

Addressing the Accidental Risks of Maritime Transportation: Could Autonomous Shipping Technology Improve the Statistics?

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ABSTRACT: A paradigm shift is presently underway in the shipping industry promising safer, greener and more efficient ship traffic. In this article, we will look at some of the accidents from conventional shipping and see if they could have been avoided with autonomous ship technology. A hypothesis of increased safety is often brought forward, and we know from various studies that the number of maritime accidents that involves what is called “human error” ranges from some 60-90 percent. If we replace the human with automation, can we then reduce the number of accidents? On the other hand, is there a possibility for new types of accidents to appear? What about the accidents that are today averted by the crew? This paper will present a method to assess these different aspects of the risk scenarios in light of the specific capabilities and constraints of autonomous ships.

1 INTRODUCTION

It is commonly believed that human errors are the main causation factor for maritime accidents and incidents. The term “human error” is a broad category covering a wide variety of unintentional unsafe behavior. From Allianz figures a range from 50 to 80% are often seen, with 75% being the figure used by Allianz (2018). With this background, it could be argued that an unmanned and fully autonomous ship should be much safer than a corresponding manned ship. However, there are several parameters which will determine the safety of an autonomous ship and this paper will attempt to present a more complete picture.

Section two will define the types of autonomous ships we believe is the most relevant in the near future, i.e. next 10 years. Section three will compare autonomous ships, as understood by the authors, with manned ships and list the main differences that can also be the basis for comparison of risk factors.

Section four discusses types of accidents and causation factors and how this picture will be modified for autonomous ships. Sections five to seven discuss different classes of accidents and try to provide some quantitative expectations for how these classes will change when autonomy is introduced. Section eight will give a summary and conclusions.

2 WHAT IS AN AUTONOMOUS SHIP?

Autonomy literally means “self-governing” and comes in very different forms. Rødseth (2018) discusses this topic and provides a characterization scheme for autonomy in ships. Maritime Autonomous Surface Ship (MASS) is by IMO defined as a ship that, to a varying degree, can operate independently of human interaction. Autonomy is also closely connected to unmanned operation: Having a completely unmanned ship is desirable as it realizes significant gains by removing the hotel section and

associated energy use, removing much safety equipment and reduces crew costs and by that also allows easier scaling down of ship sizes (Rødseth 2018b). Central in this is also the use of a shore control center (SCC) as discussed in Man et al (2015). In this context, autonomy is important to enable operators in the control center to monitor and control several ships and by that reduce costs of operations in the SCC.

It is theoretically possible to design a fully autonomous ship without any human oversight at all, but this is extremely unlikely in all but very special cases, due to the resulting extreme demands on the on-board technology. Being able to operate with "constrained autonomy" (Rødseth 2018) and having humans as back-up in cases where operational demands exceed the automation system's capabilities is a much more likely alternative. In addition, current public and private law and regulations associated with safety of ship operations as well as with the commercial issues related to shipping is also dependent on having a legally responsible person in charge of the ship. Changing laws and regulations will take a long time if it is at all possible (Rødseth 2017).

As the technology improves, the shipping community gets more experience with the operation of autonomous ships and when laws and regulations have been updated, it is very likely that fully autonomous ships will be launched, but this will take many years. Technology will be used for sensing, AI and IoT have been rapidly advanced and utilized in various fields. Automated operation systems of ships have been active with aims of further safe navigation by preventing human errors, improving working conditions of ship's etc. (Matsumoto 2018).

In line with the above discussion, in the following we will assume that an autonomous ship is a ship that is completely unmanned, but with a shore control center and limited (constrained) autonomy in the onboard control systems.

3 COMPARISON TO MANNED SHIPS

In the following paragraphs, we will attempt to identify the main factors that distinguish an autonomous ship from a conventional manned ship, based on the assumptions from the previous section: Fully unmanned cargo ship with constrained shipboard autonomy and a shore control center (SCC) to handle events that the automation cannot handle.

3.1 Fully unmanned

The most interesting autonomous ship projects are associated with fully unmanned operations as discussed in the previous section. While there will be provisions for having people onboard during maintenance and port operations, unmanned voyages have a number of important effects:

- 1 Higher demand on sensors, automation and shore control as operators in SCC lack some of the "personal touch", both on environment, ship and technical system's performance.
- 2 Much lower exposure to danger for the crew.

