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Review of ship safety domains: Models and applications

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ABSTRACT

Ship safety domain is a term which is widely used in research on collision avoidance and traffic engineering among others. Classic ship domains have been compared in multiple reports. However, up till now there has been no work summing up contemporary research in this field. The paper offers a systematic and critical review of the newer ship domain models and related research. It discusses multiple differences in approach to ship domain concept: from definitions and safety criteria, through research methodologies and factors taken into account, to sometimes largely different results obtained by various authors. The paper also points out some interpretation ambiguities related to ship domain and sums up present trends of its development and applications.

1. Introduction

Ship safety domain is a generalization of a safe distance and its introduction to maritime navigation comes from the observation that the safe distance is not the same in all directions. The term "ship domain" is widely used, but often with different meanings, depending on a particular author's definition or a purpose for developing domain's model. This may lead to confusion, especially if such domains are compared in terms of size and shape.

Papers on ship domains are numerous and their authors provide brief syntheses of what has already been done in the field. Summaries of ship domain-related research have also been included in papers reviewing collision avoidance methods (Tam et al., 2009). However, until now there has been no wider publication fully devoted to reviewing contemporary ship domain models and related research. The current paper aims to fill this gap by offering a critical ship domains summary.

Ship domains can be roughly divided into those developed by theoretical analyses, those based on experts' knowledge and those determined empirically, though it must be said that the three groups are not mutually exclusive and combinations of various methods are sometimes used, e.g. (Dinh and Im, 2016). Domain models determined empirically are usually simpler, since empirical data make it hard to isolate the impact of multiple parameters. Because of this simplicity, potential applications of these models are limited to problems, where sizes and general shapes of domains are enough to work on the statistical level and precise dimensions are less important. Therefore, empirical domains are successfully used for determining capacity of local waterways, but usually are not detailed enough for ship-ship collision avoidance. As for knowledge-based and analysis-based models, their application scope is much wider and extends from abovementioned collision avoidance to detection of near miss situations and waterway risk analysis. As these purposes are much more demanding, the domains are heavily parameterised to cover multiple elements contributing to collision risk.

What is common for all models is that they are affected by water regions, though to a varying degree. In case of determining capacity or waterway risk it is a particular water region that is of interest, mostly because of its shape, traffic density and traffic patterns. In case of collision avoidance systems it is rather a type of the water region: narrow waterways, restricted (but considerably wider) waters or open waters.

The methods of determining ship domains have evolved with time. Early models have usually been based on statistically processed radar data (Fuji and Tanaka, 1971; Goodwin, 1975; Coldwell, 1983). This empirical approach is still continued, but AIS has replaced radar as a data source and more advanced statistical methods are applied to data processing (Hansen et al., 2013; van Iperen, 2015). Utilising expert navigators' knowledge (Pietrzykowski and Uriasz, 2009), analytical approach (Wang et al., 2010; Wang, 2013) or a combination of both (Dinh and Im, 2016) is preferred when collision avoidance systems, near miss detection or collision risk analysis are concerned.

The rest of the paper is organised as follows. Domain's classic definitions are presented and analysed in Section 2, followed by a discussion of why, how and with what results domains have been determined by various contemporary researchers (Section 3). Section 4 presents their applications and Section 5 related research methods and measures

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alternative to ship domains. Finally, the conclusions, including unsolved problems and predicted future of ship domains, are presented in Section 6.

2. Domains definitions, interpretations and their practical implications

While all of the researchers determine or propose dimensions of their respective ship domain models, it must be noted here that these dimensions may result in different spacing between ships, depending on the definition of a ship domain and the associated safety criteria. Therefore, three classic definitions are recalled here and their interpretations and implications are discussed later in this section.

The term of a ship domain was first introduced in (Fuji, 1971), where the effective domain was defined as: '*a two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion*'. The dimensions of the effective domain boundary were there defined as the distance from the central ship at which the density of other ships reaches a local maximum.

Similar definitions can be found in two successive works. According to Goodwin (1975) the domain is '*the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles*'. In (Coldwell, 1983) it is '*the effective area around a ship which a typical navigator actually keeps free with respect to other ships*'. The obvious difference is that in the latter definition the results rather than preferences are accentuated.

In general, the above definitions are close to each other, yet are interpreted in multiple ways by various authors, leading to various safety criteria applied in their research. In practice, using a ship domain in an encounter situation may be combined with one of the following four safety criteria, as presented in Fig. 1:

a) own ship's (OS) domain should not be violated by a target ship (TS),
b) a target ship's (TS) domain should not be violated by the own ship (OS),
c) neither of the ship domains should be violated (a conjunction of the first two conditions),
d) ship domains should not overlap - their areas should remain mutually exclusive (the effective spacing will be a sum of spacing resulting from each domain).

