Resolving Legal Ambiguities for Safe MASS Navigation: A Socio-Technical Approach Using Human-Machine Learning

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***Abstract*—Maritime Autonomous Surface Ships (MASS) promise to reduce casualty rates and improve operational efficiency, yet two obstacles impede widespread adoption: the qualitative, often conflicting language of the COLREGs and the opacity of prevailing AI collision-avoidance algorithms. We present a socio-technical decision framework that formalises COLREG hierarchy, including the *lex specialis* ordering confirmed in *Ever Smart v. Alexandra 1*, as a tiered rule tree and encodes it in an explainable, auditable knowledge base. Using symbolic logic, the system resolves rule conflicts, logs its reasoning, and outputs a single safe manoeuvre aligned with good seamanship. Three representative scenarios (narrow-channel crossing, cascading multi-vessel conflict, and overtaking in a channel) demonstrate that the framework reproduces expert decisions while exposing a transparent proof trail. The result is a legally coherent foundation for logic-based machine learning using inductive logic programming (ILP) and future maritime autonomous systems trials, advancing the IMO goal of "at least equivalent" safety for unmanned vessels.**

***Index Terms*—Maritime Autonomous Surface Ships (MASS), COLREGs Compliance, Legal Ambiguity, Inductive Logic Programming (ILP), Trustworthy Autonomy**

I. Introduction

The maritime industry is responsible for more than 80% of global trade [1], making it an essential part of the collective critical infrastructure that allows the movement of raw materials, components, and finished goods that are part of the vital global supply chain. Despite its essential role, maritime transport remains vulnerable to serious accidents, particularly collisions and groundings, which continue to occur with concerning regularity. Human error is consistently identified as the predominant factor, and studies attribute 70% to 96% of these incidents to failures in decision making, perception, or communication of crewmembers onboard [2], [3]. A recent illustration of these risks is the 10 March 2025 collision between the container ship Solong and the oil/chemical tanker Stena Immaculate. The accident resulted in multiple injuries to both crews, fatalities, onboard fire, a large-scale fuel spill and significant structural damage to both vessels. The Marine Accident Investigation Branch (MAIB) classified the event as a 'very serious marine casualty' in its interim report [4]. Financial analysts later estimated the insured losses to fall between US$100 million and US$300 million [5], highlighting the diverse range of potentially devastating consequences of such incidents.

Marine navigation has long integrated technological innovations and regulatory frameworks to enhance safety and efficiency. Modern tools such as radar, AIS, and ECDIS have improved situational awareness, while the 1972 International Regulations for Preventing Collisions at Sea (COLREGs) [6], provides a set of universal rules for avoiding collisions. However, serious incidents persist, often due to human error or ambiguity in applying these qualitative rules. As these limitations remain unresolved, Maritime Autonomous Surface Ships (MASS) are increasingly viewed as a potential remedy to reduce human fallibility and improve safety.

The International Maritime Organisation (IMO) defines MASS as vessels operating "to a varying degree,independently of human interaction [7]", are categorised into four levels of autonomy, from automated decision support (Degree 1) to fully autonomous navigation (Degree 4) [8].

Problem. Despite their promise MASS raise various legal and technical challenges. This paper aims to provide a novel approach to address the two major challenges in its wider adoption:(i) *Collision regulations (1972) or COLREGs are qualitative and provide no explicit hierarchy or prioritisation principles in complex scenarios*; and *(ii) prevailing AI collision-avoidance modules are opaque and cannot give a courtroom-credible explanation for a helm order*.

Contribution. This paper makes the implicit hierarchy explicit and encodes it as explainable symbolic rules:

- Tiered decision tree for conflict resolution (Table I) orders Rules 2, 9, 10, 13-17 by the maxims *lex specialis*, *lex posterior*, *lex superior*, embedding precedents such as *Evergreen Marine* (2021) and *Olympian* (1957) [9], [10].
- Each manoeuvre yields a proof trace that cites every override, satisfying the "right-to-explanation" in the IMO

MASS Interim Guidelines (2023) and NIST AI-RMF [11], [12].
- The rule set is delivered in a form amenable to Inductive Logic Programming (ILP) [13], enabling verifiable, human-readable machine learning.

Evaluation. Three challenging scenarios (narrow-channel crossing, cascading multi-vessel conflict, and overtaking in a channel) show that the conflict resolution framework can successfully deduce the right priority of rules and provide safe actions. A companion article [14] details a logic-based machine learning approach using ILP; this paper focuses on building the "human" element of the human-machine learning paradigm by developing a legal reasoning model that can aid the operationalisation of safe, transparent, and certifiable MASS navigation. This reasoning model is used as background knowledge for machine learning using ILP [14].

II. Defining the Problem

Maritime autonomy is often promoted on the headline claim that 70-96% of collisions and groundings stem from human error [2], [3]. Realising this promise of increased safety, however, requires machines to satisfy both: objective safety, verifiable conformance to COLREGs, SOLAS, ISM Code and a risk profile no worse than a crewed ship [15], [16]; and subjective safety is the context dependent judgement implicit in phrases such as "safe speed", proper "look-out"and "good seamanship" [16]. Because COLREGs provide no built-in rule order, an autonomous controller can face mutually incompatible duties in narrow channels, multi-vessel scenarios or restricted visibility encounters. The resulting legal impasse leaves MASS unable to prove full compliance, regulators unable to trace responsibility, and mariners reluctant to trust the machine.

