FINAL REPORT

PRACTICAL TESTS WITH AUTONOM SAFETY

Praktiska tester med autonom säkerhet

FUD TRV 2017/62459

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Sammanfattning (svenska)

Projekt: Praktiska försök med autonom säkerhet

Inledning

Detta är slutrapporten för projektet ”Praktiska försök med autonom säkerhet”, FUD TRV 2017/62459. Projektet genomförs av RISE Viktoria, Saab Kockums, Sjöfartsverket och Stena Rederi. Projektet syftar till att definiera konceptet autonom säkerhet med stöd av praktiska försök ombord på ett större fartyg. Projektet kopplar ihop teknikutveckling genomförd hos Saab med operativ erfarenheten från Stena. Projektet koordineras av RISE som har erfarenhet att leda likande projekt inom autonoma fordon. Sjöfartsverket är också en viktig partner som idag leder ”Sea Traffic Management Validation” (STM) projektet. Detta projekt finansieras av Trafikverket.

Bakgrund

Den hållbara utvecklingen inom transportsektorn i Sverige idag har stort fokus på hjulbundna transporter. Sjöfarten har stor potential till att bidra till ett hållbarare samhälle och dess framtida behov av säkra och effektiva transporter. Arbete görs nu internationellt och i Sverige för att dra nytta av digitalisering och automation inom transportsektorn.

I Lighthouse förstudie rörande ” Autonom säkerhet för fartyg - digitaliseringens möjligheter för ökad säkerhet”, (LIGHT, 2016), identifierades flera möjligheter för svenskt näringsliv och akademier att ta tätpositioner inom området digitalisering och automatisering av sjöfart. Ett svenskt initiativ för smarta fartyg som bygger på svenska styrkor bedöms som mycket viktigt för att höja säkerheten ombord och att höja kompetensen inom det svenska maritima klustret. Nyttan går i tre riktningar; till de som arbetar ombord, myndigheter samt svensk industri och redarverksamhet som leder säkerheten framåt.

Projektbeskrivning

Målet med projektet är att genomföra praktiska försök med autonom säkerhet ombord på ett representativt handelsfartyg för att ge kunskap om hur konceptet kan implementeras på bemannade fartyg. Inom andra transportgrenar pågår idag ett stort arbete med att avlasta operatören i den operativa miljön så att han/hon kan fokusera på problemlösning på högre taktisk/strategisk nivå. Även i en krissituation, borde basala operationer kunna hanteras mer automatiserat och operatören kan då fokusera på att analysera de taktiska och strategiska konsekvenser de kommande besluten kan få. Genom dessa praktiska tester har projektet gett kunskap om hur autonom säkerhet kan implementeras på bemannade fartyg som ett nytt beslutsstödsystem på bryggan.

Projektet organiseras i tre arbetspaket:

- Projektledning
- Tester
- Utvärdering

Operationellt koncept

Automatiseringen är på frammarsch inom transportsektorn och flera försök genomförs också med autonoma fartyg. Dock är det inte sannolikt att större handelsfartyg kommer att framföras helt autonomt inom snar framtid. Idén med autonom säkerhet är att utnyttja framstegen inom automatisering och nya sensorer för att stödja bryggteamet i navigationsprocessen. Autonom säkerhet kan även betraktas som en del i nästa generation navigationssystem.

Projektet har tagit fram ett operationellt ramverk för navigationsprocessen som sedan används för att definiera hur Autonom säkerhet kan fungera i bryggmiljön. Idén går ut på att den autonoma navigationsprocessen är en bakgrundsprocess som intar rollen som ”Navigator” eller ”co-Navigator” i byggarbetet. Systemet kommunicerar med operatören både med hjälp av audio och visuellt. Med hjälp av audio kan ”closed-loop” kommunikation upprättas mellan systemet och operatören. Mer komplexinformation så som rekommendationer, identifiering av farliga situationer.

Teoretisk modell

En teoretisk modell för att estimera säkerhetsmarginalen i olika navigationssituation har diskuterats. Denna säkerhetsmarginal kan kopplas till operationella begränsningar. Vidare kan denna säkerhetsmarginal också användas för att definiera de olika operationella faserna.

Försöksbeskrivning

Praktiska försök har genomförts ombord på Stena Germanica med Saabs prototyp ”BackBridge” modul placerad på fartygsbryggan. Detta som ett verktyg för att analysera en ny typ av ”beslutsstödsystem. Parallellt övervakades fartyget från Sjöfartsverkets VTS lokaliserad i Göteborg. Försöken genomfördes den 15 – 17 januari samt uppföljande intervjuer ombord 28/2.

Resultat och nästa steg

Resultaten i projektet har gett kunskap om hur autonom säkerhet kan implementeras på bemannade fartyg. Projektet syftar till att vara ett av de första stegen på att säkerställa ett långsiktigt initiativ kring smarta fartyg och autonoma processer som bygger på svenska styrkor.

Under de praktiska försöken ombord diskuterades konceptet autonom säkerhet med besättningen. Konceptet mottogs väl och flera konkreta förslag på operationellimplementering diskuterades.

Det är viktigt att ta dessa projektresultat vidare till en framtida implementering. Nedan föreslås tre olika steg:

1. Implementera de föreslagna HMI funktionerna i en prototyp för att sedan testas och utvecklas vidare tillsammans med aktiva navigatörer genom att använda avancerade fartygssimulatorer. Detta skulle kunna vara ett nytt forskningsprojekt.
2. Fortsätta den tekniska utvecklingen av de autonoma navigationsfunktionerna. Detta skulle kunna vara ett nytt utvecklingsprojekt.

3. Utvärdering av nya sensorer i en verklig marinmiljö. Detta kan vara bredbandsradar, LIDAR eller optiska sensorer. Man bör även utvärdera om sensor som är utvecklade för fordonsnavigation skulle kunna fungera i marinatillämpningar.

Document history

Issue	Date	Comment
1.0	17-01-22	Draft, Report outline
1.1	18-02-25	Draft, section 1, 2, 3, partly 5, partly 6 included
1.2	18-02-28	First review version
2.0	18-03-02	Final Report

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1 INTRODUCTION

1.1 Scope and Purpose

This is the final report of the project “Practical Tests with Autonomous Safety”, FUD-TRV 2017/62459 funded by Trafikverket. The project result is the combined work of four organisations; RISE Viktoria AB, Sjöfartsverket, Saab Kockums AB and Stena Rederi AB.

The focus of this project is on safety of navigation with the approach to define an increased level of decision support for the bridge officers. The trend is clear, higher level of automations is entering all sectors of transportation and it stretches also to vessels. Further, there is lot of synergies with the developments of autonomous vehicles.

The basic concept of Autonomous Safety is to use current and new sensors to feed into an autonomous navigation control function. This control function works as a background process to the normal bridge work and with functionality for communication with the navigator. Hence, the Autonomous Safety concept consists of a navigation decision support tool and sensors.

The outcome of this project is a proposed concept of Autonomous Safety supported by practical trails conducted onboard Stena Line AB´s ships and monitored by Sjöfartsverket’s Vessel Traffic Service (VTS) facilities. The project also proposes what next steps to take in research and development to further detail the concept.

1.2 Document structure

This report is structured according to the following:

Sammanfattning here, a summary in Swedish is given.

Chapter 1 is this introductional section giving purpose and organisation of the study. This section also includes lists of abbreviation and references.

Chapter 2 gives the background to this project together with discussing of some earlier studies related to the project.

Chapter 3 gives the overall concept of operation for navigation decision support.

Chapter 4 outlines a theoretical base for the autonomous navigation control function.

Chapter 5 describes the data collection and the results from the practical trials.

Chapter 6 summaries the results of the project.

1.3 Project organisation

The project is conducted according to the following study logic. Basic results from the Lighthouse pre-study regarding Autonomous Safety (LIGHT, 2016) gave the idea to Autonomous Safety as a concept for “driver support” or decision support. Based on this idea a concept of operation was established by analysing user needs, the operational phases and processes. Practical tests are laying the ground for a theoretical base for the navigation control function.

