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Developing a Maritime Safety Index using Fuzzy Logics

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ABSTRACT: Safe shipping is essential for society and different measures are taken to improve maritime safety, for example through implementation of traffic separation schemes, radar surveillance and traffic management concepts. But how can maritime safety be measured to determine the effects of those implementations? In this study, a real-time maritime safety index for a ship is developed, taking into account both the probability of grounding and the probability of collision. The index is developed using fuzzy integrated systems and validated in ship handling simulator scenarios. It uses numerical data from the simulator as an input to assess the present traffic situation from the perspective of a specific ship and outputs a comprehensive index. This paper describes the concept of sea traffic management as proposed and evaluated in the EU funded STM Validation project, the motivation for developing a maritime safety index, the numerical input variables and model properties and also validates the feasibility of the approach.

1 INTRODUCTION

Presently, various measures are available to enhance safety of ship traffic. Traffic Separation Schemes (TSS) and Vessel Traffic Services (VTS) are established and sophisticated ship technologies are applied to promote safety of navigation. Further measures are investigated and tested in various domains and initiatives. To assess the actual and anticipated effects of the implementation of such measures, qualitative methods depending on expert judgement are most commonly applied.

In contrast to this practice of subjective evaluation, this paper outlines an approach for establishing a fuzzy-logic-based index intended to objectively evaluate safety in maritime traffic. This first section introduces the background of this study, including a presentation of the originating STM Validation research project, the motivation for this study as well as the present state of research in this particular field. This is followed by a description of the fuzzy logic methodology applied in establishing the maritime safety index as well of the quantitative numerical variables used as input data. The third section covers the developed fuzzy model which is used to calculate the maritime safety index. This also includes the results from a survey conducted with navigation training experts for defining membership functions. Validation of the established model as well as calculation results are discussed in the fourth section followed by the study's conclusion and outlook in the final section.

1.1 *The STM concept*

Inspired by air traffic management, the STM Validation project and its predecessors have produced a concept for sea traffic management. It consists of a number of component services aiming at improving safety and efficiency in the maritime transport chain through traffic monitoring and guidance. Through sharing of information between involved stakeholders within a common environment and structure, services such as route exchange between ships as well as with shore-based entities, voyage and route planning and optimization as well as port collaborative decision-making will be enabled. This will benefit the overall maritime transport domain at large.

1.2 *Motivation*

Within the STM Validation research project, large-scale trial runs are conducted with the European Maritime Simulator Network (EMSN). This test facility connects more than 30 ship handling simulator bridges from maritime training and research facilities located throughout Europe. The data being produced during these simulations reflects the navigators' decisions in different maritime traffic scenarios . For the assessment of navigators' behaviour in encounter situations between ships it is required to develop an approach that accounts for the full complexity of the task. While most assessment methods conventionally used depend to a large degree on expert opinions, this study aims for a more objective and quantitative approach.

1.3 *Paper review*

A first attempt to use fuzzy logic on real time AIS data has been developed by Kao et al. in 2007. With the four input parameters ship size, ship speed, sea state and radius size of a guardian ring, a danger index is determined to estimate the location and time of potential collisions between vessels. Park et al. developed a collision risk assessment system using fuzzy theory based on the input variables DCPA (distance of the closest point of approach), TCPA (time of the closest point of approach) and indicators for abnormally navigating ships, specified by accumulated changes in the speed and course of the vessels.

Since 2007, several more papers have been published focusing on fuzzy logic as a tool for avoiding collisions in real time operations. A different approach to assess safety in maritime traffic has been done by Lopez-Santander et al. estimating the risk of collisions via a statistical probabilistic model. The purpose of this paper is to present a fuzzy logic approach measuring the level of safety of different traffic situations to finally validate the service concepts developed in the STM Validation project.

2 METHODOLOGY

The term *Fuzzy Logic* was introduced by L.A. Zadeh delivering the theory of fuzzy sets in 1965 and was applied to control automated steam engines by E.H. Mamdani in 1975. Instead of dealing with the binary terms of "true" and "false" the fuzzy logic approach extends these terms on the unit interval as degrees of truth.

