ANALYSIS AND MODELING OF MARITIME TRAFFIC AND SHIP COLLISION IN THE STRAIT OF ISTANBUL BASED ON AUTOMATIC VESSEL TRACKING SYSTEM

by

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ABSTRACT

ANALYSIS AND MODELING OF MARITIME TRAFFIC AND SHIP COLLISION IN THE STRAIT OF ISTANBUL BASED ON AUTOMATIC VESSEL TRACKING SYSTEM

This thesis describes a maritime geometric collision probability model which can be used in congested narrow waterways. Geometric collision probability model is extended and applied to a spatially distributed maritime traffic, rather than the route based models. It finds out the hotspots for the collision places on a spatial representation. Model is applied to the Strait of Istanbul with automatic vessel tracking data. Results of the model are in line with the past events and theoretical studies. The aim of the study is to quantify the geometric collision probability and represent the results on probability map. A long-term maritime traffic data is collected from February 2014 to August 2016. The data is parsed and stored in a SQL database system. Size of the database is 94 gigabyte. Grid based analysis method is used for the big data management. Geometric collision method is applied with the output of this database. There are two main part of this study. One of them is the detailed analysis and modeling of maritime traffic. The other one is the geometric collision model application. Maritime traffic analysis is based on automatic vessel tracking data. Ship characteristics, navigation patterns and traffic densities along the Strait are given in the analysis. Analysis shows the captains route preferences along the Strait and speed according to their travel directions. North entry ships have a tendency to travel faster than the other directions. Also one more important finding is the net transfer of goods direction in the Strait is from north to south. Geometric collision model gives the probability map of the Strait in spatially distributed way. According to the model the highest collision probable sector is between Sariyer and Umurbey (Sector 10) and the highest probability is found between Kandilli and Rumelihisari.

ÖZET

İSTANBUL BOĞAZİ'NDA OTOMATİK GEMİ TAKİP SİSTEMİ TEMELLİ DENİZ TRAFİĞİ VE GEMİ ÇATİŞMASİ ANALİZİ VE MODELLENMESİ

Bu tez, dar suyollarında kullanılabilecek olan denizcilik geometrik çatışma olasılığı modelini anlatmaktadır. Geometrik çatışma olasılığı modeli, rota temelli modeller yerine, genişletilmiş ve alansal dağılımlı deniz trafiği kullanılarak uygulanmıştır. Model, çatışma bakımından en yüksek olasılıklı noktaları alansal sunum olarak bulmaktadır. Çalışma, otomatik gemi takip verisi kullanılarak Istanbul Boğazı'na uygulanmıştır. Sonuçlar, geçmiş kazalar ve teorik çalışmalar ile uyumluluk göstermektedir. Çalışmanın amacı, geometrik çatışma olasılığının niceliğini belirtmek ve sonuçları olasılık haritası üzerinde sunmaktır. Uzun süreli deniz trafiği verisi incelenmiş ve SQL kullanılarak, analizlere uygun hale getirilmiştir. Büyük verileri yönetebilmek için örgü temelli analiz metodu kullanılmıştır. Geometrik çatışma olasılığı metodu, analiz çıktıları kullanılarak uygulanmıştır. Çalışmanın iki ana bölümü vardır. Birincisi, detaylı deniz trafiği analizi ve modelleme çalışması, ikincisi ise geometrik çatışma modelinin uygulanmasıdır. Deniz trafiği analizi, otomatik gemi takip sistemi verisi üzerinden yapılmıştır. Analizler sonucunda Boğaz'daki gemi karakteristikleri, navigasyon şekilleri ve trafik yoğunlukları verilmiştir. Analizler kaptanların Boğaz boyunca ilerleme yönlerine göre tercih ettikleri rotaları ve hızlarını göstermektedir. Kuzey girişli gemiler, diğer yönlere oranla daha hızlı gitme eğilimindedirler. Bir başka önemli bulgu da, net yük transferinin kuzeyden güneye doğru olmasıdır. Geometrik çatışma modeli, Boğaz'ın olasılık haritasını alansal dağılım olarak vermektedir. Bu haritaya göre model, en yüksek çatışma olasılığını olan bölgeyi Sarıyer ve Umurbey (Sektör 10) ve en yüksek kaza olasılığı olan noktayı Kandilli ve Rumelihisarı (Sektör 5 içerisinde) arasında vermektedir.

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LIST OF SYMBOLS

B	Width of the Ships
D	Geometric Collision Diameter
D_{ij}	Collision Diameter of I_{th} and J_{th} Ships
$Dist$	Average Distance Between Ships
F	Mean Free Path
$f_{(z)}$	Distribution of Traffic of the Ship Class Across the Waterways
L	Length of the Ships
N_{col}	Number of Collisions
P	Probability of Ship Being Inside the Considered Area
$P(A)$	Probability of Losing Vessel Control Per Passage
$P(G\|A)$	Geometric Probability of an Collision Given Loss of Vessel Control
$P(C)$	Probability of an Collision Per One Ship
$P(G)$	Geometric Probability of an Collision
P_p	Expected Number of Collision for a Given Waterway if no Evasive Maneuver Has Been Made
Pr	Probability
S	Area of the Waterway under Consideration
Q	Number of Movements of Ship
T	Considered Time Period
V	Velocity Vector
V_i	Velocity of Ship i
V_j	Velocity of Ship j
V_{ij}	Relative Velocity of Ships i and j
W	Width of the Considered Waterway
X	Actual Length of the Path to Be Considered for Single Ship in Nautical Miles.
z	Distance From the Centerline of the Waterway
θ	Approaching Angle of Ships

ρ	Traffic Density
λ_{ss}	Failure/hour

LIST OF ABBREVIATIONS/ABBREVIATIONS

AIS	Automatic Identification System
COG	Course Over Ground
ETA	Estimated Time of Arrival
FSA	Formal Safety Assessment
HDG	Heading
LOA	Length Overall
MMSI	Maritime Mobile Service Identity
MO	International Maritime Organization
MRC	Marmara Research Center
NMEA	National Marine Electronics Association
OI	Strait of IstanbuL
SOG	Speed Over Ground
SQL	Sequential Query Listing
RAMOS	Risk Assessment of Oil Spill Accidents
TSMTR	Turkish Straits Maritime Traffic Regulation

1. INTRODUCTION

For centuries, maritime transportation has been the most economical way to transfer goods for long distances. Until a major change happens in the global transportation system, maritime transportation will be a big part of it. Special care should be given for the safety of the waterways.

Maritime accidents happen throughout the world and affect people directly or indirectly in terms of health, environment and economy. Especially in the congested narrow waterways, with the increase of the traffic density number of maritime accidents increases. The first step to decrease the number of accidents should be quantifying the accident probability, by giving quantitative accident probability information of the area, number of accidents can be decreased.

This study quantifies the maritime accident probability in the Strait of Istanbul (SOI) and generate accident probability map of the area. Main parts of the study are the accident probability model and maritime characteristics of the SOI. The model consists of four stages:

- Theory
- Experimental
- Modeling
- Accident Probability Map

Studies collision probability modeling started with mathematical models (Nichols, 1950; Wylie, 1956; Sadler, 1957). But these pure mathematical models were not reflecting the real conditions at sea (Wylie, 1962). Site specific works started in 1971. Until late 90's most of the studies in the literature were site specific Table 1.1.

Table 1.1. Existing Site-specific Maritime Traffic Models

Geographic area	Reference
Puget Sound, USA	Wentzel and Lytle (1971)
Dover Strait, UK	Draper and Bennett (1972)
Straits in Japan	Fujii and Yamanouchi (1974)
Rosario Strait, Canada	Braem (1974)
Gulf of Suez, Egypt	Rashad (1977)
Coastal waters, USA	Maio *et al.* (1991)
Northern Gulf of Mexico, USA	Li *et al.* (1996)
Lower Mississippi River, USA	Gramling *et al.* (1998)
Prince Williams Sound, USA	Harrald *et al.* (1998)
Coastal waters, UK	Safetec (1999)
Strait of Istanbul, Turkey	Tan and Otay (1999)
North Sea - English Channel	Fowler and Sorgard (2000)
Washington State Ferries, USA	van Dorp *et al.* (2001)
Cadiz, Canary Islands, Gibraltar Strait, Spain	Otto *et al.* (2002)
Greek seas and Gulf of Saronikos, Greece	Oses and Ventikos (2003)
San Francisco Bay, USA	Merrick *et al.* (2003)
Hong Kong waters, China	BMT (2004)
German inland waterways, Germany	Proske and Curbach (2005)
Oresund, Denmark/Sweden	Ramboll (2006)
Shanghai Harbour, China	Hu *et al.* (2007)
Bornholm area, Denmark/Sweden	Cowi (2008)
Gulf of Finland	Kujala et al. (2009)
Three Gorges Reservoir, China	Geng *et al.* (2009)
Coastal waters, Turkey	MRC (2010)
Kattegat, Sweden/Denmark	Johansson and Molitor (2011)
Singapore Strait, Singapore	Qu and Meng (2011)

Pioneering works that combined the motion of ships into mathematical models were Fujii and Shiobora (1971) and MacDuff (1974). In the studies molecular collision theory is modified and collision diameter is introduced where ship motions are assumed as random motion of molecules. Fujii calculated the diameter for ships to collide each other and used the maritime traffic density for finding the accident probability for a given area. MacDuff (1974) used molecular collision theory in order to find the meeting rate of the ships when they are blindly navigated. He also added the captain effect by a factor called probability of causation.

Latest physic-based studies are done by Pedersen (1995), Ylitalo (2010), Mazeheri (2009), Montewka (2010). Pedersen (1995), progressed the works of Fujii. In the study both collision diameter approach and probability of causation factor are used. Montewka (2010) improved the collision diameter, and called it minimum distance to collision (MDTC). The main idea of MDTC is to find a distance where the collision is unavoidable by any maneuver. However, Montewka's work is limited to selected points; it does not cover an area. Ylitalo (2010) used AIS data to create accident probability map of an area. By means of AIS data ship tracks are recorded and passage histogram of the area was found. Mazaheri (2009) used the same approach in order to find the grounding probability of the ships.

Site specific approaches for the Strait of Istanbul (SOI) can be classified as probabilistic type and physic based type. Probabilistic type approach depends on the past accident data and expert judgment. Uluscu (2009), used the historical accident data and expert opinions for probabilistic arguments. A scenario analysis is done for studying the behavior of accident risks. According to analysis, impact of factors on the risk profile is studied.

Physic based approach solves the ship movement equations in order to find the heading of the ship. This approach is subdivided into two as simulation and physic based stochastic solutions. Sarioz (1999) make a real time simulation of the SOI maritime traffic and tried to find the performance of Traffic Separation Scheme (TSS) under real conditions. Aydogdu (2012), study the management of local traffic in the Istanbul Strait by using fast simulation models.

Tan and Otay (1999), used random walk theory in order to find the next step of the moving ship. The schematic representation of the model is given as in Figure 1.1. In order to find the probabilities of the next step of the random walk a drift model is used which uses current and vessel characteristics as an input.

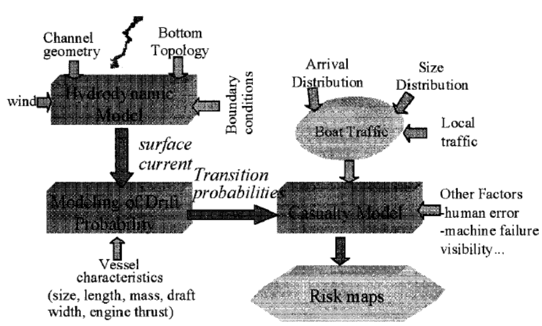

Figure 1.1. General Model Representation (Tan and Otay, 1999).

Otay and Ozkan (2003), study solves the hydrodynamic equations of ship motion. In order to find the heading of the vessel an autopilot is used with some human error functions. Strait is divided by lines. Movement of the ship is simulated by means of hydrodynamic equations and autopilot usage. In order to regulate the ship traffic, they used check lines. In addition to traffic model, they also modeled collision and grounding as a result of ship motion and surface currents.

Yazici and Otay (2009), study is a navigation safety support algorithm for the Strait of Istanbul. In the model a faster ship dynamic equation solver is used in order to predict the next movement of ship under given environmental conditions (e.g. current and manoeuvers). In each time step the algorithm predict next the movements of the base ship and target ship. According to the movement possibilities, algorithm tries to find the safest route.

There are risk based studies which cover both accident probability and the impact of accident to the environment. Merrick and van Drop (2001), model the risk of maritime transportation in dynamic environment. They also used the simulation technique, for modeling the maritime environment. In their study, not only the accident probability is studied but also damage and response models are created. MRC (2010), analyze for the entire Turkish Territorial Waters. The accident probabilities using by Bayesian tree model. Impacts are found based on expert judgment. For the assessment part IMO FSA guidelines are used.

In RAMOS study (Papadonikolaki *et al.*, 2014), a smaller part of the sea is taken into consideration. Scenario analysis has been made according to long term wind conditions and as an outcome 49 scenarios are created. For each wind condition current of the small sections are found and according to current and other factors accident frequency of the area is found according to Table 1.4.

Then an oil spill model is run for 4 most probable accident locations and oil at the coast has been found. The missing part of the project is the accident frequency model and insufficient coverage of oil spill scenarios.

Most of the physic based models based their works on molecular collision theory for contact model. A collision diameter is calculated for encountering ships. The collision diameter depends on the physical dimensions, meeting angles and velocity of the ships. If the centers of the corresponding two ships are inside the diameter, there is a contact between the ships.

There are three approaches for the ship motion model. One of them is, a statistical assumption has been made for the ship motions. Velocity, heading and position distributions are assumed. The second one is, solving ship motions and finding the positions, velocity and heading. This technique needs a pilot error function assumption. Otherwise all ships will travel on straight lines. The third type uses the real ship motion data. This can be supplied by the AIS data which includes position, heading and velocity of ships.

In this study, a modified version of the molecular collision diameter approach will be used. To model the maritime accidents, the ship motions will be extracted from AIS data.

Table 1.2. Factors Affecting the Accident Frequency (MRC, 2010.