A. Human Factors and the "Well-Run Ship"

UK MAIB statistics logged 4,354 reportable occurrences involving 4,721 vessels between 2022 and 2024, with the majority of serious incidents associated with collisions [17]. In another empirical analysis of accidents globally between 2004 and 2021, collisions and contacts alone accounted for 31.7% of incidents [18]. The consequences scale quickly: the *Sanchi* collision (2018) killed 32 crew and created a week-long fire [19], while human-error claims cost insurers "USD 1.6 billion" between 2011 and 2016 [20]. Surface analysis blames fatigue, poor lookout or late helm orders, but deeper reviews show that "56 % of major collisions include at least one COLREG breach" [21] and even certified officers misinterpret key rules under stress [20]. Existing risk metrics such as CPA/TCPA ignore many COLREG factors and therefore provide little support when workload peaks [20].

Professional practice therefore, measures a vessel against the ideal of a "well-run ship" i.e., check-list compliance and tacit seamanship, experienced-based judgement [22]. An autonomous vessel must meet the same two-tier test and expose its reasoning in human terms.

B. Why COLREGs Defy Straightforward Automation

COLREGs as rule set without rule order. Drafted for flexibility, the Code's qualitative language is crucial in a fluid environment, but invites divergent interpretation. The problem escalates once more than two vessels interact. The COLREGs language focuses on a single ship-pair and offers no explicit ordering when three or more duties overlap [23]. A constrained-draught tanker in a narrow channel may simultaneously be stand-on (Rule 9), give-way (Rule 15) and overtaking (Rule 13), creating multiple obligations without much sequential clarity.

An implicit hierarchy is recognised in practice, "emergency override" under Rule 2(b) > "privileged status vessels" in Rule 18 > geographic rules in Rule 9, 10 and 19 > encounter rules from Rule 13-17, and affirmed in case law such as *Evergreen Marine v Nautical Challenge* (2021) and *Nowy Sacz/Olympian* (1957) [9], [24]. Yet this order is codified nowhere, leaving current machine-learning modules to treat the Code as a flat list that cannot be applied or explained in real time.

Good seamanship as a tacit expertise. Officers describe good seamanship as holistic traffic awareness and cooperative manoeuvring that stabilises the wider system, sometimes at odds with a literal reading of the rules (permitted by Rule 2(b)) [25]. Mariners doubt that black-box AI can replicate this adaptive judgment [26].

Delivering objective and subjective safety thus calls for a layered decision architecture: statutory text, an explicit precedence tier grounded in precedent, and a heuristic layer for ordinary practice, with each step remaining explainable.

C. The Necessity of Explainability and Trustworthiness

A manoeuvre that lacks a courtroom-credible explanation will not satisfy bridge officers, flag administrations or insurers. Explainable AI (XAI) links each manoeuvre to the rule-chain and data that produced it, overcoming the "black-box" barrier that currently deters seafarers from relying on machine-based collision avoidance advice [27]. It enables machine learning systems to be more trustworthy and in alignment with the IMO's Maritime Safety Committee's 2023 guidelines and NIST's AI Risk Management Framework (RMF)'s demands for accountability [12], [28]. Symbolic techniques such as ILP can learn that structure from precedent-labelled examples and keep it auditable, allowing an autonomous vessel to explain why it chose Rule 9 over Rule 15 or why it broke both rules under Rule 2(b).

D. Related Work and Gap Analysis

Existing decision-support products such as, NAVDEC, Wärtsilä AIM, and most academic prototypes focus on CPA/TCPA geometry and almost all encode only Rule 8 and Rules 13-17 as these clauses map cleanly to geometry [29]. Normative multi-agent schemes (BDI/BOID) and recent LLM pilots push further, but still treat the Code as a flat set and ignore jurisprudential refinements. Where optimisation and DRL variants achieve tactically good tracks they do so as opaque black boxes, offering little post-incident auditability

Table I: *Tiered COLREG Conflict-Resolution Framework for MASS Controllers*

Tier / Node	Purpose (1-line)	Governing rule(s)	Key legal / doctrinal justification ($\leq$ 3 lines)
0 Emergency	Imminent danger; no time for normal rules	Rule 2(b)	Authorises *any* proportional action; "no right-of-way into collision". Post-hoc justification required (*Nordlake*,2016).
1 Status	NUC/RAM/CBD/ fishing/sailing outrank PDV	Rule 18 hierarchy	*Lex specialis* in Rule 18. CBD over PDV affirmed in *Ever Smart* (UKSC 2021); visibility qualifier in *Yarmouth Sea Products* (1987).
2 Visibility	Fog or vis $\leq$ limit $\rightarrow$ Sect.III applies	Rule 19	Sect.III overrides Sect.II; *Maloja II* (1979) and *Mineral Dampier* (2001) emphasise ready engine and cautious speed.
3 Geographic	Narrow channel or TSS dictates conduct	Rules 9	Rule 9 starboard-side duty (*Jaroslaw Dabrowski* 1952); *Canberra Star* 1962. TSS traffic-lane obligations are *lex specialis* over crossing.
4 Encounter	Choose overtaking / head-on / crossing	Rules 13 - 17	Rule 13 outranks 14 - 15 via "Notwithstanding…" (*Olympian* 1957). *Kiveli v Afina I* (2025) holds Rule 14 beats 15.
5 Conflict solver	Higher-tier vs. encounter clash?	*Lex specialis* + precedent	If Rule 9 collides with 15, *Ever Smart* keeps 15 until "final approach". Default: more specific or higher tier rule prevails.
6 Safe action	Residual CPA check; adjust speed/course	Rules 6 - 8	Rule 8 demands early, positive action; *Majola II* goal is to avoid close-quarters else revert to Tier 0.
7 Signals	Communicate manoeuvre taken	Rules 32 - 37	Sound/light signals mandatory; mis- or non-signalling criticised in *Hanjin Madras* (2003).
8 Audit	Log rule-path	Rule 2(a) + IMO MASS trial guides (2023)	Logging fulfils "good seamanship" traceability and IMO transparency guidance; underpins liability analysis.