- 3 May be unable to inspect equipment or systems that report errors or problems.
- 4 Lower risk of fires in accommodation, galleys, laundry and waste systems, which is relatively high on manned ships.

3.2 Constrained autonomy

Autonomy will be limited for the onboard systems and the ship will be dependent on occasional support from the SCC. To avoid known problems with human-automation interfaces (HAI) in the shore control center, the ship automation will have "constrained autonomy" (Rødseth 2018). The assumption is that this also helps in testing and qualifying sensor and automation systems to specified performance level. This has a number of effects:

- 1 More limited, but also more deterministic action responses from sensors and automation.
- 2 Dependence on shore control operators' performance and situational awareness.
- 3 Dependence on communication link to shore.
- 4 Dependence on high quality implementation of fallback solutions and definition of minimum risk conditions for the ship.

3.3 Shore control center

The shore control center will be manned with supervision operators as well as specialist intervention teams that are activated in cases of special demands from a ship (Man et al. 2015). In addition to issues mentioned in the previous sections, this will have the following effects:

- 1 Dependent on good training and cooperation in the shore control center.
- 2 Intervention crew do not have to worry about personal risk and adverse conditions on board.

3.4 Higher technical resilience

Another important aspect is the reliability of technical systems onboard and increased redundancy in the same systems. As there is no crew available to provide a safety barrier in case of technical failures, it is necessary to add new technical barriers where necessary, e.g. by using increased redundancy. This requirement is already included in the guidelines published by DNV GL (2018).

Today's crew use much of their time on maintenance of the ship and its systems. This will not be possible on an unmanned ship and to avoid increased off-hire due to more and longer dry-dockings, it will be necessary to use systems with lower maintenance requirements. This can typically be diesel-electric energy and propulsion systems, no use of heavy fuel, improved coatings on the ship and in cargo holds etc. Effects are:

- 1 More technical barriers against technical faults.
- 2 Much improved technical systems with built in predictive maintenance functionality.
- 3 More dependent on maintenance at shore.

3.5 Improved voyage planning

Finally, unmanned ships will be used in liner type operations where they trade between a relatively limited number of ports where infrastructure and trained personnel are available to handle the unmanned ship safely and efficiently. In addition to infrastructure requirements, also the current legal systems rule out tramp type shipping where the unmanned ship calls on arbitrary ports: Until international regulations have been established, unmanned operation will need to be based on bilateral agreements between the involved flag, coastal and port states. This also means that operations of unmanned ship will be able to take advantage of better cooperation with coastal state authorities, better described fairways, possibly additional infrastructure in the fairways and improved planning of the voyage. The effects of this are:

- 1 Less chance of surprises during voyage.
- 2 More support from public functions on land.

4 ACCIDENT SCENARIOS

4.1 Today's accident picture

There are a number of different papers investigating accident statistics and causation factors in the available literature. They use different data sources and different methods and results vary quite widely. The publicly available databases of marine accidents have different database structure and approaches to analyze the accident causation and consequence mitigation. There are many reasons for this, among them large variations in accidents between geographic regions, types of ships, age of ships, flags and insurance, see e.g. Eleftheria et al. (2016), Equasis (2018) and Allianz (2018).

In this paper, we will use statistics from the European Maritime Safety Agency (EMSA 2018) and mainly figures from the period 2011 to 2017. This covers accident reports from EU and associated countries.

4.2 Occupational fatalities

Working on a ship is in general considered more dangerous than similar jobs on land. In the UK, the fatality rate at sea is about 12 times higher than in the general population and in Poland it is eight times higher than that again (Allianz 2012).

From the EMSA statistics it can be seen a split between occupational fatalities, e.g. slipping, falling or being hit by objects, and fatalities caused by ship accident. In the period 2012 to 2017 such occupational fatalities amounted to 43% of a total of 683 fatalities in the period.

If a ship is operated without a crew, it is obvious that this will be a significant contribution to the safety of the voyage as seen from the now on-shore crew.

4.3 Ship accidents

EMSA uses a special classification system that is implemented in EMCIP (European Marine Casualty Information Platform). A much abbreviated version of the classification system is shown in Fig. 1.