Minumum Sea water depth	m	>200	200-100	100-50	50-40	40-30	30-20	20-10	10-5
	Coefficent	1	1	1	1.25	1.5	2	5	10
Wind speed	bofour	0-1	2-3	3-4	4-5	5-6	6-7	7-8	>7
	Coefficent	1	2	3	4	5	6	7	8
Maximum current speed	m/s	0-0.1	0.1-0.35	0.35-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	>2.5
	Coefficent	1	2	3	4	5	6	7	8
Ratio of shallow (less than 5m depth)	[-]	0	0.0<x=0.15	0.15<x=0.30	0.30<x=0.45	0.45<x=0.60	0.60<x=0.75	0.75<x=0.90	0.90<x=1.00
	Coefficent	1	2	3	4	5	6	7	8
Distance from land	km	0 - 5	10-May	15-Oct	15 - 20	20 - 25	25 - 30	30 - 35	>35
	Coefficent	5	4	3	2	1.75	1.5	1.25	1
Maneuver Restriction Index	[-]	1	2	3	4	5	6	7	8
	Coefficent	1	2	3	4	5	6	7	8
Total number of ship	[-]	0	2-Jan	5-Mar	10-May	20-Oct	20-30	30-40	>40
	Coefficent	1	2	3	4	5	6	7	8

Table 1.3. Demonstration of Accident Frequency Index (MRC, 2010).

Accident frequency	Number of accident per year in each cell	Frequency Index	Color Codes
Negligible	$= 10^{-4}$	1	Blue
Very rare	10^{-4} <frequency= 10^{-3}	2	Green
Rare	10^{-3} <frequency= 10^{-2}	3	Yellow
Probable	10^{-2} <frequency= 10^{-1}	4	Orange
Frequent	10^{-1} <frequency= 1	5	Red
Very frequent	>1	6	Brown

Table 1.4. Factors Affecting Accident Frequency Associated with Hydrographic and Navigational Characteristics of Marine Cells.

		Relative Index							
Cell Characteristic		1	2	3	4	5	6	7	8
Current	Pr(Vmax	0	0.06	0.19	0.31	0.44	0.50	0.69	0.81
magnitude	> Vcr)	- 0.06	- 0.19	- 0.31	- 0.44	- 0.50	- 0.69	- 0.81	- 1.0
Ratio of shoals	Pr				0.30				
(depth	(A_{5m} <	0	0 -	0.15 -	-0.45	0.45	0.6	0.75	0.90 -
< 5m)	A_{tot})		0.15	0.30		0.60	0.75	- 0.90	- 1.00
Distance offshore	km	>20	15 - 20	10 - 15	0 - 5	0 - 5			
Maneuver restriction index	No of adjacent dry cells	1	2	3	4	5	6	7	8
Ship traffic density	No of ships	0	1-2	3-5	6-10	11-20	21-30	31-40	>40

2. GEOMETRIC COLLISION PROBABILITY MODEL

2.1. General Model of Accidents

Accident is combination of two events. One of them is the opportunity of an obstacle (e.g. ship, shoal, etc.) on the way of the ship and the other one is losing navigational control which means that ship cannot make any evasive maneuvers during the contact time to an obstacle. By definition accident is a conditional event and accident probability can be calculated as:

$$P\left(C\right) = P\left(A\right) P\left(G|A\right) \tag{2.1}$$

where, $P(C)$ is the probability of an collision per one ship, $P(A)$ is the probability of losing vessel control per passage, $P(G|A)$ is the geometric probability of an collision given loss of vessel control,

$P(G|A)$, is hard to calculate with real model. Since the number of sample space is large enough conditional probability $P(G|A)$ can be assumed as $P(G)$.
Then basic accident probability becomes:

$$P\left(C\right) = P\left(A\right) P\left(\mathrm{G}\right) \tag{2.2}$$

2.2. Loss of Navigational Control

Loss of navigational control is out of scope of this thesis. But a short description is given in order to complete the picture of the accident probability calculations. There are two approaches for determining the probability of losing navigational control. One of them is, calculating the loss of navigational control from past accident statistics. For an area, accident probability is number of accidents divided by number of vessels passing during certain time interval. Since accident probability and geometric probabilities are known, loss of navigational control can be calculated as:

$$P(A) = \frac{P(C)}{P(\mathrm{G})} \tag{2.3}$$

An alternative to past accident data, failure of the steering system can be used to calculate the loss of navigational control. Failure of steering system is a Poisson Process with λ_{ss} (failure/hour). From the accident reports percentage of the steering system failure on the accident type can be found. Then loss of navigational control per hour can be calculated as in Equation 2.4 Equation 2.5:

$$\mu_c = P(G) \times \frac{1}{percentage} \times \lambda_{ss} \times \frac{1}{speedofvessel} \cong \left(\frac{failures}{nm}\right) \tag{2.4}$$

where,

$$\mu_c = P(A) \tag{2.5}$$

The other one is considering all the facts including environmental conditions, ships properties, human factors and etc. It is very complicated and always there will be things that cannot be taken into account.

2.3. Discussion of the Geometric Collision Probability Models

Fujii and Shiobora (1971) study based their work on molecular collision theory. Study claims that if more than one ship meets inside certain diameter, there will be a collision and this diameter is called as collision diameter. They calculated the number of collisions (N_{col}) for a certain time period (T) as:

$$N_{col} = \rho_1 \rho_2 D \left| V_1 - V_2 \right| ST \tag{2.6}$$

where D is the geometric collision diameter, ρ is the traffic density, V is the velocity vector, S is the area of the waterway under consideration, T is the considered time period,

In order to apply to real maritime traffic conditions, they introduce random sailing courses, velocity ranges, varying ship lengths and re-write the equation as,

$$N_{col} = \int_0^T \int_S \int_L \int_L^{\prime} \int_V \int_V^{\prime} \frac{1}{2}\rho^2 PD\,|V - V'|\, dV'dVdLdL'dSdt \qquad (2.7)$$

where P is the probability of ship being inside the considered area, L is the length of the ships, ρ can be obtained from radar or from traffic volume Q and velocity V.

$$Q = \int_0^W \rho V dx \qquad (2.8)$$

where W is the width of the considered waterway.

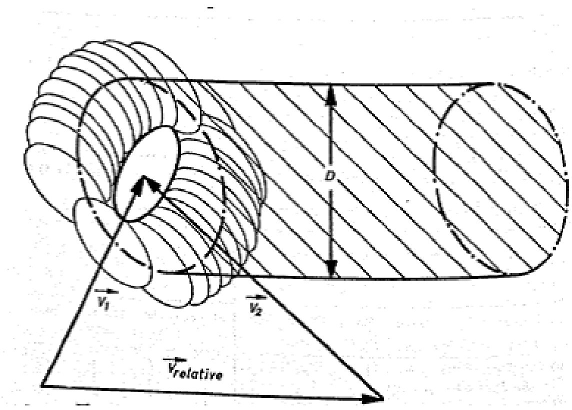

Figure 2.1. Definition of Collision Diameter (Fujii and Shiobara, 1971).

MacDuff (1974), uses molecular collision theory formulas for calculating the collision probability of ships in a different approach. In the study, it is assumed that there is ship stream and a single ship will enter this stream area with an angle θ, as seen in Figure 2.2. Different then Fujii's approach this study first calculates the mean free path of the single ship, then total travel distance through the stream is divided by mean free path in order to find the accident probability.

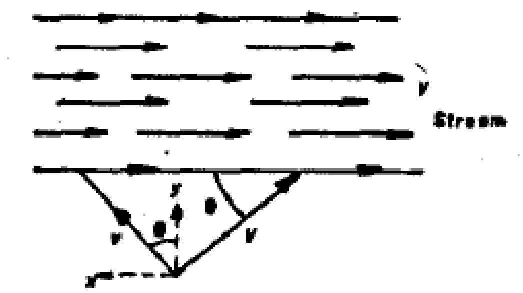

Figure 2.2. A Ship Entering a Traffic Stream (MacDuff, 1974).

Formula for mean free path (F) a single ship's expected travel distance without hitting another ship in the ship stream is calculated as:

$$F = \frac{VD^2}{L}\frac{1850}{2V\sin{}^{\theta}\!/_2} = \frac{Dist^2}{L}\frac{1850}{2\sin{}^{\theta}\!/_2} \tag{2.9}$$

where V is the speed of ships in knot, $2Vsin\theta/2$ is the relative or closing speed between two ships prior to collision, θ is the angle between track of single ships and stream of ships, $Dist$, is the average distance between ships (density measure), L is the length of ships in meters,

Then the expected number of collisions for a given length X is calculated as:

$$P_p = \frac{X}{F} \tag{2.10}$$

where X is the actual length of the path to be considered for single ship in nautical miles, P_p is the expected number of collision for a given waterway if no evasive maneuver has been made. For finding the real collision probability, P_c for collision is found and it is multiplied with P_P.

Pedersen (1995), combined the works of Fujii and MacDuff for calculating predicting the number of accidents. The study uses both collision diameter and causation probability. As an addition to Fujii's work, a general formula for collision diameter is given as:

$$D_{ij} = \frac{L_i^1 V_j^2 + L_j^2 V_i^1}{V_{ij}} \sin\theta + B_j^2 \left\{ 1 - \left(\sin\theta \frac{V_i^1}{V_{ij}} \right)^2 \right\}^{1/2} + B_i^1 \left\{ 1 - \left(\sin\theta \frac{V_j^2}{V_{ij}} \right)^2 \right\}^{1/2} \quad (2.11)$$

where L_i^1 is the length of the ship i in the waterway 1, B is the width of vessel identified by similar notation, V_i is the velocity of ship i, V_j is the velocity of ship j, V_{ij} is the relative velocity of ships i and j, θ is the approaching angle of ships.

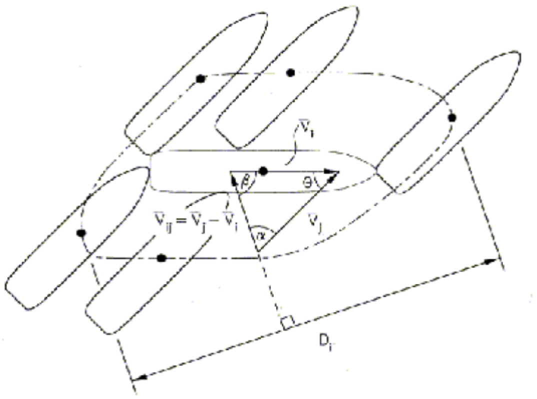

Figure 2.3. Representation of the Collision Diameter (Pedersen, 1995).

Pedersen, re-write Fujii's number of collision for a consider area as:

$$N_{col} = \sum_i \sum_j \int_{\Omega(z_i, z_j)} \frac{Q_{1i}}{V_j^{(1)}} \frac{Q_{2j}}{V_j^{(2)}} f_i^1(z_i) f_j^2(z_j) D_{ij} V_{ij} d\mathrm{A}\Delta t \quad (2.12)$$

where Q_j^2 is the number of movements of ship class j in waterways 2 per considered time period Δt $f_j^2(z_j)$ is the distribution of traffic of the ship class j across the waterways 2, z_j is the distance from the centerline of the waterway.

The biggest absence at the Pedersen's approach is the maritime traffic model. Tan and Otay (1999), filled this gap by using random walk theory. Their study find the maritime traffic distribution along the Strait, with vessel characteristics and drift probability combination. The inputs of the drift probability is given in Figure 2.4. Their study predicts the next step of the moving ship with its probability. The schematic representation of the random walk model is given as in Figure 2.5.

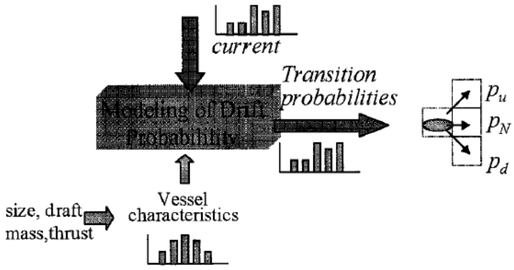

Figure 2.4. Drift Probability Model (Tan and Otay, 1999).

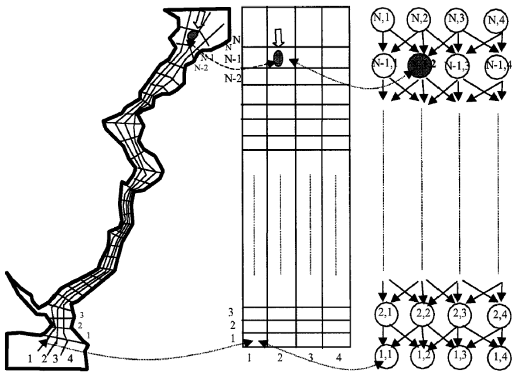

Figure 2.5. Bosphorus Representation in a Grid and State Transition Diagram (Tan and Otay, 1999).

A more physic based approach comes from Otay and Ozkan (2003), for the ship distribution along the Strait. Their study solves the hydrodynamic equations of a ship motion. In the study ship is controlled by an autopilot which contains human error functions inherently. The heading of the vessel is found by solving the hydrodynamic equations of ship which controlled by the autopilot. In order to regulate the ship traffic, there are some check lines. In these check lines, position of the ship is recorded. In Figure 2.6, distribution of the ship with 125m LOA, is given.

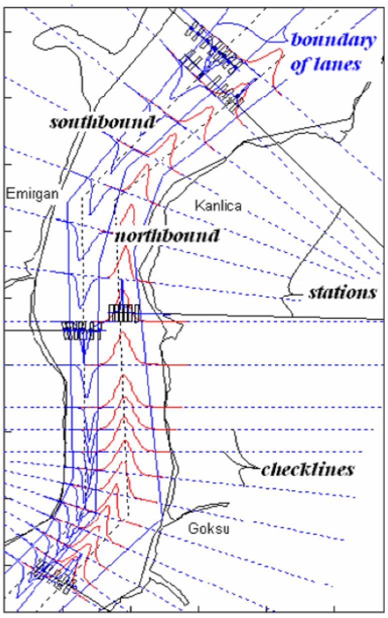

Figure 2.6. Probability Distribution of Vessel Positions for Vessels with LOA = 125 m (Otay and Ozkan 2003).

In 2010 an experimental approach comes from Ylitalo. In the study Pedersen's approach is used by replacing the traffic distribution probability with AIS data records. Normally, traffic distribution is assumed as Gaussian as given in Figure 2.7. According to maneuvers, shoals or other reasons it is know that, distribution is not Gaussian. According to AIS records of Sköldvik traffic distribution is found as in Figure 2.8.