[29]. In short, currently no end-to-end framework *(i) makes the implicit COLREG order explicit* and (ii) *formalises it in explainable, verifiable logic.*

E. This Paper's Contribution

The research aims to close this gap by presenting a tiered decision tree that:

1) Orders Rules 2, 9, 10, 13-18 via IRAC reasoning, *lex specialis* and leading precedents;
2) Quantifies subjective clauses where feasible;
3) Encodes each tier as symbolic rules learnable by ILP, producing a proof trace for every action.

III. Methodology: A Socio-Technical Approach

Safe, trustworthy, and certifiable MASS navigation is fundamentally a complex socio-technical challenge that goes beyond the scope of any single disciplinary or stakeholder boundary. Maritime navigation exists within a highly regulated and high-risk operational environment, where autonomous vessels must interact safely with human-operated ships, dynamic environmental conditions, and multifaceted legal frameworks [28]. It demands a nuanced interdisciplinary perspective rather than a purely technological or legalistic solution. This sociotechnical approach recognises MASS as embedded systems that continuously interact with societal, legal, operational, and environmental contexts [30]. Therefore, this research aims to develop an explicit decision-making framework that fuses statutory text, judicial precedent, and mariners' tacit practice with a human-readable and explainable layer using symbolic computation techniques, particularly ILP systems, to systematically resolve the inherent ambiguities of COLREGs and ensure compliance with established maritime safety principles.

This section details the four elements of the "socio" part of the overarching research project. This paper's work is a part of (i) establishing the foundational knowledge base; (ii) development of an adaptive conflict resolution ranked rule table (Table I); (iii) formalisation of the knowledge base in Table 2-8; and (iv) the three worked scenarios (Section IV).

A. The "Socio" Layer: Building an Authoritative Knowledge Base

Central to this methodology is the creation of an authoritative and comprehensive knowledge base sourced from key maritime legal and operational documents.

1) **Core instruments**. COLREG 1972 [31], SOLAS V [32], STCW [33], and the ISM Code [34], define the objective safety baseline. Contemporary "soft-law" supplements - Marine Guidance Notes (e.g. MGN 369, 199, 315) [35]–[37], classification-society guidance such as DNV-CG-0264 [38], and the IMO/MSC Interim Guidelines for MASS trials [39], codify current best practice.
2) **Commentary and handbooks**. Authoritative texts (Cockcroft & Lameijer), [40]; Hirst vols.1-2, [24], [41]; Farewell's *Rules of the Nautical Road*, [42]; Jinks' *Reeds Handbook*, [43]) formalise the mariner's tacit rule hierarchy.
3) **Empirical studies on "good seamanship"**. Recent surveys and experiments illuminate how officers interpret COLREGs in practice [22], [44]–[47].

Moreover, authoritative admiralty case laws are rigorously collated to clarify COLREGs' practical interpretation, including pivotal judgments such as:

- *Ever Smart v Alexandra I* (2021): defining conditions for Rule 9's (narrow channels) precedence over Rule 15 (crossing) [9].
- *Olympian-Nowy Sacz* (1957): affirming Rule 13's (overtaking) persistent priority [10].

- *Kiveli v Afina I* (2025): confirming Rule 14's (head-on) precedence over Rule 15 [48].
- *Empire Brent-Stormont* (1948): reinforcing Rule 9's primacy within geographic constraints [49].
- *Jaroslaw Dabrowski* (1952): Defines the limits of a "narrow channel" and reinforces the Rule 9 starboard-side duty [50].

This robust foundation ensures that the hierarchical decision-making process is transparent, legally defensible, and aligned with real-world maritime practice.

B. Legal Reasoning Layer: IRAC + Lex Specialis

The rule order is synthesised with two well-established legal reasoning and conflict resolution tools:

Issue-Rule-Application-Conclusion (IRAC). IRAC, widely employed in legal education and practice, guides the systematic identification of issues, application of relevant rules, legal reasoning based on facts, and justifiable conclusions [51]. IRAC provides a four-step template for each tier of the hierarchy (*Issue*: e.g. "Is visibility below the Sect. III threshold?"; *Rule*: invoke Rule 19; *Application*: restricted-visibility duties; *Conclusion*: slow and monitor).

Conflict Maxims. Lex specialis ("the specific over the general"), *lex posterior* ("the later rule over the earlier") and *lex superior* ("the higher norm over the lower") are the canonical triads invoked by courts when two or more rules appear to clash [52]. Maritime tribunals rely on them to decide, for example, that Rule 13 overrides Rules 14 - 15 because its wording is more specific *(lex specialis)*, or that the 1972 COLREGs displace earlier steering rules *(lex posterior)*. In national systems a constitutional safety clause would trump an ordinary statute under *lex superior*. Embedding these maxims in the decision tree gives the MASS controller the same conflict-resolution grammar used by judges and surveyors, ensuring that its manoeuvre priorities track orthodox legal reasoning rather than ad hoc engineering heuristics.

