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ARTICLE

Autonomous inland shipping: Learning from regulation in air, rail, road and sea transport

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Abstract

Autonomous inland shipping technology is on the horizon. However, without a regulatory framework that addresses emerging gaps and barriers, this technology will not be implemented in the near future. Other transport sectors, more specifically air, rail, road and sea transport, are more advanced in this regard: regulators have taken up the challenge of proposing regulatory solutions to pave the way for the introduction of autonomous processes in the market in their respective industries. Thus, to meet urgent research needs in the field of inland waterway transport, this study explores possible regulatory solutions for autonomous inland shipping using a comparative research approach. By analysing the regulatory frameworks applicable to autonomous transport modes in other industries in the light of the similar or identical issues that have been identified for autonomous inland shipping, potential regulatory answers are explored. Key findings highlight the need for a complete set of regulations that address the emerging issues in a way that provides legal certainty and reduces risks to an acceptable level without becoming too technically specific, thereby leaving some degree of flexibility to industry stakeholders to meet the regulatory requirements. The research provides a toolbox of possible regulatory answers for autonomous inland shipping technology that will be of interest to regulators and policymakers including working groups on automated inland navigation from UNECE, CESNI and the CCNR to help them work out a regulatory framework proposal.

Keywords Autonomous inland ships · Regulation · Autonomous drones · Unattended train operation · Maritime autonomous surface ships · Autonomous cars

Abbreviations

AAR	Association of American Railways
ADS	Autonomous driving system

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AFGBV	German Ordinance on the approval and operation of motor vehicles with autonomous driving functions in specified operating areas
AI	Artificial Intelligence
ALARP	As low as reasonably practicable
BMDV	German Ministry of Digital and Transport
BOSTRab	German Tram Construction and Operation Regulation
BVLOS	Beyond visual line of sight
CCNR	Central Commission for the Navigation of the Rhine
CESNI	European Committee for drawing up Standards in the field of Inland Navigation
C-ITS	Cooperative intelligent transport system
COLREGS	Collision-avoidance regulations
EASA	European Union Aviation Safety Agency
EU	European Union
EU VTMIS	European Union Vessel Traffic Monitoring & Information Systems
FAO	Fully autonomous operation
GDPR	General Data Protection Regulation
GoA	Grade of automation
IMO	International Maritime Organisation
ITF	International Transport Forum
MASS	Maritime autonomous surface ship
MRC	Minimum risk condition
MSC	Maritime Safety Committee
OECD	Organisation for Economic Cooperation and Development
OT	Operational technology
RCC	Remote Control Centre
SAE	Society of Automobile Engineers
StVG	German Road Traffic Act
TAS	Trusted Autonomous Systems
UAS	Unmanned aerial system(s)
UAV	Unmanned aerial vehicle
UITP	International Association of Public Transport
UNECE	United Nations Economic Commission for Europe
US	United States of America
UTO	Unattended train operation
VLOS	Visual line of sight

1 Introduction

Autonomous shipping technology could considerably improve safety, efficiency and competitiveness vis-à-vis other transport modes in the European inland waterway sector (UNECE 2018). Continuous advances in autonomous shipping technology hold the promise that this new technology will soon be ready to be put into operation on a large scale, but the regulatory developments are still in their early stages. Thus, in order for it to be possible for autonomous inland shipping operations to move beyond their current test beds, new regulations must be put in place to address emerging issues such as the level of technology and safety required and the roles and responsibilities of the humans involved. Without such regulations, autonomous ships will remain limited to their current testing environments, thereby considerably hindering a profound transformation of the sector. At present, there is no established regulatory regime governing the use of autonomous shipping technology for the long term and allowing the structural deployment of such vessels, except transitional legislation adopted by some European countries to promote innovation and demonstrate operational performance. Besides, some of the main public regulators in European inland waterway including the United Nations Economic Commission for Europe (UNECE), the European Committee for drawing up Standards in the field of Inland Navigation (CESNI) and the Central Commission for the Navigation of the Rhine (CCNR) are currently exploring regulatory possibilities, but are still in the very early stages. However, this type of experimental regulation is limited to the temporary and exceptional operation of highly automated ships simply through authorised deviations from existing rules.

Although interim rules and guidelines for autonomous ships can provide valuable insights into technological reliability and risk assessments, and identify shortcomings and gaps, they cannot form the basis for a comprehensive regulatory framework for the widespread deployment of autonomous ships; this is because these rules and guidelines are primarily based on exceptions rather than setting out norms. More specifically, the regulation of innovation on the sole basis of authorisation-by-exception falls short of good regulatory principles such as transparency, accountability, proportionality, consistency and targeting. In addition, the regulation of new technologies needs to be adaptive to respond to changing circumstances by finding modified or novel regulatory answers to emerging issues which were not foreseeable at the time the regulations were enacted (Orzechowski et al. 2024). Above all, regulation needs to provide for adequate risk mitigation to balance the risk amongst the different interest groups affected. Consequently, the elaboration of a future-proof regulatory framework for autonomous inland shipping technology presents a dominant concern for inland waterway regulators and policymakers.

1.1 Literature review

Most academic literature on the regulatory issues affecting autonomous inland vessels has focused on the existing rules and regulations with regard to regulatory barriers and gaps. More specifically, previous studies have examined technical regulations in light of the concept of ship safety (Bačkalov 2020) or have analysed a specific case study vessel to consider the vessel's compliance with applicable safety- and security-related regulations (Nzengu et al. 2021), and have followed this with proposals for regulatory intervention (Ahmed et al. 2024).

Other research has investigated the status quo of the overall regulatory framework currently applicable in European inland waterway transport by identifying the relevant regulatory instruments, analysing these as to common gaps and themes, and establishing potential links between the analysed instruments (Orzechowski 2024).

This research is complemented by a study that identified the factors that will have an influence on the regulation of autonomous inland ships and that discussed the different regulatory measures required in regulatory agenda-setting in the light of their impact on innovation implementation in the short, medium and long term (Orzechowski et al. 2024).

1.2 Background

In contrast to inland waterway transport, autonomous transport operations have already been adopted in other industries and thus have been subject to regulatory intervention. Therefore, in these other industries important regulatory developments have taken place in recent years.

Unmanned aerial vehicles (UAVs), also known as unmanned aerial systems (UAS), have been subject to by far the most detailed regulation amongst all autonomous transport modes. This is not surprising, insofar as aviation is one of the most regulated industries in the world, with safety being a predominant aspect of regulation to mitigate the inherent risks associated with air transport (OECD/ITF 2019). Drones are subject to stringent regulatory requirements in the United States (US) and the European Union (EU). The Federal Aviation Administration of the US has established regulations and guidelines specific to drones. In principle, current US legislation does not generally permit autonomous drone operations, since drones must always remain within the visual line of sight (VLOS) of the operator or other relevant authority. The only possibility for operating autonomous drones beyond the visual line of sight (BVLOS) under current US law is by exception, through a waiver from specific requirements.

In contrast, the most comprehensive regulatory regime for drones that has been adopted so far is that of the EU. The regulation that applies throughout the EU replaced previous national drone regulations, and follows a risk-based approach. In contrast to regulations in other transport sectors, drone regulation in EU airspace distinguishes between different categories of drones ('open', 'specific' and 'certified'), according to the intended operational space and associated risk, not just the level of automation. Under the EU regulations, an autonomous drone is one that is able to conduct a safe flight without the intervention of a pilot. It does this with the help of artificial intelligence (AI), enabling it to cope with all kinds of unforeseen and unpredictable emergency situations. While automatic drones are allowed in all categories, autonomous drones need a level of verification of compliance with technical requirements that is not compatible with the system put in place for the 'open' category. Drones operating BVLOS within EU airspace are classified in the 'specific' category. Autonomous operations are therefore allowed in the 'specific' category if the operation is to be conducted BVLOS, and in the 'certified' category in the case of the transport of people or dangerous goods.

However, one of the most widely used autonomous transport innovations is autonomous train operations: unattended train operations (UTO) or fully automated operation (FAO) refer to Grade of Automation (GoA) level 4 according to the GoA classifications specified by the IEC standard IEC 62290–1 (UITP 2014). Outside mainline railway operations, the concept of UTO was introduced in the early 1980s, with Japan and France at the forefront, and UTO have, ever since, been implemented more and more commonly, even in highly restricted and constrained environments such as urban metro lines, all around the world (Rosić et al. 2022; Tonk et al. 2023). The implementation of driverless mainline trains is more complex. Apart from driverless train systems operating in thinly populated areas, like the heavy haul freight trains in the Pilbara mining region in North-West Australia (Yusuf et al. 2020), fully autonomous train operations have not yet been implemented. In Europe, for example, Directive (EU) 2016/797 does not currently contain an exception that would allow train drivers not to be used (BMDV 2018). Due to interoperability across the European rail network, advanced automatic train operations cannot currently be allowed. Moreover, driverless train technology would require an entire paradigm shift in safety (Freise 2020). As an alternative to the very costly complete fencing of railway lines, which is currently not considered to be feasible, driverless mainline train systems would require more advanced obstacle detection systems with significant technical and operational characteristics and would be subject to adapted regulations (Rosić et al. 2022).

With respect to automated road transport, Germany has been at the forefront as regards regulation: the German Ordinance on the approval and operation of motor vehicles with autonomous driving functions in specified operating areas (AFGBV 2022) establishes the regulatory framework for autonomous motor vehicles (those corresponding to the Society of Automobile Engineers (SAE) level 4 (SAE 2021). In the SAE 4 category, the driving system is able to perform specified tasks autonomously, as in level 3, but it no longer has to be monitored by a physically present driver. This means that the system assumes complete control of the vehicle; the vehicle occupants are only passengers.

In contrast to the transport sectors presented above, the regulation of autonomous maritime ships is not very advanced. However, more regulatory work has been done in this sector than for inland shipping. For experiments in real environments, the EU and the International Maritime Organisation (IMO) have issued guidelines for trials with maritime autonomous surface ships (MASS) (EU VTMIS 2020; IMO/MSC 2019), corresponding to degrees 3 and 4 of the IMO's degrees of autonomy (IMO/MSC 2020, Annex 2). These guidelines are being further complemented by guidelines and best practice documents issued by the industry (e.g. DNV GL 2018a; Maritime 2023; TAS 2022).

1.3 Objective and research questions

With regard to inland waterways, and in the light of the slow legislative development and existing research gaps, there is an indisputable need for regulatory answers to the emerging issues relating to autonomous inland shipping. On the other hand, regulations for autonomous drones, cars with autonomous driving systems (ADS), UTO and, of course, MASS already exist. Hence, inland waterway regulations are not considered in this study. The question is therefore whether the regulation on autonomous systems in other transport sectors could provide substantial input for a proposal for a regulatory framework for autonomous inland ships, on the assumption that the emerging issues of autonomous transport are of a similar nature across all these industries.

For this reason, the study presented here follows a cross-industry approach by looking at the regulatory developments on autonomous systems in four different transport modes: air, rail, road and maritime transport. The underlying rationale is that, irrespective of the transport environment, autonomous operations create similar, if not identical, challenges that require the same, or very similar, approaches to regulation.

Therefore, based on a comparative research method, this study aims to find possible regulatory solutions for autonomous inland shipping technology by answering the following research questions (RQs):

RQ1: What regulatory solutions exist for air, rail, road and sea transport that address similar issues to those identified for autonomous inland shipping?
RQ2: Could these regulatory solutions be answers in the creation of a regulatory framework for autonomous inland ships?

The remainder of this paper is structured as follows. Section II describes the methodological approach, which is based on a comparative analysis of the current regulations related to autonomous air, rail, road and sea transport. The possible regulatory solutions retrieved from the comparative research to the emerging issues of autonomous inland ships are subsequently presented in Section III for different regulatory categories. Section IV discusses the results in the light of their relevance and feasibility for the regulation of autonomous inland shipping, describes the implications of this comparative study for future policymaking and research needs, and concludes with some key findings.

2 Methodological approach

To answer the first research question, the relevant regulations currently applicable in the different transport modes air, rail, road and sea first needed to be identified; regulations on inland waterway were not considered in this study. To do this, the first step was to investigate the state-of-the-art of the technology in air, rail, road and sea transport. Based on the highest level of automation, relevant regulatory instruments, including soft regulations, such as policy papers, guidelines, recommendations and best practices, as well as hard regulations, like national legislation and EU regulations, were collected. Regulations dealing with the public safety aspects of autonomous operations at the regional, national and international levels were found to be relevant. Regulations in English, French and German were investigated. Regulations that solely addressed remotely controlled, or highly automated but still crewed/manned, operations were not considered in the analysis, nor were regulations focusing on private law aspects, such as liability issues. The regulations identified were subsequently analysed to discover the issues that require regulatory intervention, which were identified in previous studies on autonomous inland ships (Orzechowski 2024; Orzechowski et al. 2024).