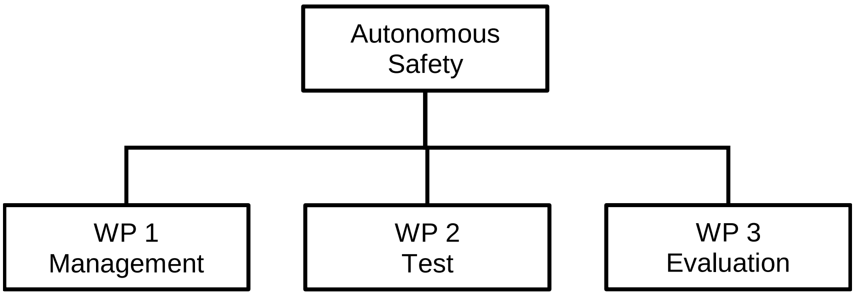

Figure 1: Work break down structure

The work has been organised into three Work Packages (WP) see Figure 1:

The WPs are shortly described below:

- ***WP1 Project management*** is handled by RISE Viktoria.
- ***WP2 Test***, this WP contains the results from the practical tests conducted onboard Stena Line's ship. This part is reported in ***chapter 5*** and constitutes the base for *WP 3*.
- ***WP 3 Evaluation***, this WP describes the concept of operation, establish a theoretical base, draws conclusions from the tests and propose next step. This part is reported in ***chapter 3, 4*** and ***6.***

1.4 Abbreviations

AAWA	Advanced Autonomous Waterborne Applications Initiative
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid (ARPA)
AtN	Aids to Navigation
BRM	Bridge Resource Management
C-ITS	Cooperative Intelligent Transport Systems
COLREG	Collision Avoidance Regulation
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
HMI	Human Machine Interface
IMO	International Maritime Organization
GPS	Global Position System
LIDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
SARUMS	Safety and Regulations for Unmanned Maritime Systems
SC	Shore Center
STM	Sea Traffic Management
TBD	To Be Determined
TCPA	Times to Closest Points of Approach
VTS	Vessel Traffic Service
WOP	Wheel Over Point
WP	Work Package
WPT	Waypoints

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2 BACKGROUND

2.1 Background

One year ago, the digitalisation in the shipping sector could be considered as a trend (LIGHT, 2016), since then the activities have increased monumentally. Large actors like Maersk has entered cooperation's with IBM regarding blockchain technology, (IBM, 2018) and Rolls Royce remote controlled tug (Rolls Royce, 2017) and their competitor COSCOS has started to implement a new class notation for their new building (LR, 2017), where the vessel MV COSCO Shipping Aries has achieved LRs notation "Cyber AL3 SECURE PERFORM" for its energy management system. The bulk vessel "Great Intelligence" (LR, 2018), the floating living lab for automation, has been christened and have or will enter service any day now. This is something new within maritime shipping.

Within the aviation industry, there are a lot of research on going about what can be done in the cockpit to relive the pilots of cognitive stress. One project was the European Union founded Advanced Cockpit for Reduction of Stress and Workload (ACROSS), among several goals it looks at systems for how to solve reduced crew operations, it could be a planned one, one pilot can go for a rest during long flights or that one or both pilots become incapacitated during flight. To support these situations they were looking in to new support systems in the cockpit and it went as far as remote operation of the aircraft, so it could be safely landed and stopped on the runway.

In a maritime context, this development would open up for new types of support system for the officers onboard the vessels.

Today, the vessel's navigator should be freed from cognitive workloads that hinder them from focusing on the task at hand. Traditionally, the bridge has been manned with junior officers that has focused on plotting the vessels movements to relieve work load the navigating officer. The cumbersome task of navigating in and updating paper charts has been removed and replaced with ECDIS, but still collisions and grounding occur (MAIB) during departures and transits along the coast, due to the fact that the crew has other duties to full fill, and navigation of the vessel usually goes well. But as incidents and accidents show, even with an extended resource at the bridge e.g. a Pilot, vessels do collide or is run aground, usually due to lack of situational awareness.

Some say that 80-90% of incidents at sea is due to human interaction or lack of human interaction, (Eagle). This seems to be similar in other transportation sectors and in an effort to address this, higher level of automation is proposed and tested. In road vehicles, it has gone as far as more or less autonomous car/heavy vehicles are soon on our streets.

Based on the need for a more active supportive system and the progress mention above in other transport sectors, an incremental approach is considered and deemed applicable for the shipping industry.

Conceptual ways forward: (LIGHT, 2016)

- "*Smart vessels – manned vessels with higher level of automation giving the officers Sense and Decision-making assistance.*

- *Hybrid solutions with remote operated vessels, vessels in convoy where a manned "Shepard"-vessel guiding several unmanned vessels in a convoy, using vessel to vessel communication.*
- *Short manned vessels with 12hrs of manned watch and 12hrs with supervision/control delegated to a Shore Control Centre.*
- *Unmanned Remote operated vessel from a Shore Control Centre 24x7 from port to port.*
- *Fully Autonomous Vessels that handles the planning and execution of the complete voyage from port to port. Only monitored from a SCC with the ability to invoke only if deemed necessary.*"

This project addresses the first bullet point – manned vessels with higher level of decision support.

2.2 Related studies

Below follows a short overview of some important studies which will serve as a good starting point for this project. It is important to note that this overview is not complete.

Advanced Autonomous Waterborne Applications Initiative (AAWA)

Advanced Autonomous Waterborne Applications Initiative (AAWA) is funded by Tekes and is a triple helix set up with universities, ship designers, equipment manufacturers, and classification societies to explore the economic, social, legal, regulatory and technological factors which need to be addressed. AAWA is probably the cutting-edge project that aims at the merchant fleet. The key focus is the construction of new vessels. Rolls Royce who is leading the AAWA is also a key actor in the Norwegian Forum for Autonomous Ships (NFAS). AAWA has equipment installed on several vessels in regular service and is collecting data for analysis, they also have a simulator centre in Ålesund Norway. (Rolls Royce, 2017) and Turku Finland (Rolls Royce, 2018) One pillar for the control of the vessel is Rolls Royce's Dynamic Positioning system that is used in Oil & Gas offshore sector.

Safety and Regulations for Unmanned Maritime Systems (SARUMS)

Safety and Regulations for Unmanned Maritime Systems (SARUMS) is a European Defence Agency Maritime Unmanned Surface (UMS) Vehicles study and is supported by EU Political and Security Committee. They have conducted UMS risk analysis and developed a Best practice guide for UMS handling, operations, design and regulations and COLREG amendment proposal. From this project, several national and international collaborations have sprung, to mention some; US Coast Guard and the UK Marine Industries Alliance MASRWG, they have both made inquiries to IMO and now IMOs MSC has asked the MASRWG (Maritime Autonomous Systems Regulatory Working Group) for a Scooping document.

MUNIN

MUNIN, Maritime Unmanned Navigation through Intelligence in Networks was co-funded by the European Commissions under its Seventh Framework Programme. It probed if autonomous ship provides an important pathway for a sustainable development of maritime transport. The main objective of the MUNIN project was to show the feasibility of an autonomous and unmanned vessel. The project also looked in to individual components of the autonomous ship in a way that they can be retrofitted to existing ships thus improving their technical or navigational performance in short term. One of the cornerstones in MUNIN was the Shore Centre.

Lighthouse study Autonomous Safety

In discussions with ship owners (Wallenius, Stena Rederi), Sjöfartsverket, Chalmers university of technology, an investigatory discussion started in January 2016. It was founded by Lighthouse and coordinated by Viktoria Swedish ICT (now RISE Viktoria). It focused on what these new automations developments in other transport sectors could do for shipping industry and to start with, for the officers on ships.

In conjunction with this pre-study a seminar was held in December 2016 with industry, academia, and authorities. One of the outcome was the identification of three uses cases for autonomous vessels:

- Autonomous safety or “Driver support” or Navigation Decision Support”;
- Autonomous urban shipping; and
- Autonomous ocean measurement platforms.

Sea Traffic Management (STM)

The STM concept, (STM, 2018) where defined in the EU project MONA LISA 2.0 with the overall aim of increasing safety, efficiency and a less environmental impact from shipping using an increased exchange of information. The STM concept uses an increase exchange of information:

- Ship-to-ship; a segment of the voyage plan exchanged to other ships within radio coverage using STM module communicating with AIS;
- Ship-to-shore center; the route plan is exchanged from ship to shore. Recommended route changes can be proposed from the shore center; and
- Ship-to-port; the voyage plan and time stamps are exchange with ports.

Based in this information exchange, today’s services can be enhanced, or new services can be established. Examples of operational STM services are:

- Pilot route service;
- Route cross check service;
- Enhanced monitoring service; and
- Shore based navigation assistance service.

The STM concept is currently validated in the EU project STM Validation Project ending in December 2018. This project is coordinated by Sjöfartsverket.