Table I condenses the proposed rule-ordering scheme into nine tiers that a MASS controller traverses from top to bottom. Tier 0 poses the IRAC, *Issue* "Is there imminent danger?"; if yes, the *Rule* is COLREG 2(b); the *Application* is any proportional manoeuvre; and the *Conclusion* short-circuits the rest of the tree. Tiers 1 - 3 represent contextual screening: vessel status (Rule 18), visibility (Rule 19) and geography (Rules 9/10). Because each of those rules is a *lex specialis* in its domain, they outrank the encounter type duties that follow. Tier 4 classifies the geometry (Rules 13-17) and, together with the conflict-solver in Tier 5, resolves the familiar "overtaking versus crossing" and "crossing versus head-on" clashes by consulting the precedent cache (e.g., *Olympian* 1957, *Kiveli* 2025). Tiers 6-8 close the IRAC loop: they verify residual risk, issue the required sound signals, and log a proof trace that cites every override used, thereby satisfying the "right-to-explanation" clauses in the IMO MASS Interim Guidelines.

The table shows at a glance (i) the governing rule(s) that control each tier, (ii) the legal maxim that gives that tier priority, and (iii) a leading case anchoring the tier's doctrine.

Table II: *Geometric Predicates for Relative Bearing*

Geometric Predicate
sector(X,Y,S).
ahead(X,Y) :- sector(X,Y,S), S = 0
astern(X,Y) :- sector(X,Y,S), S = 16
starboard(X,Y) :- sector(X,Y,S), S≥=1, S≤15.
port(X,Y) :- sector(X,Y,S), S≥17, S≤31.
aft(X,Y) :- sector(X,Y), S≥10, S≤22.
overtaking_arc(Y,X) :- sector(Y,X,S), S≥10, S≤22.

Table III: *Situational-context predicates for traffic area and hazard-related*

Situational Relation
risk_collision(X, Y).
waterway(X, open_sea).
waterway(X, narrow).
waterway(X, in_channel).
waterway(X, crossing_channel).
waterway(X, entering_channel).
waterway(X, approaching_channel).
waterway(X, shoal_water).
waterway(X, constrained_draught).

Table IV: *Privileged Status Predicates*

Vessel Type and Activity
status(X, fishing).
status(X, ram).
status(X, nuc).
status(X, sail).

Encoding this hierarchy in the controller means that, when an overtaking situation (Rule 13) is detected inside a Traffic Separation Scheme, the system automatically elevates Tier 3's lex specialis obligation, keep to lane and cross at 90°, above Tier 4's overtaking duty, exactly as the Admiralty Court did in Canberra Star 1962. In effect, every pass through a tier constitutes a micro-IRAC cycle whose conclusion either resolves the encounter or hands control to the next tier, ensuring that machine reasoning tracks courtroom reasoning step for step.

C. Formalising Foundational Knowledge

To make the rule-hierarchy machine-readable, every fragment of COLREG reasoning is distilled into small Prolog style facts and rules. The seven background knowledge tables illustrate how the hierarchy and rules applications build up, layer by layer, from raw geometry to legal priority:

- Table II: **Geometric Predicates**
  Lists sector based predicates such as ahead/2, starboard/2, and overtaking_arc/3. The purpose is to convert the numeric relative bearing returned by sensors (or, AIS / radar) into symbolic cues the legal layer can query (e.g., "Is Y within X's overtaking arc?").

- Table III: **Situational-Context Predicates**
  Declares traffic area and hazard facts: risk_collision/2, waterway(X, narrow), waterway(X,shoal_water). The purpose is to switch the reasoning engine from open-sea defaults to Rule 9, Rule 10 or cautionary logic whenever geography or visibility demands it.
- Table IV: **Privileged Status Predicates (Rule 18**)
  waterway(X,constrained_draught)., status(_,fishing)). The purpose is to identify ships that outrank a power-driven vessel before any geometric encounter is analysed.
- Table V: **Rule-Activation Clauses**
  Combines geometry, context and status into single Boolean triggers, e.g. applies(X,rule9_narrow) or applies(X,Y,rule15_crossing). The purpose is to say unequivocally which COLREG duty is "live" for each vessel pair.
- Table VI: **Duty-Allocation Rules (Rules 16 and 17)**
  Translates an activated encounter into "give-way" or "stand-on" commands, e.g. applies(X,Y,rule16_giveway). The purpose is to capture the textbook wording of who must manoeuvre versus maintain course/speed.
- Table VII: **Normal Priority Rules**
  Specifies the routine order in which overlapping duties apply, e.g., in a standard starboard side crossing, X keeps course while Y gives way. The purpose is to provide the default conflict resolution path when no special circumstances exist.
- Table VIII: **Exception Priority Rules**
  Records explicit or judicial overrides: (i) Rule 18 privilege, (ii) the Ever Smart channel entry reversal (Rule 9 prioritise over 15), (iii) Rule 13's "notwithstanding" supremacy over Rule 15. The purpose is to allow the controller to depart from the normal order when higher legal authority requires it.

