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Societal Impacts 7 (2026) 100161

Contents lists available at ScienceDirect

Societal Impacts

journal homepage: www.journals.elsevier.com/societal-impacts

Autonomous inland waterway transport for a safer and sustainable tomorrow: The AUTOBarge project

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ARTICLE INFO

Keywords:
Autonomous Shipping
Inland Waterway Transport
Sustainability
Innovation
Safe Inland Navigation

ABSTRACT

The AUTOBarge project aimed to upgrade inland waterway transport (IWT) by engaging autonomous and sustainable shipping technologies. Addressing both technical and non-technical challenges, the project stimulated safer, more efficient, and environmentally friendly freight solutions, directly supporting several Sustainable Development Goals (SDGs). The technical results encompassed ship manoeuvring models, collision avoidance algorithms, advanced sensor fusion techniques, and real-time situational awareness for safe navigation in confined waterways. Social, economic, and legal aspects were also explored, including stakeholder mapping, regulatory readiness, and liability in autonomous IWT contexts. A key outcome is the AUTOBargeSim, an open-source MATLAB toolbox for simulating autonomous vessel behaviour, assessing guidance systems, and enabling energy-efficient voyage planning. Technological innovations from the project contribute to reduced emissions, lower road congestion, and improved working conditions by shifting operational tasks onshore. Policy recommendations and regulatory frameworks were proposed to guide the safe and scalable implementation of autonomous barges in Europe. By integrating automation, digitalization, and sustainability, AUTOBarge laid the foundation for a future autonomous IWT with wide societal impact.

SPECIFICATIONS TABLE (All sections are mandatory unless marked otherwise)

Subject area	*1000: Multidisciplinary*
Category/categories of societal impact	Economic, Environmental, Legal, Societal, Technological
Sustainable Development Goals (SDGS) the research contributes to	*GOAL 8: Decent Work and Economic Growth* *GOAL 9: Industry, Innovation and Infrastructure* *GOAL 11: Sustainable Cities and Communities*
Research Project	
Project description: The AUTOBarge project is an interdisciplinary research project gathering academia and industry together to train and develop expert workforce and advances key technologies and strategies to enable advance automation in inland shipping. The project promotes innovation with advance automation and digitalization in Europea inland waterways aligning with the EU's goal for greener transport. *Grants - This project has received funding from the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No. 955768.* *Link to the summary of the project –* https://etn-autobarge.eu/project/	
Stage of research	
Project officially ended in September 2025. Disseminations of results will continue. ***(In Progress)***	

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https://doi.org/10.1016/j.socimp.2025.100161
Received 18 September 2025; Received in revised form 13 November 2025; Accepted 1 December 2025
Available online 3 December 2025

Societal impact

The European training and research network on Autonomous Barges for Smart Inland Shipping (AUTOBarge project) aims to make European Inland Waterway Transport (IWT) safer, more efficient, and sustainable in the long term. The project outcomes contribute towards the United Nations (UN)'s Sustainable Development Goals (SDG) directly through actions or indirectly by fostering technology. SDG 8,9, and 11 reflect the broader societal impacts anticipated from the development and deployment of autonomous and smart shipping technologies. These impacts have been investigated across all work packages of the project.

Technological innovation (SDG 9) in maritime infrastructure fosters sustainable industrial growth by creating new economic opportunities and improving job conditions through automation (e.g. working from the remote operating centre). These innovations contribute to sustainable economic growth and societal development (SDG 11). Furthermore, leveraging rich sensor data to enhance situational awareness is essential for avoiding collisions and groundings, thereby ensuring safe navigation and enabling remote operations through real-time insights. This supports more sustainable transport (SDG 13) by improving the digitalisation of operations and providing energy-conscious decision support. It also encourages the design of smaller, more efficient, and eco-friendly ships.

These new technologies will create safer and more inclusive work environments, [1] indirectly promoting gender equality (SDG 5). It will foster inclusivity (SDG 10) by enhancing accessibility and transport equity and affordability- expanding shipping services to remote or underdeveloped regions, and providing fair opportunities for underrepresented groups in the maritime workforce, such as women and individuals with disabilities [2]. In the AUTOBarge project, significant research results have been obtained on the innovation drivers, adopters, adoption dynamics, and policy implications based on empirical data from the IWT sector [3–5]. The project findings contribute to new research agendas and effective policy measures towards economic growth and better working conditions.