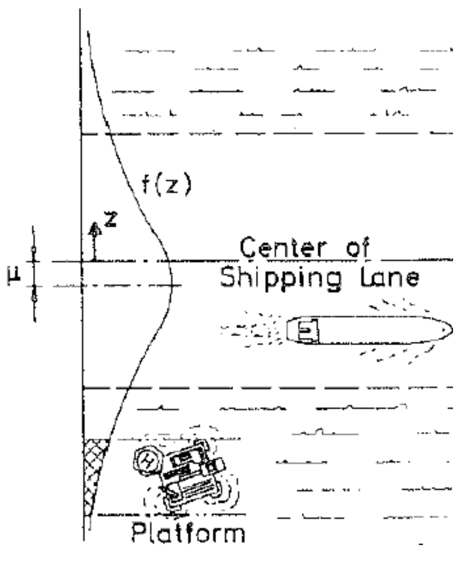

Figure 2.7. Gaussian distribution of Maritime Traffic (Ylitalo, 2010).

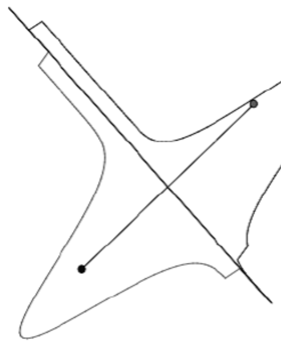

Figure 2.8. Sköldvik Maritime Traffic Distribution Histogram Created by AIS Data (Ylitalo, 2010).

Overall review of the literature gives the idea that two separate models are needed to calculate the geometric collision probability of ships. One of them is the contact model and the other is maritime traffic model. For the contact model, pioneering studies used molecular collision based theories. The difference of the models are at the maritime traffic models. Pedersen (1995) study assumes that the ships are normally distributed on a line. Ylitalo (2010) used real maritime traffic data for the ship distributions, but the assumption is that traffic moves with a line not as a spatial distribution. Tan and Otay (1999) study, used spatial distribution of the traffic with probabilistic models. Otay and Ozkan (2003) study, tried to solve the ship motion equations for the maritime traffic. This approach is gives good results but each type of ship has to be simulated too many times to get the traffic distribution and still lack at the combining of ship motions.

According to detailed literature survey, molecular collision theory based approaches have the ability to represent the contact of the ships. It can quantify the number of collisions for different approach angles, ship dimensions and given number of ships. The assumption in this quantification procedure is, ships do not change their routes during the analysis for the studied area. But the disadvantage of this assumption can be eliminated by using the loss of navigation control coefficient. When the results of the geometric collision theory is multiplied with the of loss navigational control as it is given in the Equation 2.3, the expected number of collisions can be calculated.

In this study, the molecular collision theory based contact model and for a spatial and real maritime traffic model, real ship motion data is used. The following sections of this chapter gives a detailed discussion of the geometric collision probability theory.

2.4. Geometric Collision Probability

Geometric collision probability is the encounter probability of ships for a given time period if no evasive maneuver is made. This encounter probability depends on the density of ships, velocities and meeting angles.

2.4.1. Ship Density

In the studied area number of ships have to be known in order to find geometric collision probability. Ship density is the number of ship per unit area per time and calculated as:

$$\rho_i = \frac{Q_i}{v_i \Delta T} \tag{2.13}$$

where Q_i is the number of ships travel in the i^{th} direction, v_i is the velocity of ships travel in the i^{th} direction, ΔT is the record time.

This formula not only considers number of i^{th} direction ships on the given area it also considers the travel speed of these ships. If a direction of ships are slower, they stay inside the considered area longer time and they will have higher density then the faster ones.

2.4.2. Relative Velocity

Ships are approaching to each other with relative velocity and direction and magnitude is important for finding the collision diameter direction and geometric probability respectively. It is calculated as:

$$\left|\overrightarrow{V_1} - \overrightarrow{V_2}\right| = \sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos\theta} \tag{2.14}$$

where V_1 is the velocity of the first ship (object ship), V_2 is the velocity of the second ship, θ is the angle between the velocity vectors.

2.4.3. Collision Diameter

Apart from the relative velocity and ship density, collision diameter is the most changing variable at geometric collision probability calculations. It changes according to meeting angle and size of the ships.

Foundations of the geometric collision theory is based on molecular collision theory. It says that if two particles' centers are inside a certain diameter there is a collision and this diameter is called collision diameter. The theory is adopted for maritime geometric collision probability calculations.

Two ships are approaching to each other with relative velocity. A perpendicular line to the relative velocity is the collision diameter plane. The size of the collision diameter equals to the projection of the ship sizes onto the plane. If the distance between the centers of the two ships equal to that collision diameter, it means that they have collided.

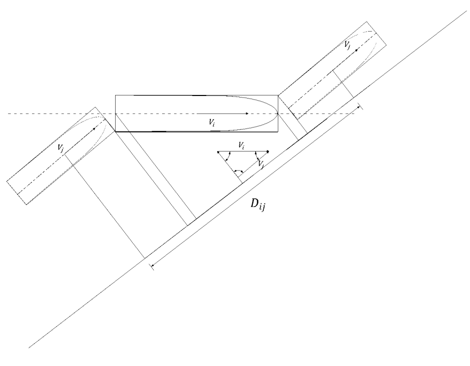

Figure 2.9. Collision Diameter Representation.

It can be calculated as: (Pedersen, 1995).

$$D_{ij} = \frac{L_i V_j + L_j V_i}{V_{ij}} \sin\theta + B_j \left\{1 - \left(\sin\theta \frac{V_i}{V_{ij}}\right)^2\right\}^{1/2} + B_i \left\{1 - \left(\sin\theta \frac{V_j}{V_{ij}}\right)^2\right\}^{1/2} \tag{2.15}$$

The calculation is the projected length of the dimensions of the ship to the collision diameter plane. It comes from the geometry of the ships and relative velocity of them which is given below:

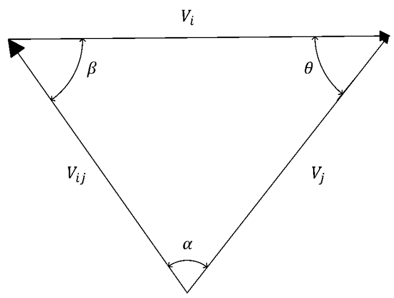

Figure 2.10. Relative Velocity and the Related Angles for the Calculations.

$$\frac{\sin\theta}{V_{ij}} = \frac{\sin\beta}{V_j} = \frac{\sin\alpha}{V_i} \tag{2.16}$$

where $\left\{1 - \left(\sin\theta \frac{V_i}{V_{ij}}\right)^2\right\}^{1/2} = \cos\alpha$

$\left\{1 - \left(\sin\theta \frac{V_j}{V_{ij}}\right)^2\right\}^{1/2} = \cos\beta$ Pedersen's (1995) formulation can be re-written as:

$$D_{ij} = L_i sin\alpha + L_j sin\beta + B_j \cos\alpha + B_i \cos\beta \tag{2.17}$$

But the calculation of the collision diameter should not be the same for molecules and the ships. Because, shape and movement of the molecules and ships are different than each other. Molecules are assumed as circle and ships are assumed as rectangular.

Since the shape of the molecules are circular heading and course will always be the same. But for ships it may not because the bow of the ship determines the heading and with the effect of the environment (e.g. current, wind and etc.) heading and course can differ. Therefore, calculation of the collision diameter needs to consider the heading and course of the ship.

For example assume two ship's heading are the same and there is cross current in the field. Because of the hydrodynamic properties, effect of current on ships are not the same, so the COG of ships are different. When a collision diameter is calculated these ships, it will give us the over-taking collision diameter which is the summation of the width of the ships. However, it is known that during the overtaking, ships can collide if their route coincides which is the result of different COG.
The Fujii's theory fails when it calculates the collision diameter of the ships given below:

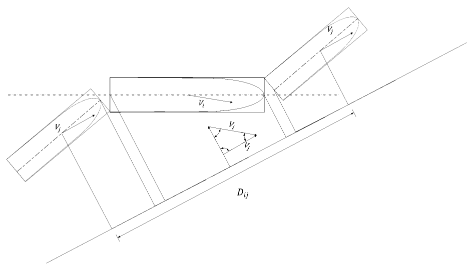

Figure 2.11. Modified Collision Diameter.

Collision diameter depends on velocity vectors, width and length of the ships.
Collision diameter is the summation of projection of ships' width and length to the line which is perpendicular to relative velocity of ships.
While calculating collision diameter first relative velocity of the ships are needed which is:

$$|V_{ij}| = \sqrt{V_i^2 + V_j^2 - 2V_iV_j\cos\theta} \tag{2.18}$$

where θ is the angle difference between the velocities and can be calculated from difference of COG of ships.

$\theta = COG_i - COG_j$
$\beta = arcsin\frac{V_j sin\theta}{V_{ij}}; \beta_y = \beta + HDG_j - COG_j$
$\alpha = arcsin\frac{V_i sin\theta}{V_{ij}};\alpha_y = \alpha - HDG_i - COG_i$

$$D_{ij}^y = L_i sin\alpha_y + L_j sin\beta_y + B_j \cos\alpha_y + B_i \cos\beta_y \tag{2.19}$$

2.4.4. General Geometric Collision Probability

In geometric collision methodology, it is assumed that ship centers are approaching to each other with relative velocity. The plane which is perpendicular to relative velocity of the ships gives the line of collision diameter. The projection of the ship dimensions on to this plane gives the collision diameter of the given accident conditions. The alignment of the ships can vary from the COG. Current and maneuver can be the causes of this variation. Therefore, heading and COG variation is added as an adjustment factor in the suggested collision diameter.

According to explanation given for the geometric collision methodology, the number of the possible collisions of an object ship is equal to the number of ships covered by the collision diameter which is travelling with relative velocity. For a simple case, it is assumed that a ship group is travelling with similar navigation characteristics (size, speed and heading), and the collision diameter for the object ship is the same. Then for unit time, the number of possible collisions of the object ship with the ship group becomes:

$$D\rho_2 \left|\overrightarrow{V_1} - \overrightarrow{V_2}\right| \tag{2.20}$$

where D is the collision diameter, ρ_2 ship density of the ship group, $|\vec{V_1} - \vec{_2}|$ is the relative velocity, $\vec{V_1}$ is the object ship's velocity, $\vec{V_2}$ is the average velocity of the ship group. When two groups of ships in an area A are considered for a given period of time T, number of possible collisions N_{col} will be;

$$N_{col} = \rho_1 \rho_2 D \left| \overrightarrow{V_1} - \overrightarrow{V_2} \right| AT \tag{2.21}$$

where ρ_1, is the density of the ships belongs to first group,ρ_2 is the density of the ships belongs to second group.

Number of collisions for a given area is proportional to, ship densities (ρ_1, ρ_2), collision diameter (D), relative velocity and time period. The most complicated parameter is the collision diameter.

In real sea conditions, there is more than two ship groups and collision types of these groups differs according to meeting angle of the ships. Collision types can be listed as:

- Head-on collision ($0° \leq \theta \leq 10°$)
- Crossing collision ($10° \leq \theta \leq 170°$)
- Take-over collision (($170° \leq \theta \leq 180°$)

Geometric probability for a given time period is the product of collision diameter, traffic densities, relative velocities and travel distances of ships under considered directions, and the considered time.

$$P_G = \sum_i \sum_j \int_{z_i z_j} \rho_i(z_i)\, \rho_j(z_j)\, D_{ij} v_{ij} T dz_i dz_j \tag{2.22}$$

where z_i is the position of the ship on the i^{th} waterway, z_j is the position of the ship on the j^{th} waterway, $\rho_i(z_i)$ is the ship density as a function of z in the i^{th} direction, $\rho_j(z_j)$ is the ship density as a function of z in the j^{th} direction, T is the time period, D_{ij} is the collision diameter of the ships on i^{th} and j^{th} waterway, v_{ij} is the relative velocity of the ships on i^{th} and j^{th} waterway.

The overall geometric collision probability scheme given in Figure 2.12.

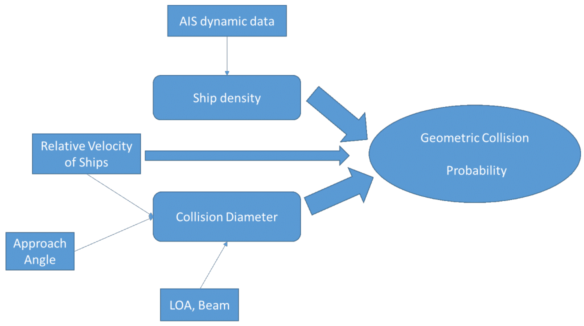

Figure 2.12. Geometric Collision Probability Schematic Representation.

According to the equation and Figure 2.12, parameters, that are directly used in the calculation, are relative velocity, ship density and collision diameter. Relative velocity affects directly and indirectly the geometric collision results. Therefore, according to mathematical formulation relative velocity is the most important parameter of the geometric collision probability.

3. MARITIME TRAFFIC MODEL

Accuracy of the geometric collision methodology directly related with how well maritime traffic represented. All the parameters for the geometric collision come from the maritime traffic model. Therefore, a special care should be given to the maritime traffic modeling of the system.

The detailed literature discussion at section 2.3 gives the inside of the maritime traffic models that are used in the past studies. In the pioneering work of Fujii, they used radar image records. It supplies ship movement information of the considered area. In other studies three different approaches are used. One of them is using Gaussian distribution approach for the ships. In this approach, possible ship routes, for area under consideration, are represented with straight lines and number of ships is taken from the past year statistics. Lateral distribution along the routes is assumed as Gaussian. The disadvantage of these studies they cannot represent the real traffic on the spatial distribution.

Second type of the studies, tries to find the traffic distribution with the simulation results. The key parameters are navigation characteristics and size of the ships with the environmental conditions. According to simulation results and number of ships, lateral distributions along the shipping routes are found for given conditions. Although, ship distributions can be represented for changing environmental conditions, the time needed for simulations to represent the whole conditions is too long. Therefore, they cannot represent the real maritime traffic.

The third approach is the collecting long-term traffic data of the area by tracking the vessels. Automatic Identification System is the source of this type of studies. The data is distributed to the given ship routes. The difference from the first type of studies, the distributions are not Gaussian and ship routes are obtained from the recorded data. Also, it gives the real movements of the ships which are simulated at the second type studies. The missing part of the third type studies, they still do not give the spatial distribution of the area.

In this study, in order to represent the spatial traffic distribution third type approach is improved with sectoring approach. The main difference from the route approach, instead of assuming ships traveling along the given routes, ships entering and exiting through the sector is determined. This approach helps to find the real spatial distribution of the maritime traffic over the considered area. Further improvement can be done by dividing the sectors into small cells. This cell division increases the input resolution and supplies two dimensional results. In this section, details of the AIS will be given, and then sectoring properties and cell divisions will be described.