2.3 Performance targets

The overall aim of this project is to increase safety of navigation. Fewer collisions between vessels and fewer groundings, could be achieved by new concepts on the bridge. Hence, a "Driver support" system that could validate new types of sensor inputs and cross checks with more classical navigational systems e.g. radar and optics. In conjunction with digital charts, it could increase the reliability of where the vessel actually is, where it is going and if there are anything in its surrounding that the navigator should be aware of or alarmed about. This would lower the cognitive work load on the navigator and free up valuable capacity for strategic and tactical strategies, especially if in congested waters with high traffic intensity. New concepts that is being tested in the automotive sector such as Cooperative Intelligent Transport Systems (C-ITS) would also benefit the shipping sector. The first level of this is already implemented on merchant vessels, Automatic Identification System (AIS). But it lacks quality assurance and has a low level of data exchange. There are other ongoing projects that tries to bridge some of these gaps, some by using extensions to AIS a route sharing protocol.

But it also has its limitations. There are other projects supporting this type of development, one is the STM mentioned earlier. A connected ship using C-ITS and it shares its intentions with other actors/vessels is less likely to end up in close quarter situations.

Several performance improvements can be reached as secondary effects, new types of vessels that can support the industry with a constant flow of resources in smaller scale where the number of crew is reduced, could enable a more energy efficient shipping and there by less pollution. Smaller vessels could be easier to manage during cargo operations, the automatic operation could maybe be performed indoors with less sound pollution and higher efficiency. It could hold the solution to lowering the congestion on roads when different types cargo and passengers are transferred from land-based transportations systems to waterways.

3 CONCEPT OF OPERATION

This section establishes a concept of operation for the Autonomous Safety. It takes a starting point in well-known user needs. It uses the method of operational analysis to derive an operational framework for the navigation process. Then, the operational concept for Autonomous Safety is established using this operational framework. The identified functions need to be implemented by an Autonomous Safety concept.

3.1 User needs

The overall objective of the Autonomous Safety concept is to increase the safety of navigation with the end objecting of leading to less incidents and accidents. However, one main task is to address user needs from the operators.

User needs where identified in a structured way during the process of developing of IMO's e-navigation Strategic Implementation Plan. In Annex 2, in the e-navigation Strategic Implementation Plan, user needs connected to e-navigation where identified. Below some of these user needs are quoted, which are relevant to Autonomous Safety (SIP, 2010):

Onboard:

- "*Mariners would be grateful if e-navigation could facilitate better detection of target.*"
- "*Mariners expressed a desire to have more effective Guard Zones to notify watchkeepers of hazards pertaining to collisions and groundings.*"

Further, in Annex 2 some user needs can be used as design requirements for new navigation systems (SIP, 2010):

- "*Improved Ergonomics Mariners have expressed a desire for bridge layouts, equipment and systems to be better designed from an ergonomic and user-friendly perspective*."
- "*Mariners expressed a desire for greater standardization of functionality for navigation displays (human/machine interface)*"
- "*Mariners need all safety-related equipment to be provided with familiarization material specific to the model and installation.*"
- "*Bridge alerts (emergency alarms, alarms, warnings and cautions) must be co-ordinated, weighted, and support decision making without undue distraction*."
- "*Before mariners can feel confident about relying on systems under the e-navigation concept, they must prove far more reliable than many of the present systems.*"

3.2 Operating environment

This paragraph defines the operating environment for the navigation process and uses an operating picture to identify operating nodes, elements, and actors.

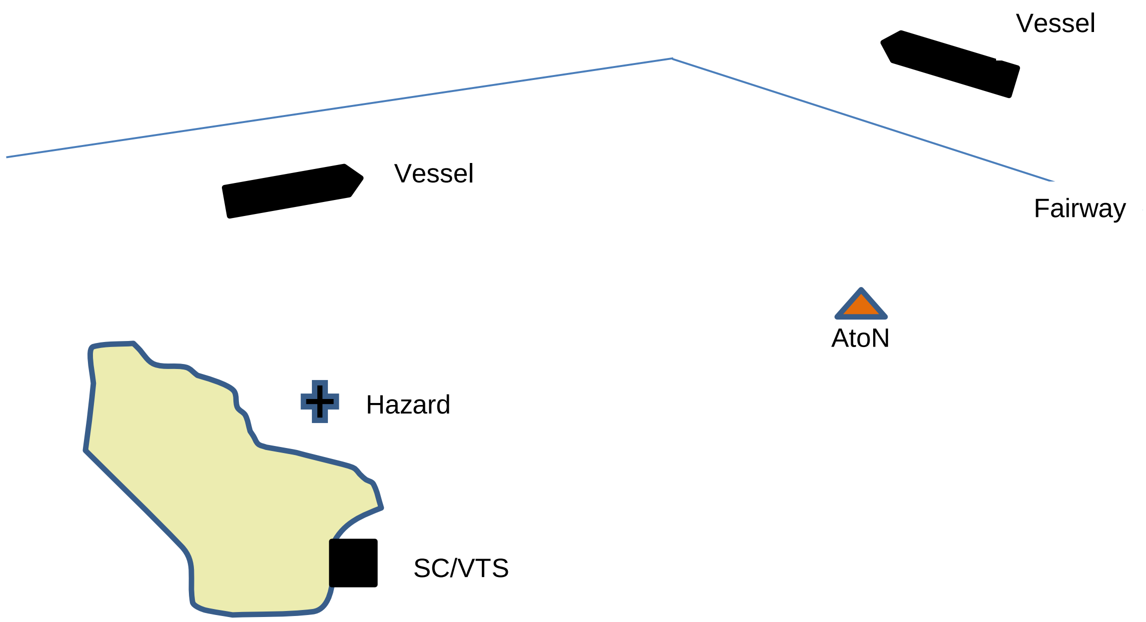

Figure 1: Operating picture capturing the operating nodes of the navigation process.

3.2.1 Operating picture

The following operating picture can be established. The operating picture illustrates the operating environment, elements, and nodes.

The following ***operating nods*** are used in this simplified model:

- Own vessel;
- Other vessels;
- Navigation hazards;
- Shore Center (SC) and VTS;
- Aids to navigation; and
- Fairway and ship's routing system.

Actors are representing the operators involved in the navigation process. In this report the following actors are considered:

- Bridge team;
- Pilots; and
- VTS operators.

The main operating parameter is the information connected to the navigation process:

- Dynamic information of own vessel;
- Static information of own vessel;
- Dynamic information of other vessels;

- Planned voyage including route information;
- Depth and bathometric information;
- Environmental information (current, wind, visibility, sea state, ice, etc) and
- Safety information.

To further understand the information and definitions used in the navigation process some basic use cases are detailed in §3.2.3. However, before that, a framework for the navigation process is established in the next paragraph.

3.2.2 Operational framework

To specify the scope of the Autonomous Safety concept and to organise the navigation tasks in a structured way, an operational framework is used. Below this framework is defined.

The overall scope is the navigation process, so we start from the four different steps in the navigation process, (Bole, 1992):

- ***Appraisal,*** which is the process of gathering all required information. Today, more of this information is provided by digital means. Also, during this stage an overall assessment of the passage should be performed;
- ***Planning,*** in this stage a detailed passage plan is performed berth to berth. The plan includes not just waypoint (WPT) and legs between the WPTs, but also Wheel Over Points (WOP), speed, aids to navigation, reporting points, minimum clearance at critical passages;
- ***Execution,*** which puts time on the passage plan framed by Estimated Time of Departure (ETD) of the current port and Estimated Time of Arrival (ETA) of the port of call. This stage asses all time depending aspects of the passage e.g. tidal waters and tidal currents, light conditions at landfall, watch schemes and bridge manning at different parts of the passage; and
- ***Monitoring***, this stage represents the continuous monitoring of the execution of the plan e.g. progress of the ship along the pre-planned track.

To define operational phases, we use the stages presented above together with the phases defined in (Snider, 2012):

- ***Strategic***, this phase covers aspects that affects the overall voyage or a large part of the voyage.
- ***Tactic***, this phase covers near-time aspects of the voyage. This can be a time span of several hours down to less than an hour.

To better cover all operational aspects, we add one more phase to ***strategic*** and ***tactic*** – ***operation***.

- ***Operation***, includes the actual action to accomplice a change in the vessels status, e.g. change of course and speed required by the navigation or maneuvering.

Combining the navigation process with the operational phases and using the definitions in (Snider, 2012), we end up with the following sub-phases. These different combinations are depicted in the table below.

Autonomous Safety covers Tactical monitoring and Operation highlighted in green in the Table 1. Each sub-phase can be further detailed into functions that needs to be implemented by the bridge in combination with the bridge team or implemented by the Autonomous Safety concept.

Onboard navigation activities are listed in: (SIP, 2010)

- Support Control Navigation;
- Support Information Management;
- Safe Navigation;
- Support Incident and Emergency; and
- Support Maritime Security.

