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On Evaluation Of Ship-Ship Accident Probability Novel Decision Support Tool

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Abstract

Introduction of a new technology pertaining to the safety critical processes in the maritime often requires the prior quantification of its effect on safety. Various studies have demonstrated the positive effects of IT solutions or design alternatives on the safety of navigation. However, these are mainly limited to the acute effects, resulting from the changes in ship operations due to technology implementation. While the diffuse effects, due to changes in organization, are rarely accounted for. Therefore, in this paper we try to quantify the potential effect of a novel navigational system EN may have on ship safety. The latter is measured by the probability of collision accounting for both acute and diffuse effects. To this end, human reliability method CREAM is adopted along with the expert's judgments, assisting in defining the potential areas of EN's influence in the process of navigation and its extent. The obtained results show the significant reduction in the probability of collision for a ship equipped with EN, compared to a standard ship. At the same time the potential areas for improvement are found.

Keywords: maritime safety, human performance, decision support tools

1. Introduction

With the increased automation of marine navigation, and development of new related technologies the safety of navigation is expected to improve, (IMO, 2018a). This is mainly done through the improvement of human performance in the process, which a particular new technology addresses, through the human-centered design, (Hänninen and Kujala, 2012; DNV, 2003; Endrina et al., 2019). However, before the new safety-related solution is introduced its expected effect on safety can be estimated adopting a methodology of Formal Safety Assessment (FSA) accepted by the International Maritime Organization, (IMO, 2018b). The effect the solution may have on navigational safety usually stems from the combination of factors pertaining to various areas, often being interrelated. Therefore, when making attempts on quantification the effects of new technologies on the safety, it is essential to adopt such modelling technique which reflects the specificity of the analysed domain and relevant safety-related factors, such as methods belonging to the field of human reliability assessment (HRA). However, the application of HRA method in maritime is rare, since experts' judgments or accident statistics prevail, (Mullai and Paulsson, 2011; DNV, 2003), even though the HRA methods are recognized and recommended by the FSA.

Behaviour of a navigator on a bridge is shaped by the context of the tasks that are carried out, and by the human nature, therefore it is not random or stochastic, (Hollnagel, 1998; Sun et al., 2012). To evaluate the human performance in each context we utilize a method for human reliability analysis (HRA) pertaining to, so called, second generation HRA, called CREAM, where not only acute but also diffuse effects are accounted for, (Kim, 2021).

This method emphasizes the influence of the context on human performance and advocates a deeper look into the characteristics of human performance, resulting with better understanding of the nature of errors arising in the cognitive process of humans, (He et al., 2008). CREAM has been widely used in various fields, however its application in the maritime is limited (Yang et al., 2013; Akyuz and Celik, 2015; Ung, 2019; Kandemir, 2023).

For this paper, CREAM is taken to calculate the probability of an accident at sea that stems from the human error in two contextual settings: 1) the ship is equipped with standard navigational technology; 2) the ship is equipped with a new technology called EN. Finally, the relative change in the probability of accident for a ship resulting from the introduction of EN is obtained, which is the main purpose of this study. The EN intends to do the following: 1) provides the navigator with the solution for collision evasive action; 2) compares the generated solution with the action taken by the navigator; 3) informs captain on any abnormal behaviour of the navigators.

2. Methods

2.1. EN system

The envisaged EN system is expected to assist navigator on board in twofold. First in assessing the navigational situation in multiple ship encounters. To this end the EN delivers collision evasive plan accounting for the collision regulation at sea, (IMO, 2010), and updates this information as the encounter develops. Second, the EN evaluates the performance of a navigator on board, by collecting and comparing the information on the planned and executed collision evasive actions. Based on that a score is assigned to a given maneuver, which further makes up a safety score for a navigator. Finally, this information is forwarded to the Master and eventually shipping company for consideration. The information on the planned and performed maneuvers is expected to be further used for the training purposes for bridge personnel, eventually improving their skills.

The general flowchart of the EN system is depicted in Figure 1, where the anticipated relations between the various actors and elements of the system are shown. The arrows point the direction of information flow and data feed.

