Methods for Testing COLREGS Compliance in Autonomous Surface Vehicles

by

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ABSTRACT

Globally there is an increasing number of uncrewed and autonomous surface vessels operating at sea. Preventing collisions at sea is of paramount importance to safeguard lives, protect the marine environment, and maintain smooth maritime operations. Effectively preventing collisions at sea between manned and uncrewed vessels requires that uncrewed vessels maneuver in a manner that is both safe and predictable to human mariners. Consequently, there is a pressing need to develop a comprehensive testing architecture that rigorously evaluates and verifies the level of International Rules for Preventing Collision at Sea, or "Collision Regulations" (COLREGS) compliance of autonomous marine vehicles.

To address the critical need for COLREGS compliance verification in Autonomous Surface Vehicle (ASV), this thesis introduces test cases. These test cases are designed to assess the ability of autonomous vessels to respond appropriately to various navigational scenarios and interactions with conventional, manned vessels. The development of test cases draws upon historical collision data, navigational incidents, and expert knowledge to encompass a wide range of real-world situations and with simplicity of real-world implementation in mind.

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Chapter 1

Introduction

1.1 Motivation

The number of uncrewed and increasingly autonomous vessels operating is growing globally, and with it the risk of collision involving uncrewed vehicles. COLREGS compliance is the primary mechanism by which crewed ships operate safely near one another. Effective teaming between manned and uncrewed surface vessels is of particular interest to the US Navy, who plans to add 100 large uncrewed surface vessels to the fleet over the next 30 years[1]. This effective teaming requires that human operators have trust in their uncrewed counterparts, and that trust is built through rigorous testing and validations. Additionally, global regulatory trends that are discussed in more detail in section 1.2.2 indicate that COLREGS compliance for uncrewed and autonomous ships will soon become mandatory [2], [3].

To address the critical need for COLREGS compliance verification in autonomous marine vehicles, this thesis introduces a systematic process for generating test cases. These test cases are designed to assess the ability of autonomous vessels to respond appropriately to various navigational scenarios and interactions with conventional, manned vessels. The development of test cases draws upon historical collision data, navigational incidents, and expert knowledge to encompass a wide range of real-world situations.

1.2 Other Work

1.2.1 Autonomy in the Marine Environment

Previous works in implementing COLREGS compliance in autonomous vessels have taken a variety of approaches to both defining and achieving that compliance. [4] proposes a COLREGS behavior using Mission Oriented Operating Suite, Interval Programming (MOOS-IvP) that explicitly references rules 13, 14, 15, 16, and 17, which are described briefly in table 1.1 and in more detail in section 1.4. Woerner's testing approach for the behavior considered safety (based on the number of collisions) and efficiency as well as performance in instance of more than two vessels interacting at a time [4]. Another approach in [5] used reinforcement learning and game theory to train the controller for a slow (less than 12 kt top speed)vessel to correctly identify a rule 15 situation and maneuver safely and for optimal fuel consumption. The training method used for this algorithm only considered interactions between two vessels [5]. The approach detailed in [6] plans a vessel's path based on avoiding collision with a target represented by a time-varying uncertainty model. This approach identifies if the vessel is the stand-on or give-way vessel, but assumes that the stand-on vessel does not maneuver in determining the uncertain set of locations [6], which does not capture all options available to the stand-on vessel in rule 17. A common theme in [4], [6], [5], [7] and [8] is that real-world on-water testing is expensive and impractical to generate enough test data to adequately validate navigational safety, including COLREGS compliance, so simulation is necessary.

1.2.2 Maritime Regulatory Practices

The International Maritime Organization (IMO) has recognized the need for a regulatory framework to address the growing number of uncrewed and increasingly-autonomous ships operating at sea and conducted a regulatory scoping exercise for the use of Maritime Autonomous Surface Ships (MASS) in 2021 [3]. The scoping exercise identified and prioritized regulatory instruments with gaps or themes that do not adequately cover MASS. COLREGS is one of the regulatory instruments identified as "High-Priority" for both clarifications of how existing rules map to MASS and amendments to address gaps. Some of the gaps identified deal with high-level responsibility (and liability) for uncrewed vessels. For example, Rule 2 of COLREGS as described in section 1.4.4 holds the "master of the vessel" responsible for following the contained rules; but who is the "master" of a completely uncrewed ship operating autonomously at sea? As another example, rule 5 of COLREGS states that all vessels shall always "maintain a proper look-out by sight and hearing as well as by all available means appropriate.."; does a remote operator monitoring camera feeds and radar information meet this rule? Rule 18 currently establishes a hierarchy of types of vessels and which ones must, pending a select few cases, keep out of the way of others. For example, a vessel that is "not under command", meaning that there is an exceptional circumstance (such as a propulsion or steering failure), is not required to maneuver around an unencumbered power-driven vessel. Should autonomous or uncrewed vessels be called out uniquely in this hierarchy? These three examples represent a non-exhaustive list of the types of questions that need to be answered and likely will be answered when the IMO publishes its planned MASS code. A non-mandatory version of this code is anticipated in July of this year, with the mandatory version to follow in 2028 [2]. That said, the focus of this thesis is on testing and evaluation of compliance with COLREGS rules that are less ambiguous in their applicability to MASS.

The American Bureau of Shipping (ABS), a classification society, released requirements for vessels with autonomous and remote control functions in 2022 [9]. Classification societies in the maritime industry are non-governmental organizations that establish and maintain technical standards for the construction and operation of ships and offshore structures, and issue certificates to ships and structures that comply with their standards. ABS is the largest of such societies by number of vessels and one of 12 member societies of the International Association of Class Societies. This set of ABS rules allows for the certification of various levels of autonomous function onboard vessels that can be either crewed or uncrewed, and requires that the test cases used match the conditions for which the vessel is certified. The ABS rules require that testing for COLREGS compliance be conducted, but do not establish standard tests or definitions of compliance.

1.2.3 Autonomy on Land

While the focus of this thesis is exclusively in the maritime domain, recent research on the safety compliance testing of self-driving cars was examined but found not to directly inform the methods for testing COLREGS due to fundamental differences in operational environments and system architectures. Autonomous cars typically do not utilize the "front-seat/back-seat" architecture prevalent in marine systems, which separately evaluates perception, decision-making, and control/execution mechanisms. In automotive applications, when faced with uncertainty, the preferred response is typically for the vehicle to stop, a strategy not feasible for ships which may not be able to halt and where stopping might not enhance situational safety [10] [11]. The testing strategies for automotive safety predominantly utilize simulation alongside limited but critical real-world driving to validate software systems before deployment. This extensive use of simulation allows for the modeling of various dynamic and interactive driving scenarios, which inform the development of adaptive control strategies that could not be directly applied to the slower and more complex maritime settings governed by COLREGS. Furthermore, autonomous cars often engage in proactive testing on closed tracks or designated roadways where minor collisions or near-misses are permissible to refine system responses under controlled conditions [12]. Such methods contrast with maritime testing, which must account for larger scales and cannot easily replicate high-risk scenarios due to the severe consequences of system failures at sea.

These insights illustrate that while both domains aim to enhance navigational safety through automation, the specific strategies and frameworks applied in automotive testing provide limited crossover utility for maritime applications due to distinct operational challenges and safety paradigms.

1.3 Background on Autonomy and MOOS-IvP

MOOS-IvP is an autonomy software system used extensively by marine vehicles. Mission Oriented Operating Suite (MOOS) is a middleware and was developed in 2001 at MIT for use on unmanned marine systems, and IvP is a mathematical programming model for multi-objective optimization that is used by the helm.

Back-seat driver MOOS-IvP separates vehicle control and vehicle autonomy, which allows the autonomy system to be decoupled from (and therefore developed separately from) the vehicle hardware. Figure 1.1 illustrates this relationship.

Publish and Subscribe MOOS provides a middleware framework using a publish-subscribe protocol where processes communicate through a centralized MOOS database (MOOSDB) in a star topology shown in figure 1.2. Each process, running on the same or distributed machines, defines its interface by the messages it publishes and subscribes to, which are

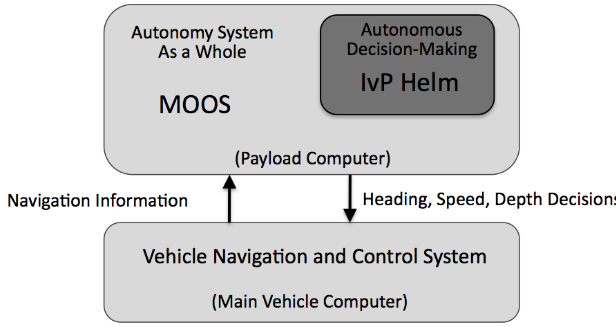


Figure 1.1: The backseat driver paradigm. Figure from [13]

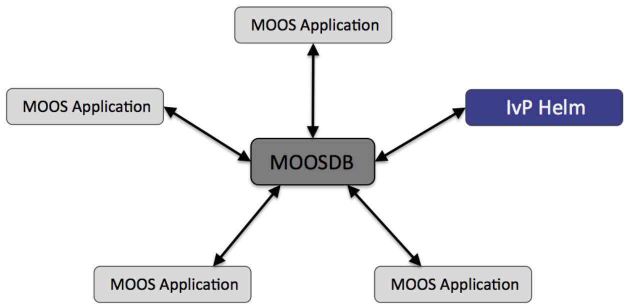


Figure 1.2: MOOS publish and subscribe architecture. Figure from [13]

primarily variable-value pairs and can include binary data. This modular approach supports high independence and interchangeability among applications, promoting easy updates and code reuse.

Behaviors and the Helm The IvP Helm operates as a single MOOS application and is central to implementing autonomous behaviors in vehicles using a behavior-based architecture. Each behavior is a self-contained module acting as a mini expert system tailored to specific aspects of vehicle autonomy. Users configure these behaviors based on mission specifics such as waypoints, search areas, and desired vehicle speeds, as well as state spaces that dictate active behaviors and state transitions based on the vehicle's situation.

In operation, the IvP Helm frequently (one to four times per second) generates IvP objective functions from active behaviors, each defining a piecewise linear utility function over the vehicle's decision space (e.g., heading, speed, depth). These functions are then optimized collectively by the IvP solver through multi-objective optimization, producing a single optimal vehicle action that is published to the MOOSDB.

The solver's effectiveness in reconciling competing behaviors hinges on its ability to rapidly solve the optimization problem constructed from the weighted sum of all active IvP functions. While traditional action selection methods, such as the Subsumption Architecture, prioritize behaviors sequentially to exclude lower-priority actions, and vector summation methods average competing behaviors' outputs, both have notable limitations. These conventional methods often fail to capture the optimal action, especially under complex and conflicting behavioral demands.

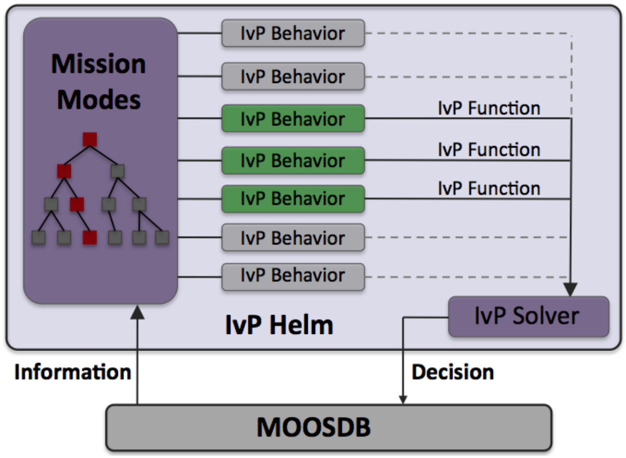


Figure 1.3: Helm architecture. Figure from [13]

The IvP Helm's method surpasses these older models by employing multi-objective optimization, providing a more accurate and computationally efficient means to determine the best action from multiple competing behaviors. This approach is particularly viable in the IvP Helm and has been proven effective across various vehicle platforms including indoor robots, land vehicles, and marine vehicles. This system represents a significant advancement in behavior-based vehicle autonomy, leveraging modern computational techniques to enhance decision-making processes under dynamic and diverse operational conditions.

1.3.1 Simulation and select MOOS Applications

In addition to its uses on real autonomous vehicles, MOOS-IvP offers a flexible framework that allows researchers and developers to model the behavior of autonomous vehicles in a controlled, virtual environment. The following sections detail a subset of the MOOS applications that are crucial to understanding this thesis.