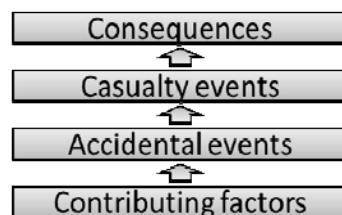


Figure 1. EMCIP elements (EMSA 2018)

Most casualties should be seen as processes that involve a number of errors, failures and uncontrolled environmental impacts, and not just the more dramatic **Casualty Event** itself. This group of events will collectively be termed **Accidental Events** (Caridis 1999). The categories of accidental events used by EMSA are listed in Figure 2. **Contributing factors** is something that helps cause a result. The latter two are often called causal factors, which in general mean general actions, omissions, events or conditions, without which the marine casualty or marine incident would probably not have occurred or have been as serious (IMO 2008). Over the period 2011 to 2017, EMSA has analyzed 1645 accidental events with a distribution as shown in Figure 2 below.

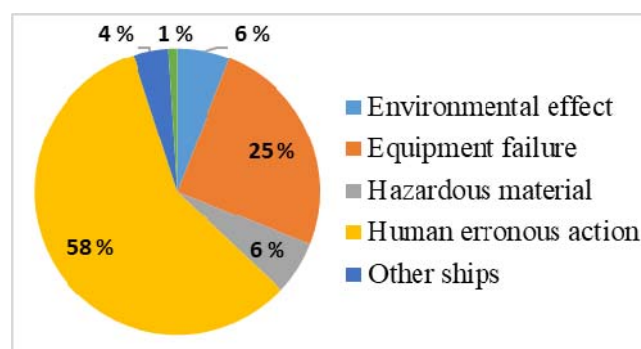


Figure 2. Accidental events from EMPIC (EMSA 2018)

This presents a lower percentage for human errors than what has been common in other literature (Allianz 2018, Baker 2009), but it is still a substantial contributing factor with 58%. It is also interesting to see that equipment failure represents 25% of the accidental events. We will come back to this in section 5.

4.4 The human factor is still an issue

Another statistics of interest is how respectively shipborne operations and shore management acts as a main contributing factor to the casualty events. This is rendered in Fig. 3, where around 2900 contributing factors have been analyzed.

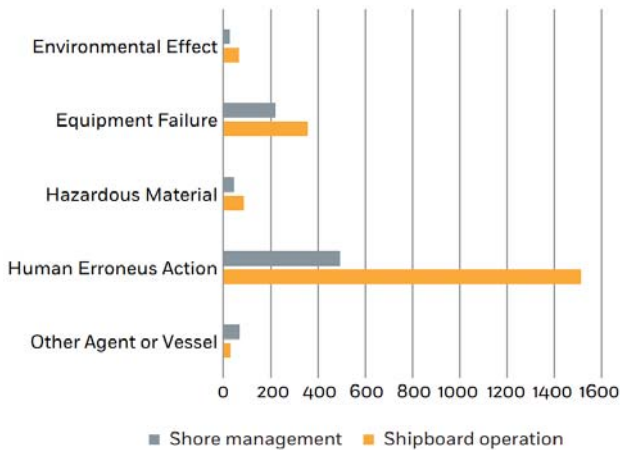


Figure 3. Relationship between ship and shore as contributing factor for marine casualties in general (EMSA 2018)

This may have an impact on expectations from a shore control center in the context of unmanned ships. However, shipboard operation is a main contributing factor to 70% of the casualty events.

This brings us to the human role in MASS operations. Humans still need to intervene with a MASS vessel, however the human element of the operations seem often to be forgotten when designing a MASS. The human, i.e. operator, still need to supervise and analyze the operations done by the autonomous systems, either from a SCC or when a MASS is manned. When looking at accident statistics of conventional shipping, we tend to look at the negative side of human intervening. In the design phase of MASS, the human machine interactions (HMI) should be addressed. A Concept of Operation (CONOPS) refer to the awareness of a situation. It gives the perception of an event with respect to time and condition, and the system behavior (actual and future). A CONOPS will address the human factors in the MASS operation aspect. Known relevant human factor challenges of remotely operated and automated systems that should be included (Karvonen 2018) are:

- Situation and automation awareness
- The understanding between automation and human role
- User experiences and usability of the solutions
- Trust in automation
- Graphical user interface and visualization

4.5 Accidents in autonomous ships

It is an expectation that more automation can remove some of the accidents today caused by human error: Automation address human shortcomings like fatigue, limited attention span, information overload, i.e. limits of the human working memory, normality bias etc. How much that automation can improve the accident statistic is still an open question. The full picture is also more complicated than this, as illustrated in Fig. 4. (Porathe et al. 2018).