The major component of the EN system is a Navigational Decision Support System NavDec, being primarily a collision avoidance module. This is a system operated by the navigator, collecting online relevant data from the own ship's navigation systems such as AIS, ARPA, GPS, log, gyrocompass, for the detailed description of the system see (Pietrzykowski, Wołejsza, and Borkowski, 2017). Its basic function is to analyse and evaluate the navigational situation within up to 8 Nm according to the COLREG. If the given encounter is classified as a collision situation, the system suggests a solution by informing a navigator on the required course or speed alteration and time horizon when the action should be taken. Basic functions of NavDec are the following:

- to acquire in automatic fashion, process and present the relevant navigational information,
- to display the navigational situation readable to the navigator,
- to analyse the navigational situation based on the COLREG and the criteria of situation assessment used by navigators (such as the closes point of approach - CPA - and associated limits - (Gil et al., 2019)), and to deliver alerts,
- to solve the collision situation through automatic determination of manoeuvre and trajectory, complying with COLREG and explanation of the proposed manoeuvres,
- to recommend solution for safe evasive manoeuvre in terms of new course or new speed as well as sector of safe courses,
- to calculate collision avoidance trajectories for own ship for user-defined input data.

2.2. Modelling navigator behaviors

To quantify the potential effect that EN may have on the probability of collision between two ships, a relevant safety-critical task to be affected by the EN is defined. It is called evasive action, and it encompasses all relevant knowledge- and skill-based subtasks required from the navigator to develop sufficient action avoiding collision in each encounter. The latter is defined as a situation where two ships on collision course or a ship on a grounding course shall perform evasive action to avoid the accident. Since the task is complex and distributed in time, it is decomposed into three major phases: 1) Detection - D; 2) Assessment - A; and 3) Action - Act.

These three phases (DAAct) reflect the basic cognitive functions of observation, interpretation and planning, execution - see for example (Hollnagel, 1998; He et al., 2008). The phases are considered dependent, since the failures tend to propagate, and the failure in detection affects the proper assessment of the situation, which in turn may lead to wrong action.

At each phase a navigator can fail in the number of ways, called failure modes, each assigned with the probability of failure. The combination of the latter along the three phases yields the probability of failure in performing collision evasive action on board one ship. If the other ship fails in the evasive action too, the collision is inevitable. The meaning of phases and the failure modes are described in the following sections, and graphically explained in Figure 2.

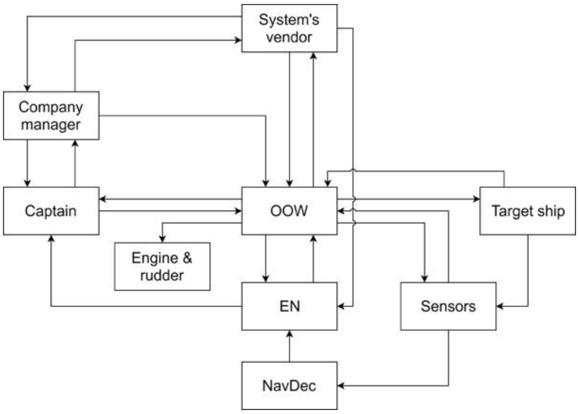

Fig. 1. An outline of the EN system.

2.2.1. Detection

This means that an OOW can detect a ship being on a course, either visually or by means of electronic navigational aids. At this stage, an OOW is aware, that the collision situation exists. Three failure modes are defined at this stage:

- wrong object - the OOW tracks wrong object, ship A instead of ship B;
- wrong identification – the OOW tracks visually ship A but the motion parameters are displayed for ship B;
- observation not made – the OOW being distracted with other tasks fails to notice the target.

2.2.2. Assessment

At this stage interpretation and planning is made with respect to the object that was detected in the previous stage. Five failure modes are anticipated, that make the OOW unsuccessful at this stage:

- delayed interpretation - the OOW assesses too late the type of encounter according to COLREGS, (IMO 2010);
- faulty diagnosis - the OOW wrongly evaluates the proximity indicators, namely the shortest passing distance and available time to perform evasive manoeuvres);
- inadequate plan – the OOW wrongly selects the feasible types of evasive actions;
- priority error – the OOW erroneously lists the objects according to their level of hazard – from the most to the less urgent;
- decision error.

2.2.3. Action

Based on the successful detection and assessment of the situation the OOW needs to act to avoid collision. There are five failure modes that makes the action unsuccessful:

- the action is missed – the OOW is not acting;
- the action is of wrong type – the OOW is swinging ship to port instead of starboard;
- the action is taken in wrong time – the OOW is swinging ship in right direction, but too late;
- the action is taken on wrong object – the OOW takes evasive suitable for ship A but with respect to ship B;
- the action is out of sequence – the OOW.