The potential regulatory solutions applicable to each mode of transport were then organised in a table according to the issues identified for autonomous inland shipping (Supplementary file), and they were subsequently grouped into three sets of regulatory requirements: regulatory aspects that are relevant before any operation can be authorised (i.e. pre-operational regulatory requirements), regulatory issues that deal with the actual operation of the ship (i.e. operational requirements), and regulatory matters that are not directly related to the operation of the ship but still require regulatory consideration for safety purposes (i.e. other requirements), as shown in Table 1. This structure also allows to identify the relevant sub-section for a particular issue, if needed. The results of the analysis are presented below in Section III for each set of regulatory requirements.

With regard to the second research question, the different regulatory solutions are discussed, in Section IV, in terms of how likely they are to be applicable and relevant to autonomous inland shipping. The results of this discussion can constitute an important toolbox for public regulators and policymakers such as current working groups from the main inland waterway regulatory institutions UNECE, CESNI and the CCNR who are working on a regulatory framework for this novel technology.

Table 1 Sets of regulatory requirements

A. Pre-operational requirements
1. Ship design and manufacturing standards
2. Situational awareness and control
3. Safety management
4. Identification, authorisation and certification
B. Operational requirements
1. Communication systems
2. Remote control centre – roles and responsibilities
3. Operator standards of training, qualifications and competencies
4. Reporting of accidents and incidents
5. Security considerations
6. Prevention of pollution
7. Carriage and transfer of dangerous goods
8. Rendering of assistance to persons in distress, salvage and towage obligations
C. Other requirements
1. Maintenance and record-keeping
2. Inspection
3. Accident investigation
4. Reporting for innovation development purposes

3 Results: Learning from regulation in air, rail, road and sea transport

In the following section, regulatory solutions found in instruments applicable to autonomous operations in air, rail, road, and sea transport are presented and compared, in order to highlight their similarities and differences as regards the relevant issues for autonomous inland shipping.

3.1 Pre-operational requirements

Pre-operational requirements describe the requirements that need to be fulfilled before an autonomous transport mode is permitted to operate. By issuing these requirements, the regulator ensures that the technology in question is ready to operate in a specific way.

3.1.1 Ship design and manufacturing standards

First and foremost, regulations usually contain *definitions* on what is meant by the respective autonomous mode of transport (e.g. for road transport: StVG 2023, §1a(2); e.g. for air transport: EASA 2024, Art. 2(17); EU Reg. 2018/1139, Art. 3(3); EU Reg. 2019/945, Art. 3(1); EU Reg. 2019/947, Art. 2(17); e.g. for sea transport: Maritime UK 2023, Part 2, Sec. 3.1.1). In principle, these definitions reflect the necessary conditions for the autonomous system to perform specified tasks without human intervention in the same manner as conventional transport with (the possibility of) human intervention.

To ensure overall technological readiness, the regulators refer to the *concept of worthiness* (meaning roadworthiness, seaworthiness or airworthiness). This concept can be found in any transport sector. 'Worthiness' describes the property or ability of any kind of vehicle to be in the proper operating condition and to meet acceptable safety standards of manufacturing, maintenance and use for its intended purpose. It is equally applicable to autonomous transport modes. Without going into technical specificities, regulations, in general, require the autonomous system to be 'worthy' by stipulating certain objectives that need to be achieved for it to attain technological 'worthiness'.

In aviation, the operation of autonomous drones in EU airspace must be compliant with specified airworthiness criteria (EU Reg. 2019/947, Art. 10; EU Reg. 2018/1139, Annex IX, at 2.1). Accordingly, 'an unmanned aircraft must be designed and constructed so that it is fit for its intended function, and can be operated, adjusted and maintained without putting persons at risk' (EU Reg. 2018/1139, Annex IX, at 1.2). The regulator further requires that the overall *product integrity* must be proportionate to the risk during the specific operational mode (EU Reg. 2018/1139, Annex IX, at 2.1.2). This implies that risk reduction needs to be relative rather than absolute to the specific operation. Manufacturers of UAVs are obliged, when placing their product on the EU market, to ensure that it has been designed and manufactured in compliance with specified requirements; manufacturers are required to draw up technical documentation and carry out relevant conformity assessment procedures if this is not outsourced (EU Reg. 2019/945, Arts. 6.1, 6.2).

Similar roadworthiness requirements apply to road vehicles with ADS, for which certain *design principles* apply that require 'vehicle manufacturers to demonstrate a robust design and validation process based on a systems-engineering approach with the goal of designing ADS free of unreasonable safety risks and ensuring compliance with road traffic regulations' (UNECE 2019, at 4.9.f)). Furthermore, 'the design and validation methods should demonstrate the behavioural competencies an automated/autonomous vehicle would be expected to perform during a normal operation, the performance during crash avoidance situations and the performance of fallback strategies' (UNECE 2019, at 4.9.f)). In this regard, the German Road Traffic Act (StVG 2023) requires autonomous cars to be compliant with specified technical requirements before their operation is permitted (StVG 2023, §1e(1)). These requirements, in essence, address all the performance functionalities that are required in a conventional car with (the assistance of) a human driver: the system must be capable of performing the driving task autonomously, must independently comply with applicable traffic regulations and must be able to recognise any impairment of its functionality or system limits. In specified scenarios (the possible violation of a road traffic law, the endangering of a person, a system limit, a deactivation of the ADS on request, or an interruption or unauthorised access to the radio connection), the autonomous car must be capable of independently putting itself into a risk-minimised state (StVG 2023, §1e(2)).

Similar design principles are applicable to MASS. To be seaworthy, the vessel must be constructed in such a way (i.e. it must be sufficiently fitted with sensors, systems and equipment) to provide feedback on its operating state, ensure compliance with traffic rules (i.e. collision-avoidance regulations (COLREGS)), determine the vessel's position, provide the control system with information on the effects of deadweight, draught, trim, speed and under-keel clearance on turning circles and stopping distances, rudder angle, propeller revolutions, propeller pitch and thrusters, monitor the vessel's mooring and docking operations, and provide substitutes for the human senses of the crew on board a vessel, such as sight (i.e. visual stimuli), hearing (i.e. hazards that may be detected by sound information) and other senses (e.g. vessel movement, visibility, ambient conditions such as strong wind, fire, temperature, vibrations) (TAS 2022, at 5.4(2)). If it is not possible for the ship to maintain normal operation, it must be able to independently enter and maintain a minimum risk condition (DNV GL 2018a, Sec. 3.1.2, at 9). The ability to detect abnormalities within the system presupposes that it has self-diagnostic and supervision competencies (DNV GL 2018a, Sec. 3.1.2, at 9). The applicable underlying design philosophy must further describe redundancy and fault tolerance for the autonomous system (DNV GL 2018a, Sec. 3.1.3, at 2.4.2). Redundancy principles are of paramount importance in any proper risk and safety management system and must, therefore, be implemented even in the manufacturing stage. They will be described in more detail below.

In order to comply with all these principles, the system that oversees all these performance requirements must be safe, secure and reliable. In other words, *software* *integrity* of the system is required. To ensure software integrity, the software used on, for example, a MASS must be developed according to appropriate standards. This includes quality assurance processes, testing, configuration control, protection against viruses, safeguarding against unauthorised actions, and analysis of software failure and degradation (TAS 2022, at 12.4).

Regulators for MASS note that, when it comes to situations outside the pre-programmed algorithm based on existing anti-collision regulations, the algorithm should be trained through the process of machine learning by conforming to the existing rules (DNV GL 2018b, at 3.1.3.1).

3.1.2 Situational awareness and control

The most critical part of the development of any autonomous system is its capability to 'know what is going on', commonly referred to as 'situational' or 'situation awareness', which has been defined as 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future' (Endsley 1995, at p. 36). Regulations on autonomous processes commonly address situational awareness.

For MASS, for instance, the system design must be able 'to sense and avoid obstacles' (Maritime UK 2023, Part 2, at 10.15.2), be they 'fixed' or 'moving'. In the same way, autonomous train systems 'should be able to detect approaching trains, including identifying locomotive headlights, horns, or bells and account for any variables that might obstruct their view' (AAR 2023).

Situation awareness requirements may also extend to the ability of the system to sense its own position. In the case of autonomous trams/streetcars, for example, the vehicle must be able to detect its own derailment and act independently (BOSTRab 2019, §36(11)). In road transport, the autonomous car 'shall be able to detect and respond to object/events that may be reasonably expected' (UNECE 2019, at 4.9.d)); in the case of a critical situation, such as the risk of collision, risk-minimising behaviour by the autonomous car must be activated (EU Reg. 2022/1426, Annex II, at 1.1.3, 2.1.1, 2.1.5).

Moreover, regulation addresses the *interconnectivity and interaction between the different stages of situational awareness*, ranging from perceiving to comprehending and ultimately acting accordingly. In road transport, for example, cars with ADS must comply with applicable traffic regulations (StVG 2023, §1e; EU Reg. 2022/1426, Annex II, at 1.3) and always maintain an appropriate safety distance (i.e. perceiving) (AFGBV 2022, Annex I, Part 1, at 1.2.a). However, if a preceding or following vehicle changes lane, the ADS must notice this (i.e. comprehending) and take appropriate action (i.e. acting accordingly) by, for example, slowing down or changing lanes without putting other road traffic participants at risk (AAR 2023, Annex I, Part 1, 1.2; EU Reg. 2022/1426, Annex II, at 1.3, 2.1.3).

Even in the case of autonomous systems, situational awareness requirements may be extended to the awareness of the human operator: for instance, in situations where the control of a MASS is given back to the human operator, they must be given sufficient time to be able to establish sufficient situation awareness themselves to account for command latency or reaction/response time (DNV GL 2018a, Sec.

3.1.3, at 2.3.1). This means that the system must be able to project the perceived environment continuously and in such a way as to deliver sufficient information for humans to make decisions based on the information received. When situation awareness is partially or totally lost for a MASS, for instance, an emergency stop must be immediately initiated, accompanied by appropriate sound and visual signals when appropriate (Maritime UK 2023, Part 2, at 10.12.5).

3.1.3 Safety management

Safety aspects play an essential, and perhaps the most important, part with regard to pre-operational regulatory requirements. Aspects relating to safety include system safety as well as safety achieved through backup systems.

System safety acknowledges that the system, as such, should be free of unreasonable safety risks (UNECE 2019, at 4.9.a); EU Reg. 2022/1426, Annex II, at 7.1). The safe system approach does not mean that the autonomous system will be free of intrinsic risks and uncertainties, as it may not be possible to eliminate these even if the verification and validation processes are fully established (OECD/ITF 2023). In the case of cars with ADS, for example, the safe system approach means that the system handles driving tasks with skills equivalent to those of a competent and careful driver. It is, therefore, not possible to eliminate the possibility of unpredictable behaviour in rare situations. Hence, the approach for autonomous cars should be to focus on preventing death and serious injuries from crashes, even in edge and corner cases (i.e. cases outside the bounds of those normal operating cases), rather than preventing any crashes, which, due to the system's imperfections, would not be feasible (OECD/ITF 2023).

In fast-changing environments in particular, such as the road environment, the autonomous system must deal with various *operational requirements* in order for it to be considered safe. To ensure system safety, for instance, the ADS of road vehicles must be able to operate at safe speeds and respect speed limitations applicable to the vehicle; maintain appropriate distances from other road users by controlling the longitudinal and lateral motion of the vehicle; adapt its behaviour to the surrounding traffic conditions (e.g. by avoiding disruption to the flow of traffic) in an appropriate and safe way; and adapt its behaviour in line with safety risks, giving the highest priority to the protection of human life EU Reg. 2022/1426, Annex II, at 1.1.2; AFGBV 2022, Annex I, Part 1, at 1.3). To assess vehicle safety, vehicle manufacturers must document the operational design domain for their vehicles, detailing the specific conditions in which the automated vehicle is intended to operate. This should include information on road types, geographical areas, speed ranges, environmental conditions, and other constraints (UNECE 2019, at 4.9.e)).

