Calculating the position parameters at the kinematic maneuver for approaching and collision courses

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Abstract. Collision risks take into consideration the CPA, the TCPA and the speed of maneuver. In specialty literature, starting distance for collision avoidance maneuver is 4-6 nautical miles, distance calculated for small speeds. The calculations and simulations for more collision situations for a container ship of 13000 TEU and speeds higher than 20-25 knots, the minimum distance for the collision avoidance maneuver should be at least 6 -8 nautical miles.

1. INTRODUCTION

The ideal case of the ship's evolution on quiet water is found when the dynamic nautical qualities [1],[6] (the smooth oscillation, the stability of the road, the maneuverability and the underway qualities) meet the ship's functionality criteria, and the environmental factors (wind and current) that cause the ship’s drift from the determined trajectory (course) are null and therefore, the external forces are null.

In this situation, the ship's evolution is predictable and depends directly on the performance of the propulsion system [3] and its static nautical qualities (buoyancy, stability and unsinkability) for different loading states.

The situation is totally different in the case of evolution on waves. In this case the ship oscillates under the action of exterior forces, caused by moving masses of water. Among the negative consequences of the ship’s oscillations on the waves, is the reduction of the ship’s speed due to drag.

Two factors – safety (of the vessel, crew and cargo) and time - are extremely important in operation of the modern shipping vessels [2][4][6].

In general, the safety of navigation is determined by a series of elements, such as:
- construction and nautical qualities of the vessel;
- the level of crew professional training;
- weather and load status.

The time needed to undergo a sea passage depends on the nautical qualities of the vessel, the performances of the propulsion system, the weather and load status. The efficiency of shipping is given by the optimal ratio between the quantity of transported cargo and the necessary time to undergo a sea passage. Without
reducing the safety of transport, it can be said that any increase in speed with the purpose of reducing the time for the voyage, is being pursued by ship’s builder, the ship owner and also by the officers onboard.

The transport speed has been increasing in the last years, from 9 – 12 knots, up to 14 – 16 knots and even 24 – 30 knots for passenger vessels. This fact is reflected in the evolution of shipping vessels, as follows: in calm waters navigation, the relative speeds – for collision courses – between two or more vessels, has increased at values of which the reaction time for avoiding a collision is insufficient[7-10]

2. MATERIAL AND METHODS

To analyze the variation of motion and maneuver parameters for two vessels on the approach courses (initial course and speed and collision avoidance course and speed), were considered the following:

1. The ideal case of unperturbed movement by external factors (wind and current) described and theoretically analyzed. The movement is carried out with constant speed, without accelerations, and the vessel size is reduced to a material point model from classic kinematics, for theoretical calculus.

2. Simulations for the mutual maneuver of vessels were execute in the Integrated Simulator for Shiphandling, in “Mircea cel Batran” Naval Academy, Constanța. The simulator is type Navi-Trainer Professional 5000 [17-19] manufactured by TRANSAS Limited Co and certified by DetNorskeVeritas (DNV) as A class (full mission) for bridge and machinery. In this case, was used a vessel type container vessel of 13.000 TEU.

The danger of collision between two vessels situated on approaching courses appears when the distance between them decreases continuously (Fig.1). It can also be considered a danger of collision when there is a future collision position or a dangerously approach position [2], [5-6].

Fig. 1. Relative movement of vessels

\[ R_{0,1} \] – position of own ship
\[ T_{0,1} \] – position of target
In order to analyze a collision situation, the following safety parameters are defined for each vessel:

- safety distance $d_{sd}$;
- critical time $t_{ct}$.

The safety distance $d_{sd}$ is a minimum accepted distance, not dangerous and is taken according to the vessel’s nautical qualities and the navigation and environmental conditions.\[8-11]\]

Any approach between vessels beneath this value leads to a dangerous situation (Fig.2 and Fig.3). Fig. 2 shows the safety distance calculated from the stopping distance and a reserve given by the actual navigation situation (hydro meteorological situation, existing maneuvering space, traffic etc.).\[8\][11] Fig. 3 shows the safety distance calculated for the vessel’s turning from the stopping distance and a resource given by the actual navigation situation [9], [10].