2.3. Modelling navigator performance

The purpose of the prospective analysis is to provide a quantification prediction of human performance in the context of probabilistic safety analysis. CREAM does this in two ways: basic and extended. For our purpose we use extended version, which consists of the following three steps: 1) Identify the cognitive activities of the task to build a cognitive profile; 2) Identify the most likely cognitive function failure for each identified cognitive activity; 3) Determine the probability for each identified cognitive function failure.

We anticipate four cognitive activities of a navigator, reflecting the main phases of evasive action: observation, interpretation and planning, execution. These can fail in several ways, called failure type, as described in Table 1. Therein 13 generic failure types are gathered, and each is assigned a nominal failure probability (CFP_0). Subsequently, those nominal failure probabilities are adjusted depending on the context, which is described using a following set of Common Performance Conditions (CPCs):

1. Adequacy of organization.
2. Working conditions.
3. Adequacy of man-machine interface (MMI) and operational support.
4. Availability of procedures/plans.
5. Number of simultaneous goals.
6. Available time.
7. Time of day.
8. Adequacy of training and preparation.
9. Crew collaboration quality.

Finally, a point estimator for the cognitive function failure (CFP) in a given context is obtained, as follows, (He et al., 2008):

$$CFP = CFP_0 10^{0.25\beta} \quad (1)$$

$$\beta = \sum_i \rho_i \quad (2)$$

where, ρ_i is a value of Performance Influence Index (PIIs), as specified in Table 2 for a given level of a CPC. The context, defined by the number of PIIs and their levels, may affect the cognitive functions in threefold. It can be neutral ($\beta = 0$), deteriorating ($\beta > 0$) or improving ($\beta < 0$).

Table 1. Nominal values for the probabilities (CFP_0) of 13 generic failure types, (He et al. 2008).

Cognitive function	Generic failure type	Basic value of CFP_0
Observation	O1. Wrong object observed	0.001
	O2. Wrong identification	0.007
	O3. Observation not made	0.007
Interpretation	I1. Faulty diagnosis	0.02
	I2. Decision error	0.01
	I3. Delayed interpretation	0.01
Planning	P1. Priority error	0.01
	P2. Inadequate plan	0.01
Execution	E1. Action of wrong type	0.003
	E2. Action at wrong time	0.003
	E3. Action on wrong object	0.0005
	E4. Action out of sequence	0.003
	E5. Missed action	0.003

2.4. Quantifying the probability of accident

To calculate the human error probability (HEP) from CREAM, a task analysed here, which is collision avoidance, needs to be decomposed, and the CFP for each sub-task (detection, assessment, action) calculated.

Then the logic relation between the sub-tasks is to be determined, which translates into the way how the sub-tasks are linked, either through parallel or serial connection. Subsequently, the level of dependency between the sub-tasks shall be evaluated and attributed to one of the two categories: high or low dependence. Based on that, the appropriate inferring rules are selected, as demonstrated in Table 3. This results in the HEP for the analysed task.

2.5. Quantifying the effect of EN on the probability of accident

The EN is expected to be decision support tool for a navigator and an instrument for a master and shipping company to assess the performance of the navigator in collision encounter situations. Therefore, it is justifiable expecting that the EN will affect the safety at various levels, such as cognition, skills and motivation.

Therefore, we estimate the influence of the EN on the cognitive functions of a navigator and common performance conditions stemming from the company organization. To this end experts' judgment is adopted. A panel of 7 experts was developed, pertaining to the following industrial and academical fields, relevant for the given purpose: ship operation and management, marine IT systems design, risk and safety assessment of socio-technical systems. Finally, the effect of the EN on the safety, is measured through the anticipated changes it will on the probability of an accident, before and after the prospective implementation of EN onboard the analyzed ship.

Table 2. Performance influence index for CPCs, (He et al. 2008).