In general, collisions with other road users and uninvolved third parties must be avoided (AFGBV 2022, Annex I, Part 1, at 1.1). Furthermore, given that a mix of highly automated, autonomous and conventional vehicles will be operating on public highways, autonomous vehicle occupants should also be protected against crashes with other vehicles (UNECE 2019, at 4.9.l)). Notably, the vulnerability of the road users involved should be taken into account by the avoidance/mitigation strategy (EU Reg. 2022/1426, Annex II, at 2.1.2). This also triggers the *ethical dilemma* regarding the question of how, or whether, the autonomous system should make decisions in the scenario of an inevitable crash. In principle, it is currently expected that, given the current technological state of the art, an ADS will have to comply with the same rules as a conventional vehicle driven by a driver (UNECE 2021a, at 4). From the safety point of view, it is at least questionable whether the rules should be any less strict for autonomous systems (UNECE 2021a, at 4). The German Road Traffic Act is clear in this regard: if a collision that would put at risk the lives of the occupants of the motor vehicle with ADS could only be avoided by endangering the lives of other participants in the surrounding traffic or uninvolved third parties (an unavoidable alternative risk to human life), the protection of the latter must not take second place to the protection of the first (AFGBV 2022, Annex I, Part 1, at 1.1). Moreover, in the event of an unavoidable alternative risk to human life, the ADS shall not provide for any weighting on the basis of the personal characteristics of the humans (EU Reg. 2022/1426, Annex II, at 2.1.1.1).

As for the *standard of safety*, regulations, in general, require a standard that is equivalent to that of conventional transport modes. For instance, the safety level for road vehicles with ADS has been defined as a level that does not cause 'any traffic accidents resulting in injury or death that are reasonably foreseeable and preventable' (UNECE 2019, at 3.7). Correspondingly, regulations on MASS require that the autonomous system must ensure 'at least the same degree of safety, security, and protection of the environment as provided by the relevant IMO instruments' (EU VTMIS 2020, at 2) or 'a level of safety equivalent or better compared to conventional ships' (DNV GL 2018a, e.g., Sec. 3.1.1, at 2). Interestingly, for automated railway transport it has been proposed that 'to the greatest extent possible carriers and equipment manufacturers should be permitted to continue to create voluntary standards for safety technology' (AAR 2023). In the case of autonomous cars, the manufacturer is required to draw up a *safety concept* for functional safety which includes carrying out a hazard analysis on the basis of this safety concept, documenting the safety concept, checking the safety of the autonomous driving function in accordance with this safety concept, and demonstrating safety to the competent authority (AFGBV 2022, §12(1)2). They must further draw up a safety concept in the area of information technology, and document this to demonstrate the feasibility of recurrent technical vehicle monitoring (AFGBV 2022, §12(1)3).

As to the other aspect of safety, the idea of a *backup system* without human intervention is pivotal for any autonomous system. When backup systems become paramount, *redundancy* plays an essential role by ensuring the reliability and resilience of the overall system. From the design philosophy perspective, redundancy can be considered as a safety net. One of the primary functions of redundancy is to enhance reliability, and to achieve better reliability manufacturers can build in safeguards against single points of failure. This ensures that even if a component malfunctions, there is a system backup ready to take over, minimising the risk of failures. Within the redundancy concept, redundancy affects hardware, software, information and time. The design philosophy of redundancy is especially deeply ingrained in aviation engineering, but in other transport industries regulators also request that manufacturers and operators establish procedures that prevent the risk of repeating errors on identical systems.

As for *redundancy of hardware and software* components, '[r]edundancy can be achieved for instance by installation of mutually independent components or by mutually independent systems capable of performing the same function. (…) Mutual independence means that the function of the redundant components or systems, their power supply and other auxiliaries should not depend on any common component or system' (DNV GL 2018a, Sec. 3.2.5, at 3.1.4).

In the case of MASS, the regulations advocate that '[n]etworks should in general be arranged with redundancy and separation' (DNV GL 2018a, Sec. 3.2.5, at 6.5.2). More specifically, control system components related to bridge/navigation systems, communication, machinery control and monitoring systems, safety systems and other systems that need to revert to a safe state in case of any failure, control systems serving redundant vessel services, cargo systems, administrative and other systems not related to key vessel functions, and systems from different system suppliers, should not be connected to the same network segments (DNV GL 2018a, Sec. 3.2.5, at 6.5.2).

Whereas *time redundancy* can be achieved through performing the same operation multiple times (e.g. through multiple executions of a programme or multiple transmissions of copies of data), *information redundancy* entails autonomous systems being designed so that the extent and need for alarm and monitoring functions correspond to the actual (limited or even non-existent) possibilities for human intervention (DNV GL 2018a, Sec. 3.1.2, at 4). The monitoring of the operating and health status of the equipment, including self-diagnosis of faults and failures, must be performed by the system itself (for autonomous cars: AFGBV 2022, Annex I, Part 1, at 5; EU Reg. 2022/1426, Annex II, at 4.1; for MASS: DNV GL 2018a, Sec. 3.2.5, at 3.1). If system failures or abnormalities are detected, redundancy (i.e. a fail-safe response) includes the capability of maintaining normal operation or, if this is no longer possible, of handling emergency conditions (DNV GL 2018a, Sec. 3.2.5, at 5.2). The control system of a MASS, for example, should be capable of monitoring compliance with traffic regulations (COLREGs) (Maritime UK 2023, Part 2, at 10.15.1), and propulsion control should ensure that safe operating speeds are not exceeded (Maritime UK 2023, Part 2, at 10.13.1). For autonomous streetcars, the control of drives and brakes must be designed so that braking commands are given priority over drive commands, and the execution of braking commands is monitored during operation without a driver (BOSTRab 2019, §38(1)). If system failures or abnormalities are detected, the autonomous system should be able to return immediately to a safe state by engaging in a risk-minimising manoeuvre to ultimately reach a minimum risk condition (for autonomous cars: UNECE 2019, at 4.9.b); StVG 2023, §1 d(4); AFGBV 2022, Annex I, Part 1, at 3; for MASS: DNV GL 2018a, Sec. 3.1.2, at 5; Maritime UK 2023, Part 2, at 10.12.4).

Whether and how redundancy is achieved through specific requirements ultimately depends on the outcome of the risk-based analysis for the particular vehicle (TAS 2022, at 5.3(1)). Test procedures for redundancy include functional testing (i.e. testing to ensure that systems are working as intended and according to their technical and operational descriptions), performance testing (i.e. testing of a system's ability to perform its intended functionality, including responsiveness, stability and reliability aspects), and failure response testing (i.e. testing of failure modes to ensure that the system handles failures safely and according to rules and given standards, and that redundancy principles are maintained after failures) (DNV GL 2018a, Sec. 3.1.3, at 2.7.2). Effective emergency plans must be provided that describe the measures put in place to ensure redundancy and/or in mitigating measures (EU VTMIS 2020, at 6).

Furthermore, to provide a structured management approach to control safety risks in operations, a dedicated safety management system is necessary. The regulations on MASS, for instance, require every operator to develop, implement and maintain a *safety management system*, including a safety and environmental protection policy, instructions and procedures to ensure the safe operation of the MASS and protection of the environment in compliance with relevant legislation, defined levels of authority and lines of communication between, and amongst, shore and the MASS, as well as procedures for reporting accidents and non-conformities, to prepare for and respond to emergency situations and for internal audits and management reviews (Maritime UK 2023, Part 2, at 6.3.3). A voyage data recorder may further be required to record mission data for subsequent analysis, and a proactive safety management system incorporating vessel data analysis for safety and compliance purposes is suggested (Maritime UK 2023, Part 2, at 6.3.3).

As part of the safety performance of the backup system, any autonomous system is required to be able to be entered into, or independently to enter into, a state that poses the least risk to the persons involved or the immediate environment, commonly referred to as a *safe state*, *risk-minimising condition* or *minimum risk condition* (MRC).

For a MASS, '[a] contingency plan must be defined for the whole voyage and all situations that may occur, including any deviation from normal operation' (TAS 2022, at 2.3(14), 11.2(2); similarly, Maritime UK 2023, Part 2, at 6.14.2). 'Each contingency plan involves placing the vessel into a state in which it poses the least risk to life, the environment and property' and 'may involve entering the vessel, or its systems, into a safe state' (TAS 2022, at 2.3(14), 11.2(2)). Another regulation prescribes an emergency stop mechanism, which must be failsafe under conditions in which normal control of the MASS is lost (Maritime UK 2023, Part 2, at 10.12.1). Under the emergency stop mechanism, propulsion must be reduced to 'a safe level in a timely manner' (Maritime UK 2023, Part 2, at 10.12.1). In this context, 'a safe level' means a level at which the vessel is not likely to cause damage either directly or indirectly; and 'in a timely manner' means within a time that is short enough to ensure that the risk from uncontrolled propulsive power can be contained before it is likely to cause damage (Maritime UK 2023, Part 2, at 10.12.1).

Emergency situations include, but are not limited to, loss of control of the MASS for a critical period of time; fire; collision; grounding; flood; violent act; main propulsion or steering failure; man overboard (if vessel manned); and an 'abandon MASS' procedure (if vessel manned) (Maritime UK 2023, Part 2, at 6.14.2). Other regulations specify events such as a loss of communication between the control station and the vessel, including the loss of passive supervision by the control station, any serious malfunctions of the navigation, situational awareness or control systems on the vessel, and the vessel exceeding the operating range limit for the autonomous activation of the appropriate contingency plan

(TAS 2022, at 11.2(6)). In such situations, the regulations recommend checklists/aide memoires onboard the MASS and at the remote control centre (RCC) (Maritime UK 2023, Part 2, at 6.14.3). In any case, it is suggested that '[t]he roles and responsibilities of all personnel in an emergency situation should be defined and recorded' (Maritime UK 2023, Part 2, at 6.14.4).

It must be possible for the appropriate contingency/emergency plan *to be initiated autonomously by the vessel* in response to specified conditions and *by the operator* at any time from the control station (TAS 2022, at 2.3(16); DNV GL 2018a, Sec. 3.1.4, at 6.2). In either case, sufficient situational awareness data is required for the task of bringing the vessel to an MRC (Maritime UK 2023, Part 2, at 10.12.2; DNV GL 2018a, Sec. 3.1.4, at 6.2). Moreover, '[t]he design of that controller or supervisor shall be fail safe, in that it shall recognise all known unsafe operating conditions with no false negatives and shall react to unknown or indeterminate safety conditions by invoking emergency stop in a timely manner' (Maritime UK 2023, Part 2, at 10.12.3). In other words, it must be possible to activate the MRC at all times.

Notably, '[w]here a contingency plan is executed, it should be accompanied by the appropriate sound and visual signals from the vessel' (TAS 2022, at 11.2(3)). MASS regulations further describe possible options for the vessel when an emergency stop is initiated: the vessel may move to a quieter or calmer area or to deeper water, the vessel may maintain its position ('safe position hold'), the vessel's engines may be disabled (stopping vessel propulsion), or there may be a full shutdown of all systems on the vessel, for example in the case of a fire (TAS 2022, at 11.3(2)). In the event that the vessel stops operating, the vessel must be retrieved as soon as practicable, taking into account its location, the risks it poses to other waterway users and its potential impact on the environment (TAS 2022, at 11.2(7)).

Similar provisions can be found in autonomous car regulations. Here, the MRC of a road vehicle with ADS will be triggered if the radio connection is interrupted or unauthorised access is gained to it (StVG 2023, §1e), or if the driving manoeuvre specified by the technical supervisor poses a hazard to other road users (AFGBV 2022, Annex I, Part 4). In either case, the system must put itself into a state that minimises the risk (StVG 2023, §1e; AFGBV 2022, Annex I, Part 4). If a defect in the vehicle triggers the MRC, the driving task must be taken over manually by the natural person appointed as the technical supervisor in compliance with the requirements until the triggering defect has been permanently eliminated (AFGBV 2022, §14(3)). In any case, if the motor vehicle is in a state that minimises risk, the natural person appointed as the technical supervisor must carry out an investigation into the triggering and the need for the minimum risk state before being authorised to initiate its termination (AFGBV 2022, §14(3)). The result of the investigation must be documented (AFGBV 2022, §14(3)).

Like the procedures for a MASS, if the risk-minimising condition becomes a hazard to the safety and ease of traffic, notwithstanding the given traffic situation, the motor vehicle with ADS must be removed from the road immediately (AFGBV 2022, §14(3)). Here as well, the motor vehicle can only leave the minimum risk state at the instigation of the technical supervisor (AFGBV 2022, Annex I, Part 1, at 2).

