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## **Quantitative assessment of risk to ship traffic in the Fehmarnbelt fixed link project**

### **Keywords**

quantitative risk assessment, QRA, ship collision, ShipRisk, facility safety assessment, FSA, IMO guideline, AIS data

### **Abstract**

Rambøll is on behalf of Femern A/S carrying out navigational studies of the vessel traffic conditions in the Fehmarnbelt in connection with the establishment of a future Fehmarnbelt fixed link, a 19 km long bridge or immersed tunnel connection crossing the Fehmarnbelt. The focus is on documenting safety and efficiency for the vessel traffic when a fixed link is crossing the Fehmarnbelt. Rambøll has developed the ShipRisk software package to perform the quantitative risk assessments in the Fehmarnbelt fixed link project. Focus in this article is on describing the background for estimating frequencies of ship accidents in ShipRisk and describe factors influencing the accident scenarios and present the work performed for testing and verifying the model.

### **1. Introduction**

Rambøll is on behalf of Femern A/S carrying out navigational studies of the vessel traffic conditions in the Fehmarnbelt. Femern A/S, a subsidiary of Sund & Bælt A/S, is responsible for the preparatory activities for the establishment of a future Fehmarnbelt fixed link a 19 km long bridge or immersed tunnel connection crossing the Fehmarnbelt (see [www.femern.com](http://www.femern.com)). The objective of the navigational studies is to deliver the optimum decision basis for the authorities' evaluation of marine safety and navigational arrangements. The focus is on documenting safety and efficiency for the vessel traffic when a fixed link is crossing the Fehmarnbelt. Fehmarnbelt is one of the world's most heavily trafficked waters with a yearly number of movements of around 40,000 commercial ships with

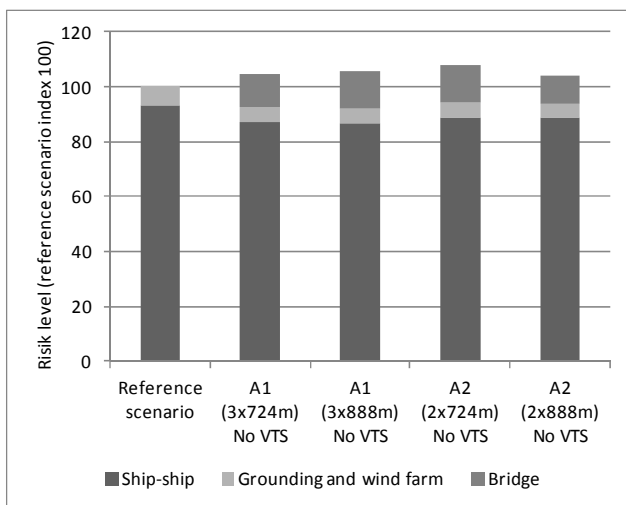
lengths up to 350m. The navigational safety studies comprise extensive and detailed analyses of existing ship traffic in Fehmarnbelt, ship traffic prognosis for year 2030 and risk modeling of ship traffic accidents in the entire Fehmarnbelt area in a reference situation without a fixed link, in the permanent situation with a bridge (FSA according to IMO guideline) and during the construction period of a tunnel or bridge. Furthermore, extensive real time simulation studies have been performed as part of the analysis for a bridge.

The ShipRisk software package developed by Rambøll is used to perform the quantitative risk assessments in the Fehmarnbelt link project. Focus in this article is on describing the background for estimating frequencies of ship accidents in ShipRisk

and describe the work performed for testing and verifying the model.

Modeling of ship accident consequences is also a part of the ShipRisk software package, but is not described further in this paper

Results from the ShipRisk can be shown as frequencies of ship accidents or capitalized as risk. An example of how results from ShipRisk can be presented is shown in *Figure 1*. The figure shows the risk in Fehmarnbelt for a reference scenario without a bridge and for two bridge alternatives (A1 with three main bridge spans and A2 with two main bridge spans) with different span widths (724m or 888m) in a situation where a Vessel Traffic Service (VTS) is not monitoring the ship traffic.



*Figure 1.* Example of how results from ShipRisk can be presented.

Section 2 presents a literature study, section 3 gives the framework for estimation of ship accident frequencies and section 4 presents the work done in the Fehmarnbelt link project to test and verify parameters in the ship accident scenarios.

## 2. Literature study

The models included in the ShipRisk software package are based a geometrical modelling of ship traffic movements and interactions and was originally suggested by Macduff [12] and Fujii [28]. In this early work on ship grounding it has been common practice to model groundings and collisions as a product of a geometrical probability and a probability of not re-acting to the danger. This approach has been denoted as the probabilistic model of ship groundings and collisions.

Other approaches have been taken, for example [1], [4] and [11] propose agent driven collision modelling and [2] propose a model based on traffic conflict inspired by collision modelling from road traffic.

However, most work on predicting collision frequency and risk scenarios for waterways extend on the probabilistic collision model.

Recently two EU projects have studied the literature and a detailed overview of the collision and grounding tools used in formal safety assessments are presented in [16]. In [14] a review of probabilistic models for ship grounding is given.

The probabilistic model based on the original idea from Macduff and Fujii has been expanded by Pedersen [22] and Simonsen [21]. A basic formulation of this model can be written as a product:

$$N_{acc} = N_{ships} \cdot P_{geometric} \cdot P_{causation} \quad (1)$$

Where  $N_{acc}$  is the number of accidents,  $N_{ships}$  is the number of ships on the route in a given time interval  $P_{geometric}$  is the geometric probability that a ship will be on collision or grounding course and  $P_{causation}$  is the probability that an accident will occur if the ship is on collision or grounding course - often denoted as the causation factor. This model has been used in previous studies [3], [8], [24], [15] and [17] where the geometric probabilities and causation factors are calculated in slightly different ways and include slightly different scenarios. Also the study of navigational safety on the Øresund bridge [29] and the collision modelling tool recommended by IALA [7] use this approach.