CPC	Definition of CPC	Level	Performance influence index
Adequacy of organisation	The quality of the roles and responsibility distribution of team members, the availability of a Safety Management System, and of precise instruction and guidelines for operative conditions. In respect to safety the concept can also be linked to the safety culture of the organization itself.	Very efficient	-0.6
		Efficient	0
		Inefficient	0.6
		Deficient	1.0
Working conditions	The nature of the physical working environment such as noise, temperature, humidity, lighting etc.	Advantageous	-0.6
		Compatible	0
		Incompatible	1.0
Adequacy of MMI and operational support	This CPC refers to the quality of the Man Machine Interface (MMI), which is to say the control panels or more in general the equipment the operator has to interact with for carrying out his/her tasks.	Supportive	-1.2
		Adequate	-0.4
		Tolerable	0
		Inappropriate	1.4
Availability of procedures/plans	They include emergency plans and procedures, familiar pattern for response etc.	Appropriate	-1.2
		Acceptable	0.0
		Inappropriate	1.4
Number of simultaneous goals	This CPC refers to the number of tasks an operator is required to perform at the same time.	Fewer than capacity	0
		Matching current capacity	0
		More than capacity	1.2
Available Time	Time available for carrying out the task.	Adequate	-1.4
		Normal	0
		Temporarily inadequate	1.0
		Continuously inadequate	2.4
Time of the day	It is well established the fact that the time of day has an effect on the quality of the work: the performance could be less effective if the normal Circadian Rhythm is not respected.	Day-time (adjusted)	0
		Night-time (unadjusted)	0.6
Adequacy of Training and experience	Level and quality of training provided to the operators, and familiarization to the technologies adopted in the working context.	Adequate, high experience	-1.4
		Adequate low experience	0
		A little inadequate	1.0
		Inadequate	1.8
Crew collaboration quality	Normally if in a crew the members work well together a task will be more easily performed efficiently. Responsibilities and working loads would be more efficiently shared.	Very efficient	-1.4
		Efficient	0
		Inefficient	0.4
		Deficient	1.4

Table 3. Calculating the HEP of a task combining sub-tasks with associated CFPs, (He et al., 2008).

Logic relation between sub-tasks	Dependence between sub-tasks	HEP of the task
Only failure of all sub-tasks would fail the task (parallel subtasks)	High dependence	$HEP_{Task} = \min(HEP_{sub\_task})$
	Independent/low dependence	$HEP_{Task} = \prod(HEP_{sub\_task})$
Failure of one sub-task leading to failure of the task (sequential subtasks)	High dependence	$HEP_{Task} \approx \max(HEP_{sub\_task})$
	Independent/low dependence	$HEP_{Task} \approx \Sigma(HEP_{sub\_task})$

3. Models

3.1. Quantifying the effect of EN on the probability of accident

As an outcome of the model, the probability of collision between two ships is taken, assuming the conditions of solo-watch on the bridge, which in most cases happen in the high seas. For a collision to occur, two ships need to be on collision course, and both need to fail in avoiding it. The probability of not avoiding collision by a target ship is fixed, while it varies for the own ship, as an effect of EN. The model, which structure is depicted in Figure 2, is developed with the use of Bayesian Networks, which are recognised tool for safety and risk modelling as well as for inferring in the presence of uncertainty, (Lehikoinen et al., 2009; Hänninen, 2014; Montewka et al., 2014; Fenton and Neil, 2012; Montewka et al., 2017; Kero et al., 2023). Therein the transparent nodes denote the effect of common performance conditions on the cognitive function failure, as per Eqs.1 and 2. The dark-grey nodes refer to the cognitive functions performed by the navigator, to avoid an accident. The light-grey nodes reflect the failure modes and associated probabilities for three cognitive functions (detection -D, assessment- A and action- Acc), which in turn yields the probability of accident. The probabilities of failures in D, A, Acc are calculated assuming the independence of failure modes contributing to each phase, assuming only one failure mode suffices to fail the whole phase. Therefore, the probability of a failure at any given phase is calculated with the following generic formula:

$$P_{fail\_at\_a\_phase} = \sum\left(P_{fail\_modes\_for\_a\_phase}\right) \tag{3}$$

However, the detection and assessment are considered as highly dependent events since any error in detection will result in wrong assessment. While the assessment and action are seen as less dependent, since even with the wrong assessment, the navigator may still be able perform proper action. Therefore, following the logic presented in Table 3, the probability of an accident in an encounter is determined as follows:

$$P_{acc} = \min\ \left(P_{fail\_detect}, P_{fail\_assess}\right) \times P_{fail\_act} \tag{4}$$

To quantify the probability of accident per year, the number of encounters need to be estimated, which depends on the ship and trade type. For the given purpose we take a container feeder type of ship, that trades mainly within the waters of northern Europe, with an average speed of 15 knots. For these settings the estimated number of encounters per day is 20, and 7300 annually. The probability of an accident per year is determined as follows:

$$P_{acc\_annual} = 1 - \left(1 - P_{acc\_single\_encounter}\right)^{No\_encounters} \tag{5}$$