3.1.4 Identification, authorisation and certification

When human operators are replaced, autonomous transport vehicles still need to be easily identifiable, physically and digitally, by those immediately surrounding them and by traffic management and enforcement authorities. Regulations on MASS, for example, explicitly state that the vessel ‘must be physically identified, so that persons nearby the vessel can contact the owner if necessary’, and that the following information must be provided: ‘a unique vessel identifier; the name of the owner displayed on the outside of the vessel; and a relevant contact phone number on the outside of the vessel’ (TAS 2022, at 2.2(10), 7(4)). An identification number makes the vessel uniquely identifiable and provides a direct link to certification and documentation matters, such as registration and legal documentation. It further enables the identification of the vessel by third parties in a digital and physical manner (Maritime UK 2023, Part 2, at 15.2.2). Additionally, regulations also stipulate that the hull must indicate how the MASS’s RCC may be contacted, along with any other pertinent security-related information, which is particularly relevant in the case of collisions or other incidents (Maritime UK 2023, Part 2, at 17.3.8).

In the same way as for conventional aircraft, drones are required to have a unique identifier. Remote identification is to be achieved through ‘a system that ensures the local broadcast of information about an unmanned aircraft in operation, including the marking of the unmanned aircraft, so that this information can be obtained without physical access to the unmanned aircraft’ (EU Reg. 2019/947, Art. 2). In this regard, the network identification service allows the continuous processing of remote identification from the UAS throughout the duration of the flight and provides remote identification of the UAS to authorised users (EU Reg. 2021/664, Art. 8).

Authorisation is granted only when the entity seeking authorisation meets the necessary regulatory requirements. In this way, regulators ensure that only authorised vehicles that meet regulatory requirements are in operation. Prior to their operation, any autonomous vehicle must seek authorisation; regulations on autonomous vehicles contain detailed authorisation procedures and requirements for operators and manufacturers.

For example, the EU regulator stipulates stringent requirements for the *certification of a UAS* to be operated in EU airspace. Accordingly, ‘the conditions, rules and procedures for situations in which the design, production, maintenance and operation of [UAS], as well as the personnel and organisations involved in those activities, should be subject to certification, should take into account the nature and risk of the type of operation concerned’ (EU Reg. 2018/1139, Recital 32). Certification may therefore be required for ‘the design, production, maintenance and operation of unmanned aircraft and their engines, propellers, parts, non-installed equipment and equipment to control them remotely, as well as for the personnel, including remote pilots, and organisations involved in those activities’ (EU Reg. 2018/1139, Arts. 56, 77).

National civil aviation authorities are in this way responsible for the following: issuing, amending, suspending, limiting or revoking, as the case may be, certificates of competency and licences of operators and remote pilots as well as operational authorisations; verifying the completeness of declarations; keeping documents, records and reports; and making available, in a common unique digital format, information on UAS geographical zones (EU Reg. 2019/947, Art. 18).

Before obtaining authorisation to operate an autonomous vehicle, specified operational risk assessments must be carried out. For example, operators of UAS are required to perform specific *operational and risk assessments* and to provide supporting material for their evaluation; this material may also be provided by third parties, such as the manufacturer of the aircraft or components holding unique design evidence (e.g. for the system performance or architecture, software/hardware development documentation, and test/analysis documentation) (EASA 2024, AMC1 Arts. 11.1.5(b), (d)-(e)). Depending on the outcome of the evaluation by the competent authority, the operator of a UAS may then obtain operational authorisation (EASA 2024, AMC1, Art. 11.1.5(f)). In addition, the designated air traffic service provider of the specific airspace must authorise the proposed flight in the particular airspace (EASA 2024, AMC1, Art. 11.1.5(g)). In the case of cross-border operations, the operator is also required to obtain authorisation from the competent authority of the other state (EU Reg. 2019/947, Art. 13).

As regards the authorisation of road vehicles with ADS, their operation under German law in a defined operating area requires an *operating licence* from the German Federal Motor Transport Authority (AFGBV 2022, §2(1); StVG 2023 §1e(1)). The defined operating area refers to the locally and spatially defined public highway (StVG 2023, §1d(2); AFGBV 2022, §7). The authority can appoint a recognised motor vehicle expert or technical service to assess the suitability of an operational area, including the road infrastructure, based on the vehicle's autonomous driving permit (AFGBV 2022, §9(3)). As with the authorisation procedure for drones, ancillary provisions may be attached to or combined with the licence at any time, to ensure the safe operation of the vehicle and its compliance with the statutory provisions (AFGBV 2022, §4(2)). The authority is further entitled to revoke or suspend any prior authorisation immediately (AFGBV 2022, §§5, §6(5); UNECE 2021b, at 10.1), and to restrict the initial operation by excluding the carriage of persons or cargo for a limited time (AFGBV 2022, §9(5)). The manufacturer of a motor vehicle with ADS must carry out a risk assessment for the motor vehicle; evidence of how the risk assessment was carried out must be provided to the competent authorities (StVG 2023, §1f(3)2–5). Notably, the manufacturer is not allowed to sell a motor vehicle with ADS without a valid operating licence (AFGBV 2022, §12(3)).

Similarly, under EU regulations, a MASS is required to be *certified* to prove that it complies with the security requirements of the issuing authority (Maritime UK 2023, Part 2, at 17.3.8). Prior to granting this certification, the administration verifies that all the necessary information, including the risk assessment, has been provided, evaluates the risk assessment presented by the applicant, and, if necessary, performs a physical inspection of the MASS (EU VTMIS 2020, at 5.4). On that basis, the authority may grant authorisation for trials in a designated sea area, with any limitations being clearly specified in that authorisation (EU VTMIS 2020, at 5.4). For a MASS, an *operating certificate* is generally limited in time; for example, the term of a certificate for operating a MASS in the UK may not exceed five years (Maritime UK 2023, Part 2, at 2.3.2). Likewise, software needs to be verified and validated. For instance, regulation on MASS require that software is developed and configured according to established processes and that a verification and validation strategy, which puts emphasis on elaborated, multi-faceted testing of the software, is established (DNV GL 2018a, Sec. 3.1.2, at 10).

To verify whether manufacturers and operators are adhering to the regulatory requirements, specialised personnel are necessary. Under EU drone regulations, competent notified entities must carry out *conformity assessments* of UAVs (EU Reg. 2019/945, Art. 30). The personnel responsible for these assessments must have 'sound technical and vocational training (…); satisfactory knowledge of the requirements of the assessments they carry out and adequate authority to carry out those assessments; appropriate knowledge and understanding of the requirements, of the applicable harmonised standards and of the relevant provisions of Union harmonisation legislation; the ability to draw up EU-type examination certificates or quality system approvals, records and reports demonstrating that assessments have been carried out' (EU Reg. 2019/945, Art. 22.7). To demonstrate compliance with the regulatory requirements, UAS operators are required to 'grant to any person, that is duly authorised by the competent authority, access to any facility, UAS, document, records, data, procedures or to any other material relevant to its activity, which is subject to operational authorisation or operational declaration' (EU Reg. 2019/947, Annex, Part B).

Similar provisions apply to road vehicles with ADS. The competent authorities may at any time check with the vehicle manufacturer, or arrange for a specified body to check, whether the requirements of the type approval have been met and the obligations associated with the approval have been fulfilled (AFGBV 2022, §4(4)). The same requirements are imposed upon the vehicle's registered keeper (AFGBV 2022, §9). Furthermore, the authority is entitled to carry out regular checks to verify whether the vehicle complies with regulatory requirements and whether the vehicle poses a risk to health, safety, the environment or other legal interests worthy of protection (AFGBV 2022, §5(2)).

The mutual recognition of authorisations across EU Member States is crucial. It is obviously particularly relevant in aviation, but is also relevant in other transport sectors because of cross-border transport within the EU's internal market. For example, for road vehicles with ADS, any operating licence granted will be equivalent to an authorisation granted by a competent authority of another Member State (AFGBV 2022, §4(3)). Similarly, in aviation, a harmonised regime of UAS licences is being sought; the EU, through its regulatory power, has established and maintains a high uniform level of civil aviation safety within the Union (EU Reg. 2018/1139, Art. 1.1). To further foster the *harmonisation* of national compliance regimes across the EU, the European regulator has proposed 'a pool of European aviation inspectors' (EU Reg. 2018/1139, Art. 63).

Ensuring effective compliance with regulations is an important factor in creating a well-functioning regulatory framework. If not properly enforced, regulations cannot effectively achieve the goals intended by the regulators. If there is non-compliance with a regulatory requirement, the competent authorities for the authorisation of UAS operations are, for instance, called on 'to take any appropriate enforcement measures necessary to ensure the u-space [i.e. the European system that is being developed to manage UAS] service providers and single common information service providers comply with requirements' (EU Reg. 2021/664, Art. 17). Member States nominate competent authorities for UAS operations and employ personnel who are able to verify that UAS operations, especially when conducted in areas far away from aerodromes, are safe, by considering common issues such as noise, privacy and security (EASA 2024, GM1 Art. 18(a)). Enforcement should be carried out by the respective law enforcement authorities, depending on the Member State's national legal framework (EASA 2024, GM1 Art. 18(a)).

3.2 Operational requirements

The following sub-section describes the requirements that are directly relevant to the safe operation of autonomous vehicles while in motion.

3.2.1 Communication systems

Conventional, highly automated and fully autonomous vehicles will share airspace, railway lines, and roads for the foreseeable future. Communication with direct and indirect stakeholders is therefore vital for risk reduction.

In certain situations, regulations explicitly require operators of autonomous vehicles to *inform* the relevant authorities of their intention to operate within these specific environments. For example, in the case of a MASS, one critical aspect of the safety management system is to ensure that the vessel does not pose a danger to other waterway users; to manage this risk, regulations stipulate the necessity of informing the waterway manager, obtaining required permissions, and informing other waterway users about the presence of the vessel (TAS 2022, at 2.3(4), 14.3(2)).

Furthermore, *permission* may be required to operate a MASS autonomously to and from its berth in specific high-risk zones, such as ports. This permission needs to be granted by the port operator and the navigational authority. If permission has not been given, a towing service will need to be arranged from the point where autonomous operation ceases (Maritime UK 2023, Part 2, at 4.4.1). It has been suggested that some MASS should permanently display information for pilots and port authorities in the event, for example, of platform manning or taking local control (Maritime UK 2023, Part 2, at 6.11.1).

In the context of drones, the EU has adopted requirements for *exchanging relevant operational data* and information between u-space service providers and air traffic service providers (EU Reg. 2021/664, Annex V). A u-space service provider is required, among other things, to provide a network identification service, a geo-awareness service, a UAS flight authorisation service, a traffic information service, and a conformance monitoring service (EU Reg. 2021/664). Specifically, u-space service providers must share relevant information, use a standard secure communication protocol, and ensure data quality and protection (EU Reg. 2021/664, Art. 7.5).

For smooth data exchange, the compatibility of systems is of paramount importance. For this, policymakers in the field of rail transport suggest that cooperation between railway undertakings and infrastructure undertakings should be made compulsory to ensure adequate safety and security (BMDV 2018). Similarly, regulators mandate a cooperative intelligent transport system (C-ITS) for autonomous road vehicles to improve safety through direct vehicle-to-vehicle and vehicle-to-infrastructure communication. Ensuring interoperability and backward compatibility are pivotal principles for the C-ITS infrastructure (OECD/ITF 2023).

To ensure the reliable transfer of data between a MASS and the control station, the regulations require the operator to have sufficient data to monitor the vessel and to be able to perform necessary functions (TAS 2022, at 6.3(8)). Data must be determined based on risk analysis, including vessel health status, navigational data, and any additional needs (TAS 2022, at 6.3(9)). Specific data, including sensor outputs and propulsion activities, must be recorded at intervals, time-stamped and protected from loss (TAS 2022, at 6.3(10)).

With regard to autonomous cars, three types of data ensure their smooth and safe operation within the digital map: *where data* for location, *what is permissible* data for rights and obligations, and *ancillary data* for local services (OECD/ITF 2023). The OECD therefore suggests that governments (regulatory authorities) provide rules for accurate and timely updates of this map data. Autonomous cars combine map data with sensor data to create a local dynamic map for driving tasks (OECD/ITF 2023). Furthermore, the data and information required for the autonomous management of the driving task in autonomous operation and the information from external (technical) units must be safely received to be used by the vehicle (AFGBV 2022, Annex I, Part 1, at 6). The transmission of such data must, in particular, comply with applicable General Data Protection Regulation (GDPR) (EU Reg. 2016/679) requirements and be secured according to the current state of the art (AFGBV 2022, Annex I, Part 1, at 6). Notably, reference in the context of data protection rules is here explicitly made to EU requirements that only apply in the EU. Obviously, analogous requirements apply outside the EU in other jurisdictions. Regulations further require that the security system addresses the risks identified in a threat analysis with effective measures, and that a data protection impact assessment is carried out (AFGBV 2022, Annex I, Part 1, at 6). Ultimately, the integrity, authenticity and availability of the data transmission must be secured (AFGBV 2022, Annex I, Part 1, at 6).