It is especially Safe Navigation that is of interest for Autonomous Safety with its sub-functions: (SIP, 2010)

- "*Establish and Maintain Situation Awareness …;*
- "*Assess Navigation Conditions …";*
- "*Assess Ship's Course and Speed …";*
- "*Assess Traffic Situation (Traffic Image) …";*
- "*Define Ship Position …";*
- "*Determine Under Keel Clearance …";*

Table 1: Definition of navigation sub-phases. The green fields representing the scope of Autonomous Safety

Sub-phase	Description
Strategic appraisal	Includes the establishment of a strategic overview plan
Strategic plan	Includes the actual detailed planning of route and schedule
Strategic execution	Develop tactical requirements regarding watch keeping, preparations, bridge manning, etc
Strategic monitoring	Monitoring of long term changes in conditions that might affect the voyage, e.g. weather, ice, currents.
Tactical appraisal	Short term overview plan
Tactical plan	Route refinement on a day-to-day or hour-to-hour basis
Tactical monitoring	The on-going monitoring of the progress of the ship and the changes in weather and ice conditions
Operating	The actual control and manouvering of the vessel/ship

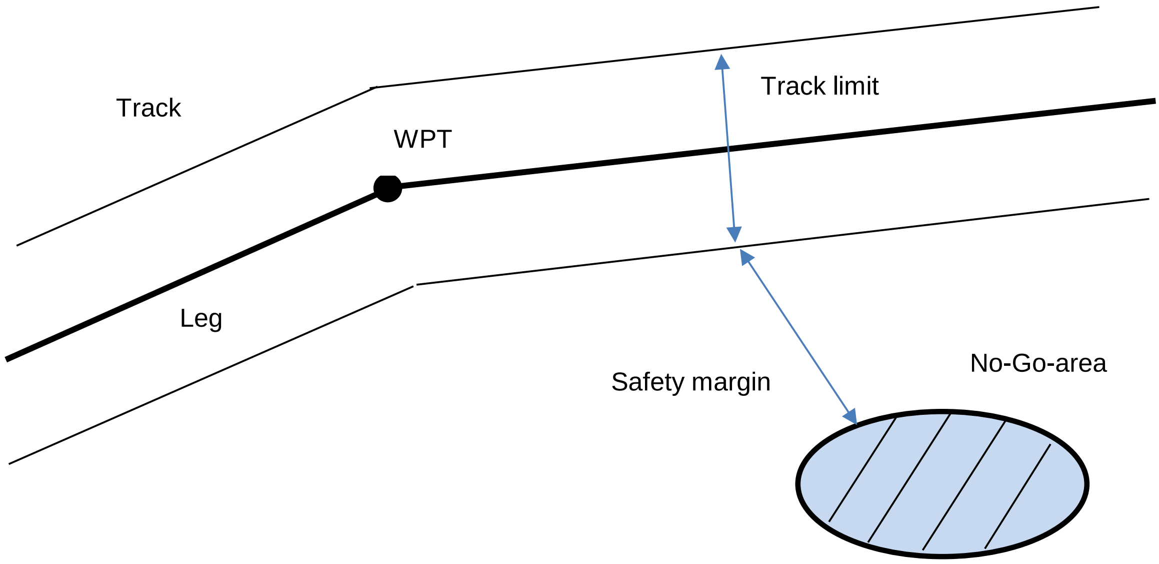

Figure 3: Operational limits in open water navigation. Track limit and Safety margin is from (De Lieto, 2015)

- *"Assess Navigation Risk …";*
- "*Assess Watchfulness of Navigator …";*
- "*Observe and Analyse Available Information …";*
- "*Decide on Actions Based on the awareness established by the observations and analyses, …"* and
- "*Conduct Ship Maneuvering …"*.

In the same way, functions can also be identified for the SC in (SIP, 2010). However, here in a VTS context: (SIP, 2010)

- "*Monitor Traffic Situation*";
- "*Provide Information Service*";
- "*Provide Traffic Organization Service*";
- "*Provide Navigation Assistance Service*"; and
- "*Manage Incident".*

The safety navigation is discussed in more detail in the next paragraph.

3.2.3 Operating description

The current navigation process is implemented by a socio-technical system on the vessel/ship's bridge and is a combination of the operator/operators, see defined actors in the above paragraph, and technical systems. The technical systems used in navigation are classified into sensors and navigation systems. (De Lieto, 2015) Examples of traditional sensors are Radar scanner, Global Position System (GPS), and Echo sounder. Examples of navigation systems Automatic Radar Plotting Aid (ARPA), Electronic Chart System (ECS) and Electronic Chart and Information System (ECDIS).

Autonomous Safety could be the next generation navigation system, why operational functions and operational limits for the sub-phases Tactical monitoring and Operation of the navigation process are discussed further. The following use cases highlights these aspects: open water navigation; restricted water navigation; and anti-collision.

In open water navigation monitoring of the safe execution of the route plan is performed. The route is represented by WPT. A leg or the track interconnects two WPTs. The vessel should follow the intended route within some pre-defined limit – track limit or cross track distance, see Figure 3. The vessel should be able to perform normal actions within this defined track limit, e.g. normal maneuvers to avoid a close quarter situation. In the case of a temporary No-Go-Area based on e.g. safety information, a margin can be defined between the track limit and the No-Go-Area. (De Lieto, 2015)

The vessel´s dynamics can be defined as a set of parameters:

- Position;
- Course over ground;
- Heading;
- Rate of turn; and
- Speed over ground.

Navigating in restricted waters, navigation hazards as land or shallow waters are added. In this case a No-Go-Area is established with respect to shallow water as a safety contour. The safety margin Under Keel Clearance sets what depth contour should be used as limit for the No-Go-Area. This is depicted in Figure 4.

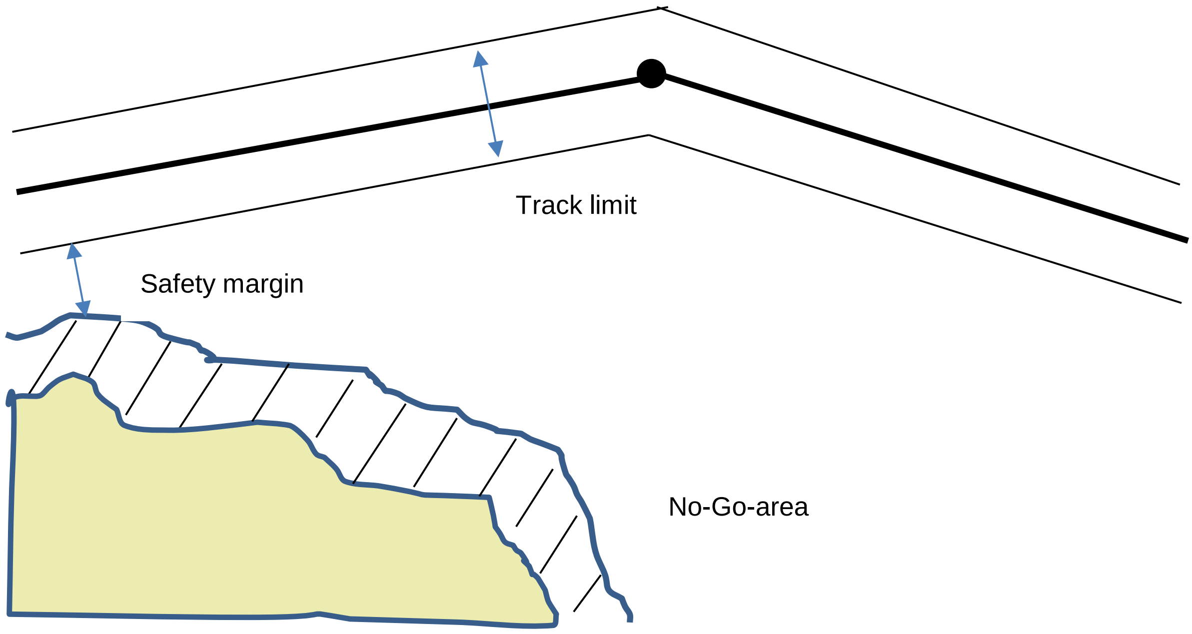

Figure 4: Operational limits in restricted water navigation. Track limit and Safety margin is from (De Lieto, 2015)

When performing a turn during fairway navigation, the vessel's maneuvering characteristics, which will define the radius in the turning circle and the Wheel Over Point (WOP) needs to be added. F in the Figure 5 represents the delay of the turn from WOP to when the vessel starts it's turn. Also, in this case, operational limits can be defined in the form of a safe span of ROT and turning radius. E.g. if the vessel meets another vessel in the turn ROT can be changed i.e. changing the radius with the effect that the vessel keeps too starboard in the turn.