2.1 *Fuzzy Logic*

2.1.1 *Fuzzy sets and membership functions*

Given a space of objects X with $x \in X$ a fuzzy set A in X is characterized by a membership function $\mu_A(x):x \rightarrow [0,1]$ with $\mu_A(x)$ representing the grade of membership of x in the fuzzy set A „. Given two fuzzy sets $A, B \in X$ the classical set operations include the complement, intersection and union. For $x_i \in X$ (where $i=1,\ldots,n$) and X being a discrete and finite space the mapping of the fuzzy set A is denoted by

$$A=\left\{\sum_i \frac{\mu_A(x_i)}{x_i}\right\} \tag{1}$$

Given a continuous and infinite space X the fuzzy set A can be expressed as

$$A=\int \frac{\mu_A(x)}{x}dx \tag{2}$$

With the classical set operations and $x \in X$, the operations for fuzzy sets A and B are defined as

$$A^C(x)=X \setminus A \tag{3}$$

$$A \cap B=\mu_A(x) \cap \mu_B(x)=\min(\mu_A(x),\mu_B(x)) \tag{4}$$

$$A \cup B=\mu_A(x) \cup \mu_B(x)=\max(\mu_A(x),\mu_B(x)) \tag{5}$$

2.1.2 *Fuzzification*

The first step of the fuzzy logic proceeding is to map the non-fuzzy input values to linguistic variables. This fuzzification process is performed by the pre-derived membership functions for the input and output variables which can have multiple different types, such as triangular, trapezoidal or Gaussian waveforms. With $x \in X$ the core, support and boundaries of a fuzzy set A are defined as

$$\text{core}(A)=\{x \in X \mid \mu_A(x)=1\} \tag{6}$$

$$\text{supp}(A)=\{x \in X \mid \mu_A(x) \geq 1\} \tag{7}$$

$$\text{bnd}(A)=\{x \in X \mid \mu_A(x)<1\} \tag{8}$$

2.1.3 *Fuzzy rules*

By means of the linguistic variables generated during the fuzzification rules can be used to describe the knowledge of an expert. Given a set of conditions

c and a set of consequences z fuzzy rules can be represented as a sequence of IF-THEN phrases:

$$\text{IF } x \text{ is } c \text{ THEN } y \text{ is} \tag{9}$$

with $c \in C$ and $z \in Z$. Having rules with multiple parts, the introduced fuzzy operators are used to combine these multiple inputs with "AND" meaning the minimum, "OR" meaning the maximum and "not" delivering the additive complement of the condition.

2.1.4 *Defuzzification*

In order to obtain an output that summarizes the input variables, output membership functions and rules the linguistic output variable has to be defuzzified. Centroid defuzzification is the most commonly used method providing the centre of the area under the curve of the membership function. Given a membership function $\mu_i: x \to [0,1]$ and an output variable $x \in X$, the defuzzified output $z_0 \in \mathbb{R}$ can be calculated as

$$z_0 = \frac{\int \mu(x) x dx}{\int \mu(x) dx}. \tag{10}$$

3 FUZZY MODEL FOR ESTIMATING A SAFETY INDEX

The maritime safety index consists of the combination of a collision and a grounding index each represented by a proposed fuzzy model. Following the definition of the input variables, the membership functions for the fuzzy models estimating a collision and grounding index are created based on the results of pre-conducted instructor surveys.

The fuzzy models estimate a safety index for a specific vessel, the own ship, at a specific time. In the vicinity of the own ship, one or several target ships could be present to affect the collision safety index and land or shallow waters nearby could affect the grounding safety index.

3.1 *Input variables*

Given a maritime traffic situation with one own ship and one or multiple target ships, Table 1, based on the work by Lopez-Santander and Lawry , lists the input variables for the collision index which are represented by membership functions later on. Table 2 lists the corresponding input variables for estimating the grounding index.

To be able to measure the safety index in real-time during a ship handling simulator exercise or using live AIS data, the input variables have been derived from data available from the AIS system (except for environmental conditions).

Table 1. Input variables for estimating a collision index.