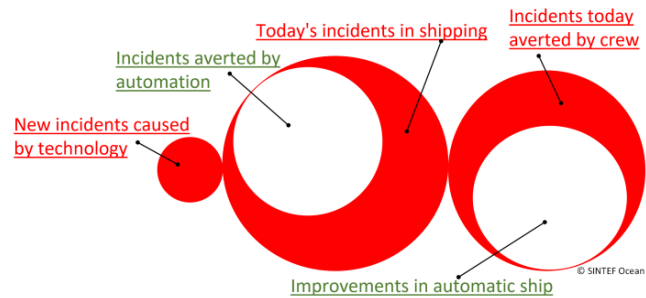


Figure 4. Three main groups of accidents and incidents

The middle circles represent today's incidents and accidents in shipping, which was discussed in section 4. The right circles represent the accidents that today's crew are able to avoid by being present onboard. The left circle represents new types of incidents that are caused by the advanced automation systems themselves. The dark circles are the damage potential and the white circles represent actions by the automation systems to avoid or minimize the effects of these incidents. This picture needs to include the effects of the SCC. Here, it is important to remember that our increasing dependence on information systems, and increasingly sharing of control of systems with automation, are creating a considerable potential for loss of information and control leading to new types of "human errors" (Leveson 2012). Which are contributing to the observed percentage of "human error" involved in the accident rates.

For the evaluation of the accident's causes, it is possible to apply Human Factors Analysis and Classification System for Marine Accidents (HFACS-MA). In a study by Wróbel et al. from 2017, 100 accidents reports were analyzed by applying this method and paying particular attention to the following two following aspects:

- If the ship were unmanned, how would that fact affect the likelihood of particular accident?
- If the accident occurred anyway, would its consequences be more or less serious if there were no crew on board?

According to HFACS-MA, the accident's causes are divided into 21 causal categories grouped in 5 levels:

- External Factors: Legislation gaps, administration oversights, and design flaws.
- Organizational Influences: Fallible decisions of upper-level management affecting supervisory practices as well as the conditions and actions of the operator (Scarborough 2005).
- Unsafe Supervision: Supervisory actions that influence the conditions of the operator and the type of environment in which they operate.
- Preconditions: latent unsafe conditions for unsafe acts that exist within a given work system (IMO 1999).
- Unsafe Acts: errors (slips and lapse), mistakes and violations performed by the operator.

The study concluded that the remoteness of the human operators and crew has the benefit of reducing the risk to the personnel significantly, and reducing the number of navigation-related accidents like collision or groundings (Wróbel et al. 2017, pp 10). However, the results also showed that the damage

assessment and control is likely to be one of the biggest difficulties for the unmanned vessel.

One drawback of the study is that they evaluated an unmanned vessel as a vessel with the same design and technical systems in place, only with the bridge and crew being remote. The design and system architecture of autonomous systems will be completely different as discussed in section 3.4. Another drawback of the study is the subjective evaluation of the effect of unmanned ships on the likelihood of the accidents and the many assumptions about which HFACS-MA causal category has the largest impact on an accident's occurrence. As one of the recommendations for further research the author emphasize the need to identify and list all anticipated hazards and their evaluated effects; *only then can the level of safety associated with the unmanned ships operations be assessed* (Wróbel et al. 2017, pp. 11).

In this paper, we take a similar approach, but instead of analyzing accident investigation reports, we look at the larger picture and qualitatively evaluate the potential for the causal factors most common for the known accidents and incidents today.

4.6 Experiences from accidents related to sensemaking and HMI

The past decades we have seen a decline in marine accidents leading to loss of property, life and environmental damage. Particularly after 1980 the introduction of new technology has been accompanied by a steady and significant improvement in ship safety. These first steps towards greater use of automation in machinery spaces continued with advanced ships with smaller crews and increased operating efficiency through new technologies, particularly with regard to navigation system (Pomeroy 2017, Hetherington, Flin et al. 2006). However, more automation has also been related to the following issues: diminished ship sense, mishaps during changeovers and handoffs, latency and cognitive horizon, potential skill degradation, and resilience in abnormal situations.

