjustments as necessary. This should be an ongoing process to adapt to changing conditions and requirements.

13. Key monitoring approaches include establishing energy consumption indicators, such as average fuel consumption per unit of cargo during port entry or passage through channels; using digital monitoring tools – flow sensors, fuel meters, AIS data – to record waterway loads and predict congestion; and employing machine learning to identify patterns in energy consumption changes depending on navigation conditions and the impact of implemented measures.

Regular adjustments of traffic schemes and navigational infrastructure parameters (depth, width, waiting zones) should also be carried out based on data about energy overconsumption or traffic slowdowns.

As a result, this approach enables improvements not only in technical and logistical efficiency but also achieves significant reductions in energy consumption within the transport cycle.

14. Environmental development. Modern optimization of inland waterway transport infrastructure is impossible without considering principles of environmental sustainability and energy efficiency. It is emphasized that the optimization process takes into account the environmental friendliness of dredging methods, the energy efficiency of infrastructure, and the reduction of environmental impact. Modernization of water area infrastructure should focus on energy saving – for example, installing LED lighting, energy-efficient pumping stations, and energy recovery systems in locks. Emissions from vessel berthing should be minimized by developing shore-to-ship power supply infrastructure (cold ironing) and encouraging the use of vessels with hybrid or electric propulsion systems. Environmental impact assessments of optimization measures should consider not only biodiversity and water quality but

also their contribution to reducing CO₂, NO_x, and SO_x emissions, as criteria for energy-efficient modernization.

Such environmental and energy integration ensures not only safe and economically advantageous operation of water areas but also compliance with the "green logistics" strategy adopted at European and global levels.

Thus, optimizing the creation of operational water areas in ports on inland waterways is a complex and multifaceted process. It requires the integration of various technologies and systems, consideration of environmental and safety factors, and cooperation with multiple stakeholders. Interaction with River Information Services is crucial for real-time decision-making and ensuring safe and efficient navigation.

The developed system for assessing navigational and energy safety aims not only to enhance the safety level of shipping on Ukraine's inland waterways but also to achieve a higher level of energy efficiency through the integration of modern monitoring technologies, digital data processing, and analytical forecasting. Its implementation allows for more rational risk management in navigation processes and reduction of energy losses, which directly impacts the economic feasibility and environmental sustainability of water transport.

The proposed strategies and technical solutions have proven effective in improving shipping productivity, reducing fuel consumption, minimizing environmental impact, and ensuring safe vessel passage. The conducted research highlights the urgent need for a comprehensive approach to energy-saving navigation management, which includes integration with river information services, use of digital charts, predictive algorithms, and involvement of all participants in the logistics chain.

Final conclusions emphasize the necessity to develop and implement energy-efficient strategies for managing port water areas and waterway routes, which will form the basis for sustainable development, increased competitiveness of inland waterways, and achieving green transport goals in Ukraine.

9.3 Improving the efficiency of navigational information services for fairways

In the context of transforming water transport towards more sustainable and energy-efficient operational models, the role of navigational information services (NIS) is increasingly important not only for ensuring safety but also for enhancing the energy efficiency of shipping on inland waterways. Optimizing vessel trajectories, reducing time spent in channels, minimizing stops, and limiting maneuvering in complex

hydrological conditions are directly linked to the quality, accuracy, and timeliness of navigation information provided by fairway services [9].

In the post-war recovery of Ukraine's transport infrastructure, improving the NIS efficiency takes on strategic significance. Timely updating of cartographic information, dynamic reporting on fairway conditions, water levels, the presence of obstacles, or changes in navigation regimes contributes to decision-making that allows pilots to select the most energy-efficient routes. The use of digital technologies, automated monitoring systems, and data analytics creates the conditions for minimizing fuel consumption, reducing operational costs, and lessening environmental impact.

River information services (RIS) are aimed at enhancing the safety, efficiency, and environmental friendliness of inland navigation on the path toward its development as a sustainable mode of transport [10]. RIS face the following specific tasks:

- to make inland navigation reliable, planned, and transparent as part of a multi-modal transport chain;
- to strengthen navigation safety by reducing the number of accidents and incidents related to vessel movement and cargo transport, providing information for legal compliance and statistics;
- to increase traffic and transport efficiency by optimizing the use of waterway capacity and vessel cargo capacity, improving the performance of ports and terminals, managing water transport chain resources through information exchange among vessels, locks, bridges, terminals, and ports, thereby lowering transportation costs, reducing fuel consumption, and increasing RIS user awareness of the current situation;
- to promote environmental safety of transportation by reducing harmful impacts on the environment.