Together these tables give Inductive Logic Programming a transparent, modular scaffold: geometry → context → duty → priority, mirroring how experienced officers reason on the bridge while keeping every step auditable.

IV. Scenario Walk-Through Demonstrations and Analysis

To demonstrate the capability of the tiered, legal-reasoning based decision framework, we present three scenarios with varied levels of complexity. Each scenario is first defined by its operational context and then encoded into symbolic logic. We then trace the step-by-step deductive process, from identifying applicable rules to resolving conflicts using legal precedence, that results in a single, safe and legally justifiable manoeuvre.

Scenario 1: Narrow channel and Crossing (Rule 9 and 15 Conflict

This scenario tackles a classic conflict where general crossing rules appear to contradict the specific rules for navigating in a narrow channel, further complicated by the vessel's special status.

Table V: *Rule-Activation Clauses*

Encounter Rules
applies(X,rule9_narrow) :- waterway(X, narrow).
applies(X,Y,rule13_overtaking) :- risk_collision(X,Y), overtaking_arc(Y,X).
applies(X,Y,rule14_headon) :- risk_collision(X,Y), ahead(X,Y), ahead(Y,X).
applies(X,Y,rule15_crossing) :- risk_collision(X,Y), not(applies(X,Y, rule13_overtaking)), not(applies(X,Y,rule14_headon)).

applies(X, rule18_privilege) :-
status(X, nuc);
status(X, ram);
staus(X, fishing);
status(X, sail);
waterway(X, constrained_draught).

Table VI: *Duty-Allocation Rules (Rules 16 and 17)*

Rule 16 and 17 (Duty Rules)
applies(X,Y,rule16_giveway) :- applies(X,Y,rule13_overtaking).
applies(X,Y,rule16_giveway) :- applies(X,Y,rule14_headon).
applies(X,Y,rule16_giveway) :- applies(X,Y,rule15_crossing), starboard(X,Y).
applies(X,Y,rule17_standon) :- applies(Y,X,rule13_overtaking).
applies(X,Y,rule17_standon) :- applies(Y,X,rule15_crossing), port(X,Y).

Table VII: *Normal Priority Rules*

Normal Priority Rules
priority(X,Y,rule16_giveway, rule17_standon, rule17_standon) :- applies(X,Y,rule15_crossing), port(X,Y).
priority(X,Y, rule16_giveway, rule17_standon, rule16_giveway) :- applies(X,Y,rule15_crossing), starboard(X,Y).
priority(X,Y, rule16_giveway, rule17_standon, rule16_giveway) :- applies(X,Y,rule13_overtaking).
priority(X,Y, rule17_standon,rule16_giveway, rule17_standon) :- applies(Y,X,rule13_overtaking).

Own Ship (OS/MASS): Autonomous, large cargo vessel, constrained by draught, proceeding east within a narrow channel at 8 knots (heading 090°T).
Target Ship (TS): Conventional, highly manoeuvrable ferry

Table VIII: *Exception Priority Rules*

Exceptions Priority Rules
priority(X,Y, rule16_giveway,rule17_standon, rule16_giveway) :- applies(X,Y,rule15_crossing), port(X,Y), applies(Y,rule18_privilege).
priority(X,Y, rule16_giveway,rule17_standon, rule16_giveway) :- applies(X,Y,rule15_crossing), port(X,Y), status(Y,in_channel), status(X,entering_channel).
priority(X,Y, rule13_overtaking, rule15_crossing, rule13_overtaking) :- applies(X,Y, rule16_giveway), applies(Y,X,rule17_standon).

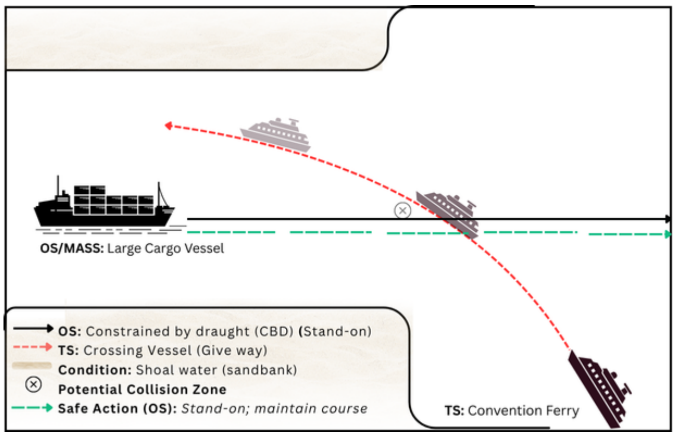

Fig. 1: **Scenario** A constrained Own Ship (OS) in a narrow channel encounters a crossing Target Ship (TS).

approaching from south (Heading, 000°T) to north, crossing the narrow channel. Travelling at 10 knots.

Bearing and Risk of Collision: TS is on OS's starboard side at 045°R; the relative bearing is steady, indicating a risk of collision.

Conditions: Clear visibility; shoal water close to both channel margins.

Symbolic encoding of the scenario:

Vessel Facts and Status

vessel(os).
vessel(ts).
waterway(X,constrained_draught).
waterway(os,in_channel).
waterway(ts,crossing_channel).

Geometric and Situational Facts

risk_collision(os,ts).
sector(os,ts,4).
starboard(os,ts).

The Own Ship is constrained by its draught while navigating in a narrow channel. It encounters a ferry crossing from its starboard side, creating a risk of collision. This situation presents a conflict between the standard crossing rule (Rule 15) and the special rules that grant priority to vessels in a narrow channel (Rule 9) or with privileged status (Rule 18).