Shipping contributes 3–5 % of global carbon dioxide (CO_2) and over 5 % of global sulphur oxides (SO_x) emissions, with a significant share from IWT [6]. Shifting to autonomous and electric barges can cut greenhouse gas emissions, lower pollution, and enhance environmental sustainability (SDG 13) by promoting cleaner, energy-efficient freight transport. It will reduce road congestion- lowering transport costs and road accidents while improving working conditions by shifting navigation tasks onshore. The transition towards full autonomy will shift operations to the remote operation centre (ROC), where one pilot will navigate a single ship, a system that has already been implemented in Flanders, Belgium. However, further development will increase efficiency, allowing one pilot to navigate multiple ships, and eventually progress towards full autonomy with no human involvement. Autonomous innovation has the potential to improve working conditions and make IWT more attractive to future crews; however, future jobs will require more IT-related expertise [3]. Intelligent systems further support sustainable logistics through smarter decision-making capabilities. However, implementation of autonomous inland shipping requires a new regulatory approach as existing regulations fall short of regulating crucial aspects of this new technology. To address this issue, an AUTOBarge researcher proposes a tailored legal approach to provide legal certainty to inland shipping stakeholders and society in general (SDG 17) and mitigate emerging risks to an acceptable level.

Methodological approaches

To meet its objectives, AUTOBarge was implemented in six work packages (WPs) as illustrated in Fig. 1. Research tasks were distributed among 15 Early-Stage Researchers (ESRs) within the first three WPs.

Four ESRs lead WP1, focusing on sensing and situational awareness. To perceive and predict the ship motion in a complex navigation

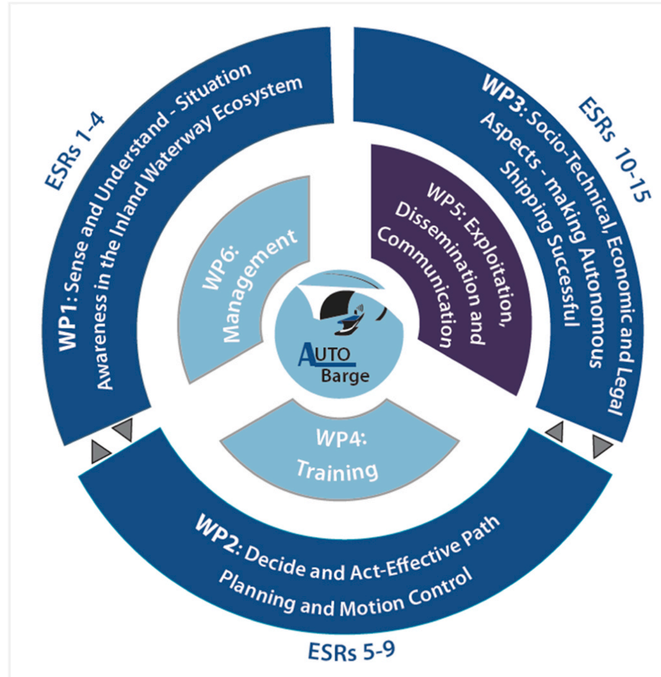

Fig. 1. AUTOBarge work organization (https://etn-autobarge.eu).

environment, AUTOBarge ESR developed a ship manoeuvring model that relates control inputs to ship motion using hydrodynamic parameters [7]. To detect and track other vessels, sensors like Light Detection and Ranging (LiDAR) are used to scan the environment, and these scans are processed with probabilistic methods to estimate the position, speed, heading, size and shape of the vessels along with uncertainty of these estimates. This method, known as extended object tracking, is crucial in the narrow margins of inland waterways [8]. Real-time environmental data, including waterway boundaries and bridge dimensions, are integrated into Inland Electronic Navigational Charts (IENCs) for continuous updates [9]. This improves model accuracy, predictions of ship motion, and supports the implementation of higher levels of automation. By addressing these complexities, research contributes to the broader goal of modernizing IWT using automation.