One of the biggest challenges in highly automated systems is the disconnect, suggested as one of the ironies of automation (Bainbridge 1983), between the demand of the ships and its system and the skills and knowledge of the people operating it both at seas and ashore is causing new types of incidents and accident. In a review of 14 MAIB accident reports from 2005–2016, Kilskar and Johnsen (In Press) identified the following safety issues concerning automation at the bridge contributing to several of the accidents, hence contributing factors:

- Loss of situation awareness / poor sensemaking
- Insufficient training
- Alarm related issues
- Poor system design or display layout
- Poor (safety) management
- Poor or missing work load assessment
- Lacking or insufficient passage planning
- Missing, poor or unclear regulations or standards

Although these safety issues were identified in accident investigation reports, they concern HMI and will apply to operators in a SCC.

5 A QUALITATIVE COMPARISON OF AUTONOMOUS AND MANNED SHIPS

We have listed the main factors that distinguish an autonomous ship from a manned ship, as discussed in paragraph 3.1 – 3.5. With the identified causal and contributing factors, conditions, activities, systems, components, etc. that are critical with respect to accidental risk, presented in section 4 and 5, we attempt to classify the potential for higher or lower contributions to today's incidents in shipping.

Table 1 lists the characteristics of different technological solutions and shortly describes their strength and/or shortcomings. For each characteristic, a color indicates to which degree this is contributing to the three risk types listed in the three last columns: New accidents caused by new technology, Today's known accidents, and accidents adverted by crew) illustrated in Fig. 4. The factors contribution to the risk types is indicated by the following colors: increased risk (red - R), neutral impact (yellow - Y), or lesser impact/likelihood (green - G). Note that for the first type of accidental risks, new accidents caused by new technology, autonomous ships can obviously not be better than today. At best, it is neutral (Y). For a fully unmanned ship, one differentiating factor from manned ship is a higher demand and reliance on sensors, automation and shore control (row 1 in table 1 below). More advanced technology means a higher degree of system complexity causing new technological failures like unknown software failures for example. This contributes to a higher likelihood (risk) of new accidents caused by new technology, indicated by a red "R" under the column "New". For today's known incidents and accidents like collisions and allisions caused by human erroneous actions due to fatigue, new technology will be able to address such human shortcomings with collision detection and avoidance systems. Hence, a green "G" indicates the positive contribution on risk, as known accidents are avoided by new technology. However, accidents adverted by crew today should also be possible in autonomous operations by remote control and operation from the SCC. The technology in a fully unmanned ship and SCC shall be designed for remote operation, and the crew will still have impact, in order to avoid accidents and incidents. Hence, the contribution is neutral, indicated by a yellow "Y".

6 DETAILED DISCUSSION

First category, **fully unmanned**, points to a higher risk for software and technical failure. Due to for example:

- Sensor failure/degradation of hardware
- Insufficient redundancy
- Loss of propulsion or steering control
- Cyber security breaches
- Loss of communication with SCC

However, unmanned vessels will improve on some of today's operators' errors caused by human erroneous actions due to fatigue or other harsh working conditions.