The accident scenarios for which the geometric probabilities are calculated vary between the studies, some focus on groundings others on head on collisions, bend collisions, overtaking collisions, or merging collisions or a combination of these. The geometrical probabilities are calculated for different categories and sizes of ships and depend on the type of the accident scenario under examination. An aid to calculating the geometric probability is that all ships above a certain size are required to use the Automatic Identification System (AIS). With AIS the location and type of all ships can be recorded and historic data on the ship traffic is readily available. With AIS it is possible to derive accurate distributions of the ship traffic based on historic data. Most of the recent work applies this approach to establish the geometric probabilities.

In the model, the causation factor represents the probability that no action is taken by the navigator when the ship is on accident course. This probability depends on many factors. In [21] human factors, weather and machine failure are taken into account. [14] further mentions vessel characteristics, route characteristics and some authors including [23] also include mitigating effects as vessel traffic service and pilot service in the estimation.

According to [19] studies have shown that human error contributes to between 75% and 96% of all accidents. Human errors in relation to the causation factor have been studied in [5]. Some authors e.g. [6], [9] and [15] use a Bayesian approach to the causation factor, while others use fault trees [25] or heuristics.

The models for groundings and collisions have been applied for quantifying shipping safety in open water [26] and in Formal Safety Assessments of off shore structures and route changes e.g. [23] and [25]. Collision and grounding models have also been applied to safety in ports [20] and to safety in inland waterways [18].

### 3. Method

In this section the framework for the estimation of ship accident frequencies in the ShipRisk software package is described. First the required input is described, then the included ship accident scenarios are presented and finally, some factors influencing the accident scenarios are mentioned.

#### 3.1. Input

The input to the model relates to the geometry and the ship traffic in the investigated area.

The input concerning the geometry in the investigated area relates to:

1. Obstacle location; extension and water depth.
2. Sailing routes; coordinates for centre line of lanes and distribution of ship movements perpendicular to sailing direction.

When the ShipRisk model is used to analyze the risk from ship collision to fixed objects (bridges, wind turbines, etc.) then coordinates for the obstacles are input to the model. Also coordinates for obstacles protecting the fixed objects (shallow water or other fixed objects) are input to the model.

Other obstacles inside the investigated area may also affect the navigational safety and therefore these obstacles are also included. These obstacles are for example reefs, coastlines and the shallow water areas.

By analysing intensity plots for ship tracks in the investigated area (typically produced from AIS data) the coordinates for centre lines of lanes belonging to line traffic routes are found.

Part of the traffic is better modelled as so called area traffic (local commercial traffic, fishing vessels, pleasure crafts, etc.). Each area traffic route defines a geographic area. Inside these areas the intensity of traffic is modelled as uniform and the sailing direction as random.

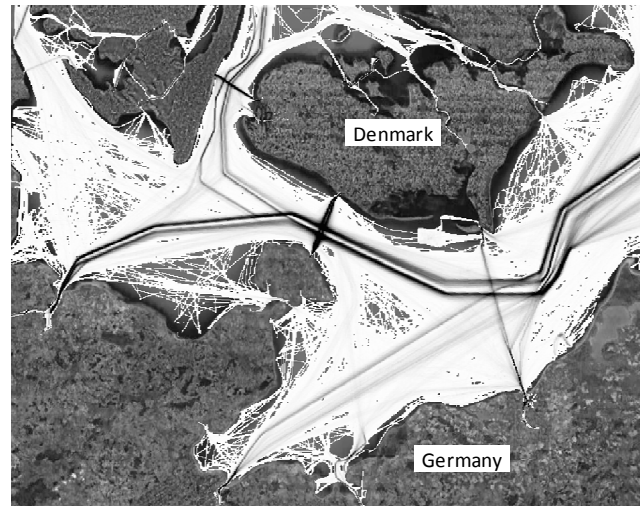


Figure 2. Intensity of ship tracks in Fehmarnbelt (based on AIS data).

Furthermore, the distribution of ship movements perpendicular to the sailing direction is also typically produced from AIS data.

A basic approximation is that the ship traffic distributions transverse to the sailing direction fit a combination of a normal distribution or log-normal distribution and a uniform distribution. This assumption is usually quite well met for routes which have a large number of movements and less so for routes with fewer movements.

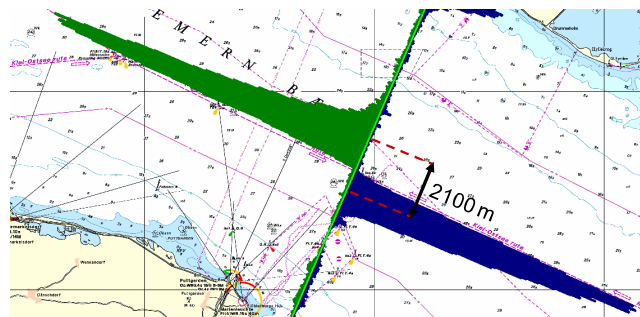


Figure 3. Ship traffic distribution transverse to sailing direction, route T in Fehmarnbelt.

The input concerning the ship traffic in the investigated area relates to:

1. Number of movements per lane.
2. Distribution of movements per lane on ship size classes.

It is assumed that all ships inside one ship size class can be represented by the same mean and standard deviation for the ship particulars length, breadth, draught, air draught, displacement and speed.

Apart from input concerning geometry and ship traffic also input about meteorological and oceanographic data is used in the modeling of drifting direction for ships losing propulsion.

Finally, accident registrations for the investigated area are always valuable in order to have a basis for comparison of the results from the model and also to give an indication if special navigational conditions in the investigated area should be taken into account when analyzing risk from ship accidents.