Deductive Reasoning and Safe Action:

1) **Identify Applicable Rules:** The system's knowledge base identifies multiple potentially applicable rules based on the encoded facts:
   - *applies(os,rule9_narrow):- waterway(os,narrow)* is true because OS is in a narrow channel.
   - *applies(os,ts,rule15_crossing):- risk_collision(os,ts), not(applies(os,ts,rule13_overtaking)), not(applies(os,ts,rule14_headon))* is true due to the geometry.
   - *applies(os,rule18_privilege):- waterway(X,constrained_draught).* is true because OS is constrained by draught.
2) **Apply Precedence:** The framework consults the conflict resolver tier. Citing the principle of lex specialis, the system asserts that a vessel's specific status takes precedence. In this situation priority should be given to *rule18_privilege* over *rule15_crossing* as a vessel's constrained status is a more specific and compelling condition than a general crossing situation.
3) **Resolve Conflict:** With Rule 18 established as dominant, the OS is confirmed to have stand-on status. The crossing rule (Rule 15) is not wholly disapplied but is "moulded" by the higher-tier rule; the duty it imposes on OS is reversed, and TS becomes the give-way vessel under Rule 16.

Safe Action: *OS maintains course and speed, keeping to the starboard side of the channel. TS alters course to starboard and passes astern of OS, satisfying its duty to not impede a constrained vessel.*

Legal and operational analysis*:* A literal reading of the COLREGs triggers mutually contradictory duties: Rule 15 casts OS as the give-way vessel, whereas Rule 9(d) and Rule 18 grant it stand-on privilege. Case law resolves the apparent paradox. The UK Supreme Court in *Ever Smart v Alexandra 1* confirmed that Rule 15 is not automatically displaced by Rule 9; however, where the vessel is also *constrained by her draught*, Rule 18 supplies a more specific privilege (*lex specialis*) and must prevail. This duty to keep clear of a constrained vessel is further supported by the ruling in *The Thomaseverett (1981)* [53], where a vessel was found solely to blame under the principle of good seamanship for impeding another that was restricted in its ability to manoeuvre during a pilotage operation. This decision tree reproduces that hierarchy explicitly, avoiding the "false dilemma" that a literal parser would face. By logging the override chain, Rule 18 > Rule 9 > Rule 15, the system offers a transparent justification that aligns with prudent-seaman practice and with judicial precedent, fulfilling the twin requirements of operational safety and legal defensibility.

Scenario 2: Cascading Conflict (Multi-vessel encounter)

This scenario demonstrates how an action taken to comply with one rule can create an immediate conflict with another, requiring the system to evaluate the “traffic system as a whole”.

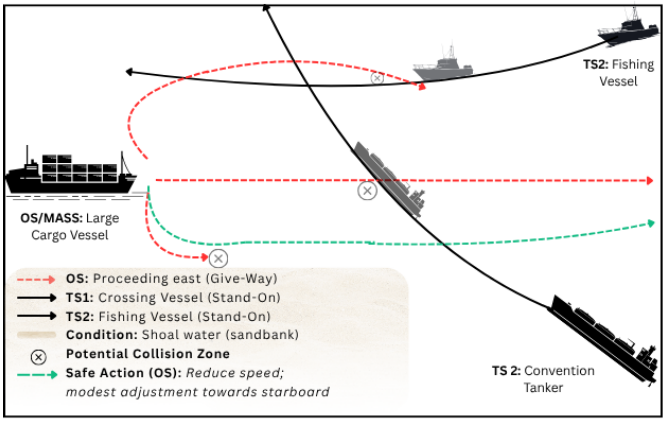

Fig. 2: **Scenario** OS must give way to TS1 but is constrained by a privileged vessel (TS2) and a shoal.

Own Ship (OS/MASS): Autonomous, large cargo vessel, proceeding east (090°) in open waters at 12 knots.
Target Ship 1 (TS1): Conventional tanker proceeding north (000°) at 12 knots. Located on OS’s starboard side, creating a crossing situation.
Target Ship 2 (TS2): Conventional fishing vessel heading west (270°) at 5 knots. Located initially to port of OS on a converging course.
Conditions: Open sea, good visibility, but a shoal water area to the immediate starboard of OS’s initial position limits evasive action in that direction.

Symbolic Encoding of the Scenario::

Vessel Facts and Status

vessel(os).
vessel(ts1).
vessel(ts2).
status(ts2, fishing).

Geometric and Situational Facts

risk_collision(os,ts1).
sector(os,ts1,4).
starboard(os,ts1).
risk_collision(os,ts2).
sector(os,ts2,28).
port(os,ts2).
waterway(os,shoal_water).

The Own Ship must give way to a crossing vessel (TS1) on its starboard side in open sea. However, its actions are severely limited by both a privileged fishing vessel (TS2) to port and a navigational hazard (shoal water) to starboard. This creates a cascading conflict where the standard give-way manoeuvre is unsafe and multiple constraints must be resolved simultaneously.