The critical time $t_{ct}$ is the time to the minimum distance that allows a safe reaction and maneuver.

The values for safety distance and critical time are not given in COLGEG (Convention on the International Regulations for Preventing Collisions at Sea) [13][15]. The value are set by the master of the vessel, according to her evolutionary qualities and the actual navigation situation (usually, the safety distance takes values from 0.5 ÷ 3 nautical miles and the critical time is between 20 ÷ 60 minutes).

The danger of collision is real when the safety distance is smaller than the minimum distance between vessels – $CPA \ (d_{sd}< CPA)$, which can be determined graphically or automatically by ARPA radars.

The danger of collision is assessed by determining the values of the hazard indices [5]:

- distance criterion $p$;
- time criterion $q$;
- danger criterion $K$.

The distance criterion $p$, is defined as the ratio between the minimum distance – CPA and the safety distance, with the relation (1):
\[ p = \frac{d_{\text{min}}(CPA)}{d_s} \]  

(1)

Where: \( p \) is the distance criterion; \( d_{\text{min}} \) or \( CPA \) – represents the smallest distance between vessels at the end of the avoidance maneuver; \( d_s \) – represents the safety distance.

If \( p < 1 \), the target is dangerous, and if \( p > 1 \), the target is not dangerous.

**The time criterion** \( q \), is defined as the ratio between the minimum time or TCPA and the critical time, and is determined with relation (2):

\[ q = \frac{t_{\text{min}}(TCPA)}{t_{cr}}, \text{for } q < 1 \]  

(2)

Where: \( q \) is the time criterion; \( t_{\text{min}} \) or \( TCPA \) – represents the time to CPA; \( t_{cr} \) – represents the critical time.

If \( q < 1 \) the target is extremely dangerous, and if \( q > 1 \) the target can be avoided in time.

**The danger criterion** or combined criterion \( K \), is defined as the complex ration of time and distance criteria. [13]

For dangerous targets, when \( p < 1 \), the hazard classification for several vessels is achieved according to the combined criterion (fig.4) according equation (3). From equation (3), results (4) and (5) [10]

\[ K = 1 - \frac{q}{\sqrt{1 - p^2}} \]  

(3)

Meaning:

\[ K = 1 - \frac{q_{\text{real}}}{q_{\text{lim}}} \]  

(4)

Where:

\[ q_{\text{lim}} = \sqrt{1 - p^2} \]  

(5)

According to the ratio value \( q_{\text{real}}/q_{\text{lim}} \) the following can be stated equation (6), (7), (8).

- is the ratio \( \frac{q_{\text{real}}}{q_{\text{lim}}} < 1 \) the target is imminently dangerous; \hspace{1cm} (6)

- if the ratio \( \frac{q_{\text{real}}}{q_{\text{lim}}} > 1 \) the target is dangerous in time; \hspace{1cm} (7)

- if the criterion \( K > 0 \) the danger of collision is imminent. \hspace{1cm} (8)
According the collision hazard indices, the dangerous status of vessels are presented in Fig.5[2], [7], [11]:

- in sector I, target A is imminently dangerous;
- in sector II, target B is dangerous in time;
- in sector III, target C is not dangerous.

3. RESULTS

Case 1: ideal case

For initial distances between 4 – 6 nautical miles and speeds above 15 knots, the relative approaching speed and collision time for directly opposite courses are determined with the below relation. Were taken into consideration three cases for speed and initial distances between 0 – 120 cables. According equation (9), (10) and Fig. 6, the results are presented in Table 1.:
\[ S_R = S_C + V_T \]  

(9)

and:

\[ T_{col} = \frac{d_0}{S_R} \]  

(10)

where: \( S_C \) – own vessel speed; \( S_T \) – target speed; \( S_R \) – relative movement speed; \( T_{col} \) – collision time; \( d_0 \) – initial distance between vessels.