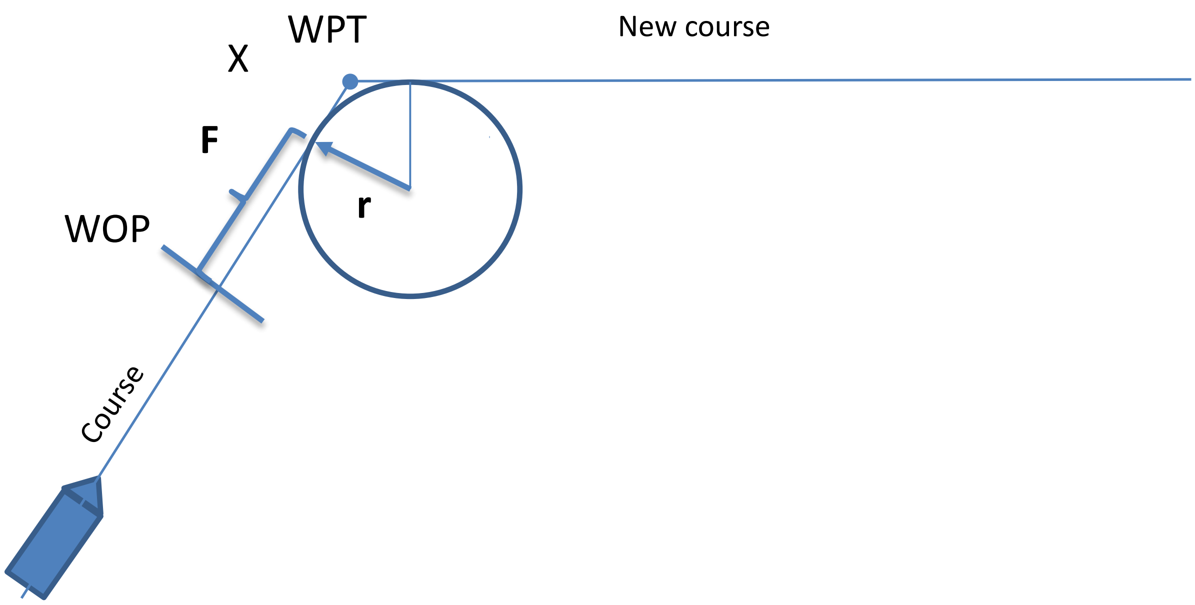

Figure 5: Well-known definition of parameters used to characterize a turn.

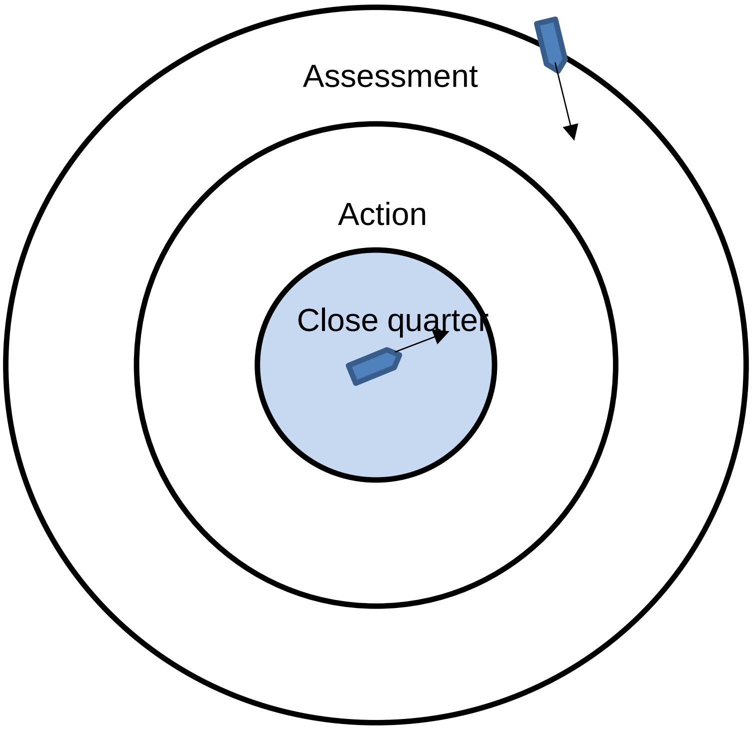

Figure 6: Definition of parameters used in anti-collision. Assessment and action ranges from (Cockcroft, 2011)

In case of navigating close to other vessels and vessel-traffic, the COLREG (Rules of the Road) applies. (Cockcroft, 2011) Hence, during Tactical monitoring, the traffic is also closely monitored in parallel with monitoring the progress along the planned route.

Figure 6 illustrates these steps when a risk of collision situation has developed. The operator needs to perform systematic observations to identify that a risk of collision exists. During next step the situation is assessed including determination of which vessel is the give a way vessel or stand on vessel and adequate action is planned for and decided upon. The action is executed to keep out of the close quarter situation.

3.3 Operating concept

The background for Autonomous Safety is that the development of autonomous functionalities goes very fast. However, the implementation of a fully autonomous vessels still is in the future. Already the Lighthouse pre-study "Autonom säkerhet för fartyg - digitaliseringens möjligheter för ökad säkerhet" (LIGHT, 2016) proposed a driver support function as an advanced decision support tool using the developments within autonomous operations and new sensor technologies.

The basic idea with the Autonomous Safety concept is to use autonomous navigation control function, not to fully control the vessel or ship, but as a navigation control system.

On larger ships, bridge team work concept and bridge layout is inspired by the aviation industry with a side by side Pilot – Co-Pilot set up or also denoted as Navigator – Co-Navigator in this document. (De Lieto, 2015)

A huge difference between a cockpit and a bridge is that in the cockpit all critical systems are available to the pilots, on ships, critical systems are normally spread over the whole bridge. This forces one of the officers to leave the co-pilot set up and handle alarms such as fire/bilge/ballast/watertight doors, AIS and radio communications. This is still a common bridge design flaw on the majority of vessels at sea.

Smaller ships might not have a Navigator/Co-Navigator bridge layout due to limited space or that they are not obligated to have redundant navigational equipment, see Figure 7.

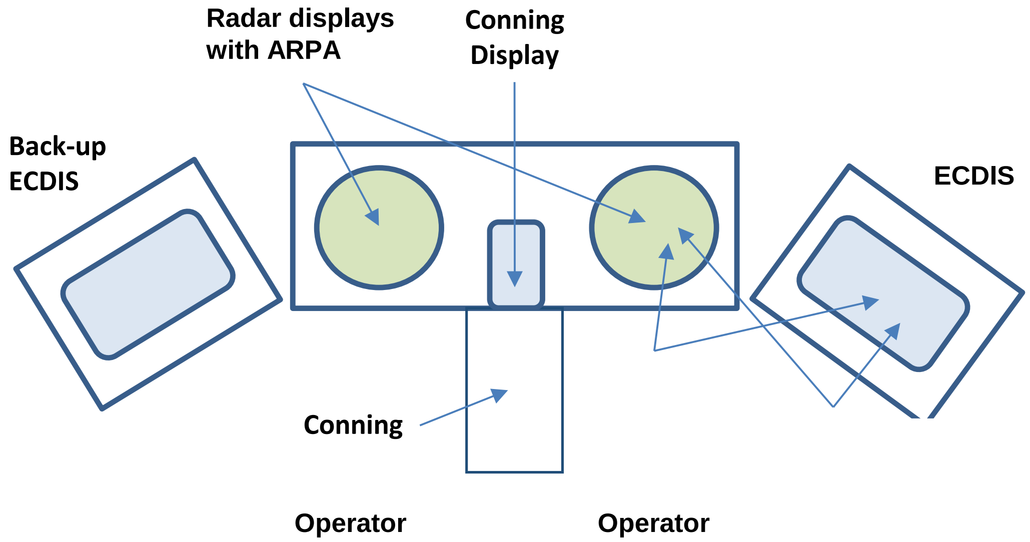

Figure 7: Modern bridge layout

3.3.1 Concept

The basic concept of Autonomous Safety is to use traditional and new sensors to feed into an autonomous navigation control function. This control function works as a background process communicating with the navigator. Hence, the autonomous safety concept consists of a decision support tool and sensors. The communication with the navigator is performed with a Human Machine Interface (HMI). The concept is depicted in the figure 8 below.