### 3.2. Accident scenarios

The basic concept in the ship accident scenarios is that the ships may – based on the location on the considered route – be at collision or grounding course, but will in normal conditions make proper evasive actions such that an accident does not occur. An accident only occurs in cases, where a failure occurs and no evasive actions are made. Hence, the frequency of an accident relates to the two probability contributions:

1. The probability of a ship being on collision or grounding course
2. The probability that the navigator(s) does not make evasive actions in due time

The ShipRisk software package deals with 7 ship accident scenarios which can be grouped in two categories:

Ship-obstacle collision (including grounding):

1. Human failure
2. Technical failure (loss of propulsion or steering machine failure)

Ship-ship collision:

3. Crossing
4. Encounter
5. Overtaking
6. Bend collision – opposite direction
7. Bend collision – same direction

The ship-ship collision models cover interaction between two ships. Interaction between three or more ships is not modelled. Real accidents typically occur as a result of a long chain of events. The ship accident scenarios, applied here, are simple predictive models aiming at estimating the frequency and risk of accidents rather than explaining the cause of observed accidents.

If fixed obstacles are placed close to the sailing route (e.g. bridge pylons) then the ship-ship collision scenarios "encounter" and "overtaking" are modeled so that they can also lead to collision with the fixed obstacle.

The ship accident scenarios are introduced in the following.

Ship-obstacle collision - human failure

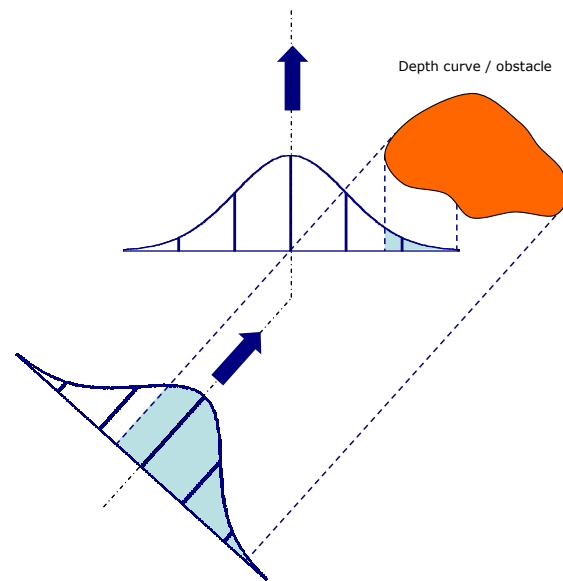


Figure 4. Illustration of human failure.

It is assumed that the occurrence of a human failure is independent of the position of the ship and that a human failure will influence navigation of the ship for an average of 20 minutes. During this period it is assumed that the ship will maintain the same course and speed as it did before the human failure occurred. It is assumed that the sailing course and speed is corrected after the human failure is detected. This approach is used and found reasonable in the verification made in [8].

This model is applied for two different situations; ships being on grounding course and ships being on collision course with a fixed obstacle.

As illustrated in Figure 4 the model for determining the number of ships on grounding or collision course (number of collision candidates  $N_{CC}$ ) consists of one or two contributions depending on the layout of the navigation route:

1. Straight route before meeting reef/coast or obstacle: All ships at collision course are collision candidates
2. Bend on the route before meeting reef/coast or obstacle: All ships on collision/grounding course before the bend are collision candidates.

Hence, the number of grounding or obstacle collisions due to human failure can be determined as

$$N_{coll/ground} = N_{CC} \cdot (1 - P_{evasive}) \quad (2)$$

where

$N_{CC}$  is the number of collision candidates

$1-P_{evasive}$  is the probability of not making an evasive manoeuvre due to human failure ( $P_{human}$ )

The probability of human failure – the probability that a collision candidate does not avoid the collision ( $P_{human}$ ) is estimated based on observations from Fujii [27] and MacDuff [12]. These analyses are supported by Terndrup Pedersen [22] and verified for navigation in Øresund by Karlsson, Rasmussen and Frisk [8].

The conclusion of Fujii is based on observation of traffic and accident data from four Japanese straights. A value for  $P_{human}$  in the interval between  $0.8 \cdot 10^{-4}$  and  $5.0 \cdot 10^{-4}$  is suggested with a best estimate of  $2 \cdot 10^{-4}$ .

Macduff has studied the traffic in the English Channel and the conclusion here is a value of  $P_{human}$  in the interval between  $1.4 \cdot 10^{-4}$  and  $1.6 \cdot 10^{-4}$ .

Terndrup Pedersen suggests a value for  $P_{human}$  of  $3.5 \cdot 10^{-4}$  using a fault tree analysis.

Finally, Karlsson, Rasmussen and Frisk have verified that a value for  $P_{human}$  of  $2 \cdot 10^{-4}$  fits well to the accident registrations in the Øresund region.

Based on the above a value for  $P_{human}$  of  $2 \cdot 10^{-4}$  is applied in the present study.

The human failure probability is also studied in the Fehmarnbelt link project (see section 4). These studies also verify using  $P_{human}$  of  $2 \cdot 10^{-4}$ .

**Ship-obstacle collision - technical failure**

Technical failures are here related to situations where the navigator loses control of speed and course. Two scenarios dealing with technical failures are included: loss of propulsion (leading to a drifting ship) and steering machine failure (leading to a ship sailing in circles).

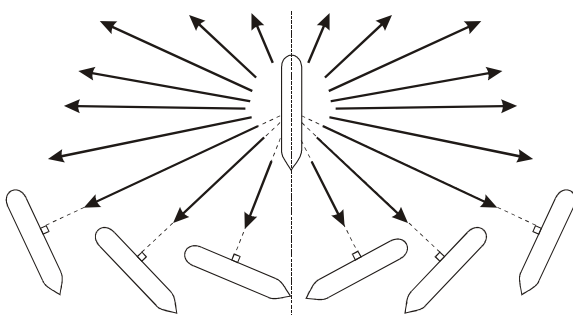


Figure 5. Illustration of a drifting ship after loss of propulsion.