Besides, regulations on MASS note that communication with stakeholders near the vessel must be secured to achieve the performance requirements. This includes, first and foremost, effective communication with the control station, for which 'maximum bandwidth, latency requirements, cyber security, interfaces, and prioritisation of data in case of insufficient bandwidth' must be considered (TAS 2022, at 7.4(5)). Furthermore, '[t]he safety management system must consider appropriate system redundancy and diversity for communications between the control station and the vessel and for maintaining the ability to control the vessel from the control station' (TAS 2022, at 2.3(11)).

In the case of passenger transport, regulations on autonomous streetcars require that communication equipment be available to enable *priority voice communication between passengers and the operating centre* (BOSTRab 2019, §§23(3), 46(6)).

3.2.2 Remote control centre – roles and responsibilities

Although remote control is not necessary for autonomous systems, regulators require constant (human) supervision and monitoring by the system of itself. In the case of a MASS, the supervision is carried out by the human operator located in the RCC; for a UAS, the remote pilot assumes the monitoring tasks; and for autonomous cars and trains, there will be technical supervisors.

The concept of situational awareness encompasses that of remote monitoring personnel, which is referred to as *remote situational awareness*. The regulation on MASS, for example, stipulates that '[l]imitations on the ability for data to be transferred from the vessel to the control station must be considered when designing the navigation and situational awareness systems' (TAS 2022, at 5.4(5)).

It should be possible to observe the real-time operational status, readiness and capacity of the vessel function or system from the RCC (DNV GL 2018a, Sec. 3.2.6, at 4.2; Maritime UK, at 12.10.1). The remote operator in the RCC should achieve situational awareness sufficient to ensure that the remote operation is performed safely, equivalent to when a crew is performing the function on board (DNV GL 2018a, Sec. 3.2.6, at 4.3; Maritime UK, at 12.10.1). Furthermore, '[t]he required level of situational awareness for a remote operator of the engineering functions should be considered in view of automatic support and automatic control functions implemented to handle standard and abnormal conditions' (DNV GL 2018a, Sec. 3.2.5, at 6.4.1).

The regulations also stipulate that: 'When personnel in a remote location are responsible for operating a function on board a vessel, the remote personnel will need sufficient situational awareness to provide a firm basis for analysing the situation, planning actions and executing remote control of the function. The situation awareness necessary for the remote operator will depend on the level of automation and decision-support functionalities supporting the control of the function. The nature and criticality of the function under control will also influence the required situational awareness' (DNV GL 2018a, Sec. 3.2.6, at 4.1).

The remote operation of a function should consider, as part of the risk analysis, how the different human senses, including sight, hearing and other senses, contribute to the situational awareness of the conventional local operation of the specific function (DNV GL 2018a, Sec. 3.2.6, at 4.3). 'Substitutes for these contributing human senses should be provided by sensor technology', and the information should be logically presented to the remote operator, ensuring that the total situational awareness for the remote operator is equivalent to, or better than, conventional local situational awareness (DNV GL 2018a, Sec. 3.2.6, at 4.3).

The regulation further stipulates *design requirements* for the control station. For a MASS, the control station is the set of equipment where the control and monitoring of the vessel is conducted; it may be on the vessel, on another vessel or onshore (TAS 2022, at 6.2(2), 6.3(1); Maritime UK 2023, Part 2, at 12.2.2). In this regard, '[t]he arrangements for the control station must be developed through risk-based analysis (…) and must have appropriate system redundancy and diversity' (TAS 2022, at 6.3(2)). The risk-based analysis of navigation and situation awareness information must be based on near real-time information (TAS 2022, at 6.2(3)). Obviously, '[t] here must be a dedicated physical area for the control station' (TAS 2022, at 6.3(3)). However, the control station must not be fixed (i.e. it could be on board another vessel) (TAS 2022, at 6.3(3); Maritime UK 2023, Part 2, at 12.2.3).

The operator or control system must be capable of determining safe operating limits, speeds, permitted geographic areas, expected water depth, and current speed and direction (TAS 2022, at 6.2(4)(a)). Furthermore, the operator or control system must be capable of measuring hazards in the physical environment and determining the risk of collision, grounding and other dangers to navigation (TAS 2022, at 6.2(4)(b)).

Notably, the RCC may also interface with other RCCs that are separately located (Maritime UK 2023, Part 2, at 12.2.2). The risk assessment will indicate which RCC is responsible for a MASS at any specific time (Maritime UK 2023, Part 2, at 12.2.2). However, it must only be possible to control the vessel from one control station at any point in time, a transfer of control between RCCs remains possible (TAS 2022, at 6.3(14); Maritime UK 2023, Part 2, at 12.10.1). The RCC should be arranged so that the transfer of control from one base station to another or from one MASS to another can be undertaken safely (Maritime UK 2023, Part 2, at 12.10.1). Two or more RCCs could be used to control one MASS from different locations (Maritime UK 2023, Part 2, at 12.10.1). Transferring control from one RCC to another should be done seamlessly (Maritime UK 2023, Part 2, at 12.10.1). In any case, '[t]here must be clear processes for transfers of control and communications between control stations and operators' (TAS 2022, at 6.3(15)) as well as 'clear processes and communications between the control station operator and other operators or members of the crew' (TAS 2022, at 6.3(16)). It is possible that certain MASS functions (e.g. payload and instruments and their data) are controlled from separate RCCs (Maritime UK 2023, Part 2, at 12.10.1). In any case, the RCC should clearly indicate the control status of the RCC and any other RCC that forms part of a networked control (Maritime UK 2023, Part 2, at 12.10.1).

All aspects of the control station and control system must be designed considering the *human-system interface* (TAS 2022, at 6.3(4)). In the case of a human operator, the arrangements of the control station must be designated to eliminate or reduce the risk of error and fatigue to acceptable levels (TAS 2022, at 6.3(5)).

The RCC should be compatible with the communications link, and must be capable of storing data, such as log data for fault diagnosis, scenario reconstruction (e.g., after a collision event) and last known coordinates following communications loss, and be sufficient to meet international and local regulations (Maritime UK 2023, Part 2, at 12.10.1).

From a physical perspective, the RCC should provide a sufficient level of security to prevent unauthorised access, which may include separate account access levels for operator, maintainer and supervisor purposes (Maritime UK 2023, Part 2, at 12.10.1).

In terms of handling, the regulations provide that the RCC should be easy to use, that the type of information displayed should be based on the priority of importance, that safety-related warnings, graphical or audible, should be displayed, that, for a MASS, the RCC should enable the operator to take direct control of the MASS at any time, and that in cases where the RCC cannot assert direct control of the MASS (e.g. when the MASS is operating in the highest level of automation, i.e. autonomously), there are special provisions and control measures to ensure safe operation (Maritime UK 2023, Part 2, at 12.10.1).

The RCC should alert the operator of any emergency warnings or a change in condition, such as a risk of collision, a fire on board the MASS, equipment or functional failure on the MASS or a defect, third-party attack or interference, and any changes to the planned mission, such as a change in speed, heading, or collision avoidance manoeuvres (Maritime UK 2023, Part 2, at 12.10.1). To avoid *lack of concentration*, the design of the RCC should further minimise distractions and should put barriers in place to ensure that operations in the RCC are not compromised by unnecessary distractions or interferences. Mitigation measures should be put in place to minimise the risk of fatigue (Maritime UK 2023, Part 2, at 12.12.3).

The *division of control and responsibility* between the control systems, the (human) operator and other personnel must be clearly defined. In the case of a MASS, these need to be defined for each stage in the voyage and each task involved in the vessel's operation (TAS 2022, at 14.5).

As for the planning of the navigation, the operation must be planned (TAS 2022, at 6.2(6); Maritime UK 2023, Part 2, at 12.10.1) on the basis of the avoidance of hazards (TAS 2022, at 6.2(7)), but the plan must allow the vessel to react to changes in its environment, such as other vessels and (other) moving objects (TAS 2022, at 6.2(8)). Furthermore, the RCC should allow the operator to re-programme the required activities and responses of the MASS in timescales appropriate to the configuration and location of the MASS and to shipping conditions (Maritime UK 2023, Part 2, at 12.10.1).

Whereas some regulations require that the operator must monitor the MASS at all times, others state that a remote operator is not expected to monitor all sensor information continuously (DNV GL 2018a, Sec. 3.2.5, at 4.3.4). In any case, the operator must be provided with sufficient information for independent analysis and supervision and must be able to override the autonomous control, initiate corrective action at any time and react to requests by the system (TAS 2022, at 6.2(15); Maritime UK 2023, Part 2, at 12.8.1). In this regard, suitable alerts should be arranged to notify the operator if distinctive sounds relevant to the operation are detected (DNV GL 2018a, Sec. 3.2.6, at 4.3.4). Similarly, the technical equipment for road vehicles with ADS must be capable of prompting the technical supervisor visually, acoustically or otherwise to specify a manoeuvre with sufficient time to spare (StVG 2023, §1e(3); AFGBV 2022, Annex I, Part 4, at 14.2).

If the operator in the RCC does not respond to an alert, the vessel should be able to reach or maintain a *safe state* and '[i]rrelevant alerts should be automatically suppressed or not implemented' (DNV GL 2018a, Sec. 3.2.5, at 6.4.2). Furthermore, '[a]n alert should include descriptive and unambiguous text and guide the operator about any actions to be taken. Self-evident actions such as standby start or reinstatement of the redundant system should be taken automatically. (…) For a function which is automatically operated, no human action should be needed to maintain the operation of the function or vessel's safe state. (…) Manual emergency operation from RCC should be possible but not necessary to enter and maintain a safe state. For this reason, relevant alarms or emergency alarms should also be given in RCC as a basis for activating such emergency controls' (DNV GL 2018a, Sec. 3.2.5, at 6.4.2).

However, to avoid a total shutdown of the system – especially in the case of a wrongly detected failure – it should be possible to respond to failures through *(overriding) manual actions* by the operator in the RCC (i.e. to reduce the consequences of a failure, the restarting of systems, a reset after failure, etc.) (DNV GL 2018a, Sec. 3.2.5, at 6.4.3). Notably, '[m]anual actions should not be needed to maintain or revert to a safe state' (DNV GL 2018a, Sec. 3.2.5, at 6.4.3).

In the case of autonomous cars, German law defines the technical supervisor as 'the natural person who can deactivate the motor vehicle during operation and release driving manoeuvres for the motor vehicle in accordance with the applicable laws' (StVG 2023, §1d(3)). The technical supervision is carried out from an external control centre that monitors the proper functioning of the autonomous vehicle and, if necessary, intervenes in its control (StVG 2023, §1e(2)5). The vehicle system must report any impairment of its functionality to the technical supervisor immediately (StVG 2023, §1e(2)6). It must always be possible for the technical supervisor or the vehicle occupants to deactivate the vehicle (StVG 2023, §1e(2)8). The technical supervisor must deactivate the autonomous driving function immediately if the vehicle system indicates this (StVG 2023, §1f(2)2), must evaluate signals from the technical equipment regarding its own functional status and, if necessary, must initiate necessary measures to ensure road safety (StVG 2023, §1f(2)3).

In the context of drones, the remote pilot must ensure that responsibilities and tasks are allocated adequately during all phases of the flight (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.050(1)(b)). Before starting a UAS operation, the remote pilot must obtain updated information relevant to the intended operation, and ensure that the operating environment is compatible with the authorised or declared limitations and conditions and that the UAS is in a safe condition to complete the intended flight safely. The remote pilot must check whether the direct remote identification is active and up-to-date, and whether information about the operation has been made available to the relevant air traffic service unit, other airspace users and relevant stakeholders (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.060(2)).

3.2.3 Operator standards of training, qualifications and competencies

With AI taking over human capabilities in autonomous transport, human interaction is limited to pre-operational planning and supervisory functions. Although the specific tasks of humans in the different industries vary, some similarities in the new roles, their training and their competencies are apparent. As for the new roles, in broad terms, as can be understood from regulations on UAVs, MASS as well as cars with ADS, one type of task relates to ensuring the overall safety of the operation, whereas another type of duty involves responsibility for ensuring that the operation is safe during its execution.

The objective of the first type of task is, first and foremost, *compliance* with established procedures and certificates. This ensures that the intended autonomous operation should be completed successfully and without any interference. The operator of the UAS, MASS, or road vehicle with ADS assumes this responsibility. More specifically, the UAS operator is responsible for establishing and ensuring compliance with the various procedures necessary for the safety of the operation (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.050(1)(a)). This includes ensuring that the remote pilot has the competency to perform their tasks in accordance with the applicable training and that the personnel other than the remote pilot comply with the on-the-job training (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.050(1)(d)-(e)). The UAS operator is also responsible for keeping records of all relevant qualifications and training completed (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.050(1)(g)).