3.1. Automatic Identification System (AIS)

Automatic identification system (AIS) is designed to be capable of providing information about the ship to ship and ship to coastal authorities automatically over AIS devices. Source of the AIS messages are the ships' navigation instruments. AIS devices broadcast information via VHF in ASCII data packets as a byte stream, using NMEA 0183 or NMEA 2000 data formats.

There are 27 different types of AIS messages and they are listed at Table 3.1 with their meanings.

The most important ones are the Type 1, 2, 3 and 5 messages. Type 1, 2 and 3 are the dynamic messages which contain the information about the navigation, and they are listed at Table 3.2. Table 3.3 messages are the static messages and contain information about the voyage and they are listed at Table 3.3.

In order to find the ship dimensions (LOA & Beam) Type 5 has to be post processed. Dimension to bow, stern and dimension to port, starboard summation gives the LOA and beam of the ships respectively. Figure 3.1 gives the sketch of the GPS placement on a ship.

Table 3.1. AIS Message Types.

Message Type	Statement
1	Position Report Class A
2	Position Report Class A (Assigned schedule)
3	Position Report Class A (response to interrogation)
4	Base Station Report
5	Static and Voyage Related Data
6	Binary Addressed Message
7	Binary Acknowledge
8	Binary Broadcast Message
9	Standard SAR Aircraft Position Report
10	UTC and Date Inquiry
11	UTC and Date Response
12	Addressed Safety Related Message
13	Safety Related Acknowledgement
14	Safety Related Broadcast Message
15	Interrogation
16	Assignment Mode Command
17	DGNSS Binary Broadcast Message
18	Standard Class B CS Position Report
19	Extended Class B Equipment Position Report
20	Data Link Management
21	Aid-to-Navigation Report
22	Channel Management
23	Group Assignment Command
24	Static Data Report
25	Single Slot Binary Message
26	Multiple Slot Binary Message with Communications State
27	Position Report for Long-Range Applications

Table 3.2. Information inside the Type 1, 2 and 3 Messages.

Message Type
Repeat Indicator
MMSI
Navigation Status
Rate of Turn (ROT)
Speed Over Ground (SOG)
Position Accuracy
Longitude
Latitude
Course Over Ground
True Heading (HDG)
Time Stamp
Maneuver Indicator
Spare
RAIM flag
Radio Status

Table 3.3. Information inside the Type 5 Message.

Message Type
Repeat Indicator
MMSI
AIS Version
IMO Number
Call Sign
Vessel Name
Ship Type
Dimension to Bow
Dimension to Stern
Dimension to Port
Dimension to Starboard
Position Fix Type
ETA month (UTC)
ETA day (UTC)
ETA (hour)
ETA minute (UTC)
Draught
Destination
DTE
Spare

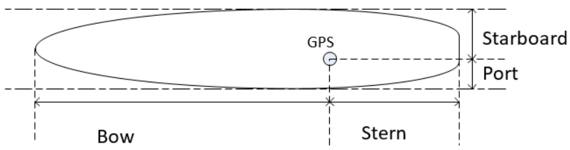

Figure 3.1. Placement of GPS Onboard.

Ship dimensions, velocity and the angle between ships are the main variables for the geometric collision probability. These variables are combined from Type 1, 2, 3 and 5 messages and list of the variables are given in Table 3.4.

Table 3.4. Variables used in the Geometric Collision Probability.

Variable Name	Description	Type	Output range	Unit	Frequency	Example
ShipType	Ship type	5	2 digits	-	300 seconds	71
MMSI	Maritime Mobile Service Identity	1 2 3 5	9 digits	-	3-300 seconds	3.74E+08
IMO	International Maritime Organization Number	5	7 digits	-	300 seconds	
LOA	Length overall	5		meters	300 seconds	128
Beam	Beam	5		meters	300 seconds	12
Draught	Draught	5		meters	300 seconds	10
SOG	Speed over ground	1 2 3		Nautical mile/hour	3-60 seconds	9.7
COG	Course over ground	1 2 3		Degrees North	3-60 seconds	352
HDG	Heading	1 2 3		Degrees North	3-60 seconds	350
Latitude	Latitude	1 2 3		Degrees WGS84	3-60 seconds	4.101.822
Longitude	Longitude	1 2 3		Degrees WGS84	3-60 seconds	2.906.451

In average 1.7 million of NMEA sentences are recorded daily. 1 million of them are Type 1, 2, 3 messages and 50 thousand of them are Type 5 messages. NMEA sentences are recorded, parsed and stored in the SQL database. Total parsed data size for the SOI is about 94 gigabyte. Size of the Type 1, 2, 3 messages is 86 gigabyte and Type 5 messages is 8 gigabyte. In order to decrease the size of the database into a manageable level, grid base analysis method is used and Strait is divided into sectors according to transit traffic waterway border points. Next section gives detailed information about the sectoring process.

3.2. Sectoring

Sectoring is the process of dividing the area into smaller pieces, in order to analyze the maritime traffic. Sectoring decreases the size of the data that is used during the analysis. The size of the sector depends on the change of the navigational conditions. Throughout the sector, no change or at least insignificant change should be observed in the navigational conditions. These conditions are:

- Speed Over Ground (SOG)
- Heading
- Course Over Ground (COG)
- Ship dimensions
  - LOA
  - Beam
- Number of ships in the considered travel directions

SOG changes due to variation of the currents in terms of magnitude and direction, speed limits, newly entering ships to the area, traffic density and maneuver of the ships. Heading and COG varies mainly due to maneuvers but also changes in the current direction and magnitude affects the two parameters. Ship dimensions and number of ships in the considered travel directions vary due to newly entering ships to the area. One more important thing for these parameters listed, they are also the inputs of the geometric collision methodology.

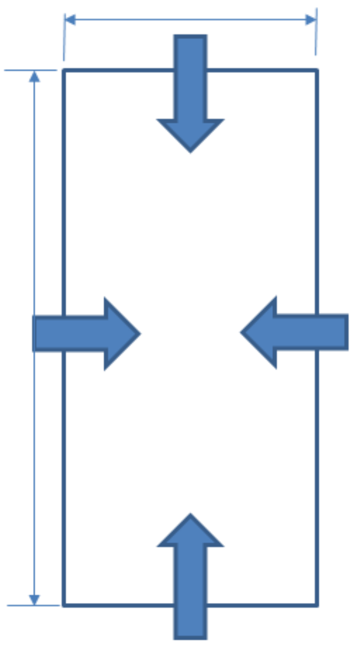

Figure 3.2. Schematic Representation of a Sector.

Schematic representation of a sector is given in Figure 3.2. The borderline of the sector determines the entrance and exit navigation patterns of the ships. Inside the sector, it is assumed that navigation patterns do not change. Ships are named according to the entrance direction (e.g. North entry). Shape of the sector can change according to geographical constrains and size depends on the change of the navigational conditions as listed.

3.2.1. Data Processing and Ship Routes

For the determining the routes of the ships AIS data is used. AIS messages come from ships in a random order. Data frequency of a ship changes according to speed, change of course and etc. Since there is no exact order at the incoming data, post process is a must for the route determination.

First thing to do is to get the AIS data as close as possible to the sector border line. Using the coordinates of the ships, a distance calculation has been made to the sector lines. Given that the sector line formula as:

$$y = ax + c \tag{3.1}$$

Point to line distance formula is:

$$distance = \ |a_i x_n - y_n + c_i| \,/ \sqrt{a_i^2 + 1} \tag{3.2}$$

where x_n is the latitude of the n^{th} position, y_n is the longitude of the n^{th} position

Since the data is in geographical coordinate system, spherical coordinates are used for the calculations. The exact point intersection point on the line cannot be found a proximity range has been determined. The idea is if the ship's coordinate is inside this proximity range of the line it is assumed that ship has crossed the line. This range is calculated according to the AIS data frequency and velocity of the ships. In order to be on the safe side, it should be assumed that at least two times the Type

1, 2, 3 message frequency and also ships average speed. Then the travel distance of a ship without a coordinate signal is given in equation

$$d_{app} = \ average\ speed\ of\ theships\ \times (2 \times\ signalperiod\ ) \tag{3.3}$$

Also in order to find the lateral distribution of ship spherical coordinates, distance between two points is used.

In order to represent the all of the ship properties static and dynamic messages should be gathered. AIS Type 5 messages contain, ship specific static data and Type 1, 2 and 3 messages contain data related to navigation information. Since each AIS device has its own specific MMSI number embedded, it is the most reliable parameter for combining the static and dynamic messages. Other information like ship name or IMO is specified by the user and in some messages they are missing. In order to cover as much as possible ship information, MMSI is used for identifying the ship and gathering the messages.

Along the route of a ship intersection points with the sector border lines are found. At these specific points ship characteristics, course over ground (COG), speed over ground (SOG), true heading, and coordinates of the intersection points are recorded. Recorded data of every ship's intersection information for each sector border line gives the lateral distribution of the ship on the line.

3.3. Cell Application

Sectors can be further divided into cells in order to increase the resolution of the inputs and results. Cell application helps to represent variation of the ship entrance along the sector border line. Usually this variation is modeled with three ways. First way is to assume Gaussian distribution for the ship traffic along the centerline. Second way is to simulate the ship motions and find a distribution function for the lateral traffic. Third way is to use AIS data and fit a function for the lateral distribution of the ships along the sector.

Advantage of the cell application, it not only increases the resolution of the inputs and results but also (may be more important) it helps to calculate the real spatial distribution of the geometric collision probability of the area. The methodology is that, rather than fitting a function for the lateral distribution of the traffic, ships entering to the cells are found. According to the ship and navigational characteristics, geometric collision probability is calculated for each cell.

Inputs are the parameters needed for the geometric collision probability calculations. These are:

- Ship density
- Collision diameter
- Velocity
- Characteristic length
- Time

These parameters can be divided into two groups as:

- Static Cell Parameters
- Dynamic Cell Parameters

3.3.1. Static Cell Parameters

Static cell parameters are inherent within the cells. Cell dimensions also used as characteristic length, are static cell parameters. These are, $L_{TRANS(i,j)}$ where, characteristic length for the transit vessel traffic and $L_{CROSS(i,j)}$ where characteristic length for the local vessel traffic.

3.3.2. Dynamic Cell Parameters

These types of parameters are depends on the incoming data

- Ship density;
  - $s.d_{TRANS(i,j)}$ (number of ships passing transit a 1 nm sector in 1 hour)
  - $s.d_{CROSS(i,j)}$ (number of ships passing across a 1 nm sector in 1 hour)
- Ship dimensions (LOA, BEAM) averaged over number of ships
- Course Over Ground (COG) averaged over number of ships
- Heading (HDG) averaged over number of ships

They are averaged for a period of $\Delta t(\Delta t \approx 1$ year) and a steady state calculation is done based on the expected values of static and dynamic variables

4. APPLICATION OF TRAFFIC MODEL

With an annual maritime traffic of over 300,000 cruises including transit and local traffic, the Strait of Istanbul (SOI) is one of the busiest waterways in the world. Combined with navigation hazards and a sensitive urban setting, the SOI poses high risk to both the passengers but also to the City of Istanbul and its environment. Until the introduction of the Turkish Straits Maritime Traffic Regulation (TSMTR 1998), it was all up to the skipper's ability with the exception of few ships hiring pilot support. TSMTR imposed certain navigation rules including a separation scheme, right-side traffic, and limitations for very large ships and ships with hazardous cargo. However a real-time monitoring and navigation support started first when the Turkish Straits Vessel Traffic Services became operational. With a command center and eight unmanned radar stations located along the Strait, the system provides 7/24 guidance by real-time monitoring the traffic in the Turkish Straits, including the SOI, the Marmara Sea and the Strait of Çanakkale.

After IMO's adaptation of the Automatic Identification System (AIS) in 2000, AIS rapidly became part of standard ship born electronics. With this new technology, vessels transmit and receive information including their position, heading, size and cargo to other ships and coastal stations. Today with the extended capability of Satellite based (S-AIS), vessel traffic information is available online. Starting 2005 IMO required that all commercial vessels larger than 300 GRT in international voyages (or vessels larger than 500 GRT in domestic voyages) to be equipped with on board AIS transceivers. In 2010 the Turkish Maritime Authority extended this regulation to all non-military vessels in Turkish waters larger than 15 m or vessels with more than 12 people onboard to have a broadcasting AIS device.

Long-term AIS data (Helcom, 2012) with a spatial coverage of an entire waterway was first used in the Baltic Sea. The Helcom AIS data was analyzed for estimating navigation patterns, ship encounters and resulting oil spills in the Baltic Sea (Gucma and Przywarty, 2008; Aarsæther and Moan, 2009). Other studies used local or satellite

AIS data to investigate maritime traffic at different locations and for different purposes. Favorable ship routes in the Yangtze Estuary, China (Zhanghao and Yangxiaojun, 2010), marine traffic patterns and ship collision risk off the Coast of Portugal (Silveira *et al.*, 2013), collision probability at the entrance of Rotterdam Harbor, Netherlands (Mou *et al.*, 2010), vessel traffic characteristics in the Singapore Strait (Meng *et al.*, 2014), ship sinking frequencies in Madura Strait, Indonesia (Mulyadi, 2014), accident risk in the Malacca Strait (Zaman *et al.*, 2014; Maimun *et al.*, 2015) and mapping of the global shipping density (Wu *et al.*, 2016) are all based on AIS data.

The maritime traffic in the SOI including accident locations has first been mapped by Kornhauser and Clark (1995) using official paper logs and incident records. Before the availability of real-time electronic data, vessel traffic in the SOI has been analyzed with probabilistic models (Tan and Otay, 1999; Otay and Özkan, 2003; Yazıcı and Otay, 2009). These models can mathematically estimate the long-term vessel distributions and the expected accident frequencies based on statistics of transit vessels. Models helped to understand the statistical characteristics of the transit traffic, however, the detailed navigation patterns of especially local traffic remained unknown. The first attempt to use AIS data for the traffic analysis in the SOI was based on a two-day visual AIS tracks at the Southern entrance of the SOI (Aydoğdu, 2012) and the second attempt is for the Izmit Bay (Yurtören, 2014).

The present study is an attempt to close an important gap in the accurate traffic data regarding the SOI. For this purpose, AIS messages have been collected, stored and analyzed within the entire SOI continuously over a period of one year. Using data mining techniques, instantaneous AIS messages from local and transit vessels at random bursts are analyzed to find vessel distributions at specified check-lines along the SOI. Multiple messages from same vessels are combined to calculate individual voyages and identified as local or transit traffic using the reported MMSI and IMO numbers. Vessel specific information including ship type, LOA (length overall), beam, draught, speed over ground (SOG), course over ground, (COG), and heading are analyzed. Their distributions are found at different locations along the SOI.