Ukraine's inland waterways have significant development potential, but low navigation safety limits their utilization. Therefore, the fairway service aims to ensure the safe passage of vessels to their destinations.

The objective of this study is to develop effective methods and identify key components of the fairway service provision system. To achieve this, it is essential to understand that one component of RIS services is the fairway information service, which provides geographic, hydrological, and administrative data on waterway infrastructure and fairways within the RIS zone, necessary for users to plan voyages, execute them, and monitor their progress. Information transmission about fairways is one-way: it is sent from shore services to vessels or from shore services to the offices of interested parties.

The fairway service collects, processes, and provides the following information:

- the status of navigational aids on inland waterway sections;
- depths and dimensions of the navigable channel;

- obstacles present on the fairway;
- restrictions under bridges and in locks;
- meteorological conditions on various sections of the waterway;
- ice conditions on the fairway;
- electronic charts of fairway sections.

Improving the efficiency of marine navigational information services for fairways is critically important to ensure shipping safety and optimize traffic in water areas.

One key area for improving the efficiency of fairway navigational information services is upgrading their technical equipment. Implementing modern navigational and hydrographic equipment allows for timely, accurate, and reliable information delivery to pilots about navigation conditions, which, in turn, helps reduce risks, minimize delays, and improve the energy efficiency of vessel movement.

Modern satellite positioning systems (GPS), combined with AIS, enable real-time precise determination of a vessel's location with high accuracy and transmission of this information to shore services [11]. This allows more effective coordination of vessel traffic, avoidance of congestion on certain fairway sections, reduction of downtime, and support for choosing optimal routes with minimal fuel consumption. Together with centralized dispatch control systems, this enables dynamic route planning that accounts for changing conditions and reduces emissions by avoiding inefficient maneuvering.

Timely updating of hydroacoustic equipment – radars, echo sounders, and multi-beam sonar systems – ensures accurate determination of fairway depths, detection of underwater obstacles, shoals, and seabed changes. High precision of such measurements is especially important for vessels with deep drafts or when navigating critical sections with limited dimensions. Clear knowledge of available depth promotes route selection with minimal grounding risk, accident avoidance, and consequently, increased safety and energy efficiency in shipping [12].

Modern solutions in the integration of navigational data enable the combination of information from various sources – GPS, AIS, meteorological stations, hydrographic sensors, video surveillance cameras, automated water level and current monitoring systems. Such integrated systems create a unified visualization dashboard for operators, traffic controllers, or ship captains, providing comprehensive real-time analysis of the navigational situation. This ensures timely decision-making, avoidance of unexpected maneuvers, and reduced fuel consumption through smoother and more predictable course and speed management.

Automation of processes within navigational information services for fairways forms the basis of modern, efficient, and safe shipping management. Its implementation reduces personnel workload, shortens response times to changes in navigational

conditions, and provides more accurate risk forecasting [13]. Additionally, automated solutions contribute to increased energy efficiency by minimizing idle time, optimizing routes, and vessel speeds.

The implementation of digital chart systems such as ECDIS (electronic chart display and information system) provides access to continuously updated data on depths, fairways, navigational warnings, weather conditions, and obstacles. These charts integrate data from GPS, AIS, meteorological stations, and hydrographic sources, forming an up-to-date real-time navigational picture. This enables vessels to avoid hazardous areas, plan movements considering depths and currents, and reduce fuel consumption through optimized course, speed, and travel time.

Automated vessel traffic services (VTS) play a critical role in coordinating traffic in complex or congested sections of inland waterways. VTS provide surveillance, control, forecasting, and rapid response to conflict situations. With the introduction of analytical modules and predictive algorithms, such systems can detect potential route conflicts, recommend optimal passing maneuvers, identify risk zones, and generate energy-efficient trajectories, minimizing unnecessary movements and abrupt speed changes.