This is different from the regulations on road vehicles with ADS, for which the manufacturer has the duty to 'develop, document and maintain employee, dealer, distributor, and consumer education and training programmes to address the anticipated differences in the use and operation of automated vehicles from those of conventional vehicles' (UNECE 2019, at 4.9.k)).

In terms of maintenance, the UAS operator is responsible for establishing maintenance instructions and employing adequately qualified maintenance staff, and for keeping up-to-date lists of the designated remote pilot for each flight and of the maintenance staff (EU Reg. 2019/947, Annex, Part B, UAS.SPEC.050(1)(i)-(k)). As regards emergency planning, the UAS operator is required, under EU Reg. 2019/947, Appendix 1, UAS.STS-01.030(1), (4) and (3), to develop an operational manual and an effective emergency response plan, and to ensure the adequacy of the contingency and emergency procedures through tests.

Similarly, the MASS operator is *responsible for the overall operation* of the MASS. Their duty is to develop the voyage plan and to carry out mission planning and execution and post-mission evaluation (Maritime UK 2023, Part 2, at 12.5.2).

As for the second role, a MASS master, for instance, has the ultimate responsibility for compliance with all applicable laws and regulations (Maritime UK 2023, Part 2, at 1) and is therefore responsible for the overall command of the MASS and the crew on the particular voyage (Maritime UK 2023, Part 2, at 12.5.2). A UAS remote pilot is responsible for performing contingency procedures for abnormal situations and emergency procedures for emergencies, as defined by the UAS operator (EU Reg. 2019/947, Appendix 1, UAS.STS-01.040(2)(g)-(h)).

In addition, a role for a MASS watchkeeper is foreseen for MASS operations. The MASS remote watchkeeper is responsible for monitoring the MASS's operational status, reporting defects, and assisting the master or remote operator (Maritime UK 2023, Part 2, at 12.5.2).

A transfer of control between the different roles is, in principle, possible. For example, any handover of control of the MASS should be formally planned, and strict procedures should be developed and adhered to so that full and itemised responsibility is always clearly allocated and promulgated in terms of personnel and jurisdiction (Maritime UK 2023, Part 2, at 12.5.2).

Regulation generally requires *fitness to perform specific duties*. For a MASS, the operator must have the competency that would permit that person to operate an equivalent crewed vessel, together with additional training or certification and vessel-specific operational training (TAS 2022, at 14.4(5)(a)-(c)). A UAS remote pilot must be fit to perform their duties and hold a certificate of theoretical knowledge and an accreditation of completion of practical training (EU Reg. 2019/947, Annex, Part

B, UAS.SPEC.060(1)). The natural person appointed as the technical supervisor of a road vehicle with ADS must be suitable to fulfil their duties, or, if the operator himself performs the tasks of the technical supervisor, the operator must be suitable for the job (AFGBV 2022, §14(1)). Notably, in general, non-routine skills that are more challenging to automate can be achieved either by upskilling (i.e. adopting new skills for the current job) or reskilling (i.e. learning new skills for a different job) (OECD/ITF 2023).

For the RCC for a MASS, regulators note that human factors should also be considered in the training given to RCC personnel to avoid *new cognitive lackadaisicalness* (i.e. lack of concentration) (Maritime UK 2023, Part 2, at 12.12.3). This includes training personnel to be aware of situational awareness for dealing with operational risks, the development of a strong culture based on strong safety behaviour, and compliance with practices that underpin safe operations. It also requires continuity of practice between the RCC and local operations, where relevant, such as the use of the same software and operational practices; this means fostering efficient teamwork between RCC personnel, the personnel of multiple control centres, support personnel locally and shore management (Maritime UK 2023, Part 2, at 12.12.3). Furthermore, workforce fitness for duty should be prioritised, and sufficient support should be provided if fitness for duty is compromised (Maritime UK 2023, Part 2, at 12.12.3).

3.2.4 Reporting of accidents and incidents (including event data recording)

Data input is needed for an autonomous system to operate. While in operation, the autonomous system produces data. Data retrieval is, therefore, paramount for keeping track of the system's functioning and further development. Regulations stipulate that the operating system must have a steady and reliable procedure for collecting and storing all data relevant to the operation and the system itself. Most importantly, the data must be secure and readable for the purpose of market surveillance and accident investigation.

The regulations on road vehicles with ADS stipulate that these must have 'the function that collects and records the necessary data related to the system status, occurrence of malfunctions, degradations or failures in a way that can be used to establish the cause of any crash' and to identify the status of both the ADS and the driver (UNECE 2019, at 4.9.i)).

Furthermore, the ADS data elements must be made available, subject to the requirements specified in EU or national law. As *data storage* is not infinite, the EU Regulation requires that, once the storage capacity reaches its limit, the existing data shall only be overwritten following a first-in-first-out procedure, under the principle of respecting the relevant data availability requirements (EU Reg. 2022/1426, Annex II, at 9.6.2).

It is the manufacturer's responsibility to build the necessary data storage and *retrieval processes*. Data retrieval becomes particularly important in the case of incidents; for this reason, the regulations stipulate that manufacturers of road vehicles with ADS must establish processes to collect vehicle data and data from other sources to monitor and analyse safety-relevant incidents/accidents caused by the engaged ADS. The manufacturer shall report relevant occurrences to the type approval authorities, the market surveillance authorities and the Commission (EU Reg. 2022/1426, Annex III, Part 2, at 5.4). Moreover, as soon as the manufacturer recognises that the motor vehicle or the electronic or electrical architecture of, or connected to, the motor vehicle has been tampered with, and particularly in the event of unauthorised access to the vehicle's radio communications, it must notify the competent authorities without delay and initiate the necessary measures (StVG 2023, §1f(3)6).

Similarly, in aviation, the competent authorities and market surveillance authorities organised at the Member State level are obliged to cooperate in *exchanging safety information* (EASA 2024, GM1 Art. 19). Specifically, each UAS operator must report to the competent authority any safety-related occurrence, and exchange information regarding its UAS (EU Reg. 2019/947, Art. 19.2). EASA and the competent national authorities must collect, analyse and publish safety information concerning UAS operations in their territories (EU Reg. 2019/947, Art. 19.3).

3.2.5 Security considerations

Security considerations for autonomous transportation involve threats arising from intentional actions to cause negative impacts. To minimise these security risks and their potential consequences, regulators target key concerns associated with autonomous transport, specifically data protection, prevention of unauthorised access, and protection against cyber threats.

Notably, the term *risk* in aviation regulation refers to 'the combination of the frequency (probability) of an occurrence and its associated severity level' (EASA 2024, AMC1 Art. 11.2.1(a), referring to SAE ARP 475 A/EUROCAE ED-79 A). Since '[z]ero risk can never be reached, only probabilities can be reduced' (Maritime UK 2023, Part 2, at 8.12.5), regulation on MASS suggests that the *as low as reasonably practicable* (ALARP) approach should be implemented (Maritime UK 2023, Part 2, at 8.12.6). The ALARP principle depends on the risk levels being considered appropriate either within the existing framework or with additional mitigation measures in place (Maritime UK 2023, Part 2, at 8.12.6).

When introducing new operational concepts for autonomous vessels, it is important to recognise the novelty, immaturity, and complexity involved (DNV GL 2018a, Sec. 3.1.2, at 3). A key focus should therefore be on identifying and mitigating the risks associated with these new operations, functionalities, and systems (DNV GL 2018aa, Sec. 3.1.2, at 3). Regulations concerning MASS recommend conducting structured risk analyses at several levels. This includes examining the operational concept, the design and implementation of the controlling functions for new technology, and the remote supervision and control from the RCC (DNV GL 2018a, Sec. 3.1.2, at 3).

In the light of the ALARP approach, regulation on autonomous cars states that, to prevent hazards or reduce the risk to an acceptable level, system behaviour must be defined or system improvements must be implemented for scenarios and events based on identified risks. The system must correspond to the state of the art in technology (AFGBV 2022, Annex I, Part 1, at 7.2). For this, the vehicle manufacturer must carry out a risk assessment and implement proportionate mitigation measures (UNECE 2021b, at 7.3.4).

Data protection issues are closely linked to autonomous operations, and are particularly significant for autonomous cars because a large number of individuals will be moved by them. The manufacturer of road vehicles with ADS must establish a data protection impact assessment compliant with the EU data protection regulation (GDPR) (AFGBV 2022, §12(1)7). The documentation must allow for the review of information technology security, and contain a detailed description concerning the guarantee of data protection and data security under the GDPR (AFGBV 2022, Annex III, at 4).

To ensure safe operation, the operating manual provided by the manufacturer for a road vehicle with ADS should include a presentation of the functionalities serving data protection and data security (AFGBV 2022, Annex III, at 2.7). More specifically, the manufacturer must inform the owner precisely, clearly, and in plain language about the privacy setting options and the processing of data when the vehicle is operated in the autonomous driving mode (StVG 2023, §1g(3)). Data stored and transmitted to the competent authority must meet the security requirements outlined in the GDPR for information technology (AFGBV 2022, Annex I, Part 3, at 13.2.d)).

Similar requirements apply to the storage of data related to the registration of UAS and their operators in national registration systems, which must also comply with GDPR provisions (EU Reg. 2018/1139, Recital 31). Notably, to enhance data exchange amongst the authorities, the information stored in those registration systems should nevertheless be easily accessible (EU Reg. 2018/1139, Recital 31).

Another security concern is unauthorised access in the physical and digital spheres. As for *physical unauthorised access*, regulation on autonomous streetcars suggests that, when operating without a driver, unauthorised access to, driving on, or use of the track must be prevented by fencing or other means (BOSTRab 2019, §16(6)). Special facilities must be provided at stops to prevent people from being endangered by moving trains (BOSTRab 2019, §31(4)).

However, this is not possible in every environment. For a MASS, for example, it has been noted that unauthorised persons should not be able to access local controls on board (DNV GL 2018a, Sec. 3.2.5, at 6.4.4). More specifically, '[b]arriers should be arranged towards unwanted events that may affect the capability and availability of remote control and supervision of functions under the responsibility of a remote operator in the RCC' (DNV GL 2018a, Sec. 3.2.6, at 3.2).

To protect the autonomous transport mode from *unauthorised digital access (cyber risk)*, regulations on autonomous cars stipulate that the system must be protected from unauthorised access (EU Reg. 2022/1426, Annex II, at 8.1).

The autonomous vehicle should be protected against cyberattacks following established best practices for cyber vehicle physical systems (UNECE 2019, at 4.9.g)). In this regard, vehicle manufacturers must 'demonstrate how they incorporated vehicle cybersecurity considerations in to ADSs, including all actions, changes, design choices, analyses and associated testing, and ensure that data is traceable within a robust document version control environment' (UNECE 2019, at 4.9.g)). To do this, the manufacturer of a motor vehicle with ADS must demonstrate to the competent authority that, throughout the entire development and operating period of the motor vehicle, the electronic and electrical architecture of, and associated with, the motor vehicle is secured against attacks (StVG 2023, §1f(3)). The security against cyber risks must comply with GDPR requirements (AFGBV 2022, Annex I, Part 5, at 15).

Besides, to prevent software manipulation, the vehicle manufacturer must demonstrate how they will use reasonable means to ensure that software updates will be protected to prevent manipulation before the update process is initiated (UNECE 2021c, at 7.1.3.1). In the case of a failed or interrupted update, the vehicle manufacturer must guarantee that the car with ADS can restore its systems to their previous version or be placed into a safe state after the update (UNECE 2021c, at 7.2.2.1.1). The approval authority or the technical servicer must test whether the vehicle manufacturer has implemented the cybersecurity measures it has documented (UNECE 2021b, at 5.1.2).

Regulation on MASS advocates the operational technology (OT) cybersecurity approach that protects the complete system, including vessels, people, and the environment (Maritime UK 2023, Part 2, at 5.11.1). Therefore, this requires a more comprehensive and robust OT-based cybersecurity system, which is defined as 'technologies, processes, and practices designed to prevent the intended or unintended use of a cyber technology system to do damage to the cyber technology (networks, computers, programs, data), and vessel or harm to people and the environment' (Maritime UK 2023, Part 2, at 5.11.3).