4.1. Sectoring

The Strait of Istanbul, is one of the most challenging waterways in the world. Bends, narrow parts, shoals and currents are continuously changing navigational conditions during the Strait passage. Therefore, extra regulations are applied to the maritime traffic. One of these rules is the waterway border points for transit traffic, determined according to Turkish Straits Maritime Traffic Regulation (TSMTR 1998) prepared by the Ministry of Transportation, Maritime and Communication.

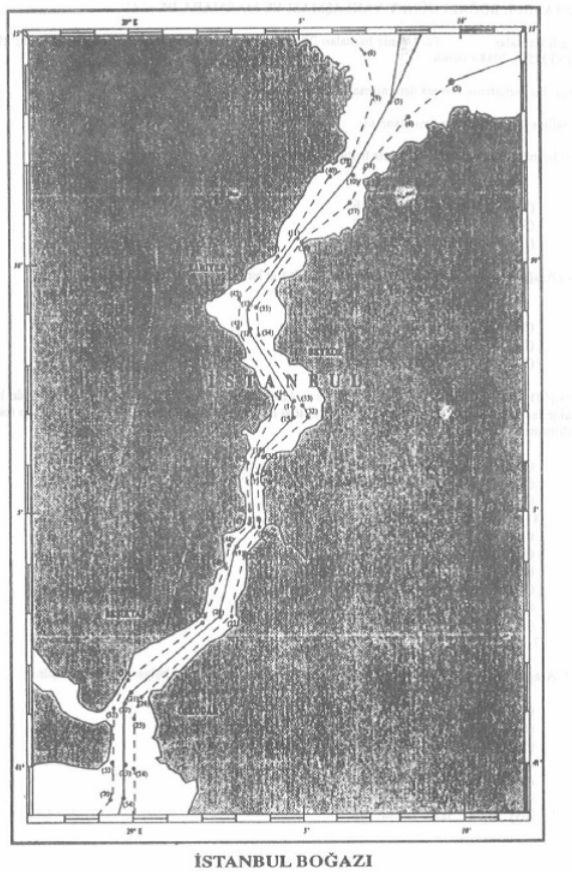

Figure 4.1. Traffic Separation Scheme and Border Points for the Transit Traffic in the SOI (TSMTR 1998).

Figure 4.1 is the Traffic Separation Scheme (TSS) published in Turkish Straits Maritime Traffic Order Rule. Strait used to be two way traffic therefore, mid points are also shown in the TSS, but during the study period of time, one way traffic is applied. Therefore, mid points are not considered during the sectoring process. Border points give limits East and West border of the transit traffic. They are located at the change of course for safe navigation.

Table 4.1. Coordinates of the Points in TSS.

WEST BORDER			EAST BORDER		
Point No.	Longitude Degrees	Latitude Degrees	Point No.	Longitude Degrees	Latitude Degrees
53	289.903	410.050	24	290.010	410.000
52	289.908	410.215	25	290.012	410.183
51	289.955	410.288	26	290.033	410.250
50	290.345	410.495	27	290.493	410.517
49	290.475	410.688	28	290.555	410.750
48	290.490	410.762	29	290.653	410.828
47	290.567	410.820	30	290.642	411.008
46	290.588	410.855	31	290.667	411.058
45	290.583	411.042	32	290.900	411.200
44	290.770	411.247	33	290.892	411.233
43	290.545	411.505	34	290.648	411.475
42	290.548	411.587	35	290.640	411.580
41	290.750	411.752	36	290.867	411.800
40	291.000	412.000	37	291.130	411.945
39	291.105	412.050	38	291.200	412.050
9	291.250	412.300	6	291.425	412.227

Table 4.2. Border Points used for the Strait of Istanbul

Line No	West		East	
	Longitude	Latitude	Longitude	Latitude
1	289.903	410.050	290.010	410.039
2	289.908	410.215	290.012	410.183
3	289.955	410.288	290.033	410.250
4	290.345	410.495	290.493	410.517
5	290.522	410.756	290.555	410.750
6	290.567	410.820	290.653	410.828
7	290.583	411.042	290.637	411.019
8	290.770	411.247	290.892	411.233
9	290.545	411.505	290.648	411.475
10	290.548	411.587	290.640	411.580
11	290.817	411.819	290.867	411.800
12	291.000	412.000	291.130	411.945
13	291.105	412.050	291.200	412.050
14	291.250	412.300	291.425	412.227

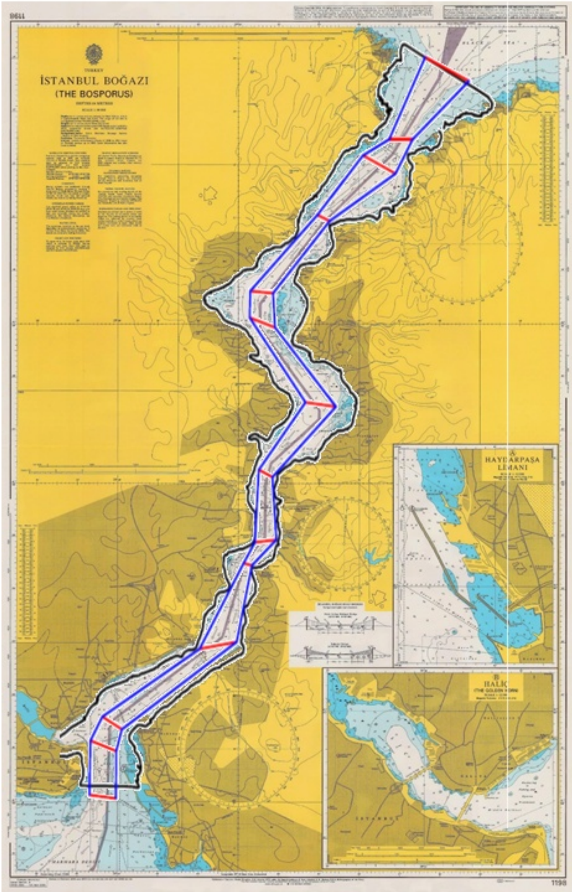

Figure 4.2. Sectoring of the Strait in the Project.

During sectoring procedure of the Strait, these way points are considered. For proper the geometric collision probability calculations, this division scheme is applied.

4.2. Data Processing and Ship Routes

In average 1.7 million of NMEA sentences are recorded daily. 1 million of them are Type 1, 2, 3 messages and 50 thousand of them are Type 5 messages. NMEA sentences are recorded, parsed and stored in the SQL database. Total parsed data size for the SOI is about 94 gigabyte. Size of the Type 1, 2, 3 messages is 86 gigabyte and Type 5 messages is 8 gigabyte. In order to decrease the size of the database into a manageable level, grid base analysis method is used and Strait is divided into sectors according to transit traffic waterway border points.

Along the route of a ship intersection points with the sectoring lines are found. At these specific points ship characteristics, course over ground (COG), speed over ground (SOG), true heading, and coordinates of the intersection points are recorded. Recorded data of every ship's intersection information for each sector border line gives the lateral distribution of the ship on the line.

Since the data is coming geographical coordinate system, spherical coordinates are used in the calculations. Since the exact point on the line cannot be found a proximity range has been determined. The idea is if the ship's coordinate is inside this proximity range of the line it is assumed that ship has crossed the line. This range is calculated according to the AIS data frequency and velocity of the ships. In order to be on the safe side, it is assumed that at least a Type 1, 2, 3 AIS message will come in 10 seconds and also ships are traveling with 10 knots (5 m/sec). Then the travel distance of a ship without a coordinate signal is:

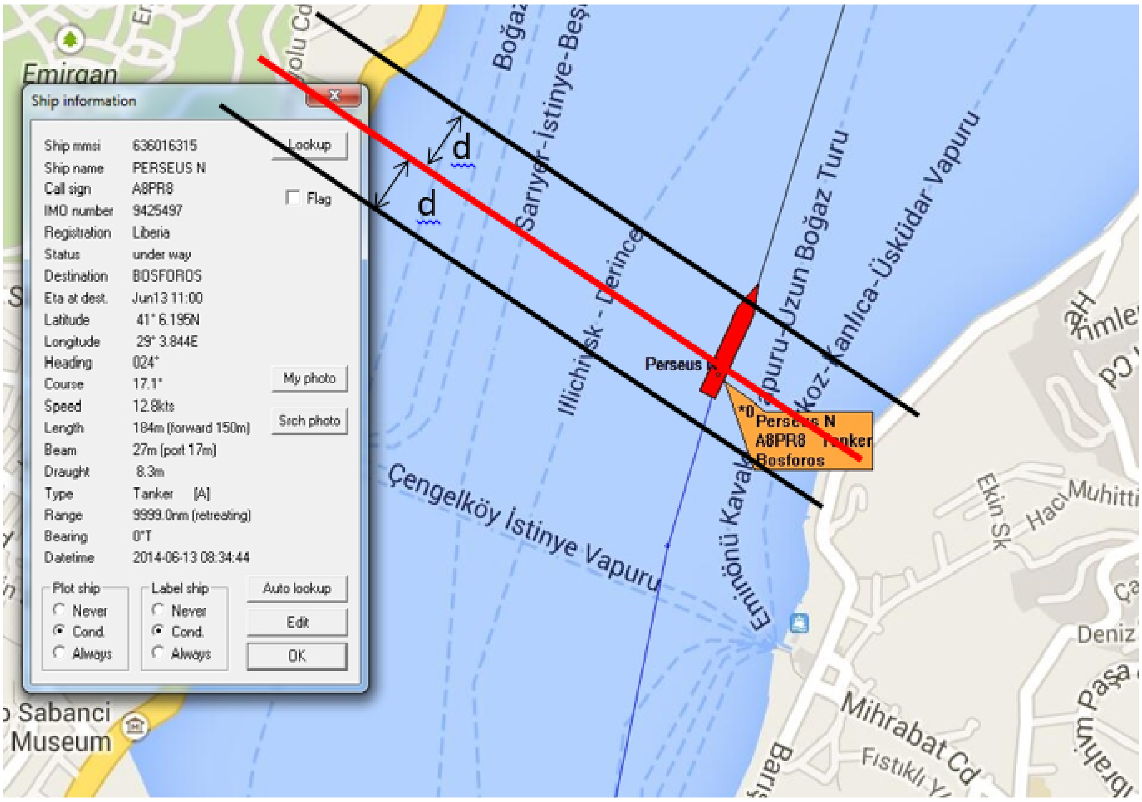

Figure 4.3. Ship Entering a Sector.

$$d = 5 {}^{m}\!/_{sec} \times 10sec = 50m \tag{4.1}$$

It means that if a ship is within 50 meters range then it is assumed that ship has crossed the line. A 10% tolerance is added to the 50 m and it is calculated as 55 m during the calculations.

Also in order to find the lateral distribution of ship spherical coordinates, distance between two points are used.

4.3. Cell Application

The SOI is divided into sectors of different navigation patterns. However, even within the same the sector ship movements change since the parameters affecting the collision probability change. Therefore, every sector is divided into 100 cells (10 pieces at north-south direction and 10 pieces at east-west direction), in order to have a better understanding of the ship movements and accurate calculations. Geometric collision probability of the each cell is calculated separately according to the cell's parameter. But after geometric collision probability calculations has finished, it is seen that cell size dimensions smaller than collision diameter, gives inaccurate results. Therefore, every sector divided into cells that are not smaller than the collision diameter.

Inputs are the parameters needed for the geometric collision probability calculations. These are:

- Ship density
- Collision diameter
- Velocity
- Characteristic length
- Time

These parameters can be divided into two groups as:

- Static Cell Parameters
- Dynamic Cell Parameters

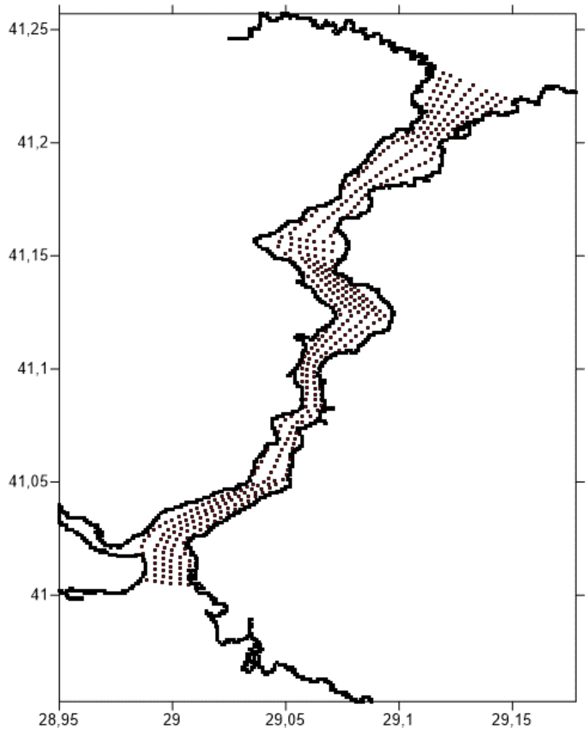

Figure 4.4. Cell Centers through the SOI.

Table 4.3. Travel Distance and Number of Cells through the Sectors.

Sector	Travel distance in nm		Number of cells
	North South	East West	
1	0.93	0.49	18
2	0.45	0.41	9
3	2.39	0.7	45
4	1.59	0.18	10
5	0.54	0.39	3
6	1.24	0.26	16
7	1.61	0.56	22
8	1.84	0.49	39
9	0.56	0.44	9
10	1.76	0.24	12
11	1.42	0.64	10
12	0.63	0.49	12
13	1.55	0.85	30

5. APPLICATION OF GEOMETRIC COLLISION MODEL

Pedersen's approach for the geometric collision probability, needs the functions of the parameters. The result can be obtained by integrating the proposed formula in Equation 2.12.

Rather than using the Equation 2.12, numerical summation is applied as given in Equation 5.1.

$$\begin{gathered}\sum_s \sum_i \sum_j \sum_{ik(s)} \sum_{jk(s)} \rho_i \left(ik \left(s\right), s\right) \rho_j \left(jk \left(s\right), s\right) \\ V_{ij} \left(s\right) D_{ij} \left(s\right) \Delta l \left(ik, s\right) \Delta l \left(jk, s\right) \Delta t\end{gathered} \tag{5.1}$$

where s represents the sector, $i\&j$ represents the entrance (N, S, E, W), $ik\&jk$ represents the cell inside the sector according to entrance,ρ is ship density, V_{ij} is relative velocity, D_{ij} is collision diameter, Δl travel distance, Δt, considered time

Equation 5.1, can be thought as the numerical integration of Equation 2.12. Parameters inside the cells are uniformly distributed. Variation of parameters through the cells make the equation inherently probabilistic. Therefore, an extra probability function do not added to the Equation 5.1.