Fig. 6. Relative speed in kinematic movement

 Graphic 1 show the view the variation of collision time between two underway vessels with speed varying from 16 to 28 knots, in which are analyzed three cases as follows:

- collision time A: \( S_C = 16 \) knots and \( S_T = 24 \) knots (Table.1);
- collision time B: \( S_C = 18 \) knots and \( S_T = 26 \) knots (Table. 2);
- collision time C: \( S_C = 20 \) knots and \( S_T = 28 \) knots (Table. 3).

Table 1 Values of relative speed \( S_R \) and collision time \( T_{col} \) - case A

| No | Initial distance [cable] | Own ships speed [knots] | Ships target speed [knots] | Relative speed [knots] | Collision time [min] |
|----|--------------------------|-------------------------|---------------------------|-----------------------|---------------------|
| 1  | 120                      | 16                      | 24                        | 40                    | 18.0                |
| 2  | 110                      | 16                      | 24                        | 40                    | 16.5                |
| 3  | 100                      | 16                      | 24                        | 40                    | 15.0                |
| 4  | 90                       | 16                      | 24                        | 40                    | 13.5                |
| 5  | 80                       | 16                      | 24                        | 40                    | 12.0                |
| No | Initial distance | Own ship speed | Target ship speed | Relativ speed | Collision time |
|----|-----------------|----------------|-------------------|---------------|----------------|
| 1  | 120             | 18             | 26                | 44            | 16.4           |
| 2  | 110             | 18             | 26                | 44            | 15.0           |
| 3  | 100             | 18             | 26                | 44            | 13.6           |
| 4  | 90              | 18             | 26                | 44            | 12.3           |
| 5  | 80              | 18             | 26                | 44            | 10.9           |
| 6  | 70              | 18             | 26                | 44            | 9.5            |
| 7  | 60              | 18             | 26                | 44            | 8.2            |
| 8  | 50              | 18             | 26                | 44            | 6.8            |
| 9  | 40              | 18             | 26                | 44            | 5.5            |
| 10 | 30              | 18             | 26                | 44            | 4.1            |
| 11 | 20              | 18             | 26                | 44            | 2.7            |
| 12 | 10              | 18             | 26                | 44            | 1.4            |
| 13 | 5               | 18             | 26                | 44            | 0.7            |

Table 2: Values of relative speed $S_R$ and collision time $T_{col}$ - case B

| No | Initial distance | Own ship speed | Target ship speed | Relativ speed | Collision time |
|----|-----------------|----------------|-------------------|---------------|----------------|
| 1  | 120             | 18             | 26                | 44            | 16.4           |
| 2  | 110             | 18             | 26                | 44            | 15.0           |
| 3  | 100             | 18             | 26                | 44            | 13.6           |
| 4  | 90              | 18             | 26                | 44            | 12.3           |
| 5  | 80              | 18             | 26                | 44            | 10.9           |
| 6  | 70              | 18             | 26                | 44            | 9.5            |
| 7  | 60              | 18             | 26                | 44            | 8.2            |
| 8  | 50              | 18             | 26                | 44            | 6.8            |
| 9  | 40              | 18             | 26                | 44            | 5.5            |
| 10 | 30              | 18             | 26                | 44            | 4.1            |
| 11 | 20              | 18             | 26                | 44            | 2.7            |
| 12 | 10              | 18             | 26                | 44            | 1.4            |
| 13 | 5               | 18             | 26                | 44            | 0.7            |

Table 3: Values of relative speed $S_R$ and collision time $T_{col}$ - case C
| [cable] | [knots] | [knots] | [knots] | [min] |
|--------|--------|--------|--------|------|
| 1      | 120    | 20     | 28     | 48   | 15.0 |
| 2      | 110    | 20     | 28     | 48   | 13.8 |
| 3      | 100    | 20     | 28     | 48   | 12.5 |
| 4      | 90     | 20     | 28     | 48   | 11.3 |
| 5      | 80     | 20     | 28     | 48   | 10.0 |
| 6      | 70     | 20     | 28     | 48   | 8.8  |
| 7      | 60     | 20     | 28     | 48   | 7.5  |
| 8      | 50     | 20     | 28     | 48   | 6.3  |
| 9      | 40     | 20     | 28     | 48   | 5.0  |
| 10     | 30     | 20     | 28     | 48   | 3.8  |
| 11     | 20     | 20     | 28     | 48   | 2.5  |
| 12     | 10     | 20     | 28     | 48   | 1.3  |
| 13     | 5      | 20     | 28     | 48   | 0.6  |