Figure 1.4 shows a standard topology of multiple MOOSDB's running in a singe mission; in simulation the shoreside and vehicle communities can either run on separate hardware was they would in the case of real vehicles OR all run on a single computer. Without the automation introduced by Monte-MOOS and described in section 1.3.2, simulations are launched by the user using a bash script and started by clicking a button on the pMarineViewer interface. Simulations end when the user stops them.

pNodeReporter The pNodeReporter is a MOOS application that generates node reports for sharing data between vehicles[14]. A node report is a standard message that contains information like position coordinates, speed, heading, and other state variables.

uFldNodeComms The uFldNodeComms application functions as an intermediary for managing communication between vehicles in simulations. It primarily handles node reports and node messages, determining which information gets passed between vehicles based on specific criteria like inter-vehicle range. The tool subscribes to incoming node reports, retains the latest for each vehicle, and redistributes them to other vehicles based on these criteria

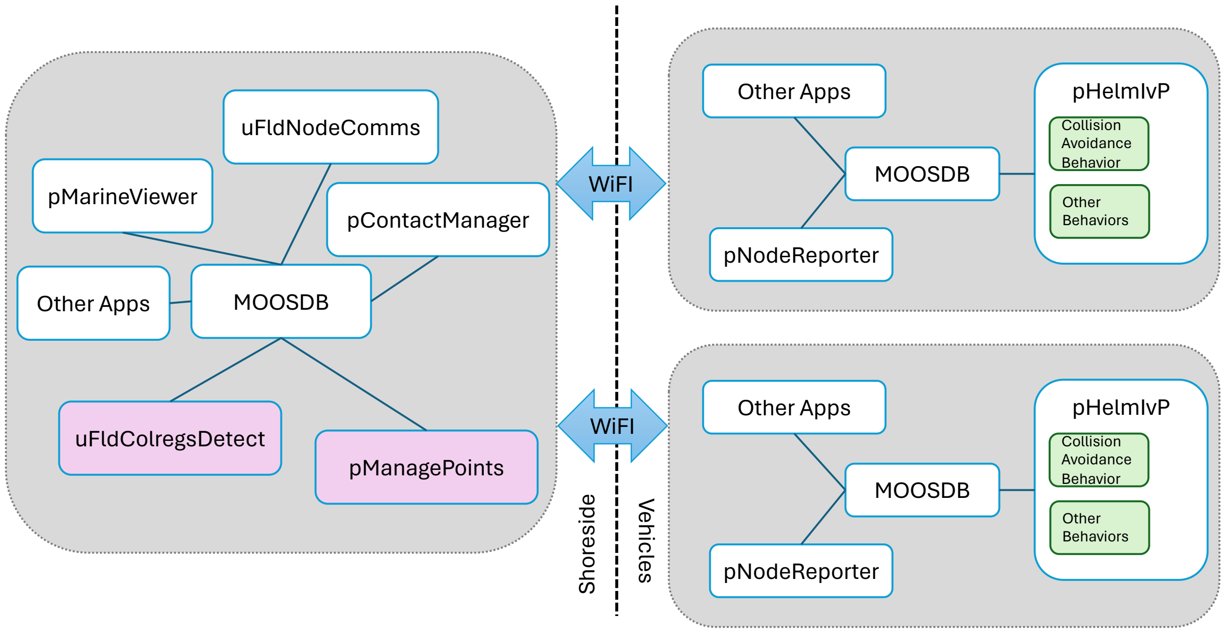


Figure 1.4: Simulation topology showing the shoreside and vehicle MOOSDB's. Application shown in pink are contributions of this thesis to the MOOS code base. pManagePoints is described in section 2.1.1

[15]. uFldNodeComms is used to artificially degrade detection range for testing as described in section 1.6.2.

uFldColregsDetect uFldColregsDetect is an incremental modification to the existing uFldCollisionDetect, which is designed to monitor and assess potential collision scenarios between vehicles by analyzing their closest point of approach (CPA). It categorizes interactions into encounters, near-misses, or collisions based on predefined range thresholds [16]. uFldColregsDetect maintains all functions of uFldCollisionDetect and classifies all encounters, near-misses, and collisions by COLREGS rule as described in section 1.4.

pMarineViewer The pMarineViewer is a MOOS application that is used for graphical rendering of marine vehicles and their operational data during missions. It provides a geographic display area to monitor multiple vehicle tracks. The application can also be configured for command and control capabilities, enabling user interactions through customizable action buttons and mouse controls for direct manipulation of vehicle operations.

pContactManager pContactManager is an application that receives node reports and queues collision avoidance behaviors based on user-configured range criteria. It is discussed in more detail in section 1.5.

pManagePoints pManagePoints is a contribution of this thesis that is crucial to the implementation of the proposed cage match test mission. The test mission is described in section 2.1 and pManagePoints is described in more detail in section 2.1.1.

1.3.2 Automated Simulations

Simulations were automated using Monte-MOOS, a distributed simulation toolbox for testing missions in MOOS-IvP developed by Kevin Becker [17]. Monte-MOOS is a largely bash script based set of tools that allowed a large number of simulations to be conducted and analyzed in an efficient manner. To illustrate the value of Monte-MOOS, this thesis, over the course of many multi-vehicle simulations, contains data from 13,167 vehicle-hours (that is about 548 vehicle-days, or roughly 1.5 vehicle-years) and 135 days of multi-vehicle simulation. In other words, 3 to 5 vehicles would have needed to run continuously for 135 days to gather the same amount of useful data.

Section 1.3.1 explains how simulations are generally executed without Monte-MOOS. Monte-MOOS allows the user to launch a simulation with or without pMarineViewer and automatically starts the mission once all MOOS communities have launched, rather than waiting for a user to initiate. Monte-MOOS ends the mission when a user-defined criteria (which may be elapsed time) is met then runs the user-provided data processing script and starts the next queued mission.

1.4 Background on COLREGS

The International Rules for Preventing Collision at Sea (COLREGS), or the "Rules of the Road", another name for COLREGS (RoR), were developed by the organization that eventually became the International Maritime Organization (IMO) and made effective in July of 1977[18]. The US has separate “Inland” rules that apply in inland US waters that are not included in this thesis.

COLREGS is divided into five parts that each covers a specific aspect of vessel operations. This thesis examines compliance with parts A and B only. Part A of COLREGS encompasses the General Rules, which outline fundamental principles and definitions essential for understanding the regulations. It establishes key concepts such as the definitions of different types of vessels and responsibilities of vessels in various scenarios[18]. Part B lists Steering and Sailing Rules, providing guidance for maneuvering. It is further sub-divided into Sections I, II, and III. Section I applies to vessels in any condition of visibility (i.e. at all times); Section II only applies to vessels that are in sight of one another; Section III only applies in conditions of restricted visibility[18]. *It is worth noting that this section only covers interactions between two vessels. Interactions between more than 2 vessels are not covered anywhere in COLREGS.* Part C covers Lights and Shapes, detailing the lighting and signaling requirements that vessels must adhere to in order to ensure visibility and provide information about their status and intentions to other vessels[18]. Part D covers Sound and Light Signals, which provide a means of communication between vessels regarding maneuvering intentions. It specifies the different sound signals vessels should use in various scenarios, such as foggy

Rule	Title: brief description
2	Responsibility: May disregard all other rules to avoid immediate danger
8	Action to Avoid Collision: Action to avoid collision should be visually obvious to other vessels, shall result in passage at a safe distance
13	Overtaking Situation: The overtaking vessel gives way
14	Head-on Situation: turn to starboard/pass port-to-port if prudent
15	Crossing Situation: furthest right vessel stands-on, other gives-way
16	Action by Give-way Vessel: take early and substantial action to keep clear
17	Action by Stand-on Vessel: maintain course and speed unless doing so will result in a collision

Table 1.1: Selected rules from COLREGS

conditions or other conditions in which visibility is restricted, and the situations where light signals should be employed[18]. Part E addresses the specific requirements for vessels operating in restricted visibility, emphasizing the precautions and actions to be taken to prevent collisions when visibility is severely limited, such as in fog or heavy rain[18]. Part F includes additional rules for vessels and aircraft in distress, highlighting the measures to be taken for their identification, assistance, and avoidance by other vessels[18].

This thesis establishes test cases in which vessels must effectively apply rules 2, 8, 16, and 17 in the situations described in rules 13, 14, 15, and interactions of more than two vessels. Table 1.1 briefly describes these rules.

To establish which rule instances are observed in each test mission described in Chapter 2, simulations are conducted and the occurrences of the following are tracked:

- Overtaking situations as defined in rule 13
- Head-on situations as defined in rule 14
- Crossing situations as defined in rule 15
- Situations in which more than two vessels meet

1.4.1 Overtaking Situation (Rule 13)

An overtaking situation can occur between any two vessels and is defined as one vessel approaching another from "a direction greater than 22.5°abaft [behind] her beam" as illustrated in 1.5. Human mariners can easily determine if they are overtaking a vessel at night because only the stern light of the vessel being overtake is visible. If an encounter between two vessels initiates as an overtaking situation, the overtaking vessel remains the give-way vessel until the situation is cleared; she cannot maneuver to create another type of situation in which she becomes the stand-on vessel.

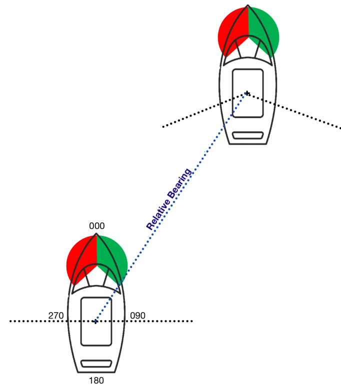


Figure 1.5: An example of an overtaking situation.

The MOOS application uFldColregsDetect classifies an encounter as an overtaking situation if both of the following criteria are met:

- The contact is forward of ownship's beam. In other words, the contact's relative bearing is between 000 and 090 OR 270 and 360.
- Ownship is greater than 22.5°behind the contact's beam. Or, target angle is between 112.5 and 247.5.

1.4.2 Head-On Situation (Rule 14)

The head-on situation is the most ambiguously defined COLREGS geometry. It occurs between two power-driven vessels when they encounter on a "reciprocal or nearly reciprocal course so as to involve risk of collision", which is further described as observing both sidelights and masthead lights in a line at night. The US Navy trains mariners that a course difference of 6°or less when the vessels have relative bearings within 6°of each others bows constitutes "nearly reciprocal" as illustrated in 1.6. In a head-on situation there is no stand-on or give-way vessel; both vessels are required to alter course to starboard (turn right) and required to do so when in doubt if the situation is head-on or not. uFldColregsDetect classifies an encounter as a head-on situation if all of the following criteria are met:

- The relative bearing of contact from ownship is between 000 and 006 OR between 354 and 360.
- The target angle is between 000 and 006 OR between 354 and 360.

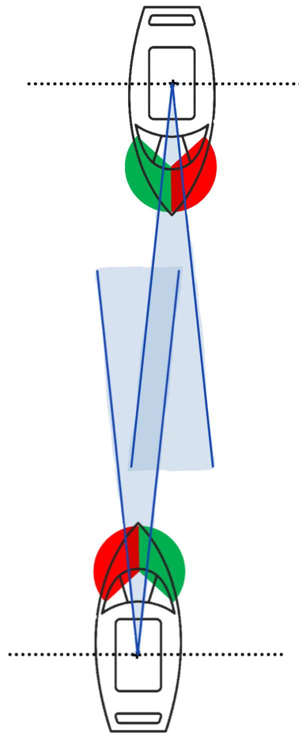


Figure 1.6: An example of a head-on situation. The 6°cone in front of each vessel is shown in light blue.

1.4.3 Crossing Situation (Rule 15)

A crossing situation as defined by rule 15 exists when "two power-driven vessels cross so as to involve a risk of collision" so this situation catches all instances in which the geometry of the encounter does not meet the criteria for head-on or overtaking. In a crossing situation, the vessel that is to port of the other is the give-way. The other is the stand-on. Notice in both examples of a crossing situation shown in 1.7, the give-way vessel is positioned so that she sees the stand-on vessels red side light, and this helpful visual cue is used to train human mariners. uFldColregsDetect classifies all encounters that do not meet the criteria for head-on or overtaking as crossing.

1.4.4 Rule 2 Situation

Compliance with rules 13, 14, and 15 will result in a safe maneuver in all cases in which two vessels encounter each other AND there are no other factors that impede their abilities to maneuver. However, ships frequently operate in environments where this not the case and instances may arise where strict compliance with rule 13, 14, or 15 results in an unsafe condition or even a collision. To this effect, rule 2 (which applies to all vessels at all times) dictates that vessels depart from the rules where necessary to avoid immediate danger.

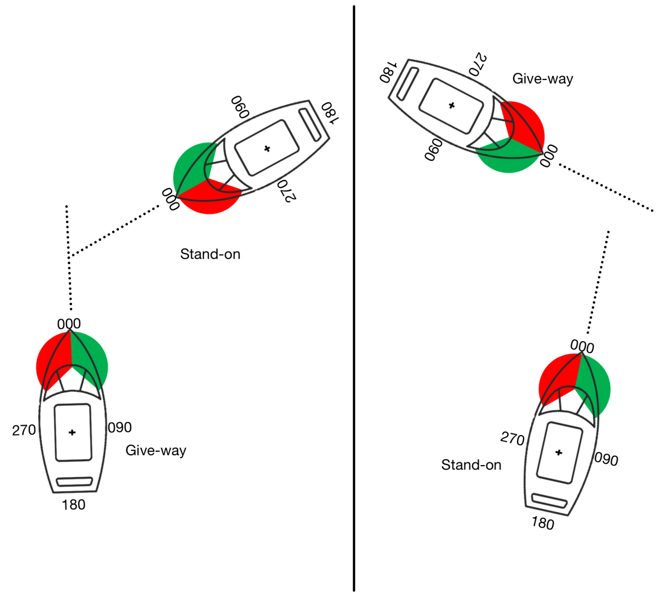


Figure 1.7: Two examples of a crossing situation

Example: Simultaneous crossing and overtaking

Figure 1.8 depicts a scenario in which the the orange vessel case competing obligations to the blue and purple vessels. The blue vessels is attempting to overtake the orange vessel, so the orange is the stand-on and shall maintain course and speed. However, the orange vessel is in a crossing situation with the purple vessel in which she is the give-way vessel and should maneuver to pass astern of purple (alter course to starboard, or, turn right). While rule 17 provides the stand-on vessel with options to maneuver in certain circumstances, none of these circumstances are met at the outset of this encounter (assuming that all three vessels are operating at safe speeds and not in extremis). In this situation, the orange vessel must "violate" rule 17 to comply with rule 2 and avoid collision. This example further deviates from COLREGS in that there are more than two vessels interacting with each other; while COLREGS does not dictate the actions of each vessel in these situations and treating each encounter separately may be unsafe, ships still have an obligation to avoid collision.