6. COLLISION MODEL AND RISK MAPS

In this section AIS signals transmitted from vessel in and around the SOI are analyzed. The following results comprise information about ship traffic, navigation details and accident related parameters.

6.1. Maritime Traffic

Random AIS reports broadcast from ships as they travel within the SOI are analyzed in 13 pre-defined sectors. Ships are called according to their entry side of the Strait. Ships entering from north of the SOI is called north entry and entering from south called south entry. For the exits, ship leaving the SOI from north called north exit; leaving from south called south exit. The following sections describe how ship densities are distributed geometrically along the SOI. Similarly, static and dynamic information about travelling ships are given.

6.1.1. Number of ship

Number of ship analysis has two important outcomes for the traffic analysis. One of them is, it gives the usage and traffic density of the area. The other one is, it allows to double check the data with the official reports. According to Ministry of Transportation, Maritime and Communication, 43,745 transit ships have used the SOI from September 2014 to August 2015. AIS measured number of ships for the same period is 45,062. The difference comes from the domestic lines that are departing inside the SOI. 45,062 ships are navigating at the south entry; 22,168 of them are south entry ships and 22,894 of them are north entry ships. When ships at the north entry are analyzed 39,513 ships has been observed. South entry and north entry ships are 18,830 and 20,683 respectively. Overall results are given in Table 6.1.

Table 6.1. Number of Ships in the Strait of Istanbul

	South entry	North entry
North entry	18.830	20.683
South entry	22.168	22.894
Transit traffic	18.463	19.417

In order to find the number of transit ship passages, ships' entries and exits to and from the SOI are tracked. After the analysis 37,880 transit ships are found in one year. Number of ships entering from south and north are 18,463 and 19,417 respectively. Yearly cross traffic of the Strait is 271,439. These include the passenger type ships that are navigating between European and Asian side of the Istanbul.

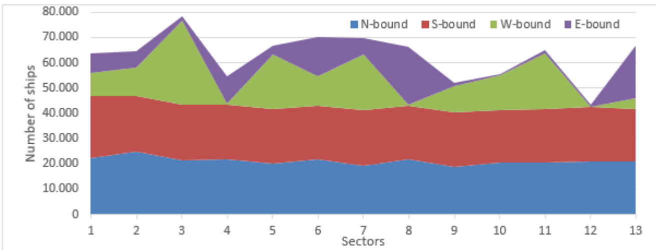

Figure 6.1. Yearly Ship Passages in North-South Directions through Designated Sectors.

Figure 22, shows the number of ships passages through the sectors. There are four entrance to each sector, their names are given according to the travel directions. Number of ships in north-south direction fluctuates between 42,000 and 47,000 depending on the sector. Cause of the fluctuation is the varying number of local ships travelling in transit direction at the given sectors. Cross traffic is between 35,000 and nearly 0 ships annually. This result is directly related with the place of the piers for the local traffic. Sector 3 has the highest cross traffic and Sector 12 has the lowest cross traffic.

Figure 4.4, also gives the total number of ships and comparison of transit and cross way traffic in the sectors. In all the sectors, transit way usage is more than the cross way usage. This figure states that, transit way ships are higher in number in the SOI. But usage of transit direction is mostly generated by the same ships (transit traffic), and cross direction usage generated by different ships which increase the number of ships in the cross direction. In Table 6.2, comparison of total number of ships and total number of ships per hour per nm^2 are given.

Table 6.2. Number of Ships per Sector and per nm^2

Sector number	Total number of ships	Total number of ships/hr.nm^2
1	63.525	1.589.811
2	64.439	3.976.243
3	78.463	5.385.947
4	54.874	2.229.849
5	66.769	3.610.178
6	70.342	2.444.515
7	69.875	8.802.751
8	66.252	846.839
9	51.973	2.426.686
10	55.605	149.482
11	65.235	8.259.578
12	43.379	1.613.266
13	66.641	5.786.804

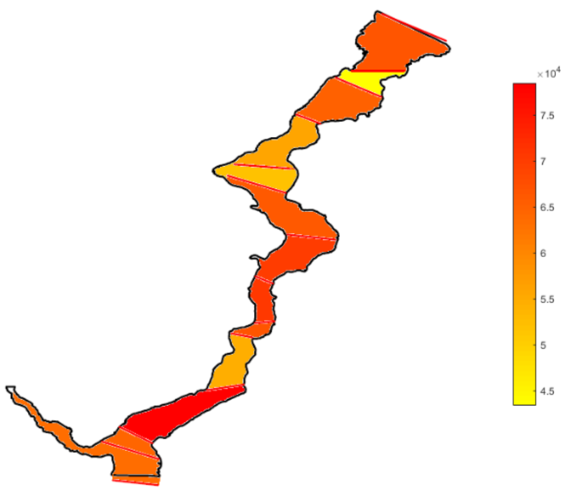

Figure 6.2. Annual Number of Ship Travels.

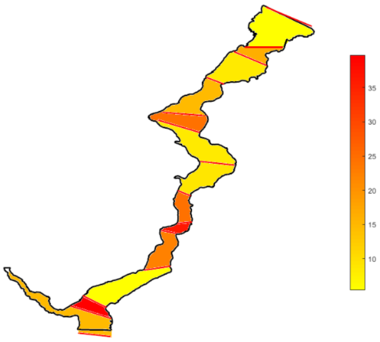

Figure 6.3. Ship Density (Number of Ships/hr/nm^2).

The annual number of ship passages and ship density, which is the number of ships entering the sector per hour per nautical mile square, are given in Figure 6.2 and Figure 6.3. According to Table 6.2 and Figure 23, Sector 3 has the highest number of ships and Sector 12 has the lowest number of ships. When ship density is considered, Sector 2 and 3 have the most and least dense traffic respectively. Sector 3 is the longest sector, which explains the highest number of ships and least dense traffic.

6.1.2. Lateral Distribution of Ships

After finding number of ships travelling in the Strait, the next important thing is the usage pattern of the sectors. Ships in transit way traffic follow a certain pattern during their Strait voyage. Captains decide their ways through each sector according to navigational conditions within the sector.

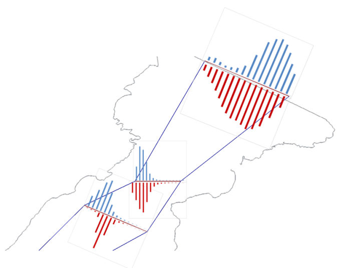

Figure 6.4. Lateral Distribution of Ships on Sector Border Lines 12, 13 and 14.

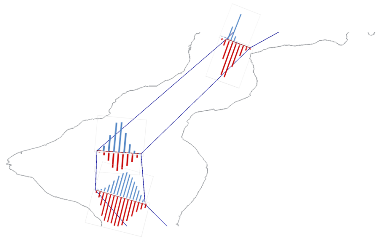

Figure 6.5. Lateral Distribution of Ships on Sector Border Lines 9, 10 and 11.

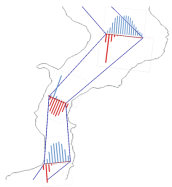

Figure 6.6. Lateral Distribution of Ships on Sector Border Lines 6, 7 and 8.

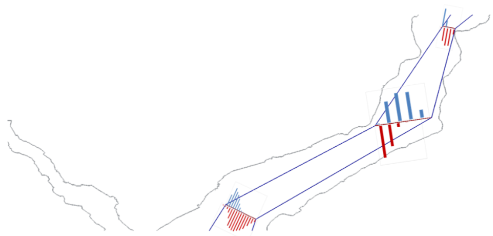

Figure 6.7. Lateral Distribution of Ships on Sector Border Lines 3, 4 and 5.

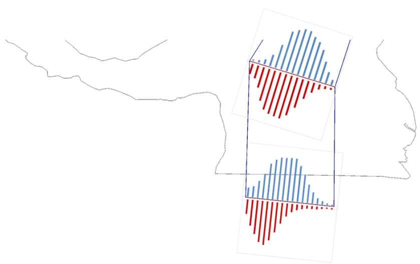

Figure 6.8. Lateral Distribution of Ships on Sector Border Lines 1 and 2.

As a general finding, captains decide ship's position in the sector according to the maneuver planned for the next sector. If a maneuver is not needed, ships are normally distributed along the sector lines. If the ship approaches a bent or a shoal in the next sector, the position distribution at the sector line is skewed. The deviation gets smaller according to the bent angle. Also as the passage gets narrower, ships tend to use the same portion of the sector, they do not spread through the sector.

6.1.3. Ship Type

Ship types are classified and shown in Figure 6.9.

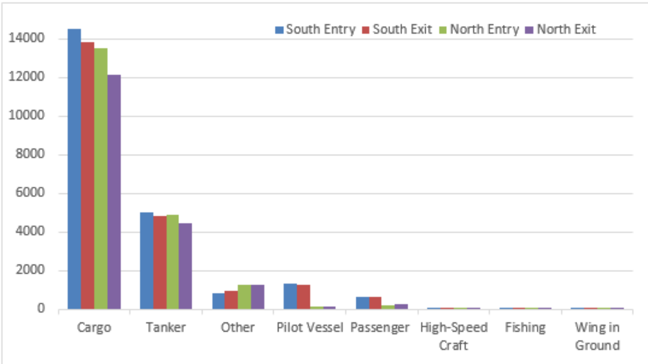

Figure 6.9. Yearly Ship Type Distribution.

The most common ship type according to AIS data is the cargo ships. Following cargo ships, the second most common ones are the tankers and other ships. Pilot vessels and passenger ships are mostly observed at south entry. Number of high speed crafts in the Strait of Istanbul is very low.

6.1.4. Ship Dimensions

Ship dimension analysis contains length over all (LOA), beam and draught of the ships. In order to eliminate error messages threshold values are set. Analysis are done for LOA with 20m interval and 10m threshold value; beam with 5m interval and 5m threshold value; draught with 3m interval and 1m threshold value. Plot of the parameters are given in Figure 6.10.

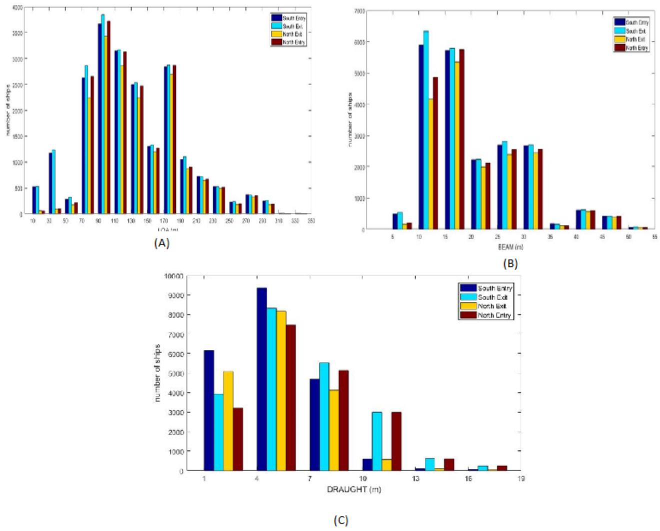

Figure 6.10. Yearly Ship Dimension Distribution.

LOA distribution for the north entry peak value is at 110m and number of ships are decreasing and a second peak is observed at 190m. When number of ships are compared at south and north sectors, there is a big difference between 20-70m and gap diminishes at 220m. The reason is mainly, LOA of the ships navigating in cross traffic is in that range and Sector 1 has a higher cross traffic.

Figure 6.10(b) shows the yearly beam distribution of the ships. At south and north entry the peak value is 10 m and15m respectively. Number of ships with 25m and 30m beam is half of the peak. In both entries, the number of ships difference between south entry and north entry ships at each sector consistently stays until 30m.

Figure 6.10(c), shows yearly draught distribution of the ships for north and south entries. Number of ships according to draught values, shows similar patterns in terms of travel direction (south entry, north entry). Peak value for the south entry ships is at 4m and a sharp decrease is observed for higher values. But for the north entry ships the peak is between 4m and 7m range. In the north entry direction, number of ships for draughts of 7m and higher are greater than the south entry ships. This means the number of loaded ships in the north entry direction are greater than the south entry ships. In other words, there is a net transfer of goods from Black Sea to Marmara Sea direction. Also in the south entry, number of ships with the same draught is higher until 10m. The main reason for this gap is Haydarpasa and Galata Port which are located at the southern sectors of the SOI.

6.1.5. Speed Over Ground (SOG)

SOG values are analyzed from AIS data and presented in Figure 6.11. During the analysis, SOG values are plotted with 1 knot interval and the minimum threshold value is 2 knots.

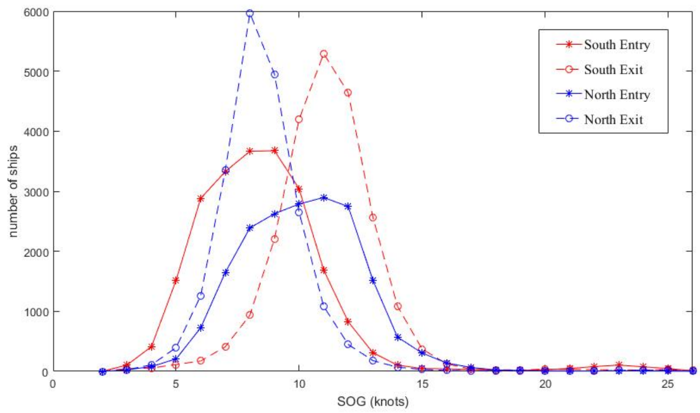

Figure 6.11. Yearly Speed over Ground (SOG) distribution.

At the south entry, the peak value for exiting ships is 8-9 knots and for north entry direction peak value is 11knots and both direction shows a skewed normal distribution. One of the main causes for the speed difference in north entry and south entry direction is the dominant current direction which is predominantly from north to south. The other reason is, 10 knots speed limit is applied for the ships exiting from SOI.

The peak value for the north entry ships is 8 knots and for the south entry ships is 11 knots. The main reason for the speed difference between the directions, north entry ships are coming from the mooring places and they cannot reach the travel speeds of south entry ships leave the SOI after the north sector and boat speed is not restricted.