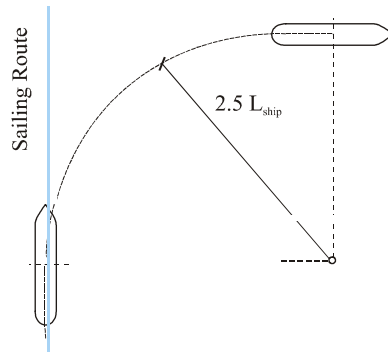


Figure 6. Illustration of a ship track after steering machine failure.

Reliable statistical data have not been reported for loss of propulsion a ship. However, according to general ship navigator and engineering judgement, the propulsion machinery on a ship is assumed to fail approximately once during a year in service. Furthermore, assuming 270 effective sailing days per year to be relevant for a typical commercial ship, the frequency of loss of propulsion machinery becomes:

$$f_{drift} = 1.5 \cdot 10^{-4} \text{ failures per hour per ship}$$

The frequency of loss of propulsion is adopted for all types of ships, although differences in reserve power and backup systems are present. Furthermore, the frequency is assumed constant throughout the passage of the investigated area.

The frequency of failure of the steering system  $f_{steering}$  has in a U.S. investigation [10], been estimated to 0.41 failures per year pr ship. With 270 effective sailing days per year assumed representative for a typical commercial ship, the frequency per hour of failure of the steering system becomes

$$f_{steering} = 6.3 \cdot 10^{-5} \text{ failures per hour per ship}$$

This frequency or rate of steering failure is adopted for all types of ships and is assumed constant throughout the passage of the investigated area.

The frequency of loss of propulsion and the frequency of steering failure is also studied in the Fehmarnbelt link project (see section 4). These studies support the order of magnitude of the applied failure frequencies.

A drifting velocity of 1 knot is applied in the model. The drifting velocity is the velocity of a ship without propulsion under influence from wind and current. The distribution of the drifting direction of drifting ships is estimated from information about wind and current in the investigated area.

When a failure of propulsion machinery occurs and the error is detected, then the person responsible for maintenance will initiate repair and in most cases be

able to regain propulsion within a certain timeframe. The model, for estimating the repair time, applied in this study is a generally applied model, when modelling drifting ships.

The probability of having repaired the failure on the propulsion machinery,  $P_{repair}(t)$ , is given by a truncated cumulative distribution function of the Weibull type ( $k = 0.5$  (shape) and  $\lambda = 0.605$  (scale)). The repair time has a mean value of 1 hour and is cut-off after 10 hours, indicating that it is assumed that all ships regain propulsion within 10 hours. The probability that a ship is still drifting at time  $t$  after loss of propulsion  $P_{drift}(t)$ , is then given by:

$$P_{drift}(t) = 1 - P_{repair}(t) \quad (3)$$

Figure 7 shows  $P_{drift}(t)$  as a function of time.

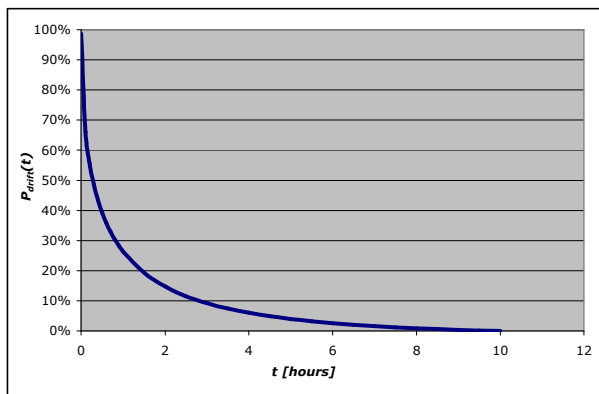


Figure 7. Curve illustrating the probability of a drifting ship as a function of the time after loss of propulsion.

The repair time after loss of propulsion is also studied in the Fehmarnbelt link project (see section 4). These studies support the curve presented in Figure 7 and even suggest shorter repair times.

A probability of 70% for successful anchoring before grounding or collision is applied if a drifting ship has a drifting direction towards shore or another obstacle e.g. a bridge pier. This probability of successful anchoring seems reasonable in the Fehmarnbelt link project since the seabed slope in Fehmarnbelt is gentle and the seabed material is well fit for anchoring. In other areas where anchoring is difficult a lower probability of successful anchoring may be more realistic.

### Ship-ship collision - crossing

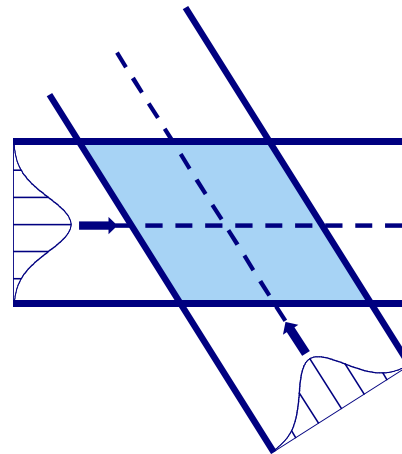


Figure 8. Illustration of crossing lanes.

This ship accident scenario is applied for ships approaching each other on two crossing lanes. The model is used for all locations where two routes or lanes cross. The model follows the model suggested in [22].

Hence, the number of collisions is determined as

$$N_{coll} = N_{CC} \cdot (1 - P_{evasive}) \quad (4)$$

where

$N_{CC}$  is the number of collision candidates

$1 - P_{evasive}$  is the probability of not making an evasive manoeuvre due to human or technical failures.  $1 - P_{evasive}$  is set to  $1.2 \cdot 10^{-4}$ , [22]

In [22] the number of collision candidates is determined as:

$$N_{CC} = \sum_i \sum_j \frac{N_i N_j}{V_i V_j} V_{ij} D_{ij} \quad (5)$$

where

$i, j$  indices for ship size classes for the two traffic flows

$N_i, N_j$  number of movements

$V_i, V_j$  speed

$V_{ij}$  relative speed between two ships (described in details in [22])

$D_{ij}$  geometrical collision diameter (described in details in [22])

Ship-ship collision – encounter

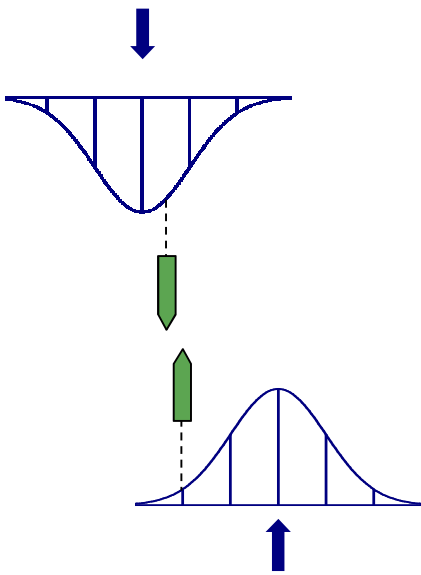


Figure 9. Illustration of encountering lanes.