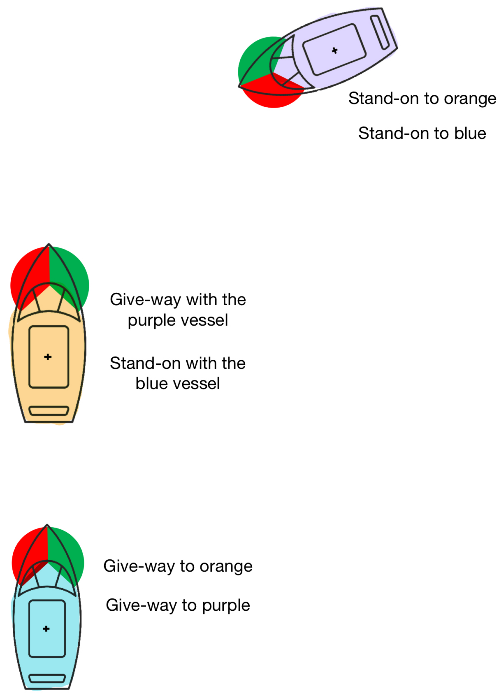


Figure 1.8: A vessel is simultaneously the give-way and stand-on vessel as she encounters two other vessels at the same time.

Example: Hazard to safe navigation

Figure 1.9 depicts a head-on scenario in which the purple vessel does not have the option of turning right as dictated by rule 14 because there is a navigational hazard off her starboard side. To maneuver safely she should turn to port sufficiently such that the orange vessel can pass safely without altering her course, even though this action "violates" the actions outlined in rule 14.

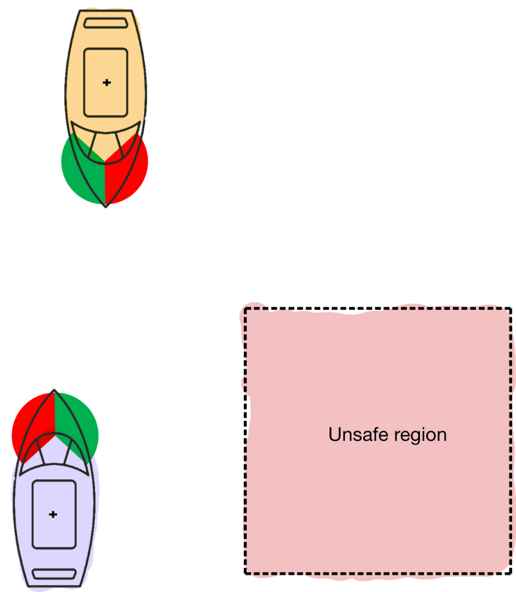


Figure 1.9: In the situation depicted here, the purple vessel, that is in a head-on situation with the orange vessel, would usually turn right to avoid collision. However, doing so would result in the purple vessel entering the "unsafe region". In this encounter, a safe option is for the purple vessel to alter course to port (left) and the orange vessel to continue straight so that the vessels do not collide or enter the unsafe region.

1.4.5 Multiple Simultaneous Encounters

As discussed in the previous section and depicted in 1.8, vessels may interact with more than one other vessel as a time. uFldColregsDetect sorts each one-on-one interaction into the geometric cases defined by rules 13, 14, and 15, but also tracks the number of active encounters each vehicle is processing at a time. An encounter starts when a vessel identifies that the risk of collision with another vessel exists (a collision avoidance behavior spawns) and ends when the vessels pass their CPA.

1.4.6 Definitions

In an interaction between two vessels, COLREGS establishes one vessel as the stand-on vessel and one as the give-way vessel. Generally, the give-way vessel should maneuver around the stand-on vessel.

1.4.7 Action by the Stand-On Vessel (Rule 17)

Part a of this rule states that the stand-on vessel should maintain course and speed while allowing the give-way vessel to maneuver to avoid them. However, parts a(ii) and b state that if the give-way vessel does not take appropriate action, the stand-on vessel is obligated to maneuver to avoid collision.

1.5 Contact Perception Pipeline

The contact pipeline provides a framework for understanding the steps that must occur for a ship to successfully avoid collision. These steps hold for both human operators and autonomous systems.

Detection The contact pipeline begins when one ship initially detects another. Since rules 13, 14, and 15 only apply to vessels in sight of one another, the crewed-ship analog to this is when one watch-stander looks out the window and sees another ship. For an uncrewed ship, this is when the ship's sensors detect a contact. For the simulated USV's within MOOS-IvP, this is the range at which uFldNodeComms is configured to pass node reports between vehicles. A node report is published frequently by each vehicle that contains state information such as the vehicle's name, position, heading, speed, type of vessel, and current helm state. uFldNodeComms, running on the shore side, passes this information between vehicles based on configured criteria.

Decision The next phase of the contact pipeline occurs when a ship makes a decision regarding the risk of a contact poses. Or, in other words, does a risk of collision exist? On crewed ships this occurs when watch-standers observe bearing rate and range to make this determination. In MOOS-IvP, pContactManager handles this step. pContactManager generates alerts that are passed to the helm based on the range and anticipated CPA of contacts. An alert is generated if a contact either is within the current alert range (contact A in figure 1.10), or is within the cpa range *and* has an anticipated CPA within the alert range (contact B in figure 1.10. Contacts that are outside the alert range and have an anticipated CPA outside the alert range do not generate alerts (contacts D and C in figure 1.10.

Action The final phase of the contact pipeline occurs when a ship maneuvers to avoid a contact. In MOOS-IvP, this occurs when the helm acts based on the input of the COLREGS or COLAV behavior. The function of the helm is described in section 1.3.

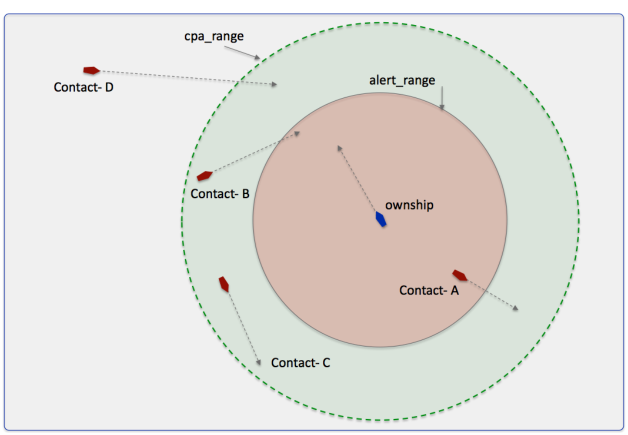


Figure 1.10: Alert triggering based on range and CPA by pContactManager. Figure from [19]

1.6 Simulation Plan

To establish that the two proposed test missions described in Chapter 2 generate instances in which vessels encounter the rules described in section 1.4, a set of baseline simulations in which all participant vessels are not maneuvering to avoid collision is conducted. These results are explained in section 2.3. Once the tests missions are established to address all rules of interest, the missions are used to evaluate the performance of a COLREGS behavior in various situations selected for their real-world applicability. The following were varied to create unique test configurations:

- Number of participants: Instances of 3, 4, and 5 participating vehicles are evaluated. 2 vehicle missions were not included because they cannot generate multi-contact interactions as described in section 1.4.4.
- Degree of Compliance: Compliance refers to participants either attempting or not attempting comply with COLREGS. While professional mariners can generally be counted on to maneuver safely and comply with COLREGS, they do not operate all of the ships at sea. Vessels that are either ignorant of or display a flagrant disregard for the RoR, are a very real type of encounter uncrewed vessels should be prepared to handle safely. Three different compliance combinations described in section 1.6.1 are evaluated.
- Perception Quality. Perception quality refers to the range at which contacts detect each other. While this is varied, it is not reduced to the point that the rules transition from those applying to vessels in sight of one another to those that apply in restricted visibility as explained in section 1.4. Two different categories of perception category described in section 1.6.2 are evaluated.

1.6.1 Compliance Combinations

Maximum Compliance In this instance, all participating vessels are attempting to comply with COLREGS. This will be referred to as "full compliance" throughout this paper. Results are presented in section 3.2.3.

Mixed Compliance - Responsible In this instance, one participating vessel is only attempting to avoid collision, not to comply with COLREGS. All other participants are attempting to comply with COLREGS. This will be referred to as "responsible non-compliance" throughout this paper. Results are presented in section 3.3.3

Mixed Compliance - Reckless In this instance, one participant is not attempting to avoid collision at all. All other participants are attempting to comply with COLREGS. This will be referred to as "reckless non-compliance" throughout this paper. Results are presented in section 3.4.3

1.6.2 Perception Quality Categories

Perfect Perception In this instance, all participants have perfect perception, meaning that each participants knows the location, course, and speed of all other participants at all times during the simulation, regardless of the range between two participants. This is implemented in MOOS by setting range at which vehicles pass node reports to exceed the size of operating region.

Imperfect Perception In this instance, detection as described in section 1.5 occurs inside the range at which the contact manager assesses a situation. Detection is controlled in MOOS simulations by reducing the range at which vehicles pass node reports.

1.7 Structure of This Thesis

Chapter 2 of this thesis introduces the cage match test mission and describes the jousting test mission, which was first introduced by Thales-UK, a British defense contractor. Included in chapter 2 are simulation results to characterize which rule cases as described in section 1.4 occur. Chapters 3 and 4 use the test missions described in chapter 2 to rigorously test a COLREGS behavior in the scenarios described in section 1.6.

Chapter 2

Missions

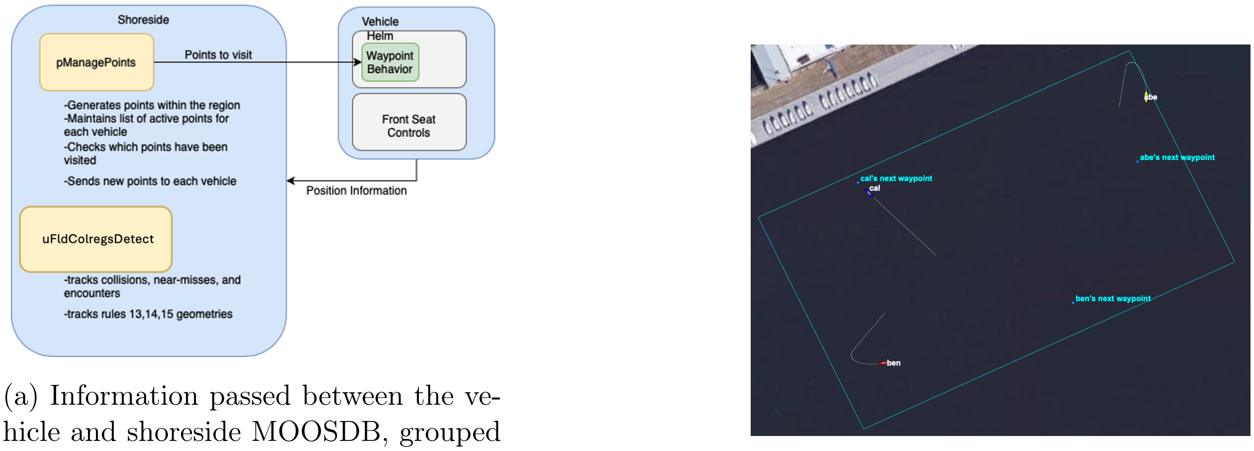
This chapter describes the cage match mission, which is a unique contribution of this thesis, and the jousting mission, which is not a unique contribution of this work. This chapter also presents the results of baseline simulations of both missions in which participating vehicles are *not* attempting to avoid collision to establish which rule cases as outlined in section 1.4 appear in each test. While the jousting mission itself is not a unique contribution of this thesis, this analysis of the jousting mission as a test for particular COLREGS occurrences is.

2.1 Cage Match Mission

The cage match mission is designed to be easy to implement both in simulation and on-water and to be sufficiently random to avoid training to the test. In the baseline cage match, vehicles are deployed in a defined region (the cage). Each vehicle is given a randomly generated initial point in the cage to visit. As vehicles visit their points, new single points are generated so that each vehicle always has a user-defined minimum number of points in their queue to visit. Figure 2.1b is a screen capture of a three-vehicle instance of the cage match mission after initial launch.

2.1.1 Implementation

The cage match mission is controlled by a single MOOS application that runs on the shore-side MOOS community, pManagePoints. For each vehicle in the mission, pManagePoints generates and assigns random points to each, tracks if a point has been visited by its assigned vehicle, and sends updates to the waypoint behavior running on the helm of each vehicle. At startup, pManagePoints begins receiving each vehicle's node reports and sends initial points to each vehicle. In each iterate loop of pManagePoints, functions 1 and 2 are called to check which points have been visited and generate a new point if needed. uFldColregsDetect is a modification to the existing MOOS Application uFldCollisionDetect that tracks the occurrences of overtaking, head-on, and crossing situations in addition to collisions and near-misses. Figure 2.1a depicts this implementation.