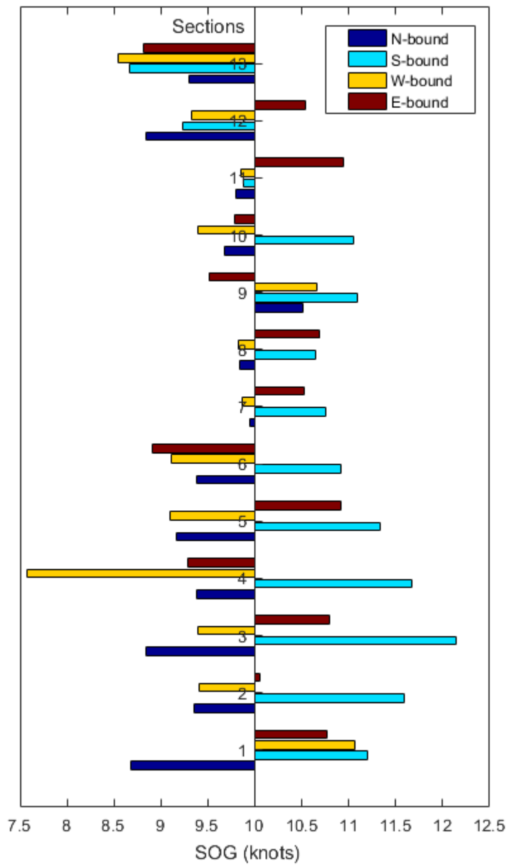

Figure 6.12. Average SOG through Sectors.

Figure 6.12 shows the SOG behavior and deviation from the speed limit, which is given as 10 knots, throughout the SOI. But for maneuver purposes, captains may increase their speed. Average SOG value of north entry ships are higher than the south entry ships except for Sector 13. Predominant current direction in the Strait (to the south), is the main reason for the higher SOG of north entry ships.

6.1.6. Course over Ground (COG) and Heading

COG and heading are analyzed with 50 resolution from the AIS database and plotted in Figure 6.13 and Figure 6.14 respectively.

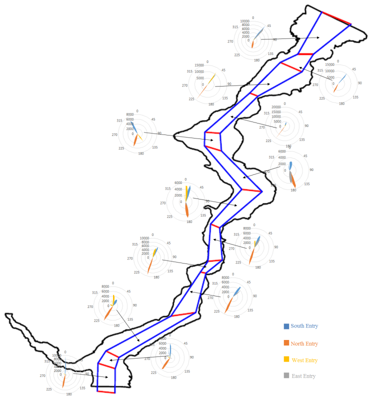

Figure 6.13. Yearly Course over Ground (COG) Distribution.

North entry ships at the south exit of the Strait leave the SOI with a COG of 185^{o}N, because they cannot navigate to west before the separation buoy, which is 1nm south of the exit. South entry ships in Sector 1 travel 0^{o}N in order to navigate through the SOI.

At the north exit, ships travel to 40^{o}N which is mainly travel direction. North entry ships travel to 200^{o}N in order to navigate in the SOI in the southwesterly direction.

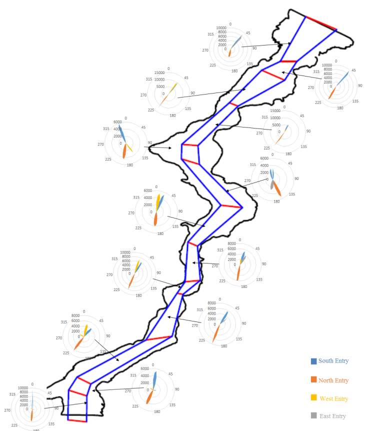

Figure 6.14. Yearly Heading (HDG) Distribution.

According to Figure 6.14, heading values at south and north entries show similar patterns with the COG values for both south entry and north entry directions. This shows that the cross current effect on ships is very limited and also those ships do not make maneuvers while entering and leaving the Strait.

Comparison of the Figure 6.13 and Figure 6.14 gives the courses that are used through the Strait. Cross traffic is mostly effected by the cross current. When both figures are compared with each other, places and traffic directions that are mostly affected from current are Sectors 5, 8 and 9.

According to database, southern sectors have a denser maritime traffic, because of the higher local traffic in southern sectors. LOA and beam distributions show that small ships dominate in the southern sectors. Analysis of SOG, COG and heading shows the effect of surface current on ships. According to SOG distributions, ships navigate at speeds between 7.5-12.5 knots. North entry ships go faster than the speed limit where the currents are strong. Another important finding is the cross current effect. Sectors that are exposed to cross current are found as Sectors 5, 8 and 9. In terms of ship types, southern sectors have more pilot boats and passenger ships. One of the most important outcome is the transfer of good direction in the Strait. The direction is found according to the draught difference between the south entry and north entry. Draught of the north entry ships are higher which means they are loaded.

6.2. Approach Angle

One of the important things during the geometric collision probability calculations is the approach angle of the ships. Approach angle not only affect the collision type but also the collision diameter. Along the Strait, approach angles change significantly. In this section, approach angles are discussed from north to south.

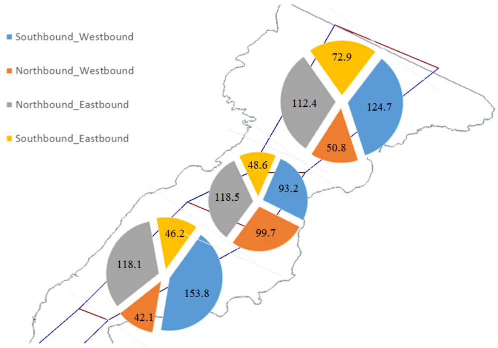

Figure 6.15. Approach Angles of Sector 11, 12, 13.

Approach angle of ships in Sectors 11, 12 and 13 are given in Figure 6.15. In Sector 13, angles are wide for north entry - east entry and south entry - west entry approaches. South entry - east entry approach is narrower with respect to north entry - west entry. At Sector 12, approach angles for north entry - east entry and south entry - west entry directions are similar. But north entry -west entry approach angle gets narrower and south entry - east entry gets wider. In Sector 11, north entry - east entry approaches are nearly head-on courses. Also south entry - west entry approach is a wide angle. But north entry - west entry and south entry - east entry approaches are very narrow.

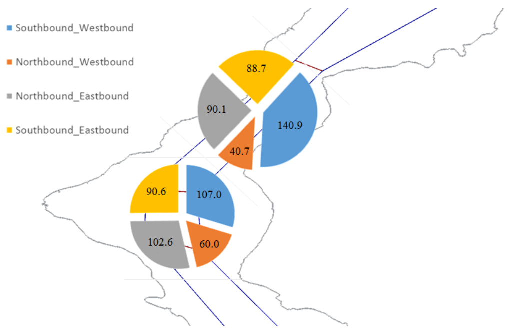

Figure 6.16. Approach Angles of Sector 9 and 10.

Figure 6.16 shows the approach angle of ships in Sectors 9 and 10. Sector 10 shows a similar pattern as Sector 13. However Sector 9 approach angles are more uniformly distributed. The heading of the south entry ships in Sector 9 slightly differ from the uniform distribution.

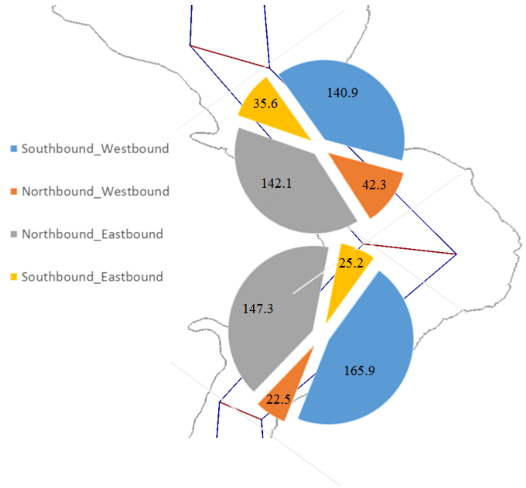

Figure 6.17. Approach Angles of Sector 7 and 8.

Sectors 7 and 8 show different characteristics in terms of cross traffic headings. Figure 6.17 shows that the cross traffic follows almost the same heading as the transit traffic. As a result, north entry - west entry and south entry - east entry approach angles are very narrow.

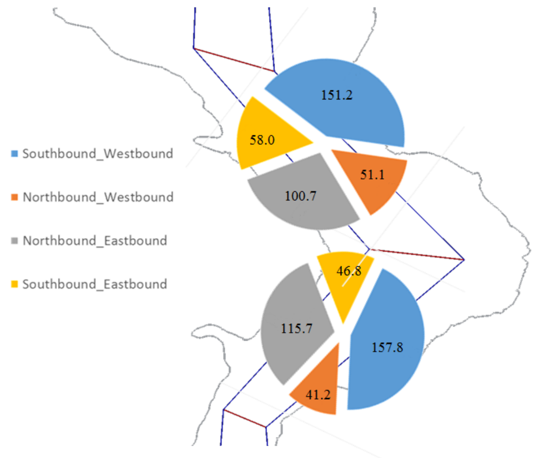

Figure 6.18. Approach Angles of Sectors 5 and 6.

Sectors 5 and 6 have double bends. Therefore, transit way ships make sharp maneuvers during the passages through these sectors. According to Figure 6.18, north entry - east entry approaches are nearly head-on for both sectors. Also south entry - west entry approach angles are wide for both of these sectors. The other two approach angles are narrow and change slightly from sector to sector.

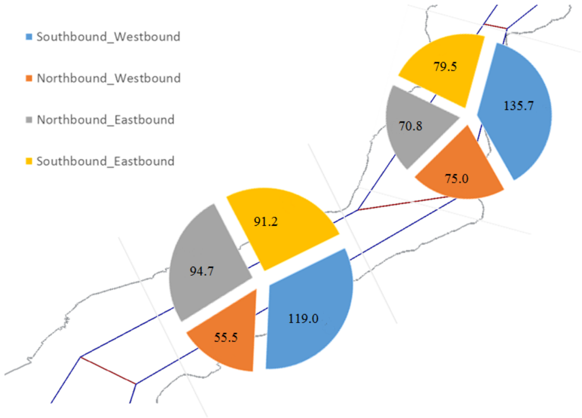

Figure 6.19. Approach Angles of Sectors 3 and 4.

Approaches in Sectors 3 and 4 are nearly uniformly distributed except north entry - east entry direction. According to Figure 6.19, north entry - east entry approaches are wide angle and south entry - east entry approaches are narrow angles. The other two directions are nearly 90 degrees.

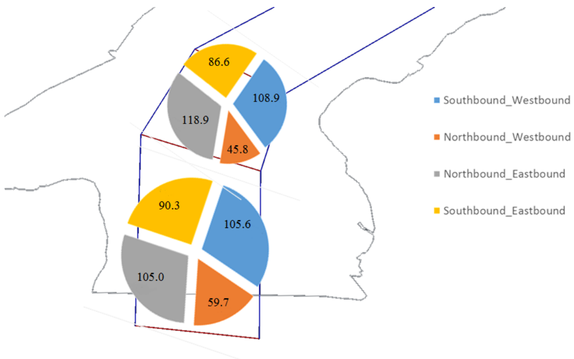

Figure 6.20. Approach Angles of Sectors 1 and 2.

Sectors 1 and 2 show similar patterns as in Sectors 3 and 4 except for the south entry - west entry direction. According to Figure 6.20, north entry - east entry and south entry - west entry directions have wide approach angles and south entry - east entry approach angles are narrow in both sectors.

Overall analysis show that east entry ships have a tendency to travel in northern direction. The main reason is the surface current which flows predominantly from north to south. In order to overcome the effect of the current, east entry ships' headings are closer to south entry ships. Also upcoming bends change the ship's approach angle dramatically. In some sectors, cross direction ships are observed as nearly on head-on collision course.

6.3. Collision Diameter

As describe in Section 2.4.3, collision diameter is a function of LOA, beam, approach angle and relative velocity of the ships. Collision diameters along the Strait are given in Figure 6.21 and Figure 6.22. The most fluctuating parameter along the Strait is the approach angle of the ships. Therefore, approach angle is the decisive parameter for collision diameter.

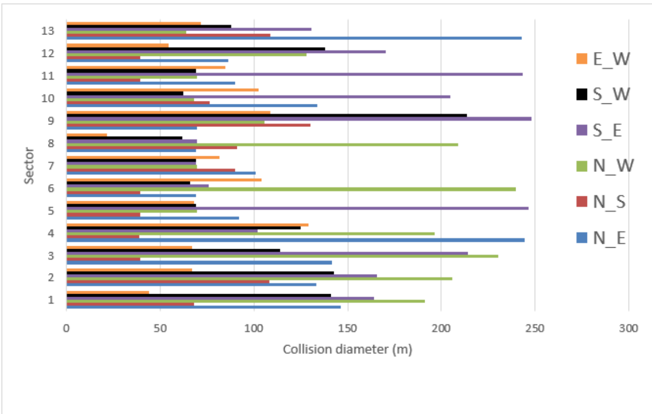

Figure 6.21. Collision Diameters through the SOI.

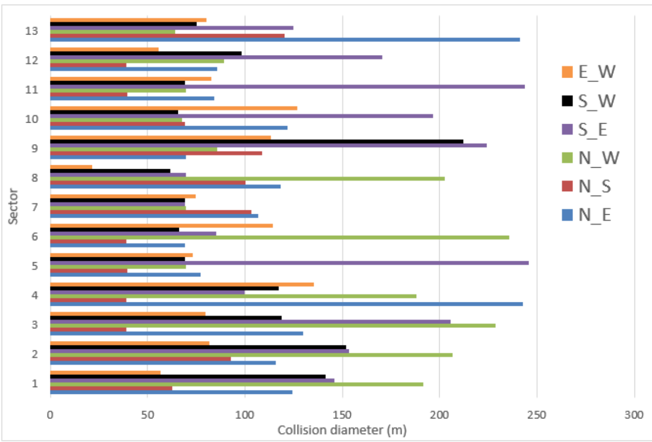

Figure 6.22. Modified Collision Diameters through the SOI.

Collision diameters of ships vary from 30 meters to 250 meters along the Strait. The modified collision diameter approach change the collision diameter up to 70%. Figure 6.22 shows that modified collision diameter mostly decreases the value for cross directions and increases for the head-on collision especially west entry - east entry approaches. A significant and consistent decrease is observed in south entry - east entry collision diameter. Since the heading of the east entry ships are much closer to south entry ships, projection of the east entry ship on the collision diameter plane gets smaller, this causes a drop in the collision diameter. A big change is observed in the south entry - west entry collision diameter at Sector 8. The cause is, Sector 8 is between two bends which increases the maneuver rate of ships. Also cross currents in Sector 8 has a strong effect on the ships. Combination of these two effects increases the deviation of COG and heading of the ships. Therefore, a dramatic change in the collision diameter is observed at Sector 8 for south entry - west entry ships.