Deductive Reasoning and Safe Action:

1) **Identify Applicable Rules:**
   - *applies(os,ts1,rule15_crossing):- risk_collision(os, ts1), not(applies(os, ts1, rule13_overtaking)), not(applies(os,ts1,rule14_headon)).* is true, making OS the give-way vessel with respect to TS1.
   - *applies(ts2, rule18_privilege):- status(ts2,fishing).* is true because TS2 is engaged in fishing, making OS the give-way vessel with respect to TS2.
2) **Apply Precedence** The system identifies that OS has a give-way duty to both vessels. However, the duty owed to TS2 under Rule 18 is of a higher legal priority than the duty owed to TS1 under Rule 15. Therefore, any action taken to avoid TS1 must not create a risk for, or impede the passage of, the privileged vessel TS2.
3) **Resolve Conflict:** The standard give-way action for TS1 (a substantial turn to starboard) is rendered unsafe by the shoal water. A turn to port to pass astern of TS1 would violate the higher-priority duty to keep clear of the privileged fishing vessel, TS2. The framework, guided by Rule 8(e) and the principle of good seamanship (Rule 2), selects the minimal-risk alternative that respects the rule hierarchy.

Safe Action: *OS reduces speed substantially and makes a modest adjustment to starboard, allowing TS1 to safely cross ahead while remaining well clear of both TS2 and the shoal.*

Legal and Operational Analysis: This scenario highlights the limitation of a simple, pairwise collision avoidance system. By reasoning about all constraints simultaneously, the Rule 15 duty, the higher-priority Rule 18 duty, and the physical constraint of the shoal, the framework demonstrates a holistic situation awareness akin to that of an experienced human mariner. The decision to reduce speed conforms to prudent seamanship by creating time and space, thereby stabilising the wider traffic system as recommended in cases like The Majola II.

Scenario 3: Overtaking and Crossing in a Narrow Channel

This scenario presents simultaneous, conflicting give-way duties in a constrained environment, testing the system’s ability to apply the explicit priority embedded within the COLREGs.
Own Ship (OS/MASS): Autonomous vessel proceeding eastbound (090°) in a narrow channel.
Target Ship 1 (TS1): Cargo vessel proceeding eastbound at a slower speed in the same channel. OS intends to overtake.
Target Ship 2 (TS2): Power-driven vessel approaching from OS’s starboard side at 045°R with the intention to enter the channel, but not yet on its final approach.
Conditions: Good visibility, narrow channel conditions, and limited room for manoeuvring. No vessels have special status under Rule 18.

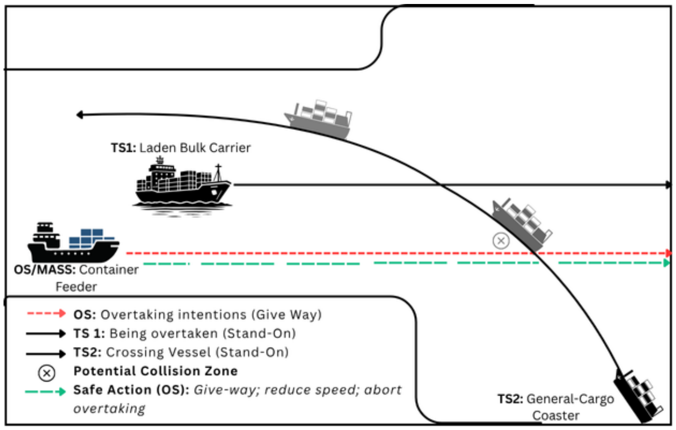

Fig. 3: **Scenario** OS has simultaneous give-way duties for overtaking (TS1) and crossing (TS2) in a narrow channel.

Symbolic Encoding of the Scenario:

Vessel Facts and Status
vessel(os).
vessel(ts1).
vessel(ts2).
waterway(os,in_channel).
waterway(ts1,in_channel).
waterway(ts2,approaching_channel)
Geometric and Situational Facts
risk_collision(os,ts1).
sector(ts1,os,16).
aft(os,ts1).
risk_collision(os,ts2).
sector(os,ts2,4)
starboard(os,ts2).

The Own Ship is in a narrow channel and faces two simultaneous give-way duties. It is overtaking a slower vessel (TS1) while also being in a crossing situation with another vessel (TS2) that is approaching from starboard. The limited space in the channel and the legal priority of the overtaking rule make it impossible to satisfy both duties with standard course alterations.

Deductive Reasoning and Safe Action:

1) **Identify Applicable Rules:**
   - *applies(os,ts1,rule13_overtaking):- risk_collision(os,ts1), overtaking_arc(ts1,os)* is true.
   - *applies(os,ts2,rule15_crossing):- risk_collision(os,ts2), not(applies(os,ts2,rule13_overtaking)), not(applies(os,ts2,rule14_headon))* is true.
   - *applies(os,ts1,rule9_narrow):- waterway(os,ts1,narrow).* is true.
2) **Apply Precedence:** The system identifies a direct conflict between the give-way duties of Rule 13 and Rule 15. The knowledge base asserts priority (rule13 , rule15). This is based on the explicit text of Rule 13(a), which states it applies "Notwithstanding anything contained in the Rules of Part B, Sections I and II...". This gives the overtaking obligation primacy, as affirmed in cases like, *the Olympian - Nowy Sacz.*
3) **Resolve Conflict** OS cannot turn to starboard to give way to the crossing vessel TS2 without violating its primary duty to keep clear of the overtaken vessel TS1, especially within the confines of the narrow channel. The framework therefore selects the only safe action permitted under Rule 8(e).