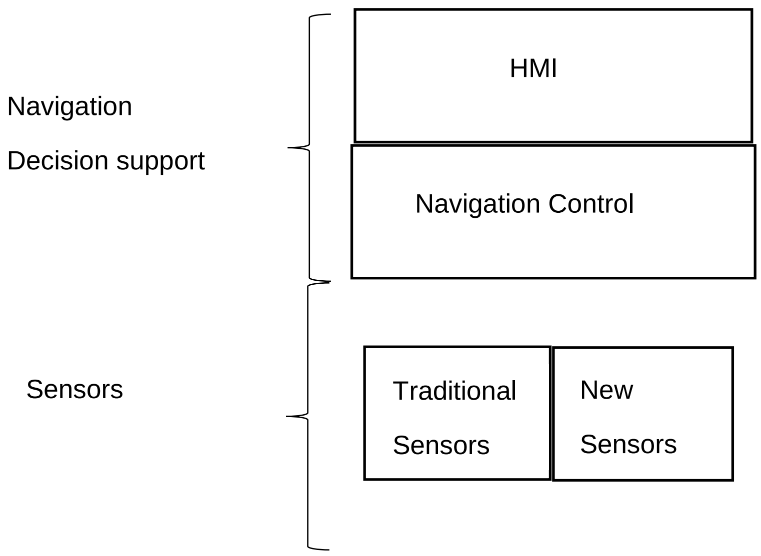

Figure 8: Autonomous Safety elements in an onboard configuration.

The operational use of Autonomous Safety as part of the next generation navigation system for navigation control can be used in two modes of operation:

- Background process to the prime navigation, which is still performed by the navigator using traditional means and methods; or
- Prime navigation function which is monitored by the navigator.

The same technical concept can be used in both modes of operation. In both cases, the navigation control needs to implement the Tactical monitoring and Operation, described in §3.2.3, with the overall objective of keeping the vessel's operations within the operating limits for all dynamic parameters. Hence, the Navigation control function needs to implement the loop 1) and 2):

1. A continuous ***route monitoring function***. If deviating from the route, a new plan is established, and a vessel maneuver is performed to act on the situation.
2. A continuous ***monitor traffic function.*** If a risk of collision situation arises, assessment of the situation, a new plan is established, and a vessel maneuver is performed to act on the situation in order not to end up in a close quarter situation.

The theoretical basis for these functions are further discussed under Chapter 4.

3.3.2 Operating procedures and HMI

Bridge operation is a complex and is fundamental for the safety of the vessels. (Bole, 1992) Today, good practice in implementing the bridge operation and its operating procedures and policies is to use some version of Bridge Resource Management (BRM). BRM discusses the role of the different members in the bridge team for different bridge manning levels and the communication and tasks between them. For example in a navigator, co-navigator configuration: (De Lieto, 2015)

Navigator's role and tasks are, e.g.:

- Route control;
- Route monitoring;
- Collision avoidance control; and
- Control of emergency situations.

Co-navigator's role and tasks are, e.g.:

- Route monitoring;
- Monitoring of ships safety;
- External/internal radio communication; and
- General monitoring of all operational functions.

As mentioned earlier, Autonomous Safety could either take the role as navigator or co-navigator. In both cases, it needs to interact with both the onboard technical systems and the operator. This is depicted in Figure 9. The Navigation Decision Support system in Figure 8 needs to implement the navigation functions listed above and assessing all operating elements (information) in a parallel manner to the current navigation systems and operator.

The basic requirement is that decision support HMI is not to add new alarms and displays. The bridge officers working environment contains today several risks, e.g.:

- To much information;
- To many minor alarms; and
- Distracting tasks.

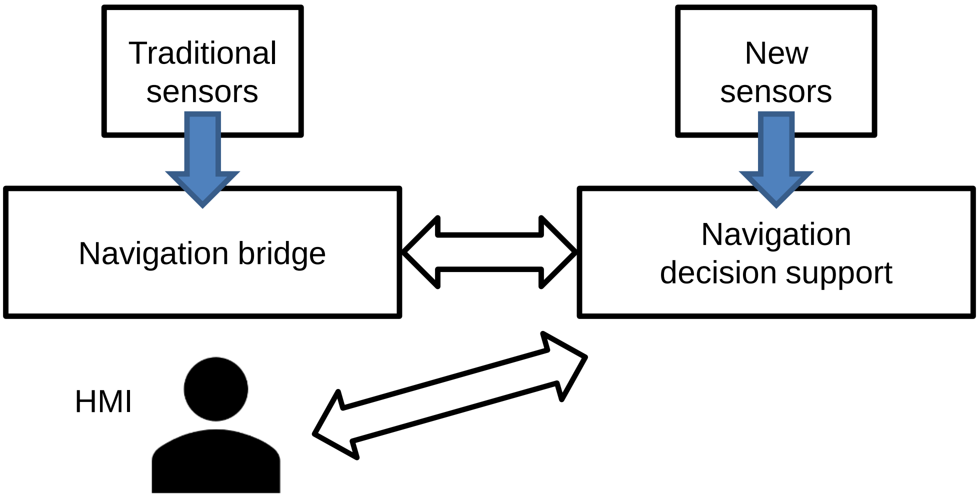

Figure 9: Interaction between navigator and Autonomous Safety.

To minimizing new alarms and displays the Navigation control functions should interact with the operator according to normal bridge procedures, e.g. closed loop communication. This implies audio communication. As a complement to the audio communication other means of alarm is needed. This for instance during noisy environment, emergency situations, or when explaining complex information. Hence, the communication with the navigator is proposed to be performed by the following methods:

- Audio;
- Visual alarms; and
- Visual directions and recommendations.

4 THEORETICAL BASE

Navigational and traffic safety now have in common that the amount of automatization is increasing towards the goal of autonomous operations. This is often referred to as operations with unmanned or autonomous, ships and vehicles. While “unmannedness” can be understood as the property of a vehicle not having a person on board, “autonomy” is related to the ability of a system to exhibit some behaviour, in a defined environment, independent of communication with external parties.

We here choose to focus on safety aspects of transportation at sea in the prospect of increasing automation, not necessarily assuming pure autonomy. The main functionality, navigation, is related above. Navigation is a dynamic activity, taking place in geography with events occurring at specific times and having some duration. As such, the selection of appropriate actions is the result of some cognitive functionality applied to an operator’s (or, in the case of high degrees of autonomy, some piece of software) interpretation of the current circumstances – monitoring. In addition to this, we need to decide on appropriate responses to developing events and be able to predict/anticipate the consequence of selected actions.

We are addressing autonomous safety in navigation based on two frameworks and an empirical study. One framework is based on early thoughts on safety in driving. The other is based on models for temporal relations in the control of socio-technical systems. The empirical study is based on data collection on Stena Germanica.

4.1 Safe travel

As early as 1938, Gibson and Crooks presented a theoretical framework for the perception of drivers of automobiles and their relation to fixed surroundings and other moving objects (GC, 1938). Among the concepts established there, we find (original cursivation):

- “the *field of safe travel* … consists, at any given moment, of the *field of possible paths which the car may take unimpeded*”.
- “*Steering … is a … series of reactions … as to keep the car headed into the middle of the field of safe travel*.”
- “There is within the field of safe travel … the zone within which our driver could stop if he had to … the size of this *minimum stopping zone* is dependent on the speed of the car …”
- “… deceleration occurs *in proportion as the forward margin of the field* [of safe travel] *recedes toward the minimum stopping zone*.”
- “The ratio … which tends to be maintained in given traffic conditions … might be designated as the *field-zone ratio* and thought of as an index of cautiousness…”

To summarise, the task of the driver (or navigator) is to uphold a perception of stopping distance and to aim for the middle of the available field of safe driving (here; manoeuvring) as limited by e.g. natural boundaries, inflexibility at higher speeds, fixed and moving obstacles, and “legal obstacles and legal taboos”.

Speed is explicitly recognized as a cause of inflexibility and affecting the size of the stopping zone. In a discussion of high speed driving, it also noted that the field of safe travel need to be extended along the road in proportion to speed, and eventually is limited as distant objects become harder to see. This can be regarded as an implicit recognition of an observational horizon, beyond which we have no information.

4.2 Temporal perspectives on control

Temporal aspects of control in dynamic systems are addressed in the Contextual Control Model (COCOM) and the Extended COCOM (ECOM) in terms of interacting feedback and feed forward loops providing behaviours on different levels of abstraction such as targeting (goal setting), monitoring, regulation and track keeping (Hollnagel 2017a, 2017b). Safety is in this perspective a result of maintaining control – or inversely, loss of control may lead to loss of safety.

Extending this reasoning to unmanned vessels and vehicles we also have the additional factor of delays introduced by communication with a sea traffic control centre. The different processes of communication, evaluation of the situation, decision making, and execution/performing the decided actions sums up to the time T_N needed for predicting future states in order to respond to a developing situation. Meanwhile, the situation at hand may only allow for a limited time to react before a potential mishap occurs. This can be called available time T_A. The relation T_N/T_A between predictability (needed time) and available time can be related to different control modes (strategic, tactical, opportunistic and scrambled) (HW 2005).