WP2 ESRs focused on the vessel's path planning and motion control objectives, thereby facilitating the design of the Guidance, Navigation and Control system for autonomous navigation. Firstly, the vessel's manoeuvring and track-keeping capabilities were optimised by developing algorithms to (i) smooth predefined waypoints, (ii) apply model predictive control for track-keeping, and (iii) ensure robust interfaces and communication protocols among navigational components and the track-keeping system [10]. A collision avoidance framework was also developed, incorporating trajectory exchange and a protocol for collision prevention [11], which led to a collision avoidance algorithm tailored for autonomous inland waterway vessels [12]. Furthermore, to ensure safety under corner cases (harsh weather conditions, faults, failures and unexpected situations), a fault detection and isolation method was designed to focus on sensor faults onboard autonomous vessels [13]. Hydrodynamic phenomena such as bank and shallow-water effects, which are predominant in inland waterways, were modelled and incorporated into model-based track-pilot controllers [14]. Machine Learning (ML) based perception models were evaluated for real-time object detection robustness [15]. Natural corruption augmented datasets with maritime specific corruptions (SeaShips-C, SMD-C, SSAVE-C) were introduced to improve dependability [16], and a runtime safety assurance framework was proposed to support the safety standards using ML monitoring techniques [17].

WP3 ESRs translate technological development into practice through socio-technical, economic and legal analysis. They focused on analysing the societal impacts of autonomous IWT system by distributing the stakeholders in a socio-technical framework to map stakeholder roles [4]. Further, WP3 researchers investigated potential business cases and preparedness of shipowners [3], legal challenges with liability in an autonomous era [18] and the establishment of a harmonised European regulatory framework for autonomous shipping [5]. Various social science methodologies were employed, such as empirical studies (e.g., surveys, interviews with stakeholders and experts), classical legal research, comparative research, participatory legal research, among others.

Table 1 provides an overview of the ESR projects, including the scientific topics addressed, the core methodology, and the corresponding verification/validation methods used.

Table 1
Summary of the individual ESR projects within the AUTOBarge project.

WP	ESR Project	Scientific topic addressed	Core methodology	Verification/ validation methods
1	1	Manoeuvring modelling for inland vessels in dynamic conditions	System identification, adaptive modelling	Experiments on a research vessel and simulations
	2	Precise situational awareness in confined waterways	Extended object tracking and mapping	Real-world maritime data and simulations
	3	Inland electronic navigational chart (IENC) that captures dynamic environmental changes	From static to dynamic IENC: multi-sensor Simultaneous Localization and Mapping (SLAM)	Real-world maritime data and simulations
	4	Collaborative collision avoidance between manned/ unmanned ships	Intention-aware, distributed model predictive control, negotiation/ communication protocol	Experiments on a research vessel and simulations
2	5	Vessel path generation and following with real-time adaptations	Model predictive curve-based line of sight control, Kalman filtering and dead reckoning	Experiments on a full-scale class VI/a inland vessel and simulations
	6	Collision avoidance algorithms catered for restricted and inland waterways	Scenario-based model predictive control, dynamic Bayesian networks, optimization	Simulations using real-world map data and historical AIS data
	7	Real-time, multi-objective voyage optimisation	Isochrone-based predictive optimisation, data-driven heuristics	Simulations
	8	Integrated voyage planning for energy efficiency on barges	Energy-efficient voyage planning	Simulations
	9	Fault diagnosis and control for safe navigation of inland vessels	Model-based fault diagnosis with nonlinear observers, model predictive control	Real-world maritime data and simulations
3	10	Safety assurance of ML models in autonomous vessels	ML assurance frameworks aligned with IEC 61508/ AMLAS	Real-world maritime data
	11	“Common ground & actor network” for collaborative decision-making	Human-centred Socio-technical system analysis, stakeholder/ actor mapping	Interviews with IWT act, observations
	12	Multimodal freight models that include externalities & AIS impacts of autonomy	Network/economic modelling with environmental externalities	Economic data
	13	Ship-owner adoption preferences and socio-economic scenarios for autonomous IWT	Behavioural & scenario analysis, adoption modelling	Surveys, interviews, and scenario simulations
	14	Regulatory recommendations	Doctrinal legal research, comparative legal research	Stakeholder consultation
	15	Liability and contract frameworks for autonomous barges	Comparative legal analysis, doctrinal legal research, participatory legal design	Stakeholders workshop, surveys

Results and implications

By addressing both technical and non-technical dimensions, the AUTOBarge project delivers a comprehensive solution that enables smart, digitalized, and automated shipping on European inland waterways. The proposed technical models and methods were extensively validated through full-scale and model-scale vessel trials, in addition to verification using high-fidelity simulation platforms and formal methods. Fig. 2 shows the various vessel platforms used for validation, covering a broad range of vessels that span different dimensions, hull types, and use cases.