A robust cybersecurity system must address potential issues across the complete system, and should include policies and procedures which address the following: the IT and the OT components of the system; roles and responsibilities; who requires what access to various parts of the system; personnel access control; security protocols such as password control, lifespan and renewals; actions to be taken if a breach results from a cyberattack; actions to be taken if a cyberattack occurs without a breach; and actions to be taken to ensure that the systems remain protected against newly created cyber threats (Maritime UK 2023, Part 2, at 5.12.1). In the same way, EU guidelines on MASS require that a cyber risk management plan is in place to demonstrate that the systems being tested provide an adequate level of cybersecurity, with measures in place to prevent and counter cyberattacks, ensuring continuity of the planned operation(s) (EU VTMIS 2020, at 6).

Other regulations on MASS require, for instance, that the vessel must have cybersecurity measures to protect navigation and situational awareness systems, control systems (including steering and routing/waypoint generation), communications systems, contingency systems, and any other vital or vulnerable systems on the vessel, as far as practicable and necessary (TAS 2022, at 12.5(1)-(2)). Protection against cybersecurity threats must be determined and implemented following a cybersecurity analysis that identifies possible security vulnerabilities and their effects on the vital systems and performance of the vessel, as well as measures to be undertaken to reduce risks to an acceptably low level (TAS 2022, at 12.5(1)-(2); Maritime UK 2023, Part 2, at 13.6.7).

In addition, the infrastructure of network components, servers, operator stations and other endpoints should be explicitly configured and hardened to reduce the likelihood and consequences of cybersecurity breaches. This applies both onboard and in any RCC (DNV GL 2018a, Sec. 3.1.2, at 11).

3.2.6 Prevention of pollution

Autonomous operations must not pose a risk to the environment. For example, the German regulation on autonomous cars requires the owner of a motor vehicle with ADS to maintain not only road safety but also environmental protection, and to take the necessary precautions to ensure this (StVG 2023, §1f(1)). In addition, the German Federal Motor Transport Authority is entitled to carry out regular checks to verify whether vehicles and vehicle parts made available on the market or already in use pose a risk to the environment (besides risks to health, safety or other legal interests worthy of protection in the public interest) (AFGBV 2022, §5(2)).

Regulations on MASS generally stipulate that MASS should meet the international, national, regional, and local requirements for the prevention of marine pollution that are applicable to the area in which the vessel is operating (Maritime UK 2023, Part 2, at 18.2.1). In this respect, following the goal-based approach, MASS must also have *a level of safety equivalent to or better than* conventional vessels with respect to safeguarding the environment (EU VTMIS 2020, at 2; DNV GL 2018a, Sec. 3.1.2, at 1.2).

In principle, when developing, implementing and maintaining a safety management system, this must include a safety and environmental protection policy and instructions and procedures to ensure the safe operation of a MASS and protection of the environment in compliance with relevant international and flag state legislation (Maritime UK 2023, Part 2, at 6.3.3). If the vessel stops operating, 'the vessel must be retrieved as soon as practicable, taking into account the vessel's location, the risks posed by the vessel to other waterway users and the potential impact of the vessel on the environment' (TAS 2022, at 2.3(24), 11.1(7)). In the same way as for conventional vessels, '[p]ollution dumping and wreck laws prohibit autonomous or remotely operated vessels from being abandoned at sea if they stop operating or where communication signals are lost' (TAS 2022, at 2.3(24), 11.1(7)). Additionally, a MASS should retain *oil or oily mixtures* on board for discharge to shore facilities (Maritime UK 2023, Part 2, at 18.3.1). When in safe-state mode, the vessel must be placed 'into a state in which it poses the least risk to life, the environment and property' (TAS 2022, at 2.3(14)).

3.2.7 Carriage and transfer of dangerous goods

Regulators are particularly concerned about the transport of dangerous goods. More stringent requirements are usually applicable to such goods. As with conventional transport, the carriage of dangerous goods is also foreseen for autonomous transport, but here it is subject to additional requirements.

For example, in aviation, a UAS operator who wishes to carry out operations in the 'specific' category for the carriage of dangerous goods should establish *a dangerous goods training programme* for the personnel involved, as required by the technical instructions (EASA 2024, AMC1 Art. 5(c)). Such training programmes should be commensurate with the responsibilities of the personnel involved in those operations (EASA 2024, AMC1 Art. 5(c)). They further must be subject to review and approval by the competent authority and should cover, at a minimum, aspects related to the terminology, classification, labelling, and identification of dangerous goods, the use of the dangerous goods list as provided, the storage and handling of dangerous goods, including but not limited to the segregation of incompatible dangerous goods, and the loading and securing of dangerous goods (EASA 2024, AMC1 Art. 5(c)). In addition, instructions and safety precautions are to be provided to employees and third parties, and emergency/reporting procedures should be included in the emergency response plan in case of an accident/incident with dangerous goods (EASA 2024, AMC1 Art. 5(c)).

For MASS, the regulation stipulates that, when carrying dangerous goods, any vessel, including a MASS, must have a *document of compliance* for the carriage of dangerous goods issued by the competent administration and held by the operator, regardless of the quantities being shipped (Maritime UK 2023, Part 2, at 19.2.4). For this, the vessel should be surveyed before carrying the dangerous goods, and a risk-based assessment should be undertaken, taking into consideration the size category and the level of autonomy (Maritime UK 2023, Part 2, at 19.5.4). There should further be *clear warnings* that a MASS is carrying dangerous goods, and these warnings must be displayed in all appropriate spaces where personnel may board the vessel in any eventuality and during normal operations, such as safety checks, loading and unloading, and maintenance (Maritime UK 2023, Part 2, at 19.3.2). Interestingly, although MASS are, by definition, usually crewless, *first aid kit requirements* have been issued even for crewless vessels. In this respect, provisions requiring that medicines be carried on ships carrying dangerous cargoes should be considered when a MASS is carrying dangerous goods, to account for loading/unloading requirements and/or any periods of manned contact (Maritime UK 2023, Part 2, at 19.6.6).

3.2.8 Rendering of assistance to persons in distress, salvage and towage obligations

Autonomous vehicles are not exempted from the assistance obligations applicable to conventional transport modes. This is based on the assumption that autonomous systems will have stand-off and close-up monitoring capability giving continuous feedback to the remote (human) controller.

With regard to the stringent maritime requirements relating to *rendering assistance to persons in distress*, the regulations on MASS stipulate that, having become aware of (a) person(s) in distress, the MASS remote controller should use their best endeavours to inform the appropriate search and rescue authorities through whatever means are appropriate (e.g. radio or camera live feed). In addition, 'in most circumstances, the MASS remote controller should ensure that the MASS is brought or remains in reasonable proximity with persons found in distress, to act as a visual reference point and communications point for research and rescue authorities' (Maritime UK 2023, Part 2, at 20.4.5). Moreover, '[e]fforts should not be made to embark persons if this cannot be done safely, relative to the peril faced by persons in distress' (Maritime UK 2023, Part 2, at 20.4.6). However, '[t]he remote controller of a MASS will not breach the duty for failing to render a particular form of assistance on account of the MASS technical limitations or for the MASS' inability to take persons on board' (Maritime UK 2023, Part 2, at 20.4.3). Interestingly, the regulators assume that '[t]he MASS's technical capabilities will define the nature and the requirements of the duty and not vice versa. However, situational cognisance and communications capability may be required by other international regulations, considered elsewhere' (Maritime UK 2023, Part 2, at 20.4.4). In the context of autonomous railway systems, the regulations require that operational precautions must be taken to enable passengers to be rescued immediately from broken-down trains (BOSTRab 2019, §56(3)).

As regards the *salvage* obligations applicable to conventional ships, in general, existing maritime salvage law applies also to MASS (Maritime UK 2023, Part 2, at 21.3.1). More specifically and similar to the provisions in the paragraph above, '[h]aving become aware of a marine casualty or incident, the MASS remote controller should make best endeavours to report the casualty or incident in accordance with the [r]egulations, through whichever means [are] appropriate (i.e. radio, camera live feed, radar, etc.)' (Maritime UK 2023, Part 2, at 16.4.5). If the MASS has survived the encounter/situation, 'the MASS remote controller should ensure that the MASS is brought or remains in reasonable proximity with other ships involved in the situation, to act as a visual reference point and communications point for any search and rescue activity that may follow the casualty or incident' (Maritime UK 2023, Part 2, at 16.4.5). For this, the regulations require a marine salvage plan to be provided which specifies the process of rescuing, repairing and re-floating the MASS, the crew (if manned), and other property from unforeseen imminent peril (EU VTMIS 2020, at 6).

As with salvage, the existing maritime *towage* law as it applies to manned ships generally also applies to MASS (Maritime UK 2023, Part 2, at 21.4.1). MASS owners should exercise due diligence at the commencement of the towage to ensure that the MASS is fit to be towed and is properly equipped therefor (Maritime UK 2023, Part 2, at 21.4.4).

3.3 Other requirements

Requirements other than those directly linked to pre-operational and operational matters but which are nevertheless important are presented in this last subsection.

3.3.1 Maintenance and record-keeping

To ensure continuous, safe and reliable operations, regulators demand ongoing maintenance of technical equipment throughout the lifecycle of the autonomous transport system.

For example, in the case of MASS, regulations stipulate that all MASS should be provided with a recommended *maintenance schedule* by the designer/manufacturer (Maritime UK 2023, Part 2, at 15.7.1). The overall *maintenance philosophy* should outline how each system will be monitored, diagnosed, maintained, and repaired, and '[b]oth software and mechanical subsystems/components should be included in the analysis' (DNV GL 2018a, Sec. 3.1.3, at 2.4.3). For example, a MASS should *periodically undergo checks* to ensure that its equipment guarantees safety comparable to that prescribed in the International Convention for the Safety of Life at Sea and the International Ship and Port Facility Security Code (Maritime UK 2023, Part 2, at 17.9.1).

Maintenance instructions are defined in more detail for road vehicles with ADS. The owner of a motor vehicle with ADS shall ensure the *regular maintenance* of the systems required for the autonomous driving function, take precautions to ensure that other traffic regulations not related to driving the vehicle are observed, and ensure that the tasks of the technical supervisory authority are fulfilled (StVG 2023, §1f(1)). In this respect, the manufacturer of a motor vehicle with ADS shall prepare *repair and maintenance information* for the motor vehicle (AFGBV 2022, §12(1)1). As for the contents of the operating manual, manufacturers of autonomous cars shall include the scope, procedure, timing and intervals of maintenance measures (AFGBV 2022, Annex III, at 2.3) and provide a functional description of the documents for maintenance and repair measures, including the necessary templates (AFGBV 2022, Annex III, at 2.6). The safety of vehicles when they are in use should be ensured through measures related to the maintenance and inspection of automated vehicles. Additionally, vehicle manufacturers are encouraged to have documentation available that facilitates the maintenance and repair of ADSs after a crash because such documentation 'would likely identify the equipment and processes necessary to ensure the safe operation of the automated/autonomous vehicle after repair' (UNECE 2019, at 4.9.j)). More specifically, the owner must ensure that, on the basis of the repair and maintenance information provided by the manufacturer, the vehicle systems for the active and passive safety of the motor vehicle with ADS are regularly checked (AFGBV 2022, §13(7)).

Furthermore, *instructions* must be made available for the proper performance of maintenance work, overall tests, further examinations and trips in manual mode, and these instructions must be followed. The instructions must be documented (AFGBV 2022, §13(3)). The operator or the responsible person must prepare signed *reports on the performance of maintenance work, overall tests and further inspections* without delay, either in writing or electronically (AFGBV 2022, §13(4)). The reports should be kept for six months by the operator or the person responsible for technical supervision and destroyed immediately after this period has expired, or automatically if stored electronically (AFGBV 2022, §13(4)). Data protection regulations apply to data relating to maintenance work as well: the requirements for the document management system for the instructions and the reports should correspond to the state of the art (AFGBV 2022, §13(4)), and the document management system must meet GDPR requirements (AFGBV 2022, §13(5)).

As for the maintenance of the software components (software updates), since autonomous situational awareness is based on an algorithm, no maintenance in the classical sense is required (DNV GL 2018b, at 3.1.2.1). 'However, algorithms are often subject to upgrades due to errors that have been detected, performance improvements or their attributes. Maintenance of the hardware and network components where the system is running will also be needed' (DNV GL 2018b, at 3.1.2.1).

In the same vein, autonomous car manufacturers should, therefore, ensure that 'system updates occur as needed in a safe and secured way and provide for aftermarket repairs and modifications as needed' (UNECE 2019, at 4.9.h)). More specifically, the software for products that have already been made available on the market may only be updated if such updates do not affect the product's compliance (EU Reg. 2019/945, Art. 4.3). Hence, the ADS must support software updates. The effectiveness of the software update procedures and processes concerning the ADS is to be demonstrated by compliance with UN Regulation No 156 (EU Reg. 2022/1426, Annex II, at 8.2, referring to UNECE 2021c). Accordingly, approval authorities shall grant, as appropriate, type approval concerning *software update procedures and processes* (UNECE 2021c, at 5.1).