(a) Information passed between the vehicle and shoreside MOOSDB, grouped by applications required to implement the cage match mission

(b) Cage match mission with three participants

Figure 2.1: Example instance of the cage match mission after initial launch. The light blue rectangle shows the region in which points are generated. Each vehicles next point to visit is labeled. In this moment, none of the particapnts are interacting.

Algorithm 1 updatePoints()

$N \leftarrow$ number of vehicles
$n \leftarrow$ minimum unvisited points required
$m \leftarrow$ each vehicle's unvisited points
while $i < N$ **do**
    while $m < n$ **do**
        generateNewPoint(region)
        send point
    end while
end while

Algorithm 2 checkVistited()

$N \leftarrow$ number of vehicles
$m \leftarrow$ each vehicle's unvisited points
while $i < N$ **do** update vehicle position from node report
    while $j < m$ **do**
        calculate distance between position and unvisited point
        if distance $<$ capture radius **then**
            point has been visited, remove from unvisited points
        end if
    end while
end while

Algorithm 3 generateNewPoint(region)

```
randomly generate a newPoint in the region
calculate distance between newPoint and all activePoints
if distance < minimum distance then
    generateNewPoint(region)
end if
Return newPoint
```

2.1.2 Parameters

Every helm behavior running on each vehicle has user-defined parameters that impact performance. The following parameters were initially set based on values historically used in other similar missions conducted safely and *not* varied over the course of this thesis:

- Waypoint Behavior - Priority Weight: every behavior has a priority weight that determines the "height" of the objective function generated. The waypoint behavior was set to the default weight of 100.
- Waypoint Behavior - Capture Radius: The tolerance for determining a vehicle has "arrived" at a waypoint. 2m
- Waypoint Behavior - Speed: The speed at which a vehicle travels between waypoints. This should be lower than the vehicles maximum speed to allow the vehicle flexibility in maneuvering. 1.2 m/s
- AvdColregs/AvdCollision Behavior - Completed Distance: The range that once the contact exits, the behavior stops producing an objective function. 30m
- AvdColregs/AvdCollision Behavior - CPA distance of maximum utility: The CPA range to a contact outside which any considered maneuvers will generate the maximum utility. 14m
- AvdColregs/AvdCollision Behavior - CPA distance of minimum utility: The CPA range to a contact inside which any considered maneuvers will generate the minimum utility.6m
- AvdColregs/AvdCollision Behavior - Priority weight, inner range: Range to contact within which the behavior has maximum priority weight. 10m
- AvdColregs/AvdCollision Behavior - Priority weight, outer range: Range to contact outside which the behavior has zero priority weight, 25m
- AvdColregs/AvdCollision Behavior - Priority weight grade: Grade of priority growth as the contact moves from the outer range to the inner range. The options are linear, quadratic, or quasi. linear

The priority weight for the AvdColregs or AvdCollision behavior is set to either 300 or 0 depending on the compliance configuration as described in section 1.6.1. In addition to the vehicle behavior parameters unique to the MOOS-IvP implementation, generic variations on the cage match mission can be achieved by varying the number of participating vehicles and the size of the region. The region used in all of these simulations a practical region used for on-water testing at the MIT sailing pavilion. The implementation described in section 2.1.1 also includes a user-defined minimum distance between newly generated points and existing unvisited points in the region. This is included for safety in real world testing, and was set to 10m for all simulations conducted in this thesis based on the speed, size, and maneuverability of available test platforms.

2.2 Jousting Mission

In the jousting mission, participating vehicles are randomly assigned a starting position on a circle and all attempt to cross the circle at the same time. After the initial crossing, vehicles return to their starting positions on the circle and cross again. Figure 2.2 shows an instance of the joust mission with four vehicles during their second pass through the circle. The action of participating vehicles repeatedly driving a straight line across the circle is achieved through the use of the Leg-run behavior, documented in <**empty citation**>

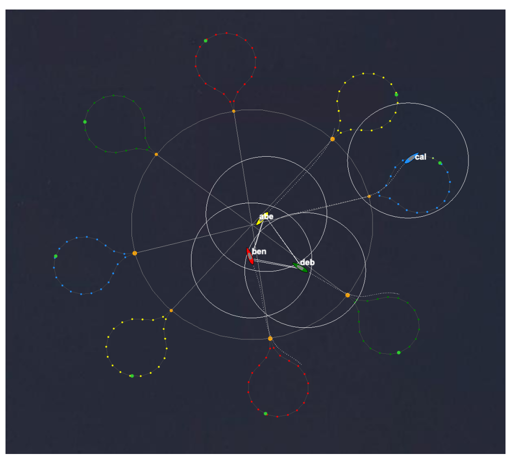


Figure 2.2: Image of a 4-participant jousting mission. The large circle contains the starting locations of each vehicle. The small circles centered around the vehicles show the alert range as described in section 1.5. The lines connecting vehicles indicate that the connected vehicles are engaged in an encounter. In this instance, abe, ben, and deb are encountering each other. Cal is conducting a williamson turn to make another pass through the large circle.

2.2.1 Parameters

The AvdColregs and AvdCollision behaviors tested with this mission use the same parameters detailed in section 2.1.2. The other behavior that participants are fulfilling in this mission, the Leg-run behavior, has a priority weight of 100. Generic variations of the jousting mission can be achieved by varying the number of participating vehicles and the size of the circle. A minimum or maximum angular separation between participants on the circle can be enforced if desired, and this parameter is likely useful in forcing more of a particular rule case (13, 14, or 15) to occur.

2.3 Mission Performance

Of the parameters described in section 1.6, number of participating vehicles is the only one that impacts the number of encounters that occur; compliance and communications impact behavior during encounters, but not the occurrence of or type of encounter. When the goal of a test is to evaluate how vessels perform while interacting with each other, time in which vehicles are not interacting provides no useful information. Figure 3.1a is a helpful visualization from a 1-hour simulation of the cage match mission with 3 vehicles for this metric. Of particular interest is the relative amount of time each vehicle spends interacting with more than one other at the same time, as explained in section 1.4.4. To establish the proposed tests, a set of simulations in which all participating vehicles are recklessly non-compliant (so, in other words, not making any maneuvers to avoid collision) was conducted to ensure that the vessels were placed in encounters in which maneuvering was required to avoid collision

The statistical analysis of each mission's performance assumes that the occurrences of each rule case as well as the occurrences of collisions and near-misses follow a Poisson distribution, which is appropriate for events that are independent and occur at a constant mean rate over the course of the simulation [20].

2.3.1 Cage Match Performance

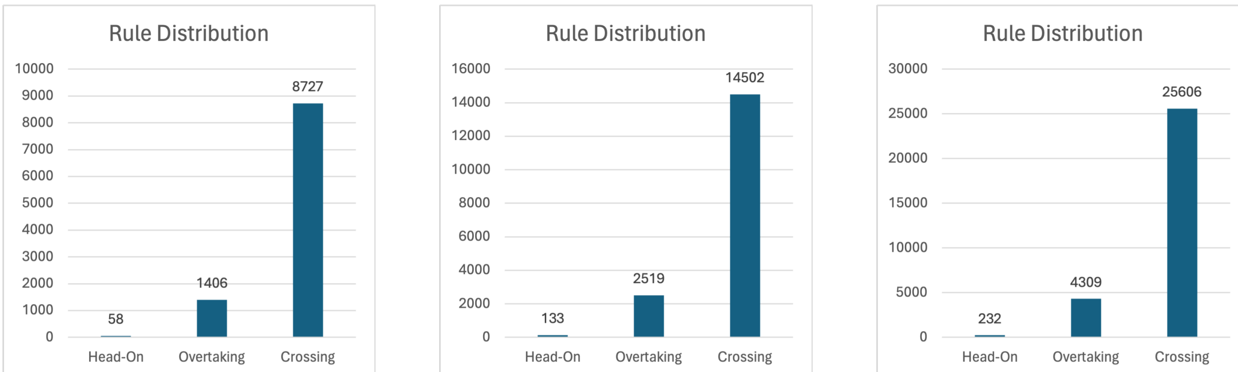
Table 2.1 lists the average percentage of total simulation time vehicles spend at each level of interaction, along with the standard deviations and total simulation time each set of results is extracted from. Crossing and overtaking situations occurred in all 1-hour simulations. Head-on situations occurred in 25% of 3-vehicle simulations, 55% of 4-vehicle simulations, and 73% of 5-vehicle simulations. Figure 2.3 depicts the data summarized in table 2.2. Table 2.3 summarizes the total number of collisions and near-misses, as well as these counts by rule, for the cage match baseline mission.

Participants	**Dead Time**	**1 other**	**2 others**	**3 others**	**4 others**	**Total Hours**
3	33.73% (6.33%)	35.35% (5.15%)	32.02% (6.38%)	-	-	104
4	29.63% (5.34%)	30.47% (4.21%)	27.08% (3.84%)	12.82% (8.53%)	-	99
5	26.26% (4.20%)	26.74% (3.48%)	25.23% (2.79%)	17.44% (5.91%)	4.32% (5.91%)	100

Table 2.1: Average percentage of total simulation time spent at each level of interaction in the cage match mission. Standard deviations shown in parentheses.

Participants	Total Encounters	Head-On Encounters	Overtaking Encounters	Crossing Encounters
3	10,191	58	1,406	8,727
4	17,154	133	2,519	14,502
5	30,147	232	4,309	25,606

Table 2.2: Counts of each rule occurrence in the cage match baseline mission.



(a) 3 Vehicle (b) 4 Vehicle (c) 5 Vehicle

Figure 2.3: Rule-case occurrences in the baseline cage match mission for each number of participating vehicles

	Head-On			Overtaking			Crossing				
Participants	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Total Collisions	Total Near-Misses
3	58	16	7	1,406	157	28	8,727	584	123	158	757
4	133	48	11	2,519	329	77	14,502	977	235	323	1354
5	232	82	24	4,309	625	155	25,606	1,933	427	606	2640

Table 2.3: Collisions and near-misses by rule type for each number of vehicles in the baseline cage match mission.

		Head-On			Overtaking			Crossing			Totals		
	Participants	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Total Encounters	Total Collisions	Total Near-Misses
Cage Match	3	0.41	0.08	0.02	12.81	1.27	0.17	82.15	5.16	0.97	96.09	1.28	6.76
	4	1.12	0.35	0.05	24.45	2.96	0.60	144.10	9.25	2.07	170.68	2.91	12.95
	5	2.02	0.64	0.14	41.80	5.76	1.31	252.92	18.47	3.86	298.07	5.58	25.39
Joust	3	2.53	1.37	0.02	6.82	0.04	0.00	147.58	23.23	1.33	157.71	1.39	24.92
	4	10.07	6.62	0.25	12.87	0.07	0.01	296.50	54.65	2.95	320.68	3.31	61.84
	5	16.49	10.58	0.57	23.67	0.37	0.00	499.83	87.46	5.82	541.58	6.57	99.09

Figure 2.4: Lower bounds of the 95% confidence intervals for the instances of each event per hour of simulation assuming a Poisson distribution by number of participants for the baseline cage match and joust missions. Values < 1 are denoted in red.

		Head-On			Overtaking			Crossing			Totals		
	Participants	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Encounters	Near-Misses	Collisions	Total Encounters	Total Collisions	Total Near-Misses
Cage Match	3	0.70	0.23	0.12	14.23	1.75	0.37	85.67	6.07	1.39	99.89	1.76	7.80
	4	1.57	0.62	0.18	26.44	3.68	0.95	148.87	10.49	2.68	175.87	3.62	14.41
	5	2.62	1.00	0.34	44.38	6.74	1.79	259.20	20.19	4.68	304.87	6.54	27.41
Joust	3	3.19	1.87	0.12	7.89	0.16	0.00	152.40	25.17	1.82	162.70	1.90	26.92
	4	11.35	7.66	0.48	14.31	0.22	0.03	303.26	57.57	3.66	327.70	4.06	64.95
	5	18.11	11.89	0.91	25.60	0.64	0.08	508.59	91.15	6.80	550.70	7.61	103.01

Figure 2.5: Upper bounds of the 95% confidence intervals for the instances of each event per hour of simulation assuming a Poisson distribution by number of participants for the baseline cage match and joust missions. Values < 1 are denoted in red.