- In Strategic mode, there is plenty of time and need for a medium to high degree of attention. $T_A >> T_N$.
- In Tactical mode (attended) there is limited but adequate time available and need for a medium to high degree of attention. The task is not quite route, or very important. $T_A > T_N$.
- In Tactical mode (unattended) there is also plenty of time but the task is very familiar or even boring. There is a low degree of attention. $T_A > T_N$.
- In Opportunistic mode, there is short or inadequate time available. The task is familiar but not fully recognised. A high degree of attention is needed. $T_A \approx< T_N$.
- In Scrambled mode, available time is highly inadequate and the situations is not recognised. Full or even hyper-attention is executed. $T_A << T_N$.

Let us now assume that the relation between the needed and available road (as of Gibson and Crooks) or time (as of Hollnagel and Woods) may be developed into a metric useful to estimate safety margins.

4.3 Quantifying the safety margin

The basic relation investigated here, is that for a safe system,

$$\frac{available\ time}{needed\ time} = \frac{T_A}{T_N} \geq K$$

… where *k* may be considered a safety margin related to the operational limits and margins discussed as discussed above and in Figures 4 and 6. In order to estimate the temporal durations we need to add some understanding of the components of the system.

The needed time T_N is based on the sum or union (some events may occur in parallell) of

- communication, understood as the time needed for transferring the intended amount of information with the available bandwidth, given available communication technology.
- evaluation and assessment of the situation, as performed by an operator or software
- decision making, as performed by an operator or software,
- execution/performing the decided actions, including the time needed for returning a command of the selected means of communication and actually applying the intended maneuver with the vessel at hand.

All of these parameters are changing with the situation and context. In shipping, the dominant factor is likely resulting from inertia with the vessel. However, the focus of T_N will change depending on e.g., the allocation of operators onboard or on shore, latencies from communication systems, general preparedness/skill with the operators and better maneuverability of smaller vessels. For this test we assume that needed time is dominated by the time needed for the vessel to come to a stop from current speed, added with a fixed duration to represent other latencies.

The available time T_A is fully dependent on the context and not generalized in this test. As mentioned above we assert that the factor *K* is relevant for safety. Therefore, we choose to make an indirect assessment of available time T_A through comparisons between moving vessels for different factors *K* . The case for one vessel is

$$\frac{T_A}{T_N} \geq K \Rightarrow T_A = K * T_N = K * (t_{stop} + latency)$$

The time-to-stop is specific for the vessel at hand and depends on current speed. It is converted to a stopping distance in meters for the graphical presentation. So, T_N can be assessed for all vessels given their speed, maneuverability (notably deceleration) and general control process latency (a duration given in seconds).

For comparison of vessels in order to assess the safety margin *K* we then do the following:

1. Get information on current speeds and (relative) locations. Here, based on AIS data.
2. Calculate T_N for all vessels, given their speed and maneuverability.
3. Calculate and plot the respective distances covered during the time T_N needed to stop, given the current speed, possible rate of turn and course. This plot of possible paths during the decreasing of speed to zero can be represented as a red "mushroom" on a digital chart.
4. Calculate the possible paths and distances covered by the respective vessels in steps of tenths of *K*. and assuming that (conservative) the vessel also is accelerating to its maximum speed.
5. For *K*=1 when $T_N = T_A$ and given that the vessel has used the available time to accelerate to full speed ahead, is presented as a blue-lined area ahead or around (depending on initial speed and maneuverability) of the vessel.

6. Whenever such *K*-based spanned paths of two vessels intersect, the intersection is plotted as a red line. The K-factor is printed, as is the respective vessels needed time to stop, and the available time until reaching the intersection line, if the vessels should decide to sail in that direction.

See Figure 10 for an example of a plot of two vessels meeting in an archipelago. Red areas are spanned by possible stopping paths. We can also see the two-vessel intersection line (red), associated safety margin K, durations Tn needed to stop (seconds) and available time Ta (seconds) until the intersection line would be reached if such a maneuver would be applied.

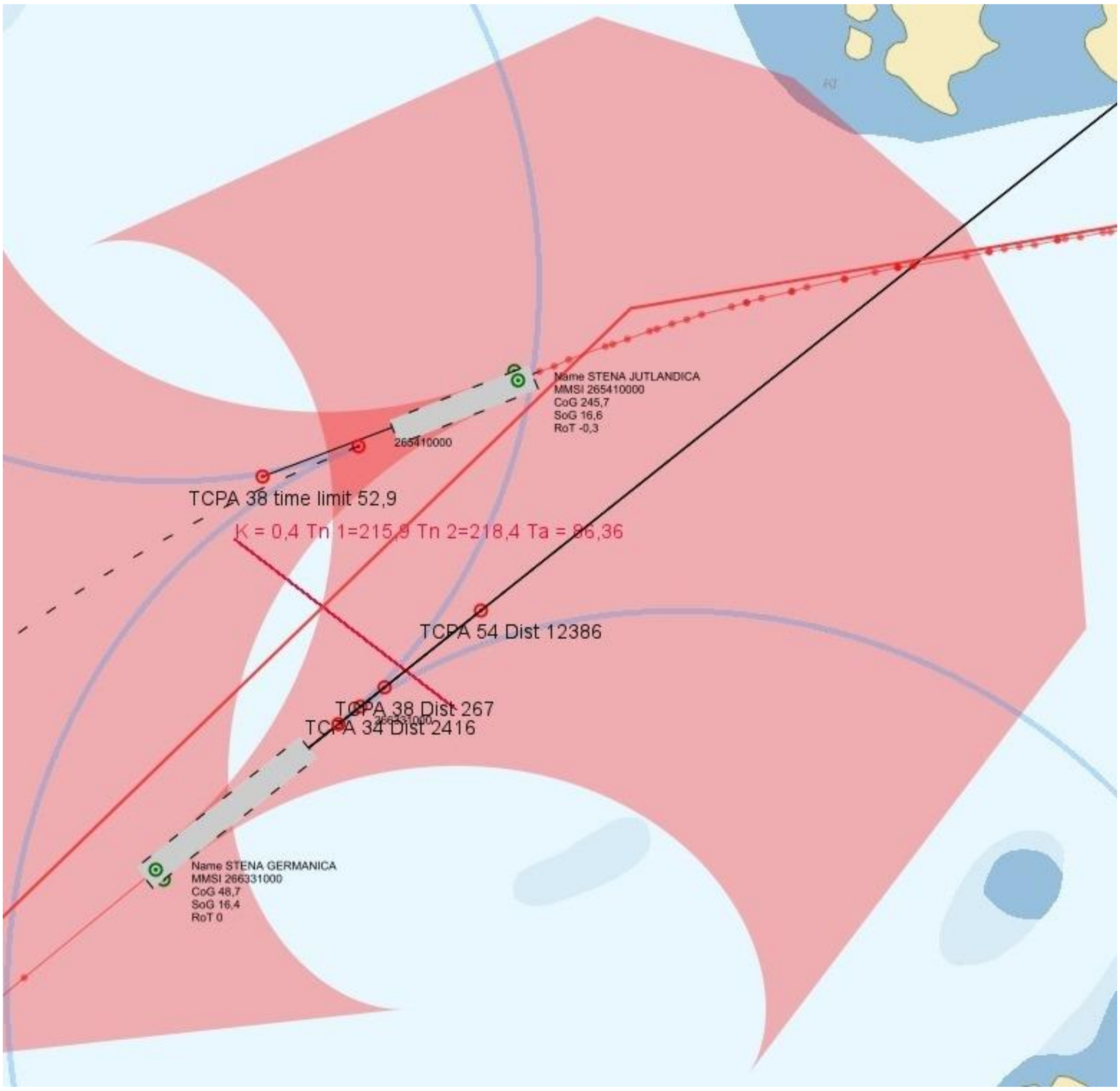

Figure 10: Example of plot of two vessels meeting in a narrow passage.

In addition to this, times to closest points of approach (TCPA) and the associated distance (meters) at that time is plotted as a red ring on a straight-line prediction of current course. The dotted line ahead of vessels predicts the trajectory given current rate of turn.

5 BACK BRIDGE TESTS

This section describes the tests and the results from the trials performed during the project. Today, a fully operational autonomous navigation control function does not exist. However, Saabs back bridge module has been used on board as a tool to support the discussions performed in Chapter 3 and 4. Also, land based AIS traffic data has been used.

5.1 Description of test

Practical trails were conducted aboard Stena Germanica during a voyage between Gothenburg and Kiel during the period 15th to 17th of January. The voyage was also monitored from shore by Sjöfartsverkets VTS located in Gothenburg.

The trials used Saab's software also containing chart information and a standalone AIS transponder located on the ship's bridge. The software used reasonable approximations of the ships manoeuvring parameters. Data collection was correlated with observation of event taking place, e.g., meeting other ships.