This accident scenario is applied for ships on the same route encountering each other with opposite sailing directions.

The distribution of the ship traffic transverse to the sailing directions for the two sailing directions is used to estimate the geometrical probability of having two ships with opposite sailing directions on collision course.

If two ships are on collision course then it is assumed that the situation may result in a collision between the two ships.

The conditional probability of collision  $P_{coll}$  given that two ships with opposite sailing directions are on collision course is given in [22] as  $P_{coll} = 4.9 \cdot 10^{-5}$ .

The number of collisions ( $N_{coll}$ ) from encountering ships is then determined as:

$$N_{coll} = N_{CC} \cdot (1 - P_{evasive}) \quad (6)$$

where

$$N_{CC} = N_{encounter} \cdot P_{coll\ course}$$

$N_{encounter}$  is the number of encounters per year on a considered route section, with a length  $L_w$ , determined as:

$$\sum_i \sum_j L_w \cdot \left( \frac{1}{V_i} + \frac{1}{V_j} \right) \cdot N_i \cdot N_j$$

$i, j$  indices for ship size classes for the two traffic flows

$N_i, N_j$  number of movements

$V_i, V_j$  speed

$P_{coll\ course}$  is the geometrical probability of two ships, with opposite sailing directions, being on collision course.

$1 - P_{evasive}$  is the conditional probability of collision given that two ships with opposite sailing directions are on collision course ( $P_{coll}$ )

Ship-ship collision - overtaking

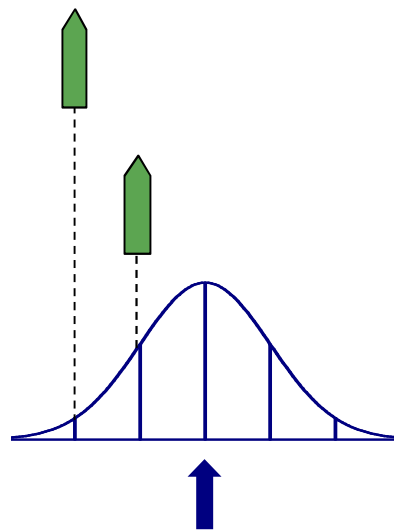


Figure 10. Illustration of overtaking.

This ship accident scenario is applied when one ship overtakes another ship on the same lane.

The number of collisions during overtaking is then estimated as:

$$N_{collision} = N_{CC} \cdot P_{human} \cdot (1 - P_{collision\ avoided}) \quad (7)$$

where

$$N_{CC} = \sum_i \sum_j N_{overtaking, i, j} \cdot P_{close\ overtaking}$$

$i, j$	indices for combination of ship size classes
$P_{close\ overtaking}$	probability of an overtaking where the ships are close. This probability is set to 5%, based on the safety ellipse theory [27] and analysis of AIS data in Fehmarnbelt.
$P_{human}$	probability of human failure on one of the two ships involved, $2 \cdot 10^{-4}$
$P_{collision\ avoided}$	probability that the navigator on the other ship avoids the collision, 0.5

The estimated number of overtakings ( $N_{overtaking}$ ) on a lane depends on mean values and standard deviations for the speed of the ships.

The situation with ships with same average and standard deviation of speeds occurs when two ships on the same lane in the same ship size class overtake each other. The number of overtakings is then estimated as formulated in [13]:

$$N_{overtaking,i,i} = N_i^2 \cdot \frac{D[V_i]}{E[V_i] \cdot \sqrt{\pi}} \cdot \frac{L_w}{E[V_i]} \quad (8)$$

where

$N_i$	number of movements
$E[V_i]$	average speed
$D[V_i]$	standard deviation of speed
$L_w$	length of considered route section

The situation with ships with different average speeds occurs when two ships on the same lane from different ship size classes overtake each other. The number of overtakings is then estimated as:

$$N_{overtaking,i,j} = L_w \cdot \left( \frac{1}{V_i} - \frac{1}{V_j} \right) \cdot N_i \cdot N_j, i \neq j \quad (9)$$

where

$N_i, N_j$	number of movements
$V_i, V_j$	speed ( $V_i > V_j$ )
$L_w$	length of considered route section

For overtakings between ships in different ship size classes the standard deviation in ship speed is not used as a parameter in the model.

### Ship-ship collision - bend collision – opposite direction

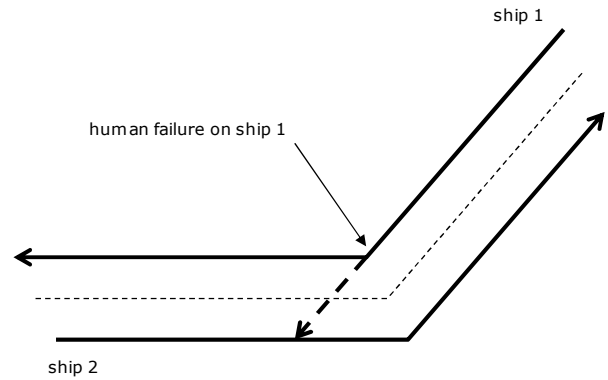


Figure 11. Illustration of bend collision – opposite direction

This ship accident scenario is applied in bends of sailing routes with two lanes with opposite sailing directions.