2.3.2 Joust Performance

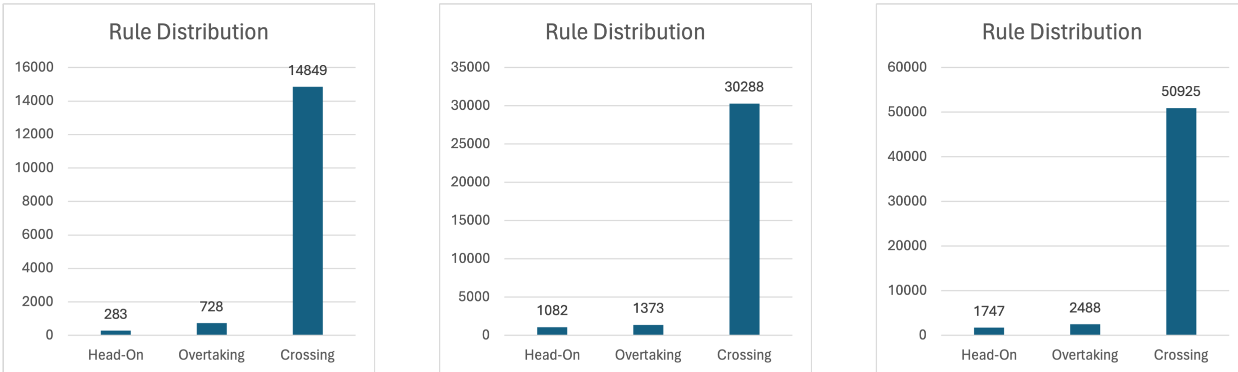
Table 2.4 lists the average percentage of total simulation time vehicles spend at each level of interaction, along with the standard deviations and total simulation time each set of results is extracted from. Crossing and overtaking situations occurred in all 1-hour simulations. Head-on situations occurred in 10% of 3-vehicle simulations, 10% of 4-vehicle simulations, and 15% of 5-vehicle simulations. Table 2.5 summarizes the data depicted in figure 2.6

Participants	Dead Time	1 other	2 others	3 others	4 others	Total Hours
3	36.05% (6.80%)	35.89% (5.45%)	26.44% (8.63%)	-	-	99
4	28.79% (4.42%)	28.59% (4.02%)	26.44% (3.56%)	15.17% (8.75%)	-	101
5	26.04% (4.61%)	25.89% (4.01%)	23.87% (3.60%)	17.46% (5.54%)	6.38% (7.11%)	101

Table 2.4: Average percentage of total simulation time spent at each level of interaction in the joust mission. Standard deviations shown in parentheses.

Participants	Total Encounters	Head-On Encounters	Overtaking Encounters	Crossing Encounters
3	15,860	283	728	14,849
4	32,743	1,082	1,373	30,288
5	55,160	1,747	2,488	50,925

Table 2.5: Counts of each rule occurrence in the joust baseline mission.



(a) 3 Vehicle (b) 4 Vehicle (c) 5 Vehicle

Figure 2.6: Rule-case occurrences in the baseline joust mission for each number of participating vehicles

2.3.3 Commentary on Mission Performance

The missions perform similarly when looking at the portion of time participants spend interacting with each other and at each level of simultaneous interactions. Based on the averages and standard deviations in tables 2.1 and 2.4, there is a high degree of confidence that participants will interact with two others in all cases, and that in the 4 and 5 vehicle cases, participants will interact with 3 others. That means that there is high confidence that these test cases place participants in situations where they must apply rule 2 as described in section 1.4.4.

The following categories of event have a 95% confidence interval of less than 1 occurrence per hour in at least 1 test case as listed in figures 2.4 and 2.5: overtaking near-miss, overtaking collision, head-on collision, head-on near-miss, head-on encounter. Tables 2.6 and 2.7 list the cases in which each event may not occur as well as the confidence level at which at least 1 instance per hour occurs.

Event	Cases	Confidence Level(s)
Overtaking Collision	3 and 4 vehicle cage match	0%, 0.62%
Head-on Collision	3, 4, and 5 vehicle cage match	0%, 0%, 0%
Head-on Near-miss	3, 4, and 5 vehicle cage match	0%, 0%, 2.44%
Head-on Encounter	3 vehicle cage match	0%

Table 2.6: Events with <95% confidence of at least one occurrence per hour in the cage match mission.

Each "X" in table 2.8 indicates that the corresponding event occurs at least once per hour of simulation with a 95% confidence level. A test plan that includes the 5-participant cage match mission and any joust mission captures all events with the exception of a head-on collision at this level. In the 5-participant jousting mission, head-on collisions occurred in 75% of 1-hour simulations. Any of the proposed missions result in vehicles managing more than one encounter at a time. A test-plan that includes at least 4 hours of both the

Event	Cases	Confidence Level(s)
Overtaking Collision	3, 4, and 5 vehicle joust	
Overtaking Near Miss	3, 4, and 5 vehicle joust	
Head-on Collision	3, 4, and 5 vehicle joust	Functionally zero OR the event did not occur
Head-on Near-miss	3 vehicle joust	
Head-on Encounter	3 vehicle joust	

Table 2.7: Events with <95% confidence of at least one occurrence per hour in the joust mission.

5-participant cage match and joust will provide participants the opportunity to demonstrate compliance with rules 13, 14, and 15, as well as ensure participants encounter multiple contacts at a time as described in section 1.4.4.

	Encounters			Near-Miss			Collision		
Mission and Number of Vehicles	**Head-On**	**Overtaking**	**Crossing**	**Head-On**	**Overtaking**	**Crossing**	**Head-On**	**Overtaking**	**Crossing**
Cage Match 3		X	X		X	X			X
Cage Match 4	X	X	X		X	X			X
Cage Match 5	X	X	X		X	X		X	X
Joust 3	X	X	X	X		X			X
Joust 4	X	X	X	X		X			X
Joust 5	X	X	X	X		X			X

Table 2.8: Summary of test cases and which events occur at least once per hour of simulation with a 95% confidence interval

Chapter 3

Compliance

Chapters 3 and 4 describe a set of simulations conducted using the missions described in chapter 2 in configurations described in section 1.6. The purpose of these is to evaluate the performance of the COLREGS behavior and identify any patterns in avoidable collisions. Statistical hypothesis testing assuming a Poisson's distribution and a 0.01 significance level was employed to determine differences in performance.

3.1 MOOS Behaviors to Control Compliance

The degree to which a participating vehicle is attempting to comply with COLREGS is determined by which collision avoidance behavior is running. "Fully compliant" participants as described in section 1.6.1 are running the COLREGS behavior detailed in section 3.1.2. Responsibly non-compliant participants are running the CPA-based collision avoidance behavior detailed in section 3.1.1.

3.1.1 COLAV Behavior

The MOOS behavior AvoidCollision documented in <**empty citation**> produces an objective function based on the anticipated CPA to a contact. For each point in the domain of heading and speed combinations, utility is assigned based on the CPA that would occur for that maneuver. User inputs determine the minimum tolerated CPA, and behavior performance is sensitive to these parameters.

A simple example to illustrate the difference between this behavior and the COLREGS behavior is the objective function generated in a head-on situation. COLREGS rule 14 states that vessels should alter course to starboard (turn right), but this behavior assigns equal utility to left and right turns.

3.1.2 COLREGS Behavior

The behavior AvdColregs documented in [21] produces an objective function based on CPA with a contact *and* an assessment of the applicable rule (13, 14, or 15) and if ownship is the stand-on or give-way vessel. In the rule 14 example listed in the previous section, this behavior assigns a higher utility to right turns than to left turns. However, if a vessel running this behavior determines itself to be "in extremis", avoiding collision becomes the priority over strict compliance with rules 13, 14, or 15 and this behavior will generate an objective function identical to the one produced by the AvoidCollision behavior explained in section 3.1.1.

3.2 Full Compliance

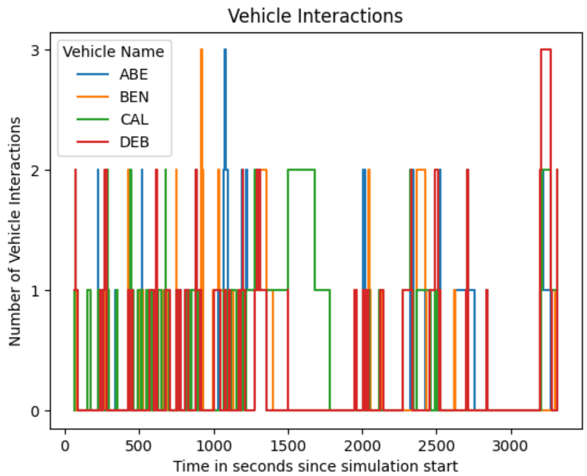
All vessels in the scenario are attempting to comply with COLREGS by running the behavior described in section 3.1.2. All of the simulations described in this chapter were conducted with perfect communications as described in section 1.6.2. In a full compliance simulation, ideally, there are zero collision or near-misses. A significant reduction in the number of collisions and near-misses from the baseline case described in section 2.3 indicates that the AvdColregs behavior is improving the safety of the vessels operations.

3.2.1 Full Compliance - Cage Match

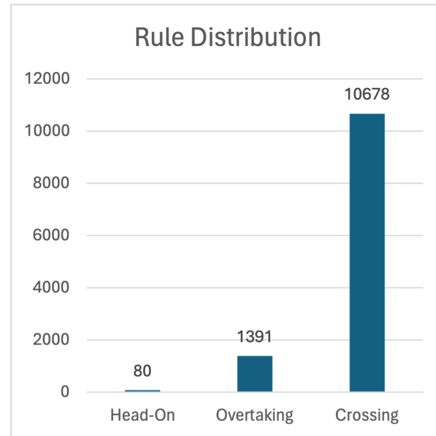
Table 3.1 lists the number of collisions, encounters, and near-misses that occurred. Figures 3.1b and 3.2b summarize how encounters sort by rule instance. In the 3-participant cage match, the single collision that occurred was during a crossing situation between Abe and Cal in which Abe was the give-way vessel and made a large right turn, and Cal was the stand-on vessel and made a 15 degree left turn. Cal was not engaged in any other encounters at the time. The 3 near-misses also occurred during crossing encounters. In the 4-participant cage match, all 4 near-misses occurred during crossing encounters and one of these occurred when a participant was interacting with two others at the same time. In the 5-participant cage match, all 8 collisions and 19 near-misses occurred during crossing encounters with no other notable factors.

Number of Participants	**Collisions**	**Near-Misses**	**Total Encounters**	**Total Hours**
3	1	3	6,113	100
4	0	4	11,535	131
5	8	19	8,104	100

Table 3.1: Collisions and near-misses for compliant-perfect cage match simulations. A collision is a CPA <1m, and near-miss is a CPA <3m.

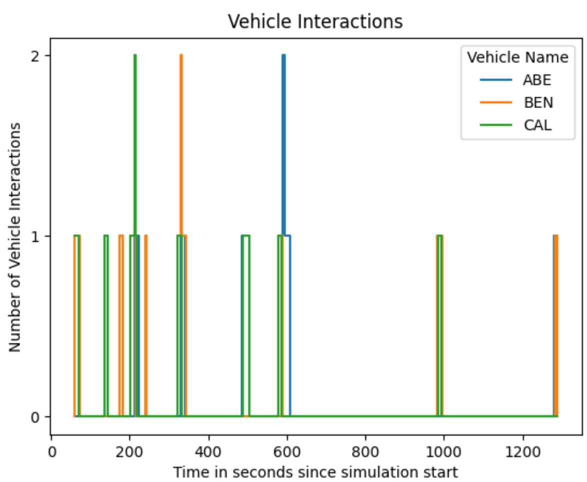


(a) Number of other vehicles each one is interacting with over time from a 1 hour simulation.

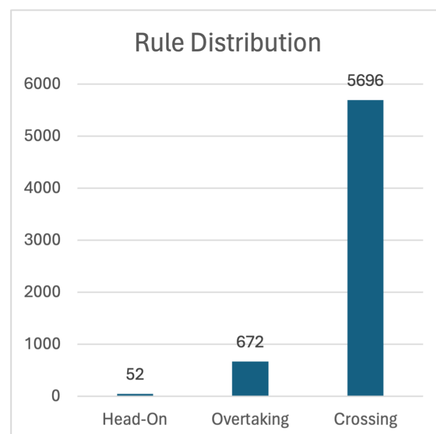


(b) Number of occurrences of each rule situation from 131 hours of simulation

Figure 3.2: Four vehicle cage match with full compliance and perfect communications



(a) Number of other vehicles each one is interacting with over time from a 1 hour simulation.



(b) Number of occurrences of each rule situation from 100 hours of simulation

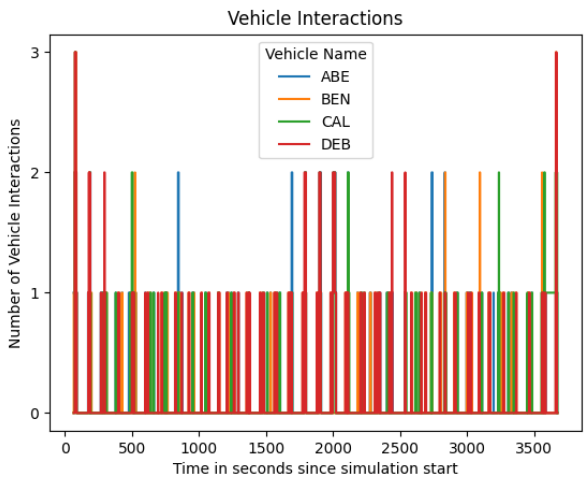
Figure 3.1: Three vehicle cage match with full compliance and perfect communications

3.2.2 Full Compliance - Joust

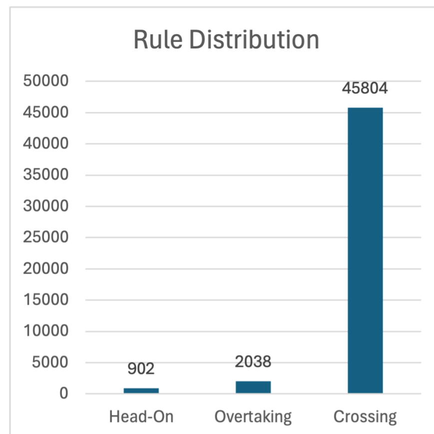
In the 3-participant simulation, the 2 collisions and 12 near-misses occurred during crossing situations. I the 4-participant simulation, all collisions and near-misses occurred during crossing situations. In the 5-participant simulation, 1 near-miss occurred in an overtaking situation; all other events in table 3.2 occured during crossing situations.

Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	2	12	14,440	100
4	6	52	47,973	189
5	11	78	63,280	150

Table 3.2: Collisions and near-misses for joust mission compliant-perfect simulations. A collision is a CPA <1m, and near-miss is a CPA <3m.



(a) Number of other vehicles each one is interacting with over time from a 1 hour simulation.



(b) Number of occurrences of each rule situation from 189 hours of simulation

Figure 3.3: Four vehicle joust with full compliance and perfect communications

3.2.3 Full Compliance - Results

The data in tables 3.3 and 3.4 demonstrates a significant reduction in the number of collisions and near-misses that occurred from the baseline missions described in section 2.3. There was also a significant reduction in the number of encounters. Collisions and near-misses per encounter were not reduced. Both sets of non-compliant results are compared to the baseline results and to these compliant results.

3.3 Responsible Non-Compliance

In the responsibly non-compliant simulations, one participant (Abe) is running the collision avoidance behavior detailed in section 3.1.1 and all other participating vehicles are running the COLREGS behavior detailed in section 3.1.2. Ideally, a COLREGS-compliant vessel should successfully avoid collision, regardless of the compliance of other vessels.

3.3.1 Responsible Non-Compliance - Cage Match

The number of collisions, near-misses, and total encounters is summarized in table 3.3. The number of each type of event involving Abe is listed in parentheses. In the 3-vehicle simulation, all three collisions involved Abe; one was a crossing situation in which Abe was the give-way vessel, one was an overtaking situation in which Abe was the give-way vessel, and the third was an overtaking situation in which Abe was the stand-on vessel.

In the 4-vehicle simulation, the three collisions involving Abe include a crossing in which Abe was the stand-on, a crossing in which Abe was the give-way, and an overtaking in which Abe was the stand-on. The near-misses include 3 overtaking situations in which Abe was the give-way vessel, 10 crossing situations where Abe was the give-way vessel, and 5 crossing situations where Abe is the stand-on vessel.

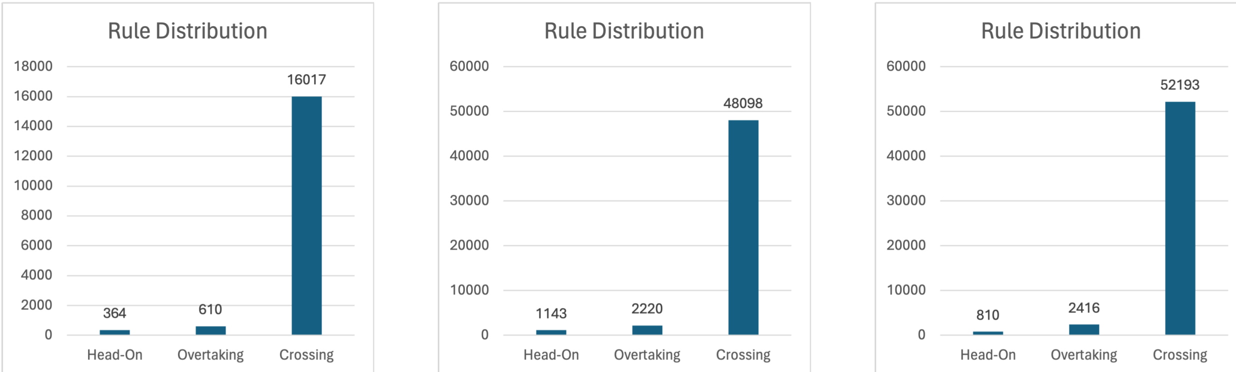
In the 5-vehicle simulations, the 4 collisions involving Abe include 3 crossing situations where Abe was the give-way vessel and 1 crossing situation where Abe was the stand-on vessel. The near-misses include 3 overtaking situations where Abe was the give-way vessel, 16 crossing situations where Abe was the give-way vessel, and 4 crossing situations where Abe was the stand-on vessel.

Number of Participants	**Collisions**	**Near-Misses**	**Total Encounters**	**Total Hours**
3	3 (3)	17 (16)	8,961	101
4	4 (3)	20 (18)	14,100	100
5	6 (4)	31 (23)	18,122	100

Table 3.3: Collisions and near-misses for responsible-perfect cage match simulations. A collision is a CPA $<$1m and a near-miss is a CPA $<$3m.

3.3.2 Responsible Non-Compliance - Joust

The number of collisions, near-misses, and total encounters is summarized in table 3.4. The number of each type of event involving Abe is listed in parentheses. Encounters by rule instance are summarized in figure 3.4. Figures 3.5, 3.6, and 3.6 sort Abe's encounters and near-misses by rule and vessel obligation; the orange wedge in each is crossing encounters in which Abe was the give-way vessel.

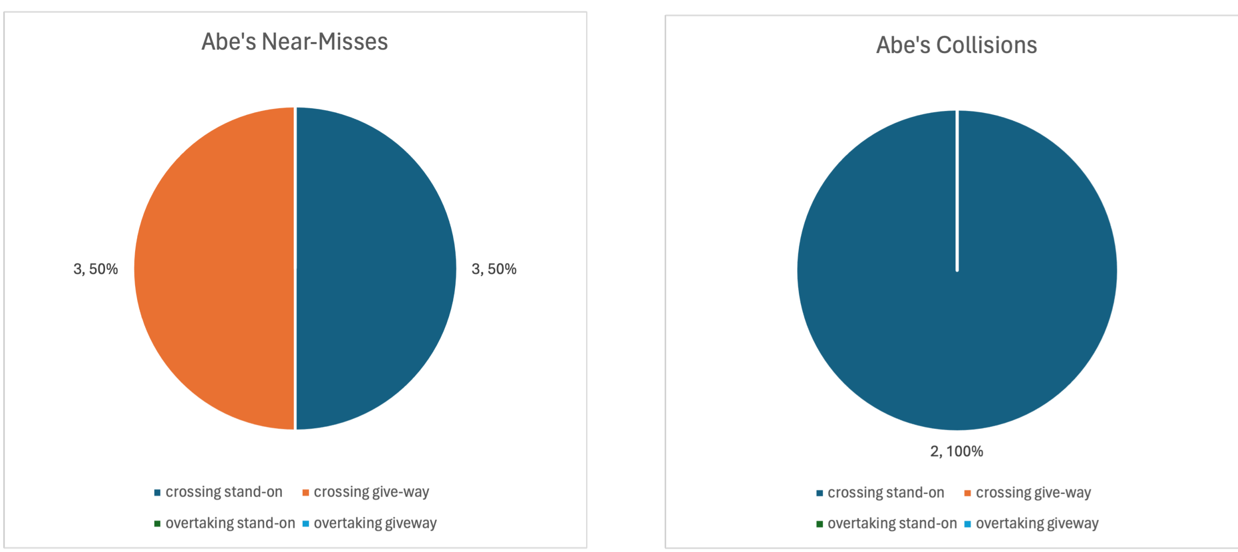


(a) 3 Vehicle (b) 4 Vehicle (c) 5 Vehicle

Figure 3.4: Rule-case occurrences in the responsibly non-compliant joust mission for each number of participating vehicles

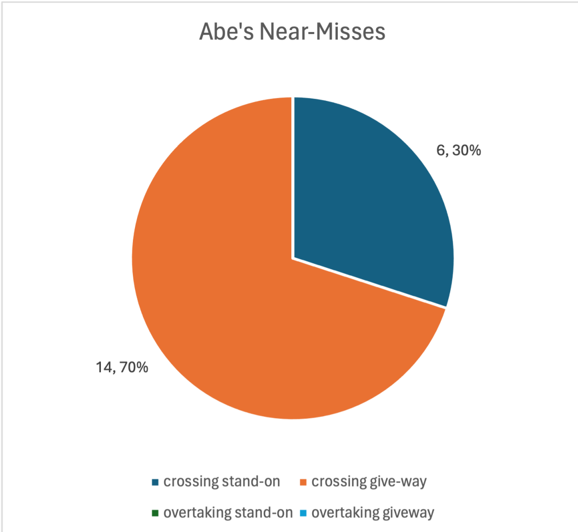
Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	2 (2)	8 (6)	16,991	106
4	3 (1)	66 (20)	51,461	177
5	8 (2)	76 (10)	55,419	118

Table 3.4: Collisions and near-misses for responsible-perfect joust simulations. A collision is a CPA <1m and a near-miss is a CPA <3m.

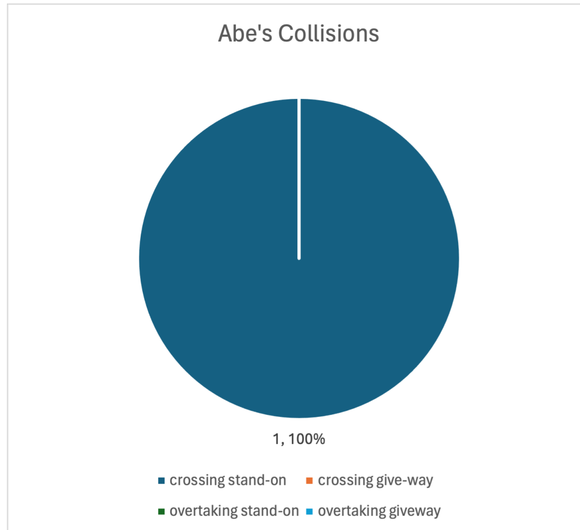


(a) Abe's near-misses, 3 vehicle (b) Abe's collisions, 3 vehicle

Figure 3.5: Break down of Abe's collisions and near-misses from Table 3.4 by rule case and vessel obligation from the 3-vehicle responsibly non-compliant joust simulation

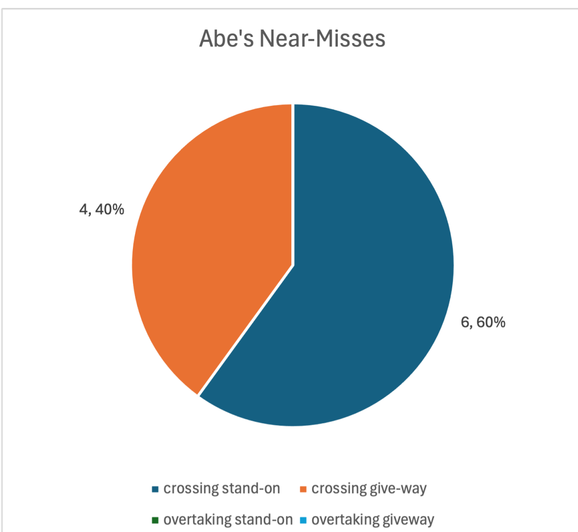


(a) Abe's near-misses, 4 vehicle

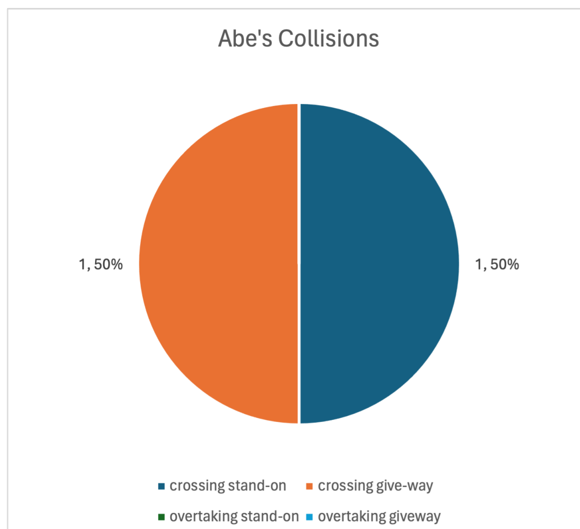


(b) Abe's collisions, 4 vehicle

Figure 3.6: Break down of Abe's collisions and near-misses from Table 3.4 by rule case and vessel obligation from the 4-vehicle responsibly non-compliant joust simulation



(a) Abe's near-misses, 5 vehicle



(b) Abe's collisions, 5 vehicle

Figure 3.7: Break down of Abe's collisions and near-misses from Table 3.4 by rule case and vessel obligation from the 5-vehicle responsibly non-compliant joust simulation

3.3.3 Responsible Non-Compliance - Results

The total number of collisions and near-misses in tables 3.3 and 3.4 are a significant reduction from the number of occurrences in the baseline cases described in section 2.3 but do not vary from the fully compliant results in section 3.2.