Variable	Description
CPA	Closest Point of Approach
TCPA	Time to Closest Point of Approach
BCR	Bow Cross Range to the target ship
ET	Encounter type
EC	Environmental Conditions
Intentions	Previously shown intentions for performing a collision avoidance manoeuver
GTS	General Traffic Situation
MAN	Vessel's manoeuvrability

Table 2. Input variables for estimating a grounding index

Variable	Description
UKC	Under Keel Clearance
SM	Safety Margin
DA	Drifting Angle
DS	Drifting Speed

3.1.1 *Closest Point of Approach (CPA)*

The CPA is the distance calculated from the own ship's and target ship's position, course and speed. The distance is measured in meters so that the CPA is defined by

$$CPA = \sqrt{\frac{(u \cdot v \cdot \sin y - t \cdot w \cdot \cos y - u \cdot v \cdot \sin x + t \cdot v \cdot \cos x)^2}{v^2 + w^2 - 2 \cdot v \cdot w \cdot (\sin x \cdot \sin y + \cos x \cdot \cos y)}} \tag{11}$$

where x is the own ship's course, y is the target ship's course, v is the own ship's speed, w is target ship's speed, t is the longitudinal distance and u is the lateral distance between own ship and target ship.

Five membership functions are used to define the CPA; zero, small, medium, large and very large.

3.1.2 *Time to Closest Point of Approach (TCPA)*

The TCPA is the time for the vessels to reach the CPA. To calculate the TCPA the own ship's and target ship's positions, courses and speeds are used. The TCPA can either be positive or negative depending on whether the vessels are approaching or not and is defined by

$$TCPA = \frac{t \cdot v \cdot \sin x - t \cdot w \cdot \sin y + u \cdot v \cdot \cos x - u \cdot w \cdot \cos y}{v^2 + w^2 - 2 \cdot v \cdot w \cdot (\sin x \cdot \sin y + \cos x \cdot \cos y)} \tag{12}$$

with the parameters x, y, v, w, t, and u as defined in section 3.1.1. To define the TCPA six membership functions are used; history, passed, zero, small, medium and large.

3.1.3 *Bow cross range*

The distance at which the target ship crosses the own ship's heading line is called bow cross range (BCR). The value of the BCR is positive if the crossing is ahead of the own ship and negative if the crossing is astern of the own ship. Five membership functions are used to define BCR; ahead, close ahead, zero, close astern and astern.

3.1.4 *Encounter type*

According to the international collision regulation COLREGs , the rules that apply in a specific traffic situation to avoid collision depends on the encounter type. Encounter types can be defined using differences in the course, speed and the relative bearing from the own ship to the target ship.

Six membership functions are used to define the encounter type; head-on, crossing from starboard, crossing from port, overtaking, overtaken and safe situation. In this context, a traffic situation is considered to be safe when no potential risk of collision exists.

3.1.5 *Environmental conditions*

The safety depends on some environmental factors, such as wind direction, wind speed, current direction, current velocity, sea state and visibility. All environmental factors are condensed to an output consisting of three membership functions representing the environmental influence in the situation; no influence, small influence and high influence.

3.1.6 *Intentions*

The collision safety index of a traffic situation is not only a matter of geometrical and environmental factors. If one vessel performs a large and positive avoiding manoeuver in ample time in accordance with COLREGs , the safety index increases due to the "communication" between the vessels. It indicates that the situation has been identified and that action will be taken according to the rules.

To classify pre-shown intentions, first a manoeuver must be identified and second, an assessment whether this manoeuver is an avoiding manoeuver or not has to be made. A manoeuver is identified by the changes in course or speed over a certain period of time using a moving average value.

To distinguish between manoeuvers made as part of ordinary navigation and those of an avoiding manoeuver, the following criteria are used :

1. Risk of collision exists between the vessels
2. The manoeuver is performed within a specified action range for the type of situation
3. The manoeuver is performed when TCPA is positive
4. The CPA should increase due to the manoeuver
5. There is no other target with higher risk of collision at the moment

Shown intentions also take into account the vessels navigational status (power-driven vessel, sailing vessel, vessel engaged in fishing, vessel constrained by her draught, vessel with restricted ability to manoeuver and vessel not under command) as well as the size of the vessel.

Three membership functions are used to describe the shown intentions; no intentions shown, fuzzy intentions, clear intentions.