**Graphic 1** The variation of collision time depending on the speed values when the vessels is in kinematic approach maneuver

The analysis of results found in Graphic 1 shows that the collision time is decreasing directly proportional with the initial distance and relative speed down until 8 cable, after which the variation of collision time is slow.[16]

Thus, for initial distances between 4 – 6 nautical miles and speeds above 15 knots, the relative approaching speed and collision time on approaching courses (the difference between \( C_R \) and \( C_T \), \( \Delta C \) was made with variations from 10° to 10°) are calculated with the following relations (11), (12). According Graphic 2, the results are presented in Table. 4.
\[ S_R = \sqrt{S_C^2 + S_T^2 - 2S_C S_T \cos \Delta C} \]  \hspace{1cm} (11)

and:

\[ T_{col} = \frac{D_i}{S_R} \]  \hspace{1cm} (12)

where:

- \(C\) is the difference between the courses of the vessels in maneuver on approaching courses;
- \(D_i\) initial distance between vessels.

**Table 4** Values of relative speeds and collision time for initial course differences between 0° and 180°

| \(\Delta C\) | \(S_C=16\) knots | \(S_T=20\) knots | \(S_C=18\) knots | \(S_T=22\) knots | \(S_C=20\) knots | \(S_T=24\) knots |
| --- | --- | --- | --- | --- | --- | --- |
| \(S_R\) [knots] | \(T_{col}\) [min] | \(T_{col}\) [min] | \(S_R\) [knots] | \(T_{col}\) [min] | \(T_{col}\) [min] | \(S_R\) [knots] | \(T_{col}\) [min] | \(T_{col}\) [min] |
| 000° | 4,0 | 90,0 | 60,0 | 4,0 | 90,0 | 60,0 | 4,0 | 90,0 | 60,0 |
| 010° | 5,1 | 71,0 | 47,3 | 5,3 | 68,0 | 45,3 | 5,5 | 65,1 | 43,4 |
| 020° | 7,4 | 48,7 | 32,5 | 8,0 | 45,1 | 30,1 | 8,6 | 41,9 | 27,9 |
| 030° | 10,1 | 35,7 | 23,8 | 11,1 | 32,6 | 21,7 | 12,0 | 29,9 | 20,0 |
| 040° | 12,9 | 28,0 | 18,6 | 14,2 | 25,4 | 16,9 | 15,5 | 23,2 | 15,5 |
| 050° | 15,6 | 23,0 | 15,3 | 17,3 | 20,8 | 13,9 | 18,9 | 19,0 | 12,7 |
| 060° | 18,3 | 19,6 | 13,1 | 20,3 | 17,7 | 11,8 | 22,3 | 16,2 | 10,8 |
| 070° | 20,9 | 17,2 | 11,5 | 23,2 | 15,5 | 10,4 | 25,4 | 14,1 | 9,4 |
| 080° | 23,3 | 15,4 | 10,3 | 25,9 | 13,9 | 9,3 | 28,4 | 12,7 | 8,4 |
| 090° | 25,6 | 14,1 | 9,4 | 28,4 | 12,7 | 8,4 | 31,2 | 11,5 | 7,7 |
| 100° | 27,7 | 13,0 | 8,7 | 30,7 | 11,7 | 7,8 | 33,8 | 10,6 | 7,1 |
| 110° | 29,6 | 12,2 | 8,1 | 32,8 | 11,0 | 7,3 | 36,1 | 10,0 | 6,6 |
| 120° | 31,2 | 11,5 | 7,7 | 34,7 | 10,4 | 6,9 | 38,2 | 9,4 | 6,3 |
| 130° | 32,7 | 11,0 | 7,3 | 36,3 | 9,9 | 6,6 | 39,9 | 9,0 | 6,0 |
| 140° | 33,9 | 10,6 | 7,1 | 37,6 | 9,6 | 6,4 | 41,4 | 8,7 | 5,8 |
| 150° | 34,8 | 10,3 | 6,9 | 38,7 | 9,3 | 6,2 | 42,5 | 8,5 | 5,6 |
| 160° | 35,5 | 10,2 | 6,8 | 39,4 | 9,1 | 6,1 | 43,3 | 8,3 | 5,5 |
| 170° | 35,9 | 10,0 | 6,7 | 39,8 | 9,0 | 6,0 | 43,8 | 8,2 | 5,5 |
| 180° | 36,0 | 10,0 | 6,7 | 38,0 | 9,5 | 6,3 | 44,0 | 8,2 | 5,5 |
The analysis of the results found in Graphic 2 shows that the variation of collision time, according to relative speed and course differences of the two vessels, is a power trend line.