5.2 Results from on board tests

The results from the onboard tests indicates that the T_A/T_N ratio K can be used as a figure of merit regarding a ship's safety margin in anti-collision situations. Calculations and graphical representations were improved during the test period. Collected AIS-data is saved as reference material and subject for future computations (algorithm development).

The initial assumption / hypotheses to be tested was that a safety margin $K \geq 1$ would be respected. After all, a temporal margin less than one means that the vessels are unable to come to a full stop.

As observed, the minimal temporal margin K was not often over 10 and mostly between 4 and 8. This is based on the assumption that all vessels have the same manoeuvrability as Stena Germanica. A more robust statistical measure could be calculated if better approximations of the respective vessels encountered at sea could be applied.

The observational horizon provided by AIS and relation to no-go areas were such that all other vessels were taken into consideration at first observation/indication. Specific attention was given to e.g. fishing vessels that were known by experience, to navigate in unpredictable paths close to fairways. One strategic course adjustment was observed, a minor turn about 25 to 30 minutes ahead of the anticipated situation.

K-factors under 1 were frequent and as low as 0.1 was observed, typically in archipelagos, narrow passages and take-over situations with parallel courses. Their occurrences falsifies the initial hypotheses that $K<1$ is to be avoided. These situations were regarded by the onboard operators as a normal and controlled, however motivating increased attention. In the ECOM framework, this would qualify as a tactical attended or opportunistic control mode.

Scrambled control modes were not observed. It was discussed that the release of vessels from the Kiel canal lockers always motivated specific dialogue with the local authorities and sometimes also required specific avoidance manoeuvres. These may be regarded as scrambled

Figure 11: View to port side of Stena Germanica during the passage plotted in Figure 10.

situations, even though they normally would be anticipated and speed adjusted to maintain margins.

Based on the above, a first estimate could be that:

- $K > 10$ is regarded as Strategic mode.
- $1 < K < 10$ is regarded as Tactical (attended)
- $0.2 < K < 1$ is regarded as Opportunistic
- $K < 0.2$ is regarded as Scrambled

There were no observations of Tactical (unattended) control modes.

For low K-values, it was frequent to have “red-on-red” and “grey-on-red” situations. Red-on-red means that it exists a possibility that the ships can collide if both are doing a bad manoeuvre. Grey-on-red means that one ship is exposed to the capability of the other to manoeuvre so that they will pass. It is not possible to stop if the path is directed towards the ship in the red, minimum-stopping-zone. Grey-on-grey would imply an actual collision and was not observed.

The reason that these close situations are considered normal and controlled seems to be the assumption that vessels are staying close to nominal course and maintains predictable behaviours with low random deviations. This is currently not part of the metric and models.

Hence, we can conclude that the *K*-ratio may be suitable for continuous and autonomous process of assessing the situation. Some *K*-ratio can be used as a definition and the boundary between different control modes. In Tactical monitoring the vessel is in a safe mode with respect to potential navigational hazards as other vessels or shallow waters. The models need to be developed with representations of expected normal behaviors, in order to reflect actual navigation in archipelagos and passages.

5.3 Shore-based tests

In parallel, the trials were monitored from shore using shore based AIS traffic data.

5.3.1 AIS

The most critical phase of the voyage with respect to time margin is during fairway navigation. Shore based AIS traffic data was view for a typical merchant vessel inbound and outbound in the Gothenburg fairway. To understand the accuracy of the shore-based monitoring track changes in ROT has been plotted. Figure 12 shows several large tracks from one specific vessel. Green means “steady” and red means “turning”. Each dot is a received AIS update, if the ship is traveling on a steady course and speed up to 14 knots, the AIS will broadcast its dynamic data such as position, heading, course and speed over ground and if it is available, the ships rate of turn, every 10 seconds (IMO AIS) and if it turns, every 4 second. In short, this means that there is not only system delays and latency, there is also a designed latency. And for an operator or system that remotely monitors a ships progress this means they will always be a couple of seconds behind in situational awareness.

Figure 12: Several in- and outbound tracks from one vessel in the Gothenburg fairway. Green means steady with a ROT = 0. Red means “Turn” with ROT not equal to zero.

The next picture, Figure 13 zooms in on one of the turns. The inbound (south side) and outbound path (north side) of the fairway. The actual start of turn is clearly visible at good accuracy when green turns to red if the ship feeds the AIS with its rate of turn. If the ship is not equipped with that capacity, there will be a larger latency and harder for an operator or a system a shore to detect when the ship starts its turn.

Figure 13: Several in- and outbound tracks from one vessel at one turn. Green means steady with a ROT = 0. Red means "Turn" with ROT not equal to zero

5.4 Discussions with active nautical officers

During the practical onboard trials, the Autonomous Safety concept was discussed with different members of the crew. The general view was positive and especially if this could be part of next generation navigation system. The basic idea of navigator / co-navigator set up discussed in chapter 3 was well received. Also, the different ways of communicating with the system.

Important aspects for a future navigation system are:

- The navigation system should be simple, implementing simple functions that are easy to find. Today, several important functions might be far down in the menu tree.
- Simpler presentation of relevant information. Today, navigation information is presented on different displays. There is a risk of too much information. It is important for the operator to get right information at the right time.
- Alarms should be managed in a different way than today. Today, several alarms at different level are presented for the operator. There is too much information and a risk of missing important alarms. Autonomous processes could be part of a better alarm management.

Some more specific functions where also discussed:

- Today's tools in collision avoidance could in future be more of a decision support tool with a higher degree of automatization.

- Today's curved heading line function is a very good tool for monitoring turns in fairway navigation. It would be beneficial of this type of functions were more of a decision support tool with a higher degree of automatization.

All these are in line with the user needs in §3.1.

6 CONCLUSIONS

This section summarizes the conclusions from this project and proposes how to continue building on these results.

6.1 Findings

This project has defined on a highlevel the Autonomous Safety concept, first proposed in the Lighthouse pre-study "Autonom säkerhet för fartyg - digitaliseringens möjligheter för ökad säkerhet", (LIGHT, 2016), and how it could be implemented in an operational environment.

The basic concept of Autonomous Safety is to use current and new sensors to feed into an autonomous navigation control function. This control function works as a background process to the normal bridge work and with functionality for communication with the navigator. Hence, the Autonomous Safety concept consists of a navigation decision support tool and sensors. To minimizing new alarms and displays the Navigation control functions should interact with the operator according to normal bridge's principles, e.g. closed loop communication. The concept where defined from an operational point of view defining a possible HMI solution in order to interact with the operator in an optimal way. This interaction builds on:

- bi-audio communication concept;
- visual alarms;
- visual recommendations.

Further, a theoretical base for safety margins in autonomous safety critical functions was discussed. This safety margin can be related to the operational limits and margins. It also means that the safety margin can be used as a definition and the boundary between Tactical monitoring and Operations.

The outcome of the project was supported by practical trails conducted onboard Stena Line's ships and was monitored by Sjöfartsverket's Vessel Traffic Service (VTS) facilities located in Gothenburg. During these practical onboard trials, the Autonomous Safety concept was discussed with different members of the crew. The general view was positive and especially if this could be part of the next generation navigation system.

6.2 Next steps

This project was a first step in describing Autonomous Safety a larger strategic initiative It is important to take the results further to a future implementation. Below, some proposed next steps are listed:

1. Implement the proposed HMI functions in a prototype:
    - bi-audio communication concept;
    - visual alarms;
    - visual recommendations; and

- a new type of display integrated with today's conning display or a new integrated navigation display.

This prototype should be tested and further developed together with users using high fidelity ship simulators. Hence, the tests should be performed together with active navigators and masters. The prototype should be tested and developed further with respect to usability and information need, i.e. right information at the right time. This project is classified as a research project.

2. Assess new type of sensors in a real environment. This could be LIDAR, broad-band Radar and optical sensors. Also, sensors used in vehicle navigation should be assessed in a marine environment and during applicable rangers and visibility in marine navigation. This project is classified as a research project.
3. Continue the technical development of the autonomous navigation control function. This project is classified as a development project.
    - Reassess calculations based on saved AIS data and better approximation of the characteristics and maneuverability of other vessels.
    - Extend calculations to include also fixed obstacles and no-go areas (chart data based).
    - Look into the possibility to identify a K-based safety zone index, allowing for different degrees of operator attention for quantifiable durations.
    - Look more to details of the path planning in opportunistic/scrambled control modes (close situations), here understood as "red-on-red" and "grey-on-red".
    - Develop safety factor based planning algorithms for tactical and strategic navigation. This would have to also take into account navigational rules, good seamanship and assumptions on maneuverability and intentions of other vessels.