3.1.7 *General traffic situation*

If the traffic density is high, the risk of collision increases and the safety level will be lower than the lowest safety indication for each individual traffic situation.

The traffic density is defined by three membership functions; low, medium and high.

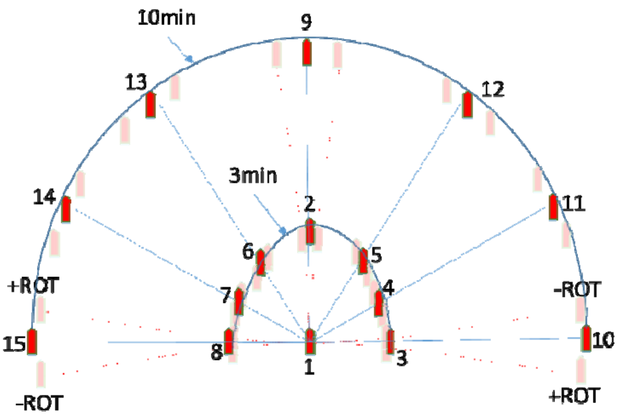

Figure 2. Illustration of 15 UKC points used within the model.

3.1.8 *Manoeuvrability*

An avoiding manoeuver normally is performed by a course change to starboard. According to rule 14 in the COLREGs vessels meeting in a head-on situation should change their course to starboard. According to rule 15 in COLREGs vessels which have the other vessel on starboard side, shall keep out of way and avoid passing ahead of the other vessel, which means a turn to starboard, normally. If the own ship has no or only a small ability to turn to starboard due to other target ships or shallow water, the safety level decreases in the index.

The ability to turn to starboard side is handled by an input variable called "manoeuvrability" and consists of three membership functions; good, poor and none.

3.1.9 *Under keel clearance (UKC)*

The UKC is calculated as the distance between the keel and the sea bottom, the difference of the water depth and the ship draught. The UKC is measured at 15 different locations around the vessel as illustrated in figure 2. Seven points are located "3 minutes away" and seven "12 minutes away" from the current position. The seven points are located straight ahead, *+90, +60, +30, -30, -60* and *-90* degrees from present course over ground (including the vessel rotation). The 15 points have the same five membership functions; aground, low, medium, high and very high. Figure 3 illustrates the trapezoidal membership functions for these input parameters.

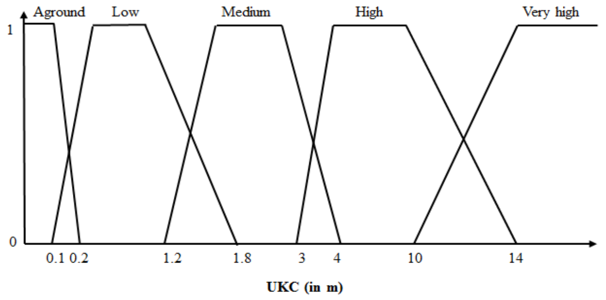

Figure 3. Membership functions for UKC.

3.1.10 *Safety margin*

The "safety margin" input parameter regulates the UKC that is considered to be safe for the specific ship.

The "safety margin" input parameter has five membership functions, four triangle and one trapezoidal, which are illustrated in figure 4.

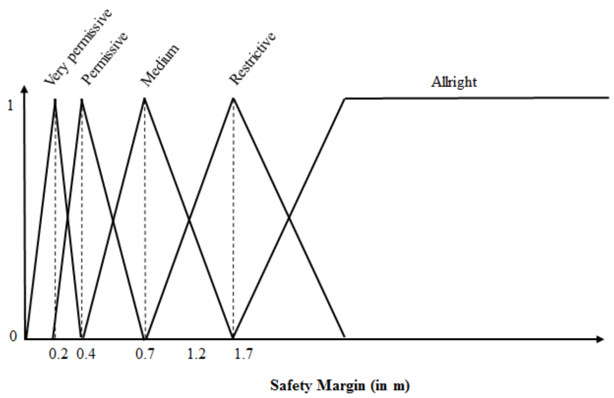

Figure 4. Membership functions for safety margin.

3.1.11 *Drift*

A vessel is drifting due to the effects of wind and current, which could be divided into a drifting angle and drifting speed.