In Figure 11 the planned tracks of ship 1 and ship 2 are marked with solid lines. The timing is so that ship 1 forgets to turn at the bend ship 1 and ship 2 will collide in case evasive actions on ship 2 fail to avoid the collision.

The following model is applied:

$$N_{collision} = N_{CC} \cdot P_{human\ failure\ on\ ship\ 1} \cdot (1 - P_{ship\ 2\ avoids\ collision}) \quad (10)$$

where:

$N_{CC}$  Number of collision candidates if ship 1 forgets to turn at the bend, estimated as for the crossing routes scenario, see equation (5)

$$P_{human\ failure\ on\ ship\ 1} = 2 \cdot 10^{-4}$$

$$P_{ship\ 2\ avoids\ collision} = 0.5$$

$P_{ship\ 2\ avoids\ collision}$  is set to be low since ship 2 will expect ship 1 to turn and only have very short time to identify the collision course and initiate evasive actions.



Ship-ship collision - bend collision – same direction

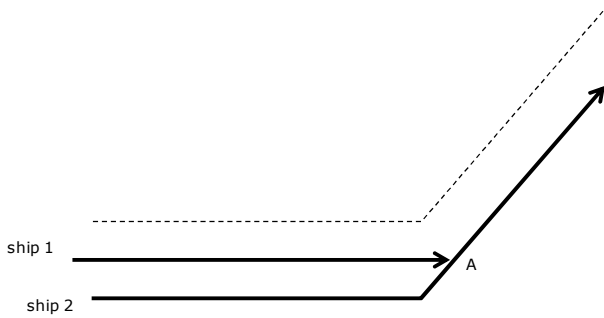


Figure 12. Illustration of bend collision – same direction

This ship accident scenario is applied in bends of sailing routes.

In Figure 12 the planned tracks of ship 1 and ship 2 are marked with solid lines. If ship 2 begins to turn at the bend and ship 1 does not start evasive actions then the timing is so that the two ships will collide at point A.

The following model is applied:

$$F_{collision} = N_{CC} \cdot P_{ship 1 \text{ behind ship 2}} \cdot P_{ship 2 \text{ turns before ship 1}} \cdot P_{human \text{ failure on ship 1}} \quad (11)$$

where:

$N_{CC}$  Number of collision candidates if ship 1 is behind ship 2 and ship 2 turns before ship 1, estimated as for the crossing routes scenario, see equation (5) where  $i \geq j$ . The condition  $i \geq j$  is made since all ships belong to the same traffic lane and not two different lanes. The condition is made to ensure that crossings are not included twice.

$$P_{ship 1 \text{ behind ship 2}} = 0.5$$

$$P_{ship 2 \text{ turns before ship 1}} = 0.8$$

$$P_{human \text{ failure on ship 1}} = 2 \cdot 10^{-4}$$

### 3.3. Factors influencing the accident scenarios

Many local factors in any investigated area will influence the accident scenarios. When performing analysis of navigational safety it is important to take the influence from local factors into account when estimating the risk using ShipRisk or when interpreting the results from ShipRisk.

In the following the influence from three effects which influence the results in the Fehmarnbelt link project are mentioned in brief:

1. Effect from pilot
2. Effect from Vessel Traffic Service (VTS)
3. Increased causation factor

It is judged that having a pilot onboard a ship will reduce the probability of human failure. In general, it is assumed that the failure probability for ships sailing with pilot is reduced to 33% of the general failure probability; i.e. 67% of all failures are avoided.

The reduction factor for VTS depends on the type of VTS and the information level provided: VTS with information service is given a reduction factor of 0.2; i.e. 20% of all accidents are avoided. This effect comes from increased information level and increased navigator awareness. VTS with information service and navigational assistance is given a reduction factor of 0.6; i.e. 60% of all accidents are avoided. This effect comes from increased information level, increased navigator awareness and acute accident avoidance.

Certain parts of Fehmarnbelt are more difficult to navigate than open sea, particularly when the possibility of successful evasive action is compromised by restricted waters. To include this in the model the causation factor for ship-ship collisions are increased in certain critical locations. Typically the causation factor in ShipRisk can be increased by a factor of 2, 5 or 10 depending on the navigational complexity of the considered area.

### 4. Testing and verifying the model

During the Fehmarnbelt link project much effort has been put into testing and verifying parameters in the ship accident scenarios and the results from the ShipRisk software package.

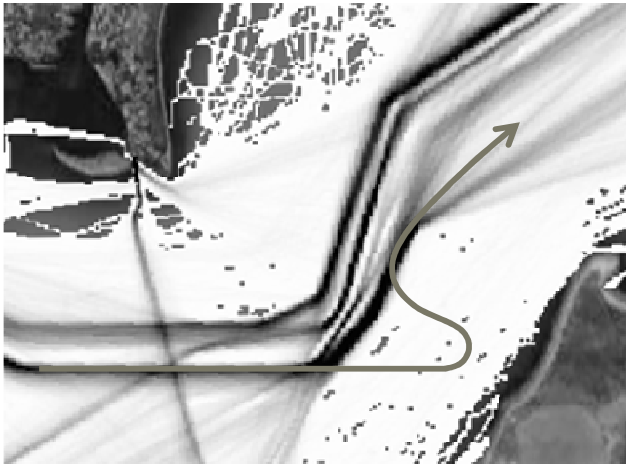
Here the most interesting investigations, in relation to the ShipRisk software package, are mentioned in brief:

1. Human failure probability
2. Frequency of propulsion failure
3. Frequency of steering machine failure
4. Repair time after loss of propulsion
5. Benchmark of ShipRisk frequency results against observed ship accidents

#### Human failure probability

The probability of human failure (as introduced in section 3.2) has been studied by looking at ship tracks in Kadetrenden (Figure 2 shows the entire Fehmarnbelt. Kadetrenden is located in eastern part). In Kadetrenden a Traffic Separation Scheme (TSS) is guiding the ships through the bends in Kadetrenden.