Automated fairway control through remote monitoring involves installing hydrometric sensors, surveillance cameras, thermal imagers, and other real-time data collection tools at strategically important waterway locations. These systems continuously monitor water levels, currents, wind speed, obstacle presence, status of floating navigation aids, and technical infrastructure (bridges, locks, etc.). Collected data is automatically processed and integrated into a unified decision-support system, enabling prompt response to navigational changes and preventing inefficient use of energy resources by vessels.

Reliable, timely, and efficient communication is a key element of modern inland waterway traffic management systems. In the context of energy efficiency, improving communication infrastructure helps avoid delays, inefficient maneuvering, and idle time, directly reducing fuel consumption and emissions.

Traditional VHF/UHF radio systems are supplemented by modern digital channels that provide higher quality voice and data transmission. The implementation of the global maritime distress and safety system (GMDSS) standards, including simplified versions for river navigation, ensures continuous and reliable communication among vessels, traffic control centers, locks, and ports. Multichannel communication systems capable of transmitting not only voice but also text and graphical messages improve the speed of information exchange and support faster decision-making regarding routes or changes in navigational conditions.

Integration of vessels and shore-based services into a single information network is facilitated by the deployment of broadband data transmission networks. In particular, the use of satellite communication channels enables continuous information exchange even in remote or poorly covered areas, such as isolated river sections or mountainous regions. This capability is especially critical for navigation safety and prevention of unscheduled stops or emergency situations that may lead to excessive energy consumption. Additionally, such networks allow centralized monitoring and coordination of a large number of vessels in real time.

Fairway information services increasingly rely on automated warning systems capable of sending real-time alerts to captains about changes in hydrographic or meteorological conditions. These systems notify about sediment shifts, shoaling, rising water levels, current changes, fog, storm warnings, and more. This allows captains to adjust routes or speeds proactively, avoiding accidents and optimizing energy use.

Contemporary challenges in inland water transport require not only technical upgrades but also fundamental transformations in the ways navigational information is exchanged, processed, and stored. In conditions of high traffic density, variable hydro-meteorological factors, and the need for energy-efficient vessel traffic management, optimizing information flows plays a crucial role. The goal is to create a system that ensures fast, reliable, and efficient data transmission and analysis among all transport process participants.

Information interoperability between stakeholders – ports, traffic control centers, vessels, locks, meteorological services – is a necessary prerequisite for efficient navigation. Implementation of unified data formats (e.g., IALA S-100, XML, JSON) and standardized communication protocols enables seamless interaction between information systems. This reduces the likelihood of delays, data processing errors, and information duplication, thereby contributing to reduced time and fuel consumption during maneuvering and route planning.

Integration of intelligent systems takes traffic management to a new level. Using large volumes of historical and real-time data, machine learning algorithms can predict fairway traffic loads, identify bottlenecks, congestion, or potential hazard zones. For example, based on analysis of vessel traffic frequency, depth, current speed, and weather conditions, dynamic recommendations can be generated for the most optimal route with minimal water resistance and risk of delays. Such recommendations can be automatically transmitted to vessel onboard systems or traffic controllers, significantly enhancing navigation energy efficiency.

Centralized cloud platforms provide convenient access to up-to-date information for all users regardless of their location. Data on depths, movement restrictions, current lock situations, weather conditions, warnings, and recommendations can

be updated and delivered in real time via unified protocols. Cloud architecture also simplifies system scalability, backup, software updates, and cybersecurity measures. Moreover, these platforms facilitate the implementation of the digital twin concept for fairways, where each river segment is virtually modeled and analyzed for more precise situation forecasting.

The physical infrastructure of fairways plays a crucial role in ensuring the safety and efficiency of navigation. Its current condition directly affects the navigational situation, vessel transit speeds, and fuel consumption levels. Wear, instability, or inadequacy of infrastructure leads to additional maneuvers, speed reductions, delays, or even accidents, which significantly reduce the energy efficiency of the transportation process. Therefore, a systemic approach to improving elements of fairway infrastructure is of paramount importance.

To enable timely detection of changes in seabed configuration, sedimentation, emergence of obstacles, or shifting sandbanks, it is necessary to implement regular and automated monitoring of water areas.

For this purpose, the following technologies are recommended:

- drones equipped with high-precision cameras and LIDAR sensors, capable of aerial photography and mapping of coastal areas;
- autonomous surface and underwater vehicles (USV/ROV) capable of real-time hydroacoustic seabed scanning and rapid data transmission to navigation services;
- automated bathymetric charting systems that monitor depth changes dynamically and update navigational databases accordingly.