**Case 2: Simulated movement**

The calculation were made for the case of emergency maneuver for avoiding collision by turning to starboard, taking into consideration the sea state (Table 5 and Graphic 3). [12] The emergency maneuver represents the maneuver made by a vessel, in order to avoid collision, by changing the course with 90°. This maneuver is done with maximum of ruder angle.

Advance represents the distance measured on initial course in the emergency maneuver. The transfer represents the lateral distance from the initial course in the emergency maneuver. Emergency limit represents the minimum distance for starting the emergency action. This distance includes the advance and safety distance. This minimum distance must by at least 3 times of the full maneuvering circle/advance at full speed. According Table 5, the emergency limit must by at least 1.5 nautical mile. [18] Maneuvering limit represent the minimum distance or the time for starting the maneuver in order to comply with the safe passing limit requirements for a give way vessel.

**Table 5** Emergency maneuver: hard to starboard

| Speed Sea state | Advance [m](RLc) | Transfer [m] | Course [°] | Time [s] | Advance [m] | Transfer [m] | Course [°] | Time [s] |
|-----------------|-----------------|--------------|------------|----------|-------------|--------------|------------|----------|
| 26.3 knots      | 1223.97         | 679.49       | 99°.00     | 02:30    | 1067.69     | 521.95       | 98°.02     | 02:30    |
### Sea state 0

| Speed 26.3 kt | 1193.92 | 688.87 | 100°.65 | 02:30 | 1100.60 | 723.29 | 105°.65 | 02:30 |

### Sea state 2

| Speed 26.3 knots | 1204.35 | 640.32 | 088°.53 | 02:30 | 1082.42 | 653.69 | 099°.08 | 02:30 |

### Sea state 5

| Speed 26.3 knots | 1078.84 | 540.05 | 093°.74 | 02:20 | 1017.33 | 596.60 | 090°.02 | 02:30 |

### Sea state 6

| Speed 13.3 knots | 1046.27 | 616.63 | 101°.58 | 04:20 | 966.06 | 609.13 | 102°.59 | 04:10 |

### Graphic 3.
The variation of the course, advance and the transfer of ship in the emergency maneuver

#### 4. CONCLUSIONS

The increasing underway speeds for maritime vessels determinate a dramatically decrease of analysis and reaction time that the officer of the watch has to start a collision avoidance maneuver.

The increasing traffic on navigation routes also limits the maneuvering possibilities for collision avoidance maneuvers [14].

In case of container vessel, it can be observed that according to various sea states and different loading conditions of the vessel, the critical time for avoiding collision maneuver at full speed is 2.5 minutes. In this situation the advance is between 0.58 – 0.66 nautical miles.
For the situation of economical speed (13.3 knots) the critical time for avoiding collision maneuver is 4.3 minutes. In this case, the advance is between 0.52 – 0.56 nautical miles.

Thus, it is imposed that the avoiding collision maneuver should begin at higher distances: minimum 6 – 8 nautical miles for avoidance maneuver and minimum 4 nautical miles for the escape maneuver, in comparison with literature (4 – 6 nautical miles, respectively 3 nautical miles).

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