Each of these criteria is represented by some researchers. Fuji's definition implies that a give way ship should try not to violate the domain of a stand-on one, while according to Coldwell a navigator takes care of his own domain rather than that of a target. As for Goodwin, the term of "central ship" used in the paper does not imply explicitly whether a ship should avoid violating its own domain or that of a target. However, it might be argued that if the definitions concern every navigator than neither domain should be violated during an encounter of two ships, which supports the third of the listed criteria. The fourth one (domains not overlapping) has been lately used in (Rawson et al., 2014; Wang and Chin, 2016).

The practical differences between those four criteria are essential and will be analysed in detail further in the text. In general, their impact is equally important as the size and shape of a domain, since it largely affects effective spacing between ships.

The first two criteria may be considered asymmetric – even if the same domain is used, they may lead to different estimations of safety, depending on which ship does the assessment. The other two are symmetric – as long as the same domain is applied, the assessment of the situation would be the same regardless of the point of view. Of these four criteria the last one is by far the strongest and it must be stated clearly here that it is not compliant with any domain's definitions given above. According to these definitions the domain is the area that stays or should stay clear of other vessels, not of other vessel's domains (the latter would mean a recursive definition and would be unintuitive for a navigator). Unfortunately, all of the four criteria, including the last one, are used by researchers, who then compare their domain dimensions with other domains, which is meaningless in case of different criteria. Depending on which of the four criteria listed above is to be applied, different minimum spacing will be kept, even if the same domain model is used. In practice the differences in spacing due to applying different criteria will be comparable and sometimes even substantially larger than the differences in domain dimensions according to different authors. The details are provided below.

To make the analysis easier to follow, let us assume a ship domain's shape and size according to Coldwell, whose dimensions (multiplies of a ship length given as *L*) are given in Fig. 2. Coldwell specified different dimension values for meeting (head-on and crossing) and overtaking encounters (Fig. 2). Since his "meeting" domain does not have the aft sector (which is understandable in case of a head-on encounter, but problematic for a crossing), the "meeting" domain has been adjusted for the experiment in accordance with the general trend identified by most researchers (the aft sector smaller than the fore sector), as shown in Fig. 3.

Thus, the domain dimensions are as follows.

- For overtaking encounters: semi-major axis - 6 L, semi-minor axis – 1.75 L.
- For head-on and crossing encounters: semi-major axis – 5 L, semi-minor axis – 2.5 L.

Additionally, for head-on and crossing encounters the ship is moved from the ellipse's centre towards port by 0.75 L and towards aft by 1.1 L, with the resulting safe distances for respective sectors being:

- fore sector – 6.1 L,
- aft sector – 3.9 L,

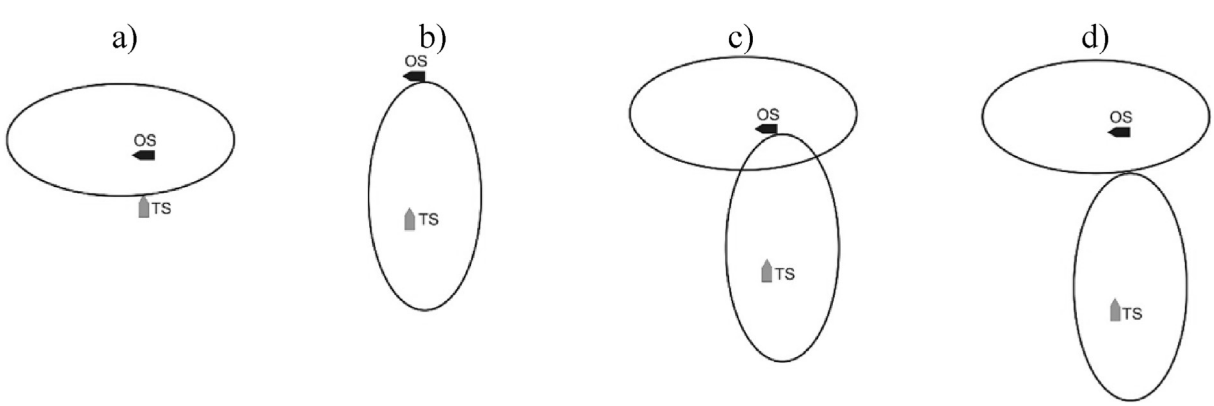

Fig. 1. Different domain-based safety criteria: a) OS domain is not violated, b) TS domain is not violated, c) neither OS nor TS domain is violated, d) domains do not overlap.