Table 1. Qualitative comparison of autonomous and manned shipping

Main differentiating factors		Brief description of effects	New	Today's	Averted
Fully unmanned					
1	Higher demand on sensors, automation and shore control as one lack some of the "personal touch", both on environment, ship and technical systems' performance.	More technology means more complexity and possibility for technological failure, but will also improve on some of today's operators errors (human error).	R	G	Y
2	Less exposure to danger for the crew.	40% of deaths at sea are occupational hazards.	Y	G	G
3	May be unable to inspect equipment or systems that report errors or problems.	This may cause problems, especially if sufficient back-up systems are not in place.	R	Y	Y
4	Slightly lower risk of fires in accommodation, galleys, laundry and waste systems.	Improvement on today's accident events, but more difficult fire handling and control.	R	G	Y
Constrained autonomy					
5	More limited, but also more deterministic response from sensors and automation.	Better HAI, due to time to get situational awareness before action.	Y	G	Y
6	Dependence on shore control operators' performance and situational awareness.	Always rested, but not directly in the loop.	R	Y	Y
7	Dependence on communication link to shore.	Loss of communication may cause new accident types, but high integrity req. and clear operational design domains will help.	R	Y	Y
8	Dependence on high quality implementation of fallback solutions and definition of minimum risk conditions for the ship.	More conservative and hence safer operational procedures.	Y	G	G
Shore control center					
9	Dependence on good cooperation in the shore control center.	Training and resource management is critical.	Y	G	R
10	Intervention crew do not have to worry about personal risk and adverse conditions on board.	May be likely to find solutions to critical problems that would otherwise be lost.	Y	G	Y
Higher technical resilience					
11	More technical barriers against technical faults.	In case of trouble, backup systems shall be in place.	Y	G	Y
12	Much improved technical systems with built in predictive maintenance functionality.	Less chance of trouble	Y	G	Y
13	Dependent on maintenance at shore.	Something may be forgotten	R	G	Y
Improved voyage planning					
14	Less chance of surprises during voyage.	Better planned voyage	Y	G	G
15	More support from other functions on shore	Improved traffic regulation	Y	G	G

Important factors to address in the design and development of MASSs is robust sensor quality, redundancy on key technology, and good education for land-based operators, that builds the situational awareness based on technology. Next factor that has been pointed to is less exposure to danger for the crew. Statistics tells that about 40% of deaths at sea are occupational hazards. Another element is that it is expected that it will be slightly lower risk of fires in accommodation, galleys, laundry and waste system, because of no installation of such technology due to the fact that there is no need for it since there are no people on board. The expectations are fewer accidents, but when an accident happens, it might be more difficult to combat when people is not available and the only trust is technology, as addressed by Wróbel et al. (2017).

For a **constrained autonomy** vessel, we have pointed to better human-automation interfaces, due to time to get situational awareness before action. The design of SCC will learn from accidents where alarm related issues and poor HMI were major causal factors. It is likely that the humans are not directly in the loop (manually steering and navigating the vessel). To let the SCC take control there are dependencies to the infrastructure, such as the communication infrastructure, that will have enough coverage and bandwidth to bring data from the vessel to the SCC for awareness before decisions are taken. This also points to more conservative and safer operational procedures, to both operational practices and a higher safety degree.

Shore control center is another category that has been pointed to. The same applies for a SCC as on a vessel's bridge today, a good crew is those who collaborate and use each other's expertise in operations and problem solving. It is even more important at a SCC since the possibility to inspect the vessel is not the same. We assume here an increased risk of accidents that is today adverted by crew, as we know there will be controllability issues with a remote crew, and a high dependence on the SCC team's skills and knowledge. At the same time, the human risk factor is lower since the intervention crew do not have to worry about personal risk and adverse conditions on board. Training and resource management are important.

The category **Higher technical resilience** brings us back to the technology. It is important to build technical barriers towards technical failures with built-in predictive maintenance functionality.

Technical resilience is essential for MASS. The danger is that new unpredictable situations, that have not been thought of, can occur due to a high number of technical systems. Component interaction accidents are becoming more common as the complexity of system designs increases (Leveson 2012).

Improved voyage planning is a safety-critical function for autonomous vessels. Good planning means to prepare the voyage, the loads, the maintenance and all reporting during a voyage. This is a significant requirement compared with conventional vessels, where good planning is crucial for success, but often overlooked (NTSB 2015, DMAIB 2013, Bell 2006).

7 CONCLUSION

This paper provides a more realistic description of what an autonomous ship will be in the foreseeable future, i.e. unmanned, having monitoring and control personnel on shore, exhibiting constrained autonomy and having better operational planning and technical equipment than a manned ship.

While the overall risk picture for autonomous ships may look unpromising (Fig. 4), the differences in implementation have significant impacts on the individual risk types. The qualitative assessment done in Table 1 indicates that there is indeed a significant possibility to improve overall safety for autonomous ships compared to manned, although there are also areas that require special attention.

This paper only provides a cursory and qualitative analysis of the risk issues, but it is hoped that it can contribute to a more systematic process for risk assessment, also more accurately incorporating the positive technical contributions from autonomous ship designs.

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