A concrete technical deliverable from the project is AUTOBargeSim (Fig. 3)- an openly available toolbox for designing and analyzing guidance and control systems for autonomous inland navigation [19]. It simulates vessel dynamics under various constraints and environmental conditions, offering performance metrics to support the design and evaluation of autonomous navigation systems and autopilots for inland navigation. The metrics used to evaluate the performance, robustness, and safety of the autonomous vessel included the cross-track error, cumulative heading error, estimated time of arrival (ETA), safe inland navigation metric (SINM), and inland waterway robustness index (IWRI) [14,19]. At present, there are no regulatory thresholds for these metrics. Accordingly, their minimum absolute values were emphasized during testing in real and simulated environments, which indicates higher accuracy, efficiency, and robustness.

Individual research covered diverse aspects of autonomous inland navigation, leading to promising novel results for its implementation. Beyond the technological domain, the AUTOBarge research has implications for sustainable transport and social impact. By enabling safer, more efficient use of underutilized waterways, the work promotes greener logistics solutions, potentially reducing road traffic congestion and emissions. In a nutshell, the key deliverables of the AUTOBarge are:

– establishment of a real-world testing platform consisting of the Maverick research vessel and a vessel-agnostic sensor suite [20].
– a scenario-based modeling framework that adapts model complexity [7] and accounts for changing environmental disturbances.
– novel algorithms to track smaller vessels using LiDAR and integrating AIS information to track larger inland barges [8] for improving situational awareness. Validation on real data shows the ability to track both single and multiple vessels simultaneously while accurately estimating their extent.
– a new track-keeping pilot concept designed to meet industry standards, featuring dead reckoning capabilities and scalability for static obstacle avoidance. An innovative solution for dynamically updating static IENCs using LiDAR and RTK-GNSS data [9], the development of the Inland-LOAM for robust LiDAR-based localization and semantic mapping in GNSS-denied environments [21], and identification and safe path following control of an inland vessel using IENC data [10].

Fig. 2. Vessel platforms used for validation through river trials, including (a) an inland vessel class VI/a (Video: https://www.youtube.com/watch?v=DYOIgBhf7ic), (b) the research vessel, "Maverick" (Video: https://www.youtube.com/watch?v=MwBjXc9ndfQ), and (c) "The Otter" USV (Video: https://www.youtube.com/watch?v=vC5FTxeVpJg).