If a ship continues past a bend with unchanged course and speed (as illustrated in *Figure 13*) then it is probably due to a human failure onboard the ship.

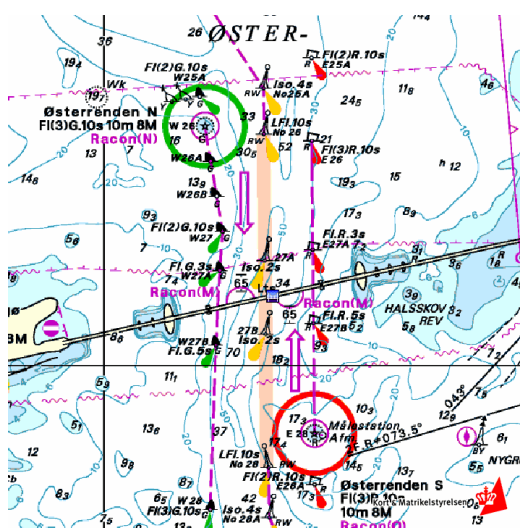


*Figure 13.* Illustration of a ship continuing past a bend with unchanged course and speed.

By analyzing traffic situations in Kadetrenden from 2007 to 2010 it is found that it does not seem unreasonable to assume a human failure rate of  $2.0 \cdot 10^{-4}$  and a duration of 20 minutes. Actually, the analyses indicate that the human failure rate could be increased to  $2.5 \cdot 10^{-4}$ , and that the average duration may be decreased; at least if a VTS system is in operation as it is in the German territorial waters between Kadetrenden and the German coastline.

Frequency of loss of propulsion and steering machine failure

When international ship traffic passes the Great Belt bridge (see *Figure 14*) a TSS guides the ships through. Furthermore, VTS Great Belt monitors the ships.



*Figure 14.* Traffic Separation Scheme (TSS) in Great Belt.

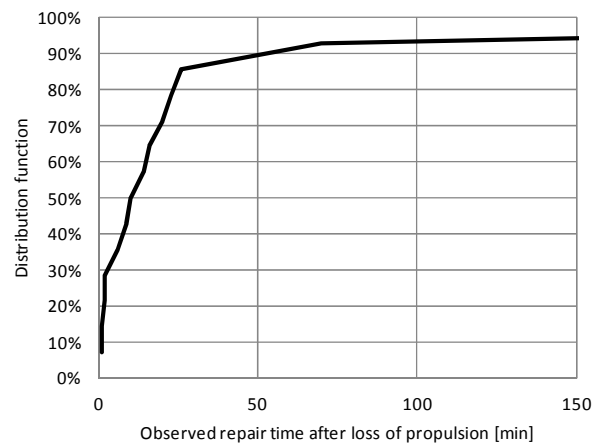
From analyzing incident reports prepared by operators of the VTS Great Belt it has been possible to test the values used for frequency of loss of propulsion and steering machine failure.

12 cases of loss of propulsion inside the TSS are reported in incident reports from 4 years. With 21,000 ships per year this gives an estimated frequency of loss of propulsion of around  $0.6 \cdot 10^{-4}$  per hour per ship, which corresponds well to the frequency assumed in the ShipRisk software package (see section 3.2).

During the same 4 years 2 cases of steering machine failure inside the TSS is reported, this gives an estimated frequency of steering machine failure of around  $1 \cdot 10^{-5}$  per hour per ship, which is below, but in the same order of magnitude as the frequency assumed in the ShipRisk software package (see section 3.2).

Repair time after loss of propulsion

A curve of the recovery times can be plotted based on the 12 cases with loss of propulsion for which it is possible to get an estimate for the recovery time of the technical systems; see *Figure 15*.



*Figure 15.* Observed repair time after loss of propulsion.

From the curve it is estimated that around 70% have recovered within 20 min and around 90% of the ships have recovered within an hour.

When comparing to the curve used in ShipRisk for probability of a drifting ship as a function of the time after loss of propulsion (shown in *Figure 7*) it is seen that the incidents in Great Belt support the curve used in ShipRisk and even suggests shorter repair times.

Benchmark of ShipRisk frequency results against observed ship accidents

During the Femern Link project the frequency and risk from ship accidents in the Fehmarnbelt was

estimated using the ShipRisk software package both in a reference situation without a bridge and for different scenarios with a bridge crossing Fehmarnbelt.

In order to benchmark these results the ShipRisk software package was also used to generate results for the Great Belt bridge area and the Øresund bridge area. Danish waters are heavily trafficked with international ship traffic entering or leaving the Baltic Sea. So benchmarking results from Fehmarnbelt to results from the Great Belt bridge area and the Øresund bridge area makes good sense.

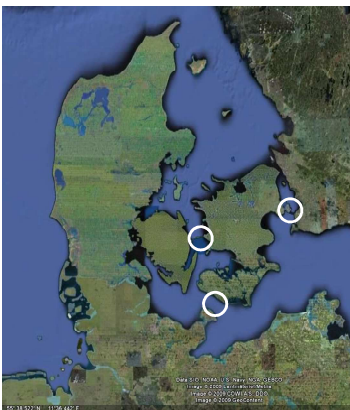


Figure 16. Location of Fehmarnbelt (lower ring), Great Belt bridge (upper left ring) and Øresund bridge (upper right ring).

Results from ShipRisk for the present situation in Fehmarnbelt, Great Belt and Øresund were compared to observed counts of ship-ship collisions, ship groundings and ship collisions with fixed objects (5.5 years of data from Fehmarnbelt and 9 years of data from Great Belt and Øresund) as part of this benchmark study.

The comparison showed that generally the frequency of grounding and collisions estimated in ShipRisk compares well to the frequency of observed accidents. Results from ShipRisk estimated 56 accidents (49 obstacle collisions or groundings and 7 ship-ship collisions). The observation counts showed 41 accidents (30 obstacle collisions or groundings and 11 ship-ship collisions).