Apart from records on maintenance work, the owner of a motor vehicle with ADS is obliged to *store* the following *data* when operating the motor vehicle: vehicle identification number, position data, number and times of use, and activation and deactivation of the autonomous driving function; number and times of approval of alternative driving manoeuvres; system monitoring data including data on the software version; environmental and weather conditions; networking parameters such as transmission latency and available bandwidth; name of the activated and deactivated passive and active safety systems, data on the status of these safety systems and the instance that triggered the safety system; vehicle acceleration in the longitudinal and lateral direction; speed; status of the lighting equipment; power supply of the motor vehicle with autonomous driving function; and commands and information sent externally to the motor vehicle (StVG 2023, §1g(1)).

Furthermore, data must be stored in the following cases: intervention by the technical inspectorate; conflict scenarios, particularly accidents and near-miss scenarios; unscheduled lane changes or evasive manoeuvres; and disruptions to operations (StVG 2023, §1g(2)). The manufacturer of a motor vehicle with an autonomous driving function must equip the vehicle so that data storage in the specified cases is actually possible for the owner (StVG 2023, §1g(3)). The relevant motor vehicle software should provide options for storing and transmitting the data processed in the autonomous driving function, and should enable the owner to enter the appropriate settings (StVG 2023, §1g(3)). Moreover, the keeper of a road vehicle with ADS is obliged to *transmit specified data* to the competent authorities, including the vehicle identification number, data related to the vehicle's position, and system monitoring data (StVG 2023, §1g(1)).

Under the German law on road vehicles with ADS, the stored data may only be used by the competent authority and only to verify compliance with the licence requirements and monitoring obligations (AFGBV 2022, §15(2)). The Federal Motor Transport Authority is *authorised to collect, store and use* specified data from the owner insofar as this is necessary to monitor the safe operation of the motor vehicle with ADS (StVG 2023, §1g(4)). However, the Federal Motor Transport Authority must *delete the data* as soon as it is no longer required for monitoring the operation, and at the latest three years after the corresponding motor vehicle ceases to be operated (StVG 2023, §1g(4)). The authorities responsible for the approval of specified operating areas are *authorised to collect, store and use* the specified data from the keeper insofar as this is necessary for checking and monitoring whether the specified operating area is suitable for the operation of motor vehicles with ADS, and in particular for checking and monitoring whether the requirements of the respective approval are being met and the associated conditions are being complied with (StVG

2023, §1g(6)). The authorities responsible for authorising specified operating areas must *delete* this data *as soon as it is no longer required*, and at the latest three years after the corresponding motor vehicle ceases to operate (StVG 2023, §1g(6)).

Similarly, for drones, the *record-keeping system* should ensure that all records are stored in a manner that protects them from damage, alteration, and theft (EASA 2024, AMC1 UAS.LUC.020(5)). They should be accessible at the request of the national aviation authority, whenever needed, within a reasonable time (EASA 2024, AMC1 UAS.LUC.020(5)). These records should be organised to ensure traceability, availability, and retrievability throughout the required retention period, which starts when the record was created or last amended (EASA 2024, AMC1 UAS.LUC.020(5)). Adequate backups should be ensured (EASA 2024, AMC1 UAS.LUC.020(5)).

U-space services providers and single common information service providers should establish a record-keeping system that allows adequate storage of the records and reliable traceability of all their activities, and that covers, in particular, all the elements of their management systems (EU Reg. 2021/664, Recital 30). Similar provisions apply to MASS. For instance, '[s]urvey and maintenance records should be kept up to date by the operator and readily accessible for inspection' (Maritime UK 2023, Part 2, at 15.8.1).

3.3.2 Inspection

In general, the inspection and certification of autonomous transport systems should be carried out in accordance with *established standards*. For example, the inspection and certification of the autonomous metro system GoA4 Shenzhen is done by TÜV Nord China according to established industry standards (EN 50126, EN 50128 and EN 50129) (TÜV NORD 2022).

Before any trip, cars with ADS must undergo a check of operational functionality. For this, an extended *pre-trip departure check* must be carried out every day before the start of the operation, based on the repair and maintenance information provided by the manufacturer. The extended pre-trip inspection must begin with a test drive to activate the systems (AFGBV 2022, §13(7)). After the test drive, the following areas must be inspected: braking system, steering system, lighting system, tyres/wheels, chassis, safety-related electronically controlled vehicle systems and sensors for recording external and internal parameters, and mechanical vehicle systems for active and passive safety (AFGBV 2022, §13(7)). In addition, the owner must carry out a more general departure check every 90 days after the date of registration for road use, following the specifications of the operating manual. The results of the general inspections, including a description of all defects detected and repairs carried out, must be documented in a report and sent to the respective authorities without delay upon request, provided that this is necessary for the fulfilment of their tasks (AFGBV 2022, §13(1)).

To conform with regulatory requirements, an inspection of the car must be carried out by an independent, external inspector who is not the car owner himself. The owner must therefore have a *main inspection* carried out on a motor vehicle with an autonomous driving function (AFGBV 2022, §13(8)). The deadline for this main inspection is six months from the date of registration of the motor vehicle with an autonomous driving function (AFGBV 2022, §13(8)). The suitability of the functional and structural design of the motor vehicle must be checked in a *periodic technical vehicle inspection* (e.g. manual driving, accessibility of brakes) (AFGBV 2022, Annex I, Part 1, 7.3). In particular, it must be possible to drive on brake test stands, light adjustment stands, lifting platforms or in pits, and all prescribed tests must be able to be carried out (AFGBV 2022, Annex I, Part 1, at 7.3).

3.3.3 Accident investigation

Accident investigation is a crucial component of effective health and safety management systems for disruptive technologies. By learning from incidents and near misses, regulators can identify the root causes of accidents, implement corrective measures, and prevent future occurrences.

In this regard, manufacturers and keepers of motor vehicles with ADS are obliged to support the German Federal Motor Transport Authority in carrying out market surveillance activities, and provide the Authority, upon request, with documents and information required for market surveillance, as well as other technical specifications, free of charge; the manufacturers must also provide access to software and algorithms upon request (AFGBV 2022, §5(5)). For this reason, the manufacturer must put in place processes to collect vehicle data and data from other sources, in order to monitor and analyse safety-relevant incidents/accidents caused by the engaged ADS (EU Reg. 2022/1426, Annex III, Part 2, at 5.4, Part 5). Besides, the manufacturer must *report relevant occurrences* to type-approval authorities, market surveillance authorities and the Commission (EU Reg. 2022/1426, Annex III, Part 2, 5.4, Part 5).

In the particular circumstance in which the minimum risk condition of a road vehicle with ADS was triggered by a defect in the vehicle, a technical inspection must be carried out on the basis of the stored driving data following its removal (AFGBV 2022, §14(3)). In general, the ADS of a road vehicle should have adequate protection against manipulation (e.g. data erasure) of stored data, for example by way of an anti-tamper design (EU Reg. 2022/1426, Annex II, at 9.9.1).

In the context of MASS, notably, '[t]he vessel owner will, in all circumstances and at all times, own the data produced. However, it is expected that owners/operators will make all vessel onboard and offboard data available to accident investigators as required' (Maritime UK 2023, Annex A to Chapter 6).

3.3.4 Reporting for innovation development purposes

Reporting in the case of innovation implementation and development is particularly important because it provides regulators and policymakers with the necessary data and insights to adapting existing regulatory frameworks.

As a consequence, regulation on MASS stipulates that test reports and relevant documents, but not commercially sensitive information, should be made available to the competent administration for the purpose of *evaluating and assessing* the results in view of future developments in the area and of policy for MASS operation at (EU

VTMIS 2020, at 7). All stakeholders involved in trials are encouraged to share relevant dynamic and static data for machine-to-machine communications during the trial, without compromising business secrets, to enable safe, secure and environmental-friendly trials at (EU VTMIS 2020, at 7).

Likewise, the Federal Motor Transport Authority in Germany is entitled to make non-personal data collected from vehicle keepers available to the following bodies for traffic-related public welfare purposes, and in particular for the purposes of scientific research in the field of digitalisation, automation and networking and road traffic accident research: colleges and universities; non-university research institutions; and federal, state and local authorities with research, development, transport planning or urban planning tasks. However, these bodies may only use the data for the specified purposes, and the general transmission regulations remain unaffected (StVG 2023, §1g(5)). Moreover, periodic evaluation by the competent authorities of the effects on the development of autonomous road vehicles, their compatibility with data protection regulations and the findings obtained on the basis of test permits on a scientific basis in a non-personal form are foreseen in regulation on road vehicles with ADS (StVG 2023, §11).

Monitoring, evaluation and optimisation, as part of the implementation and performance review phase, constitute the final part in the integration cycle of new technologies and are the means by which public regulatory bodies can ensure the successful, sustainable and long-lasting market introduction of such technologies.

4 Discussion, conclusion and study implications

This comparative analysis of the regulations governing different autonomous transport modes provides two major findings for regulators and policymakers. The first takeaway from this study is that, not surprisingly, it is most likely that proposals stemming from instruments for MASS regulation will have the greatest impact on the regulatory framework for autonomous inland ships. The second takeaway is that the regulatory regimes for autonomous air, rail and road transport can also be of significant importance to inland waterway regulatory bodies.

As for the first key finding, it is notable that the technology behind the two transport modes is of a very similar nature with regard to design and operational functionalities. However, two important limitations hinder a blind transfer of regulatory provisions from MASS to autonomous inland shipping.

First, the operational environment of seagoing ships differs substantially from that of inland waterway vessels. Regulatory requirements for technology readiness for inland barges will need to be more detailed and elaborate because the intended operational environment is much narrower than the open sea and there is a greater possibility of interference with much smaller (floating or stable) objects. Secondly, regulation of MASS is also still in the early stages, and therefore lacks substantive feedback that could be used to adapt existing regulatory provisions. Nevertheless, the regulation on MASS provides a first important tool for making proposals for a framework for autonomous inland shipping technology.

However, and turning now to the second takeaway from the comparative study, the regulatory solutions identified from the other industry sectors can be used to validate the proposals carried over from the MASS regime, on the one hand, and, on the other, can provide answers, in greater or less detail as the case may be, to fill the regulatory gaps that are not (sufficiently) addressed by the existing MASS regulation.

The second research question of whether the regulatory solutions identified across the different transport modes are potential answers to the regulatory issues regarding autonomous inland shipping technology can be answered in the affirmative. More specifically, regulatory solutions found in the regulations on MASS and validated by the regulations in one or more of the other industries are likely to be applicable to autonomous inland shipping technology. Provisions from industries other than maritime shipping that address regulatory issues in more detail than the regulation on MASS can complement the propositions from MASS regulators, whereas regulatory provisions not found in the context of MASS but relevant in at least one other industry can supplement existing MASS regulation and provide a starting point for inland shipping regulation.

To conclude, the aim of the study was to find possible regulatory solutions for autonomous inland shipping technology. Using a comparative research method, regulations on autonomous transport modes including aviation, air, rail, road and sea transport were analysed to answer the two research questions. With respect to the first research question, regulations across these industries follow similar, if not identical, approaches to address the regulatory issues identified regarding pre-operational, operational and other requirements. Regarding the second research question, the regulatory provisions stemming from the comparative analysis can serve as potential regulatory solutions for autonomous inland shipping. Notably, language restrictions hindered the inclusion of regulations in languages other than English, French and German in the comparative analysis. It must therefore be mentioned, as one of the limitations of the study, that the regulations identified and analysed here are only examples of regulations on autonomous transport modes and do not represent all the regulatory instruments that currently exist in this area.

As for the study implications, the regulatory solutions found can, in essence, be potential answers. However, a regulatory framework for autonomous inland shipping must be guided by certain principles to provide clarity and directions, even if not suggesting specific actions. Once a proposal for a regulatory framework has been created using the outcomes of this comparative study, its feasibility must be evaluated and validated by the industry. Further research is needed to identify the guiding principles, to use these to work out a proposal for a regulatory framework and to discuss the regulatory proposals with relevant inland shipping stakeholders. Until then, this comparative study investigating regulatory solutions from autonomous transport systems in the air, rail, road and sea sector can be used as a toolbox for public regulators and policymakers who are currently working on regulatory frameworks for highly automated and autonomous inland shipping technology, such as UNECE, CESNI and the CCNR.

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Declarations

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