The input parameter "drifting angle" is the direction that the ship would travel without any propulsion. The parameter is the resulting angle of current forces acting on the vessel below the water surfaces and the wind forces acting on the vessel above the water level. The drifting angle has four membership functions; ahead, starboard, stern and port.

The input parameter "drifting speed" is the speed over ground that the ship would travel without any propulsion. The parameter is the current forces acting on the vessel below the water surfaces and the wind forces acting on the vessel above the water level. The drifting speed has three membership functions; slow, medium and fast.

3.2 *Results of the instructor surveys*

To get reference values for estimating the safety index, 42 maritime traffic experts were asked for their assessment of the safety of different traffic situations presented to them. The respondents are simulator instructors at the simulator centres associated with the European Maritime Simulator Network (EMSN). 75% of the respondents have more than 7 years' experience as navigational officers and more than 3 years as simulator instructors. The survey consists of 145 different traffic situations divided into two-vessel situations, situations in traffic separation schemes, situations with shallow waters close by, situations were one vessel has made an avoiding manoeuver and finally multi-vessel situations. Each participant assessed 50 situations randomly selected out of a total of 145 situations. The scale used for assessment was from 0 to 10 where the value 0 signifies a "very unsafe situation", the value 10 a "totally safe situation". The respondents were given graphical overview, the relative motion line and values for CPA and TCPA (fig. 5). Each situation has been assessed by 5-20 respondents.

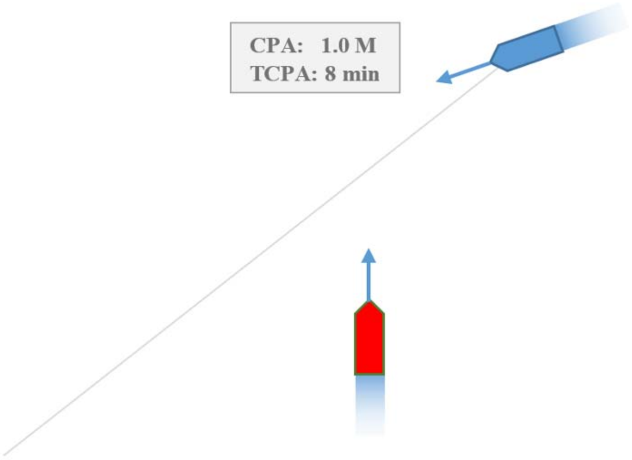

Figure 5. Traffic situation used within the survey.

The assessed safety index for each situation was compared with the corresponding index of a similar situation from the opposite direction, for example a crossing situation from starboard side were compared to a crossing situation from port side with the same CPA and TCPA.

According to the response from the survey, the following conclusions for estimating the fuzzy rules could be made:

1 Crossings from port side are considered to be more unsafe than crossings from starboard side.
2 Overtaking situations are considered to be more unsafe if the target vessel is located on the starboard side of the own ship.
3 In a crossing situation with a vessel passing ahead of the own ship with a CPA of 1.0M, the minimum safety index, the most unsafe situation, is when the target vessel still has to pass the heading line and the value of the TCPA is approximately 4 minutes.
4 For a situation with a CPA of 0.0M, a head-on situation is assessed to be safer than a crossing situation, at the same TCPA.
5 If an avoiding manoeuver has been made by a target vessel on the port side of the own ship, the situation is assessed to be more safe than a corresponding situation without a previously made avoiding manoeuver.
6 In multi-vessel situations, the comprehensive safety index is always equal or lower than the indices assessed individually for each situation. In situations where the own ship has another vessel

close to the starboard side, which makes an avoiding manoeuvre more difficult, the safety index results in considerably lower values compared to other situations.

3.3 *Fuzzy model for estimating a collision index*

The collision safety index model will be based on several input variables (see section 3.1); CPA, TCPA, bow cross range, encounter type, shown intentions of performing a collision avoidance manoeuvre, environmental conditions, manoeuvrability and traffic density.

Parameters that probably will affect the collision safety index, but which are not taken into account in this version of the model are "traffic in narrow channels or shallow waters" and "traffic in traffic separation schemes".

The calculation of the collision safety index is realized in four different modules combined as shown in figure 6.