3.4 Reckless Non-Compliance

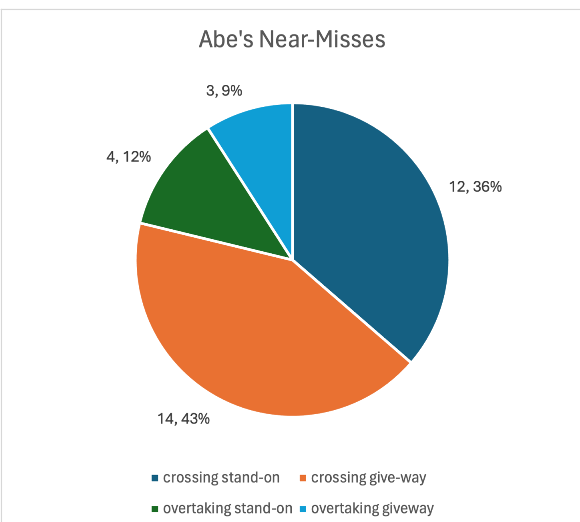
In the recklessly non-compliant simulations, one participant (Abe) is configured such that its collision avoidance behavior has a priority weight of 0. This allows the behavior to still post flags marking the start and end of an encounter, does not result in the helm maneuvering due to the behavior. All other participants are running the COLREGS behavior described in section 3.1.2. As stated in section 3.3, a COLREGS behavior should be able to avoid collision regardless of the cooperation of other vessels. This section focuses on interactions that involve Abe, the recklessly non-compliant participant.

3.4.1 Reckless Non-Compliance - Cage Match

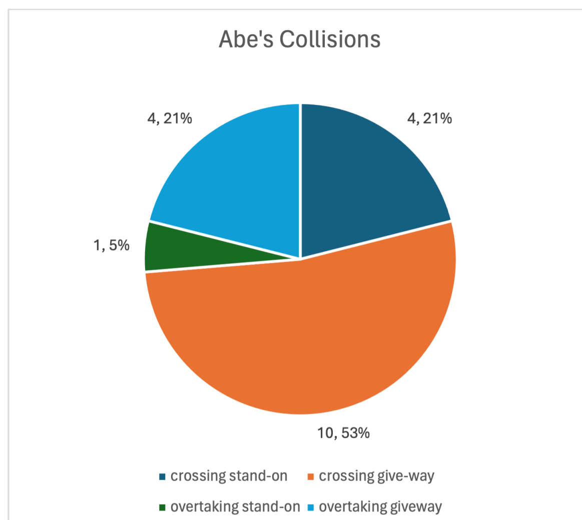
Table 3.5 lists the total number of collisions, near-misses, and encounters by number of vehicles in the simulation. Figures 3.8b, 3.9b, and 3.10b sort Abe's encounters and near-misses by rule and vessel obligation; the orange wedge in each is crossing encounters in which Abe was the give-way vessel.

Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	24(19)	74 (33)	8,360 (2,917)	100
4	15 (11)	47 (43)	13,378 (3,609)	100
5	41 (29)	89 (81)	28,565 (6,492)	124

Table 3.5: Collisions and near-misses for cage match reckless-perfect simulations. A collision is a CPA <1m, and near-miss is a CPA <3m. (abe)

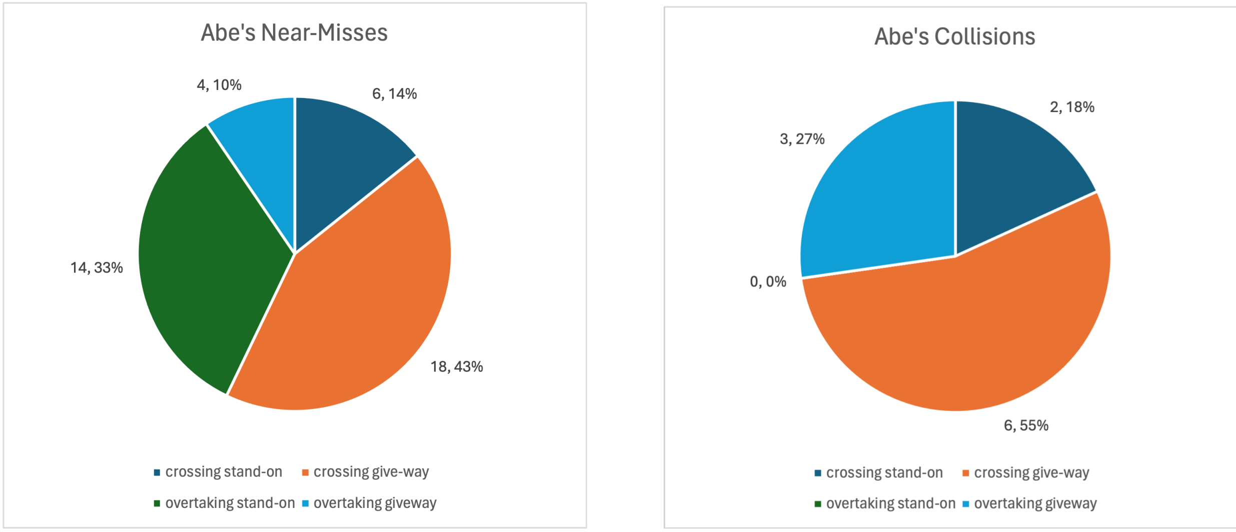


(a) Abe's near-misses, 3 vehicle



(b) Abe's collisions, 3 vehicle

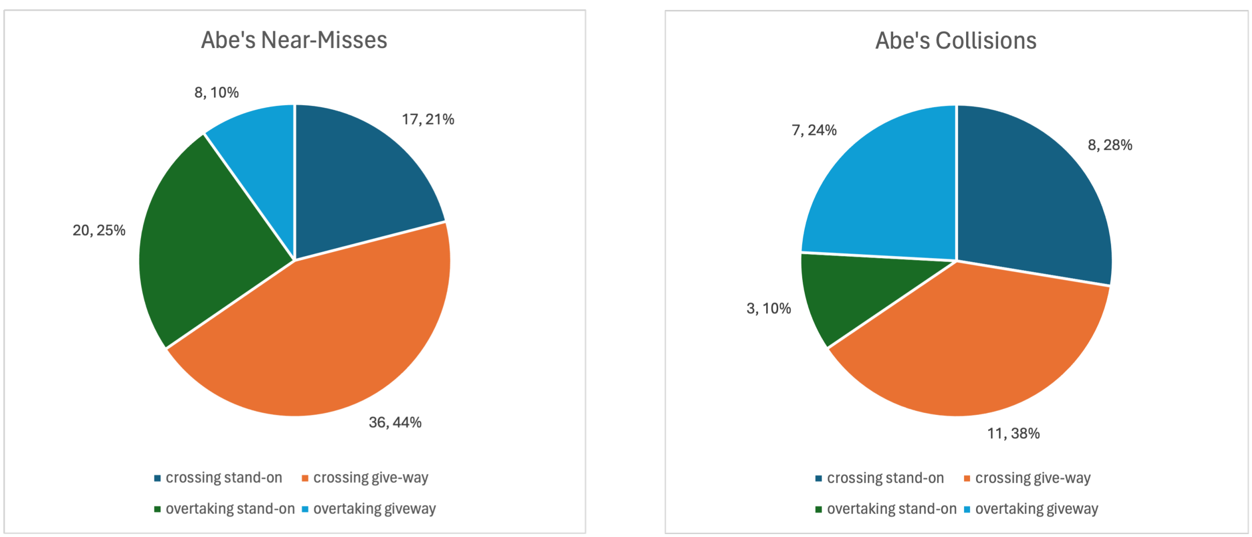
Figure 3.8: Break down of Abe's collisions and near-misses from Table 3.5 by rule case and vessel obligation from the 3-vehicle recklessly non-compliant simulation



(a) Abe's near-misses, 4 vehicle

(b) Abe's collisions, 4 vehicle

Figure 3.9: Break down of Abe's collisions and near-misses from Table 3.5 by rule case and vessel obligation from the 4-vehicle recklessly non-compliant simulation



(a) Abe's near-misses, 5 vehicle

(b) Abe's collisions, 5 vehicle

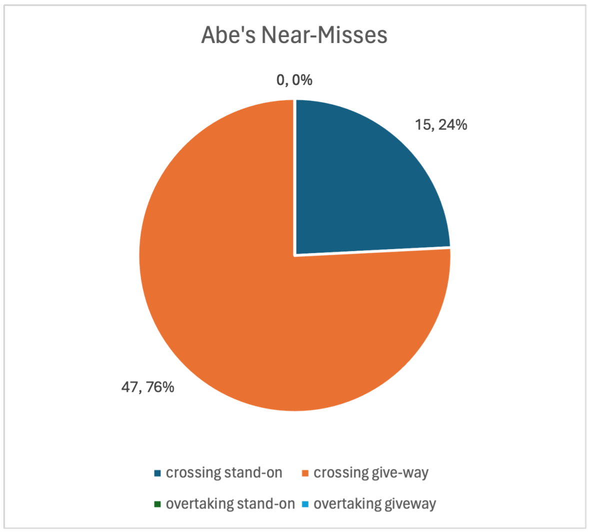
Figure 3.10: Break down of Abe's collisions and near-misses from Table 3.5 by rule case and vessel obligation from the 5-vehicle recklessly non-compliant simulation

3.4.2 Reckless Non-Compliance - Joust

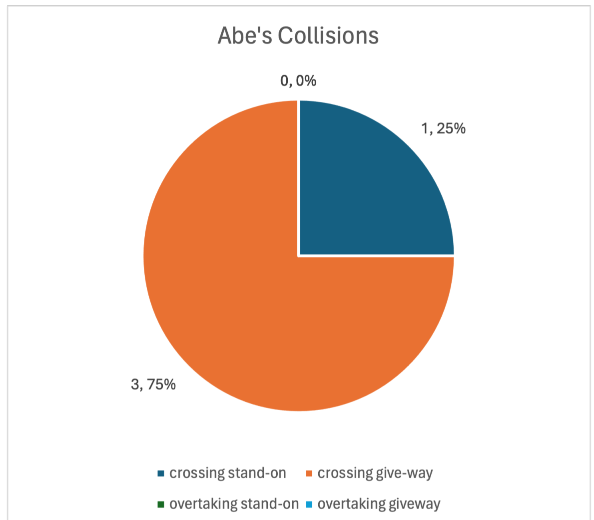
Table 3.6 lists the total number of collisions, near-misses, and encounters by number of vehicles in the simulation. Figures 3.11, 3.12, and 3.13 sort Abe's encounters and near-misses by rule and vessel obligation; the orange wedge in each is crossing encounters in which Abe was the give-way vessel.

Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	4 (4)	102 (62)	9,608	70
4	13 (10)	100 (91)	14,834	57
5	43 (36)	268 (220)	56,117	131

Table 3.6: Collisions and near-misses for joust reckless-perfect simulations. A collision is a CPA <1m, and near-miss is a CPA <3m. (abe)