## 5. Conclusion

All efforts in the Femernbelt link project used on testing and verifying parameters in the ship accident scenarios and the results from the ShipRisk software package indicates that the values of the parameters in the models for ship accidents are sensible and that the frequency results from ShipRisk compares well to the frequency of observed accidents.

This indicates that the models for ship accident scenarios used in the ShipRisk software package are sound and can be used in quantitative risk assessments of navigational safety given that the local conditions in an investigated area are taken into account.

## References

- [1] Dand, I.W. & Colwill, R.D. (2003). Simulation of Traffic Flows using Dynamic Ship Modelling. *Proceedings, International Conference on Marine Simulation and Ship Manoeuvrability*. Kanazawa, Japan.
- [2] Debnath, A.K. (2009). *Traffic-conflict-based modeling of collision risk in port waters*. Singapore: National University of Singapore.
- [3] Fowler, T.G. & Sjørgård E. (2000). Modeling Ship Transportation Risk. *Risk Analysis*, 20(2).
- [4] Froese, J. & Mathes, S. *Computer-assisted collision avoidance using ARPA and ECDIS*, Deutsche Hydrographische Zeitschrift, Vol. 49, Issue 4, 519-529.
- [5] Hänninen, M. (2008). *Analysis of human and organizational factors in marine traffic risk modeling - literature review*. SAFGOF. Helsinki University of Technology.
- [6] Hänninen, M. & Kujala, P. (2011). *The Effects of Causation Probability on the Ship Collision Statistics in the Gulf of Finland*.
- [7] IALA. (2009). *The IALA Risk Management Tool for Ports and Restricted Waterways - Edition 2*. Saint Germain en Laye.
- [8] Karlsson, M. & Rasmussen, F.M. & Frisk, L. (1998). Verification of Ship Collision Frequency Model. *Proceeding of the International Symposium on Advances in Ship Collision Analyses*.
- [9] Kite-Powell, H.L., Jin, D., Jebsen, J., Papakonstantinou, V. & Patrikalakis, N. (1999). Investigation of Potential Risk Factors for Groundings of Commercial Vessels in U.S. Ports. *International Journal of Offshore and Polar Engineering*, 16-21.
- [10] Kristiansen, S. (1990). *Risikoanalyse for Marine Systemer*, NTH.
- [11] Liu, Y., Yang, C. & Du, X. (2007). *A Multiagent-Based Simulation System for Ship Collision Avoidance*. In D.-S. Huang, L. Heutte, & M. Loog. *Advanced Intelligent Computing Theories and Applications. With Aspects of Theoretical and Methodological Issues* (Vol. 4681, pp. 316-326). Berlin : Springer Berlin / Heidelberg.
- [12] MacDuff, T. (1974). The Probability of Vessel Collisions. *Ocean Industry* 144 – 148.

- [13] Mark, R., Virkler & Rajesh Balasubramanian. (1636). *Flow Characteristics on Shared Hiking/Biking/ Jogging Trails*. Transportation research record 1636.
- [14] Mazaheri, A. (2009). *Probabilistic modeling of ship grounding - a review of the literature*. Helsinki University of Technology.
- [15] Merrick, J.R., & van Dorp, J.R. (2006). Speaking the Truth in Maritime Risk Assessment. *Risk Analysis*.
- [16] Nyman, T. (2009). *Review of collision and grounding risk analysis methods which can utilize the historical AIS data and traffic patterns in seaways*. Maritime and logistics co-ordination platform SKEMA Coordination Action.
- [17] Otto, S., Pedersen, Preben, T., Samuelidis, M. & Sames, P. (2001). Elements of risk analysis for collision and grounding of a RoRo passenger ferry. *Proceedings of 2nd International Conference on Collision and Grounding of Ships*.
- [18] Roeleven, D., Kokc, M., Stipdonkd, H., & De Vriese, W. (1995). Inland waterway transport. Modelling the probability of accidents. *Safety of Transportation*.
- [19] Rothblum, D.A. (2000). *Safety, Human Error and Marine Safety*. National Safety Council Congress and Expo. Orlando: U.S. Coast Guard Research & Development Center.
- [20] Royal Haskoning. (2006). *Port of Melbourne Marine Risk Assessment*. Peterborough.
- [21] Simonsen, B.C. (1997). *Mechanics of ship grounding*. Technical University of Denmark.
- [22] Terndrup Pedersen, P. (1995). *Probability of Grounding and Collision Events*. Risk and Response, 22nd WEGEMT Graduate School
- [23] The Royal Danish Administration of Navigation and Hydrography, The Danish Maritime Authority and The Swedish Maritime Administration (2006). *Navigational safety in the Sound between Denmark and Sweden (Øresund). Risk and cost-benefit analysis*. August 2006.
- [24] Thevik, H.J., Sjørgård, E. & Fowler, T. (2001). A method for assessing the risk of sea transportation: Numerical examples for the Oslofjord. *Proceedings of the European Conference on safety and Reliability Conference Esrel*.
- [25] (TØI), I. o. (2009). *Effects of proposed ship routeing off the Norwegian coast*.
- [26] Ulusçu, Ö.S., Özbaş, B., Altıok, T., & Or, İ. (2009). Risk analysis of the transit vessel traffic in the strait of istanbul. *Risk Analysis*, 29 , 1454-1472.
- [27] Yahei, Fujii (1983). *Integrated Study on Marine Traffic Accidents*. IABSE Colloquium Copenhagen 1983.
- [28] Fujii, Y., Yamanouchi, H. & Mizuki, N. (1974). Some factors affecting the frequency of accidents in marine traffic. II – The probability of stranding and III – The effect of darkness on the probability of collision and stranding. *J. of navigation*, Vol. 27, 235-247.
- [29] Øresundsbro Konsortiet (1999). The Øresund Link. Operational Risk Analysis. *ORA-98*. March 1999.