Such measures help reduce the risks of passage through hazardous zones, avoid forced stops, and prevent routing decisions that lead to fuel overconsumption.

Traditional buoys and navigational marks remain essential visual orientation aids for vessels; however, their functionality can be significantly enhanced through digitalization. Promising directions include:

- equipping buoys with sensors to measure water level, current speed, temperature, and other hydrological parameters impacting navigation;
- connecting navigational aids to centralized monitoring systems via LoRaWAN or LTE/5G networks, enabling prompt data transmission to shore control centers;
- integrating energy-efficient LED lighting with automatic brightness adjustment based on weather conditions and time of day, improving both energy savings and safety.

These initiatives ensure timely notification of crews about changes in the fairway and improve the overall quality of the navigational environment.

The modern paradigm of inland water transport development focuses on digital transformation of logistics processes, notably through the implementation of the Smart Port concept. This high-tech ecosystem integrates digital services for vessel

traffic management, infrastructure, cargo turnover, and energy consumption into a unified dynamic environment. Integrating fairway navigation information services with such ecosystems is a crucial step toward enhancing energy efficiency, reliability, and sustainability of inland water transport.

A key condition for achieving effective waterway traffic management is the coordination between vessels, fairway navigation services, and port administration. Ensuring operational data exchange between vessel traffic services (VTS) and port planning platforms enables:

- coordinated vessel approach to ports considering current navigational conditions;
- avoidance of queues and idle time in anchorage areas, leading to reduced fuel consumption and emissions;
- optimized berth allocation, minimizing the need for additional maneuvers.

The implementation of a shared information environment based on API integration principles and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities) standards allows construction of efficient logistic routes with predictable energy consumption levels.

The Smart Port ecosystem actively employs IoT devices that provide continuous monitoring of environmental parameters, port infrastructure, and water areas. Integrating fairway navigation services into this network enables:

- monitoring fairway conditions (depths, obstacle presence, water level) via underwater sensors and telemetry-equipped buoys;
- real-time detection of structural wear in hydraulic engineering facilities or soil shifts;
- direct transmission of data to vessel traffic management systems, allowing prompt route adjustments and avoidance of zones with increased energy consumption (e.g., due to strong currents or insufficient depth).

Additionally, IoT devices can be utilized to control lighting parameters, climatic conditions, vibration loads on equipment, and more, contributing to reduced operational costs and improved energy efficiency of the entire infrastructure.

Thus, deep integration of fairway navigation information services with Smart Port digital platforms and IoT technologies forms a new quality of inland waterway management. This approach is based on principles of dynamic adaptation, increased process transparency, and energy consumption optimization at all stages of the logistics chain. It opens broad prospects for implementing green shipping initiatives at the national level.

These measures will enhance the accuracy, speed, and safety of fairway information services, which is critical for modern navigation.

9.4 Conclusion

The results of the conducted study confirmed the importance of implementing a comprehensive approach to energy-efficient navigation management on inland waterways. This approach should be based on integration with river information services, the use of digital navigation tools, predictive models, and effective coordination of actions among all participants in the transport and logistics process.

The summarized conclusions point to the strategic necessity of developing and implementing energy-saving management systems for port water areas and water routes. This will ensure sustainable development, strengthen the competitiveness of inland water transport, and achieve the goals of environmentally friendly ("green") transport in Ukraine.

Modernization of technical equipment not only enhances the overall efficiency of navigation management on inland waterways but also lays the foundation for implementing intelligent transport systems aimed at reducing energy consumption, lowering CO₂ emissions, and realizing the principles of green shipping. Overall, improving communication infrastructure is an integral component of the digital transformation of water transport. It not only increases the overall level of safety and operational efficiency but also creates conditions for sustainable, predictable, and energy-efficient navigation on Ukraine's inland waterways.

Optimization of information flows within navigation services significantly reduces navigational risks, minimizes unnecessary stops or waiting times, and, most importantly, ensures more efficient fuel use through reduced transit times and more precise speed planning. As a result, this leads to lower operational costs, reduced emissions, and an overall improvement of the environmental profile of inland water transport.

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