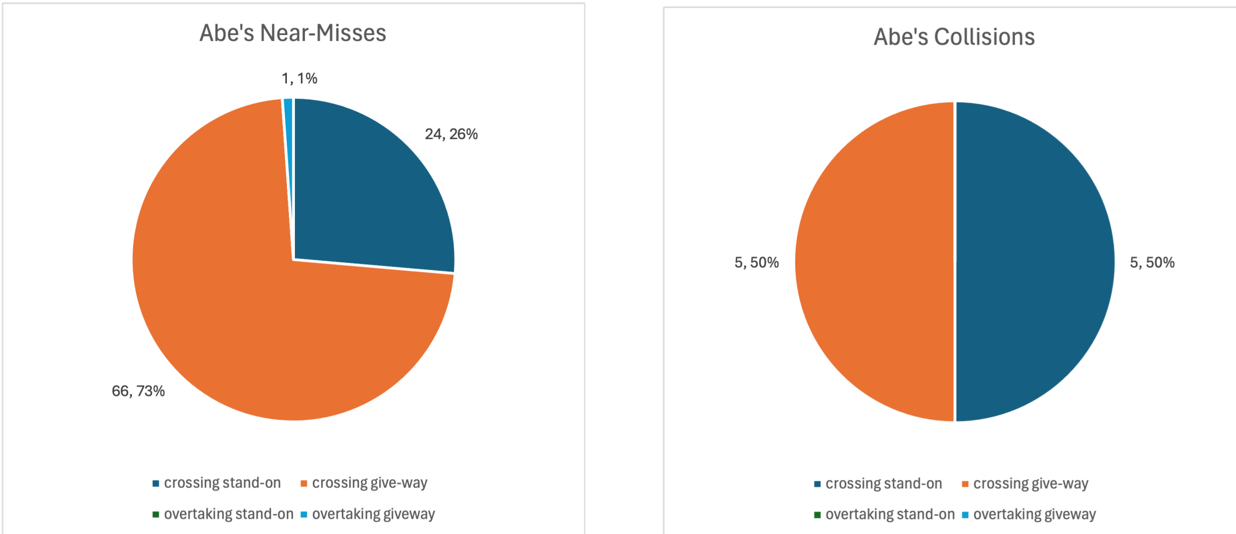


(a) Abe's near-misses, 3 vehicle



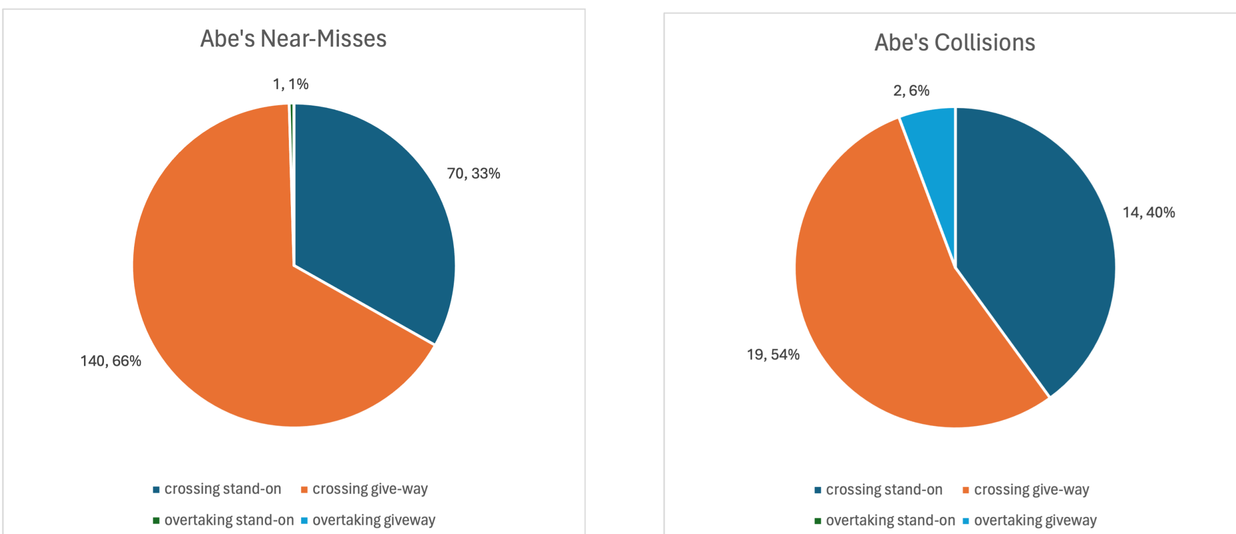
(b) Abe's collisions, 3 vehicle

Figure 3.11: Break down of Abe's collisions and near-misses from Table 3.6 by rule case and vessel obligation from the 3-vehicle recklessly non-compliant joust simulation



(a) Abe's near-misses, 4 vehicle (b) Abe's collisions, 4 vehicle

Figure 3.12: Break down of Abe's collisions and near-misses from Table 3.6 by rule case and vessel obligation from the 4-vehicle recklessly non-compliant joust simulation



(a) Abe's near-misses, 5 vehicle (b) Abe's collisions, 5 vehicle

Figure 3.13: Break down of Abe's collisions and near-misses from Table 3.6 by rule case and vessel obligation from the 5-vehicle recklessly non-compliant joust simulation

3.4.3 Reckless Non-Compliance - Results

The total number of collisions and near-misses in tables 3.5 and 3.6 are a significant reduction from the number of occurrences in the baseline cases described in section 2.3 but a significant increase in the number of collisions and near-misses from the fully compliant results in section

3.2. The majority of the collisions and near-misses involved Abe, the non-compliant vessel, and of those events, the majority occurred when Abe was the give-way vessel.

The results summarized in sections 3.2.3 and 3.3.3 indicate that the COLREGS behavior being tested is extremely effective at preventing collision when all vessels are attempting to avoid collisions with one another, but there is a reduction in performance when there are participants that are not attempting to avoid collision. The fact that in the recklessly non-compliant simulations, collisions and near-misses most frequently occurred when the non-compliant participant was the give-way vessel and did not maneuver to avoid indicates that the behavior in question does not appropriately shift from its implementation of COLREGS rule 17a to 17b as described in section 1.4.7.

Chapter 4

Perception Quality

Chapters 3 and 4 describe a set of simulations conducted using the missions described in chapter 2 in configurations described in section 1.6. The purpose of these is to evaluate the performance of the COLREGS behavior and identify any patterns in avoidable collisions. Statistical hypothesis testing assuming a Poisson's distribution and a 0.01 significance level was employed to determine differences in performance.

4.1 Imperfect Communications - Cage Match

In both the cage match simulations listed in this section and the jousting simulations in section 4.2, all participants had the range at which they would receive node reports from the other participants reduced from 500m to 30m. 30m is also the configured alert range as described in section 1.5 for all simulations described in this thesis. Table 4.1 lists the collisions, encounters, and near-misses for the cage match simulations with imperfect communications and full compliance as described in section 1.6.

Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	2	7	5,601	100
4	1	8	7,067	100
5	0	13	10,619	100

Table 4.1: Collisions and near-misses for cage match compliant-imperfect simulations. A collision is a CPA <1m, and near-miss is a CPA <3m.

4.2 Imperfect Communications - Joust

Section 4.1 describes the imperfect communications mission configuration. Table 4.2 lists the number of collisions, near-misses, and encounters for the joust simulations with imperfect communications and full compliance as described in section 1.6.

Number of Participants	Collisions	Near-Misses	Total Encounters	Total Hours
3	0	13	6,252	38
4	5	23	9,711	32
5	6	121	52,225	105

Table 4.2: Collisions and near-misses for joust compliant-imperfect simulations. A collision is a CPA $<$1m, and near-miss is a CPA $<$3m.

4.3 Imperfect Communications - Results

The total number of collisions and near-misses in tables 4.1 and 4.2 are a significant reduction from the number of occurrences in the baseline cases described in section 2.3 and are *not* higher than the fully compliant results with "perfect" communications that are detailed in section 3.2. This does not mean that there is not a relationship between the range at which vehicles detect each other and the number of collisions; common sense and the fact that the majority of collisions at sea occur in conditions of restricted visibility (in other words, when the range at which ships detect each other is reduced) [9] tell us that this relationship does exist. These results indicate that, at the speeds participants in these simulation are operating, a 30m detection range is sufficient not to impact performance. These results are not sufficient to establish a threshold for minimum detection range for the behavior to ensure safety.

One interpretation of these results, since there was no reduction in performance from the results in section 3.2.3, is that for a detection range of 30m, the participant vessels were complying with COLREGS rule 6, which was not one of the rules this thesis was intended to evaluate. Rule 6, which applies to vessels in any condition of visibility, states that all vessels shall proceed a "safe speed" at all times, and one of the factors used to determine safe speed is the state of visibility.

Chapter 5

Conclusions

5.1 Summary of Contributions

This thesis makes the following contributions:

- Introduces the cage match test mission described in section 2.1 as a method of testing autonomous vessel compliance with COLREGS rules 2, 8, 13, 14, 15, 16, and 17.
- Adds MOOS applications pManagePoints and uFldColregsDetect to the MOOS-IvP code base.
- Establishes the confidence interval with which instance to demonstrate compliance with rules 2, 13, 14, and 15 occur in the cage match test mission and the previously-proposed jousting test mission.
- Uses the cage match and jousting mission to characterize aspects of performance of the existing MOOS COLREGS behavior.

5.2 Proposed Future Work

Several opportunities for future work were identified. The entirety of this thesis was conducted with a behavior priority weight for COLREGS or collision avoidance set by anecdotal observation running missions on the water at MIT; this method can be applied to determine a minimum priority weight for the COLREGS behavior as well as to tune the other parameters listed in section 2.1.2 for optimal performance.

More instances of the imperfect communication simulation described in chapter 4 can be used to tune and add rule 6 capability to the COLREGS behavior or a separate speed-governing behavior. Since rule 6 applies to all vessels at all times, not just when a vessel is maneuvering to avoid a contact, the current spawn-able implementation of the COLREGS behavior does not make the continuous assessment of speed and prevailing conditions to comply with this rule.

Room for improvement in the rule 17 implementation is identified in section 3.4.3. The fact that there is an increase in the number of collisions when non-compliant participants are introduced and most of those additional collisions occur when the compliant vessel is the stand-on vessel indicates that the transition from rule 17(a) to 17(b) as explained in section 1.4.7 occurs too late.

MOOS-IvP Mission Oriented Operating Suite, Interval Programming

MOOS Mission Oriented Operating Suite

ASV Autonomous Surface Vehicle

COLREGS International Rules for Preventing Collision at Sea, or "Collision Regulations"

RoR "Rules of the Road", another name for COLREGS

IMO International Maritime Organization

ABS American Bureau of Shipping

MASS Maritime Autonomous Surface Ships

CPA closest point of approach

References

[1] *2022 national defense strategy*, Oct. 2022. [Online]. Available: https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF (visited on 01/09/2023).

[2] *News brief: MSC 106*, Nov. 2022.

[3] "Joint MSC-LEG-FAL working group on maritime autonomous surface ships (MASS-JWG) 2nd session." (), [Online]. Available: https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/Joint-MSC-LEG-FAL-Working-Group-on-Maritime-Autonomous-Surface-Ships-%28MASS%29-.aspx (visited on 01/28/2024).

[4] K. Woerner, "COLREGS-compliant autonomous collision avoidance using multi-objective optimization with interval programming:" Defense Technical Information Center, Fort Belvoir, VA, Jun. 1, 2014. DOI: 10.21236/ADA609415. [Online]. Available: http://www.dtic.mil/docs/citations/ADA609415 (visited on 04/06/2023).

[5] F. Shokri-Manninen, J. Vain, and M. Waldén, "Formal verification of COLREG-based navigation of maritime autonomous systems," in *Software Engineering and Formal Methods*, F. de Boer and A. Cerone, Eds., ser. Lecture Notes in Computer Science, Cham: Springer International Publishing, 2020, pp. 41–59, ISBN: 978-3-030-58768-0. DOI: 10.1007/978-3-030-58768-0_3.

[6] J. C.
bibinitperiod H.-T. C. Jeonghong Park, "COLREGS-compliant path planning considering time-varying trajectory uncertainty of autonomous surface vehicle," Feb. 2019.

[7] T. A. Pedersen, J. A. Glomsrud, E.-L. Ruud, A. Simonsen, J. Sandrib, and B.-O. H. Eriksen, "Towards simulation-based verification of autonomous navigation systems," *Safety Science*, vol. 129, p. 104 799, Sep. 1, 2020, ISSN: 0925-7535. DOI: 10.1016/j.ssci.2020.104799. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S092575352030196X (visited on 01/19/2024).

[8] L. Perera and B.-M. Batalden, "Possible COLREGS failures under digital helmsman of autonomous ships," presented at the IEEE Oceans, Marseille, France, Jun. 2019.

[9] "Requirements for autonomous and remote control functions 2022," 2022.

[10] N. Rajabli, F. Flammini, R. Nardone, and V. Vittorini, "Software verification and validation of safe autonomous cars: A systematic literature review," *IEEE Access*, vol. 9, pp. 4797–4819, 2021, ISSN: 2169-3536. DOI: 10.1109/ACCESS.2020.3048047. [Online]. Available: https://ieeexplore.ieee.org/document/9310181/ (visited on 01/19/2024).

[11] H. Wu, D. Lyu, Y. Zhang, G. Hou, M. Watanabe, J. Wang, and W. Kong, "A verification framework for behavioral safety of self-driving cars," *IET Intelligent Transport Systems*, vol. 16, no. 5, pp. 630–647, 2022, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1049/itr2.12162, ISSN: 1751-9578. DOI: 10.1049/itr2.12162. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1049/itr2.12162 (visited on 01/19/2024).

[12] C. Pek, P. Zahn, and M. Althoff, "Verifying the safety of lane change maneuvers of self-driving vehicles based on formalized traffic rules," in *2017 IEEE Intelligent Vehicles Symposium (IV)*, Jun. 2017, pp. 1477–1483. DOI: 10.1109/IVS.2017.7995918. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/7995918 (visited on 01/19/2024).

[13] Michael R. Benjamin, Henrik Schmid, P. M. Newman, and J. J. Leonard, "Nested autonomy for unmanned marine vehicles with MOOS-IvP," *Journal of Field Robotics*, vol. 27, pp. 834–875, 2010.

[14] "pNodeReporter: Summarizing a node's position and status." (), [Online]. Available: https://oceanai.mit.edu/ivpman/pmwiki/pmwiki.php?n=IvPTools.PNodeReporter (visited on 05/08/2024).

[15] "uFldNodeComms: Simulating inter-vehicle communications." (), [Online]. Available: https://oceanai.mit.edu/ivpman/pmwiki/pmwiki.php?n=IvPTools.UFldNodeComms (visited on 05/08/2024).

[16] "uFldCollisionDetect: Detecting collisions." (), [Online]. Available: https://oceanai.mit.edu/ivpman/pmwiki/pmwiki.php?n=IvPTools.UFldCollisionDetect (visited on 05/08/2024).

[17] K. Becker, "Development of a distributed simulation cluster for MOOS-IvP," Ph.D. dissertation, Massachusetts Institute of Technology, May 2024, 49 pp. (visited on 04/01/2024).

[18] *Navigation Rules and Regulations Handbook*. Department of Homeland Security, Sep. 2020, ISBN: 978-0-16-095406-1.

[19] "pContactMgrV20: Managing platform contacts." (), [Online]. Available: https://oceanai.mit.edu/ivpman/pmwiki/pmwiki.php?n=IvPTools.PCManagerV20 (visited on 05/07/2024).

[20] A. Mood, F. Graybill, and D. Boes, *Introduction to the Theory of Statistics*, 3rd. McGraw Hill, 1974.

[21] M. R. Benjamin, *Autonomous COLREGS modes and velocity functions*, May 2017.