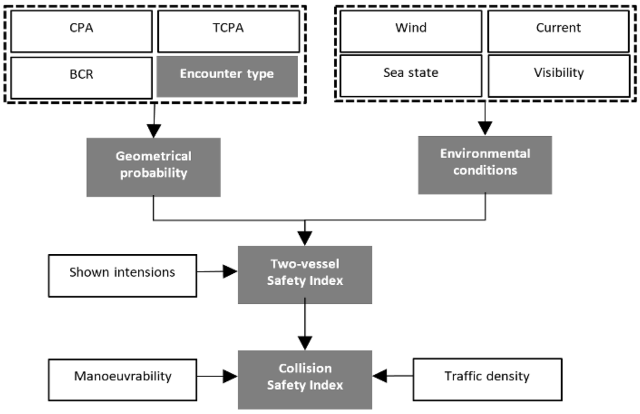

Figure 6. Overview of the collision safety index.

First, the geometrical probability of a close quarter situation is measured by a fuzzy interference system (FIS) using CPA, TCPA, BCR and the encounter type as input variables. The output for the geometrical probability is based on five different output membership functions; totally unsafe, unsafe, medium, safe and totally safe.

In parallel, the environmental conditions are defined by wind, current, sea state and visibility (see section 3.1.5). A second level FIS is using the geometrical probability output, environmental conditions and shown intentions to calculate a "two-vessel safety index", defined by five membership functions; totally unsafe, unsafe, medium, safe and totally safe.

The output value of this FIS is used together with the manoeuvrability (the possibility to change course to starboard due to other vessel in vicinity or shallow water) and traffic density in a third level FIS to get a final value of the collision safety index for a vessel.

3.4 *Fuzzy model for estimating a grounding index*

The fuzzy model for estimating the grounding index consists of the calculated under keel clearance (UKC) as 15 different input parameters, one input parameter describes the safety margin, one input parameter describes the drifting angle and one parameter describes the drifting speed (see section 3.1).

The fuzzy logic for the grounding index is divided into four different modules; the first module uses the UKC points ahead (point 1, 2 and 9), safety margin and drifting. This module consist at present state of 225 rules (5x3x5x3) where the membership functions for each UKC point is combined with the safety margin and the membership functions for the drifting speed.

The next two modules are equal, hence mirrored, one for starboard (point 3, 4, 5, 10, 11 and 12 in figure 2) and one for port (point 6, 7, 8, 13, 14, 15 in figure 2) UKC points. These modules are similar to the first module, hence with less rules implemented. For example are UKC points 10 and 11 ignored when the drifting speed is low.

The last module combines the other three modules with the drifting angle and aggregates to a total grounding safety index.

4 VALIDATION AND RESULTS

The model will be validated through scenarios run in a ship handling simulator and assessed regularly at one minute intervals by experienced simulator instructors. The instructors will be told to assess the traffic situation from a specific vessel's perspective (own ship). The scenarios are established to correspond to situations in the expert survey when possible. The average value from the instructors' assessments in the validation scenarios will be compared to the output value calculated in the safety index model.

5 CONCLUSION AND OUTLOOK

The maritime safety index could be used in many different applications, e.g. in the assessment of safe navigating of a ship, comparison of safety before and after implementation of a new or revised regulatory regimes (e.g. implementation of new or changed traffic separation schemes), comparison of safety with or without certain navigational tools (e.g. route exchange tools within the STM Validation Project).

Safety is difficult to measure and it can be done in various ways. To get a complete assessment of safety levels in a certain situation, both numerical values and human factors measures must be duly considered. In the maritime safety index, only numerical values have been taken into account. The maritime safety index has been designed only to be used to measure safety by using a statistical perspective or to point out possible unsafe situations. More information is needed for a complete assessment.

Are fuzzy integrated systems the best approach to measure safety from a numerical perspective? Experienced officers tend to assess the same traffic situation in different ways. While one watch-keeping officer might assess the situation as relatively safe, another officer will consider the same situation to be unsafe. Most commonly, most will agree on general terms, e.g. to the fact that a medium CPA is safer than a small CPA, but the boundary values between small and medium CPA is quite subjective and thus fuzzy.

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