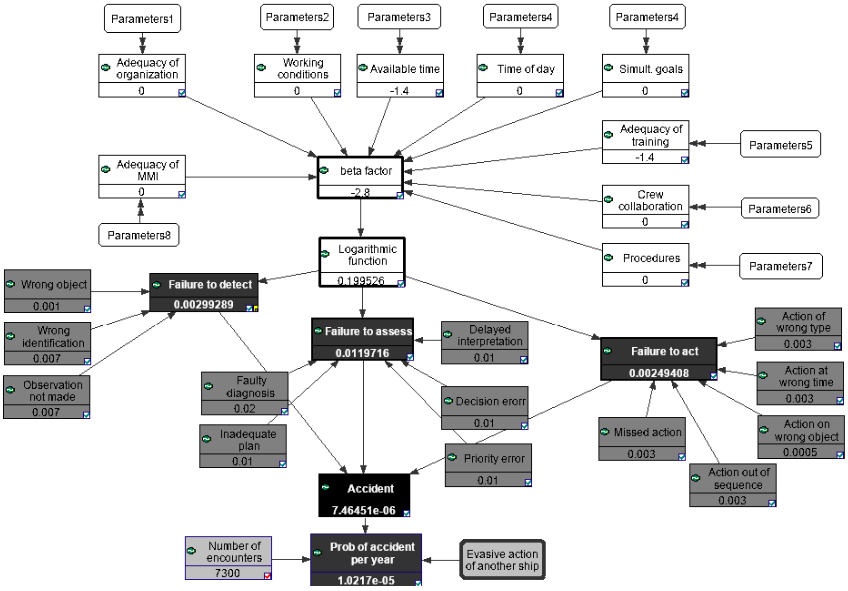

Fig. 2. A structure of framework estimating the probability of accident.

3.2. Quantifying the effect of EN on the probability of accident

The anticipated effect of EN on the safety of a ship, is assessed in a systemic manner, evaluating the potential relations that EN may have or develop in the analysed system, adopting experts' judgment. In Table 4 we marked the potential areas, which EN may influence, either positive or negative, indicating the strength of such influence and providing justification for the claims. However, it remains unknown whether these CPCs will all be affected all at once, or separately.

Table 4. Definitions of *Common Performance Conditions* - CPCs - and the potential effect of EN on those.

CPC	Comments on the anticipated effect of EN on the safety management system within the shipping company	Effect of EN on CPC
Adequacy of organisation	The inclusion of EN into the daily routine of ship operations and associated evaluation of navigator behaviours and periodic trainings using the patterns developed by EN may increase the safety culture.	No
Working conditions	The EN is not expected to affect the nature of the physical working environment such as noise, temperature, humidity, lighting etc.	No
Adequacy of MMI and operational support	This CPC refers to the quality of the Man Machine Interface (MMI), which is to say the control panels or more in general the equipment the operator has to interact with for carrying out his/her tasks. For the EN to affect this CPC it shall be fully integrated with other navigational systems, so the number of devices and displays the navigator needs to follow is kept at the minimum.	No
Availability of procedures/plans	The incorporation of the EN in the process of ship navigation may trigger the development of new procedures, related to the use of the system as well as the periodic assessment of navigators based. However, the EN alone is not expected to change the existing approach of the company to the plans and procedures drafting and obedience.	No
Number of simultaneous goals	On one hand the EN is assisting the navigator in providing the solution for the collision situation, on another in requires data input and verification. Therefore, the number of tasks may not be significantly reduced.	No
Available Time	Navigator on a bridge needs to verify the solution the EN produces. Verification can take less time than development of collision avoidance, especially in the case of multiple ship encounters. We expect the EN to change the parameter of this variable from *Normal* to *Adequate.*	Yes
Time of the day	Not applicable	No
Adequacy of Training and experience	Additional training with the use of patterns and cases that EN provides may contribute to the increase in the level and quality of training offered to the operators, and familiarization to the technologies adopted in the working context. We expect the EN to change the value of this variable from *Adequate low-experience* to *Adequate high experience.*	Yes
Crew collaboration quality	Not applicable	--