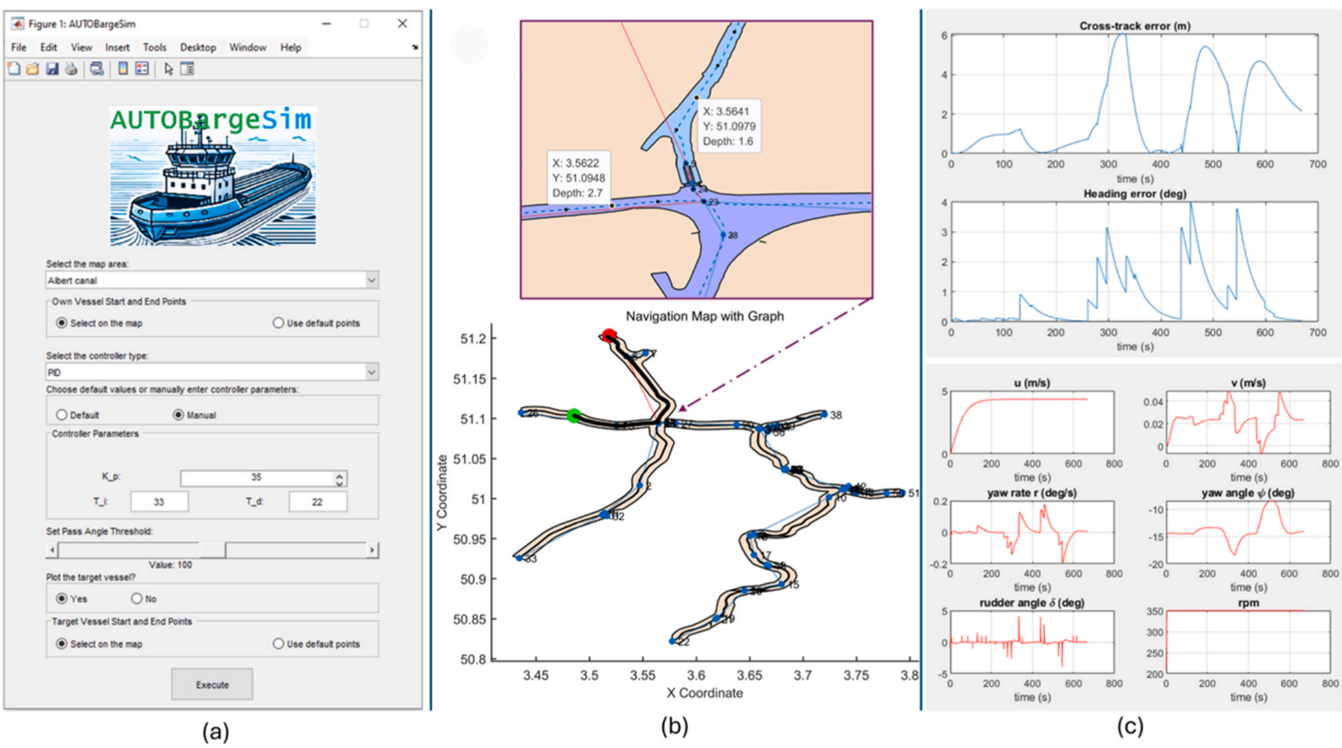

Fig. 3. The AUTOBargeSim toolbox for MATLAB provides (a) graphical user interface for an easy and quick execution of the toolbox, with the possibility to adjust some critical inputs. (b) mapping capabilities for accurate visualization of the vessel path and fairway boundaries. (c) time series graphs plot the parameters describing the vessel's states and obtained performance metrics.

– voyage planning framework for energy monitoring and optimisation of autonomous inland vessels [22].
– an innovative conceptual framework for communication [23] and a communication protocol [24] to increase ships' safety through collaboration in a mixed traffic environment involving both human-crewed and autonomous ships.
– a multiple sensor fault diagnosis algorithm for detecting and isolating faults impacting onboard navigational sensors [13,25].
– the quantification of key risks in vision-based models [16] and provides a safety framework for ML monitoring aligned with the latest safety standards such as ISO/IEC 5469 [17].
– Formulation of a regulatory framework that provides legal certainty and mitigates risks inherent to the implementation of the new technology across the pan-European inland waterway network, within the EU and beyond [5,26,27].
– Analysis of risk distribution for the commercial implementation of autonomous barges [18,28,29].

Funding declaration

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 955768 (MSCA-ETN AUTOBarge). This publication reflects only the authors' view, exempting the European Union from any liability. Project website:http://etn-autobarge.eu/

Authors contribution

Every author contributes equally to the original draft. In addition, RS did the conceptualization, and VR did the supervision.

Ethical statement

The authors declare that this is an original work by the authors. The manuscript is not yet publisher nor currently under consideration

anywhere else.

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 955.768 (MSCA-ETN AUTOBarge).

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Chengqian Zhang: Writing – review & editing, Writing – original draft. **Dhanika Mahipala:** Writing – review & editing, Writing – original draft. **Amirreza Haqshenas Mojaveri:** Writing – review & editing, Writing – original draft. **Yunjia Wang:** Writing – review & editing, Writing – original draft. **Abhishek Dhyani:** Writing – review & editing, Writing – original draft. **Rana Saha:** Writing – review & editing, Writing – original draft, Conceptualization. **Sophie Orzechowski:** Writing – review & editing, Writing – original draft. **Dhaneswara Al Amien:** Writing – review & editing, Writing – original draft. **Martin Baerveldt:** Writing – review & editing, Writing – original draft. **Vasso Reppa:** Supervision. **Yan-Yun Zhang:** Writing – review & editing, Writing – original draft. **Camilla Domenighini:** Writing – review & editing, Writing – original draft. **Hoang Anh Tran:** Writing – review & editing, Writing – original draft. **Zhongbi Luo:** Writing – review & editing, Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: All authors reports financial support was provided by Horizon Europe. ALL AUTHORS reports a relationship with European Union that includes: funding grants. This publication reflects only the authors' view, exempting the European Union from any liability. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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