Safe Action: *OS aborts the overtaking manoeuvre, reduces speed substantially to allow TS1 to pull ahead, and maintains its position on the starboard side of the channel, thereby giving TS2 sufficient room to cross ahead safely.*

Legal and Operational Analysis: This encounter illustrates the layered nature of COLREG obligations. A literal reading presents OS with incompatible duties. By embedding the explicit textual precedence of Rule 13 and the judicial clarification from *Ever Smart* that Rule 9's priority is not yet triggered, the decision tree produces a single, coherent manoeuvre: slow down and maintain channel discipline. This solution honours all legal precedents, satisfies the prudent seaman test under Rule 2(b), and avoids the dangerous, oscillatory behaviour a rigid pairwise interpreter would exhibit.

V. Discussion and Implications

The principal contribution of this research is the development of a tier-based decision framework that formalises the International Regulations for Preventing Collisions at Sea (COLREGs) into an auditable, symbolic knowledge base suitable for Inductive Logic Programming (ILP).This approach departs from existing work in the field by directly addressing, rather than simplifying, the inherent ambiguities in maritime law. By mapping subjective clauses such as "early and substantial action" and "good seamanship" [40], [43] into a ranked rule set, the work converts qualitative maritime doctrine into machine-executable logic while retaining legal meaning. This explicit hierarchy, ordered by *lex specialis*, *lex posterior* and *lex superior* and structured with the Issue-Rule-Application-Conclusion (IRAC) loop, supplies the first end-to-end pipeline that links statutory text, case-law precedent, and operational heuristics to explainable collision-avoidance decisions.

Prevailing collision-avoidance research often treats COLREGs as a flat list focused on geometry (CPA/TCPA) [29]; even recent LLM pilots largely ignore jurisprudential refinements [54]. In contrast, this framework embeds legal precedence, for example, Rule 2(b) emergency override, Rule 9 precedence over Rule 15 confirmed in *Ever Smart* [9], and the persistent priority of overtaking duties established in Olympian-Nowy Sacz 1957 [10] into a deterministic rule engine. ILP then produces human-readable proof traces that cite every invoked clause and priority, satisfying the transparency pillar of the NIST AI-RMF [12] and the audit requirements of IMO MASS Trial Guidelines [11]. Such traceability restores a clear chain of accountability that black-box neural networks cannot provide, thereby enhancing operator trust.

A. Benefits and challenges of a socio-technical approach

Positioning MASS as socio-technical systems ensures that legal experts, mariners and engineers co-design the rule base, bridging "work-as-imagined" and "work-as-done" [55]. The explicit, explainable logic supports human oversight and adaptive trust calibration while aligning with calls for socio-technical AI governance [56]. Nevertheless, such integration is complex: maintaining consistency across human factors, institutional norms and evolving technology requires continuous curation, and partial coverage of COLREGs may leave residual risk gaps. Moreover, new hazards, cyber-security, sensor spoofing, or unforeseen human-automation interactions, must be evaluated within the same framework.

B. Scalability to new scenarios and case-law updates

ILP's generalisation from sparse examples [13], [14], [57] and its support for predicate invention enable the framework to assimilate fresh admiralty decisions or regional soft-law guidance without retraining opaque models. As courts in the US, China, or Scandinavia refine interpretations, e.g., localised traffic-separation schemes, new rules can be 'folded in' and re-ranked automatically. The same tier logic accommodates multi-vessel cascades, restricted-visibility encounters, or emerging vessel classes by extending background predicates, ensuring lifelong learning while keeping the reasoning chain auditable.

C. Implications for Marine Law and Policy

By demonstrating that qualitative duties embedded in COLREGs can be rendered machine-verifiable without eroding legal nuance, the work offers a concrete pathway for forthcoming instruments such as the IMO non-mandatory MASS Code (2025) and its mandatory successor (2028) [28]. Regulators gain an objective yard-stick for certifying "intent-based" compliance: a vessel either produces the legally ordered proof trace or it does not. Flag states and insurers can allocate liability with greater confidence, and policy-makers can draft future provisions knowing that interpretability and auditability are technically achievable. Ultimately, the framework bridges the gap between long-standing maritime jurisprudence and autonomous-ship technology, paving the way for safe, accountable and widely accepted MASS operations.

D. Limitations

Our analysis assumes perfect sensor inputs and a restricted set of COLREG clauses; restricted-visibility rules and probabilistic collision risk are left for future study. The knowledge base has yet to confront adversarial conditions such as AIS spoofing or simultaneous equipment failures.

VI. Conclusion and Future Work

This study delivers a proof-of-concept socio-technical architecture that resolves COLREG ambiguities through an eight-tier qualitative rule set, that is legally coherent anchored in *lex specialis*, IRAC reasoning and creation of symbolic rules for ILP learning and validation. By coupling each manoeuvre with a machine-generated proof trace, the controller meets emerging IMO and NIST "right-to-explanation" expectations and restores accountability that black-box AI cannot offer. Results from three worked scenarios demonstrate that the framework reproduces expert decisions while remaining fully auditable, positioning it as a practical bridge between existing maritime law and certifiable autonomous navigation. Ongoing work will (i) automate hierarchy extension and maintenance via continual ILP learning as new case law appears (see our companion article [14]), (ii) broaden the knowledge base to cover additional jurisdictions and soft-law guidance, and (iii) validate the system from high-fidelity simulation to scale-model and full-mission trials, critical steps toward demonstrably "at-least-equivalent" safety for Maritime Autonomous Surface Ships.

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