4. Results

The results obtained are depicted in Figure 3, where the baseline probability attempts to reflect the normal operational conditions, and the β factor - as given in eqs. 1 and 2 - is set to 0. While calculating the updated probability of collision, the effect of EN is evaluated by adjusting the value of the β factor, through the selection of the most probable CPCs. These can manifest themselves individually or collectively, but our knowledge on that is limited. Therefore, two values of annual probability of accident are obtained for a ship that is equipped with EN, developing an interval. One value represents the effect of individual CPC and the other denotes the combined effect of CPCs. The obtained change in the probability of collision between two ships in the high seas is significant, as compared to the base line values, either for single of combined effect of CPCs - 4 times and 10 times reductions of the probability correspondingly. This is far more than in the available studies on similar topics in the maritime, (Hanninen et al.; 2014; Endrina et al., 2019). Several explanations for this can be formulated. First, the earlier studies tend to focus on the operational aspect, excluding or limiting the effect of organization, which seems to play an important role in shaping the safe of transportation, (Gamero et al., 2018). The model presented here attempts to combine both: the effect of organization and operational factors, through a set of CPCs. Second, the variables describing CPC can take only single value, assuming that a given CPC remains constant over the analyzed period. This may be true for factors pertaining to the organizational factors; however, it is not necessarily reflecting the reality of ship operations. For example, the CPC called *Available Time* or *The number of simultaneous goals* may depend on the route and resulting burden due to number of tasks to be carried out and available quality of rest. In case of a ship that calls every day to a different harbor the crew may be sleep deprived, thus more prone to errors. In similar manner, the effect of EN is taken as constant over the whole lifetime of the ship. Obviously in some cases the EN may affect the performance of a navigator stronger that in another. Third, the model assumes positive effects that EN may have on the bridge team. Whereas the negative effect of EN on the human performance, although discussed among experts in the panel, are not accounted, (Fries, Wiesche and Krcmar, 2016). This can be seen as an area that needs to be closer looked at in the future, since it can lead to the much narrower gap between the base line and expected probabilities. Since, ***decision support systems introduced in the maritime domain often face skepticism, misuse, non-use, and trust issues, some of which may not be faced in newer, globally distributed technological systems with shorter decision time frames and a history of new technology introduction, such as aviation***, (Dhami and Grabowski, 2011), therefore, both effects must be accounted for in the prospective analysis of any systems of this kind in the maritime settings, especially in the early stage of the technology lifecycle.

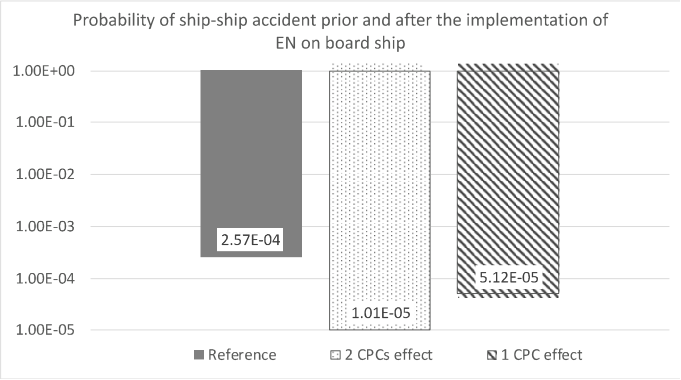

Fig. 3. The anticipated effect of EN installed on board the own ship on the probability of ship-ship collision.

5. Conclusions

The aim of this paper is to quantify the effect of the newly developed solution, called EN, assisting a navigator in ship-ship encounters in the high sea, on the probability of collision between two ships. To this end experts' judgment technique is used to elaborate the potential areas of ship operation and management that may be affected by the EN in the given context. Secondly, the human reliability method called CREAM is taken to calculate the probability of the collision, however we do not seek the absolute value of the probability, rather we are interested in the expected relative change of this quantity comparing two conditions – with and without the new technology onboard. The analysis is performed for a medium sized container feeder operating in the seas of the northern Europe. The obtained results indicate the ship equipped with EN may feature lower probability of collision, compared to the ship without EN system. It also points to the most likely areas, where the system will contribute to the safety of navigation, addressing the following CPCs: *Adequacy of Training and Experience* and *Available Time*. However, there exist several uncertain areas, that have not been addressed here in great details, e.g. the potential negative effect of the EN or the time variance of the system and associated effects of EN. These are potential areas for future work on the effect of new solutions entering the area of marine navigation on its safety.

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