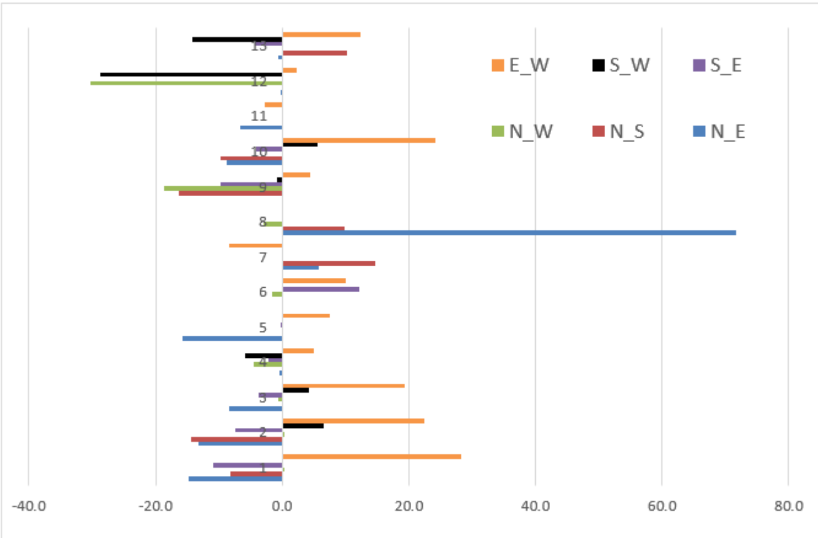

Figure 6.23. Deviation of Proposed Collision Diameters from Pedersen (1995).

6.4. Geometric Collision Probability Results

Final output of this study is the spatial distribution of geometric collision probability along the Strait. Since the collision is a rare event, more than one collision at the same time is not considered in the study. In this section, first geometric collision probability with modified and unmodified collision diameter and the change through the Strait are mapped. Then, the geometric collision probability of south entry and north entry ships are compared. Next, accident probabilities are discussed in different to sectors. Finally seasonal changes are compared.

Geometric collision probability map of the Strait is given in Figure 45 and Figure 46. In most of the sectors geometric collision probability increases from the sector border to the middle of the waterway. Since, transit ships are travelling within the Traffic Separation Scheme (TSS), ship density increases toward central points. Inside the TSS, accident probabilities change according to lateral distribution of the ships. Figure 47 shows the comparison of the two collision diameter approaches. In Sectors 9 and 10, there is a big decrease in the geometric collision probability with the modified collision diameter. An increase is observed at the southern part of the Sectors 4 and 8. Sector 1, has also a decrease in the geometric collision probability. The overall geometric collision probability for one ship inside the Strait is 0.3257 and 0.3241 with unmodified and modified collision diameter respectively. When geometric accident probabilities are observed for direction case, for south entry ships 0.1378, for north entry ships 0.1294 and the remaining part 0.0585 is the geometric collision probability for the cross traffic. Results of the modified collision diameter approach geometric accident probabilities for south entry ships 0.1354, for north entry ships 0.1274 and the remaining part 0.0613 is the geometric collision probability for the cross traffic. The modified collision diameter increases the cross-traffic geometric collision probability as it can be predicted from the changes in the collision diameter and decreases the south entry and north entry ships. Although the geometric collision probability of the cross traffic is nearly half of the south entry or north entry ships, the total number of cross traffic ships are nearly 5 times larger. Therefore, the effect of cross traffic is higher in the overall geometric collision probability.

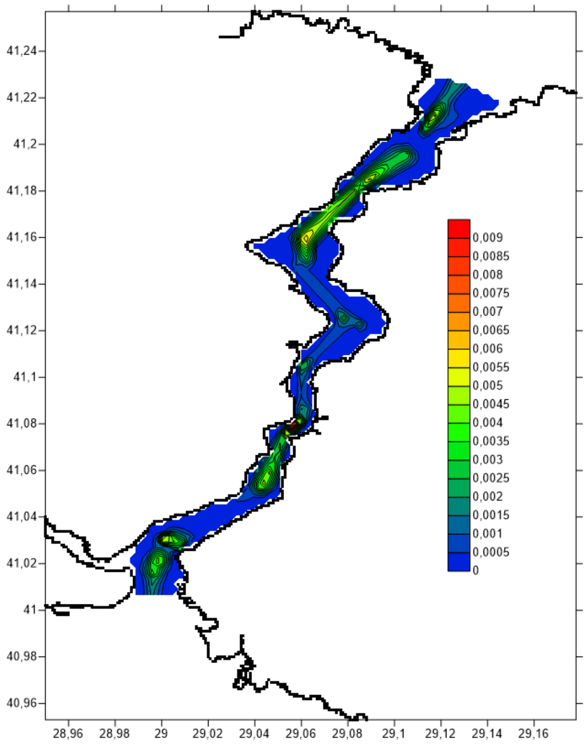

Figure 6.24. Geometric Collision Probability Map.

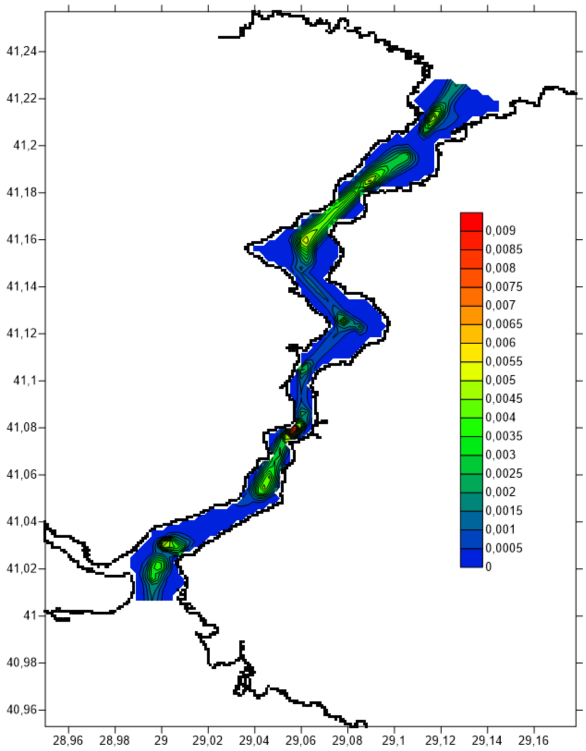

Figure 6.25. Geometric Collision Probability Map with Modified Collision Diameter.

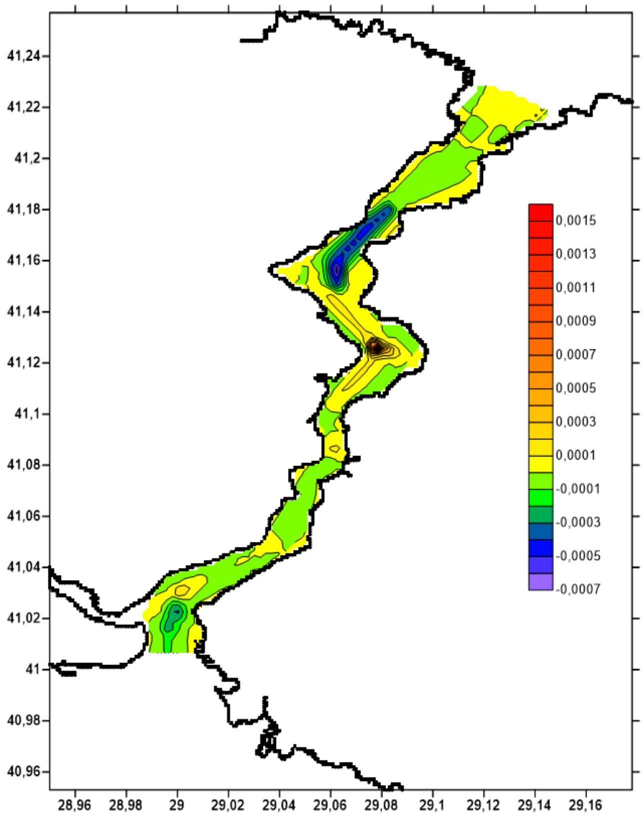

Figure 6.26. Deviation of Geometric Collision Probability from Pedersen (1995).

Spatial distribution of geometric collision probability indicates the accident hot spots along the Strait. But for the overall understanding, a general approach is needed for the geometric collision probability of the Strait. Therefore, Table 6.3 is prepared for the geometric collision probability per sector. When the table is observed for normal collision diameter approach, Sectors 10 and 12 have the highest and lowest geometric accident probabilities respectively. Sectors 13, 3, 11 and 4 are above average for geometric collision probability. For the modified collision diameter approach, the highest and lowest sectors do not change. Change is observed for the sectors above average as Sectors 13 and 3. Also Sector 7 passes, Sector 9 in terms of geometric collision probability.

Geometric collision probability per sector gives a good overview of the Strait in terms of which sectors are more prone to accidents. However, these probabilities are biased with the size of the sector. In order to eliminate the area effect, geometric collision probability per sector is divided by the area of the sector. So geometric collision probability per nautical mile square can be found. Table 6.4 gives an idea of the attention needed for each nautical mile of the sectors. According to Table 6.4, Sector 10 has the highest geometric collision probability for each nautical mile square and Sector 12 has the lowest value. Sector 4, 5, 2 and 9 are above the average value. With the modified collision diameter approach Sector 4 has the highest geometric collision probability for each nautical mile and lowest is Sector 12. Sectors 10, 5 and 2 are above the average and the order changes between 8 and 13 and also 6 and 1.

Table 6.3. Geometric Collision Probability per Sector.

	Geometric probability with normal collision diameter	Geometric probability with modified collision diameter	Change in geometric collision probability (%)
1	0.025818	0.02412	-6.58
2	0.022889	0.021384	-6.58
3	0.043374	0.043975	1.39
4	0.038238	0.038102	-0.36
5	0.027059	0.026751	-1.14
6	0.017163	0.017581	2.43
7	0.019106	0.020686	8.27
8	0.027789	0.033605	20.93
9	0.020182	0.017747	-12.07
10	0.059426	0.054433	-8.4
11	0.038438	0.038316	-0.32
12	0.00334	0.003305	-1.07
13	0.044146	0.044666	1.18
average	0.029767	0.02959	-0.18

Table 6.4. Geometric Collision Probability per Sector per nm^2.

	Geometric collision probability per nm2 with normal collision diameter	Geometric collision probability per nm2 with modified collision diameter	Change in geometric collision probability (%)
1	0.056602338	0.053407984	-5.64
2	0.123722927	0.110365549	-10.8
3	0.026081661	0.026904777	3.16
4	0.136117185	0.138003317	1.39
5	0.12816421	0.127154558	-0.79
6	0.052249901	0.053876514	3.11
7	0.021084561	0.023027632	9.22
8	0.031115767	0.038152021	22.61
9	0.082549379	0.071349717	-13.57
10	0.139943646	0.131384101	-6.12
11	0.042632582	0.043235073	1.41
12	0.01088281	0.010781212	-0.93
13	0.033580745	0.034436447	2.55
average	0.068055978	0.066313762	0.43

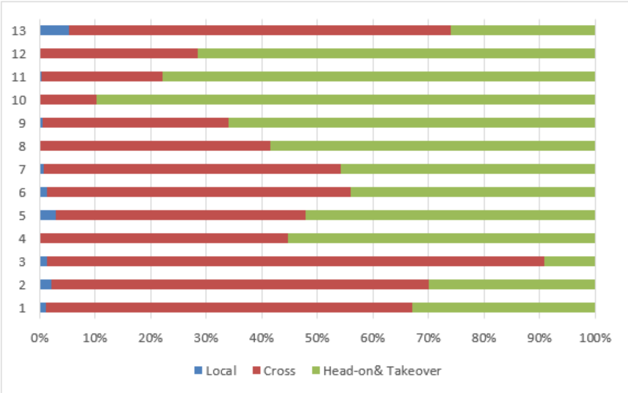

Figure 6.27. Geometric Collision Percentage per Sector.

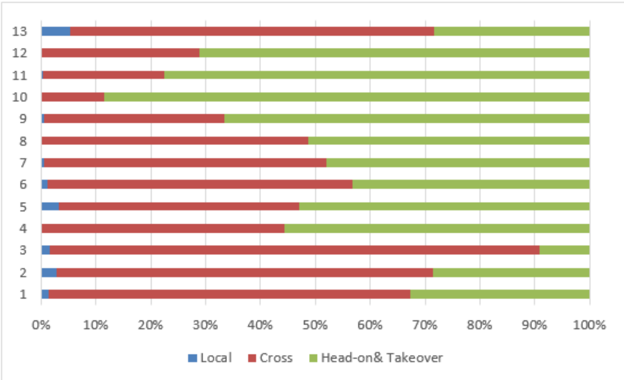

Figure 6.28. Geometric Collision Percentage per Sector Suggested Collision Diameter.

The probability of occurrence of different collision types are given in Figure 6.26 and Figure 6.27, for Pedersen's and present collision diameter respectively. From the figures, the effect of the cross traffic density can be seen. Geometric collision of the local ships which a ship belongs to cross-traffic collides to a ship also belongs to the cross-traffic. Since the collision diameters and encounter rates are small compared to other types, geometric collision probability of the cross traffic do not reach 10%. Cross collision means, cross-traffic ship collides to a ship which travels in the transit way. Especially at Sector 3, geometric cross collision probability is nearly 85%. Head-on & take-over collision contains the collision of the ships that are traveling at the transit direction. In Sector 10 nearly 85% of the geometric collision probability is head-on & take over type collisions. With the decrease of the collisions that at least one of the ships belong to cross traffic, head-on and takeover collision probabilities increase relatively. Also with the increase of the collision diameter which is related with the approach angle of the ships.

Seasonal variation of geometric accident probabilities are analyzed and plotted in Figure 6.28, through Figure 6.30. In fall, geometric collision probability is 0.1077 and 0.1074 for unmodified and modified collision diameter respectively. In winter, geometric accident probabilities become 0.0894 and 0.0887. For the spring season, geometric accident probabilities become 0.0946 and 0.0935. Finally in the summer geometric accident probabilities become 0.1037 and 0.1029.

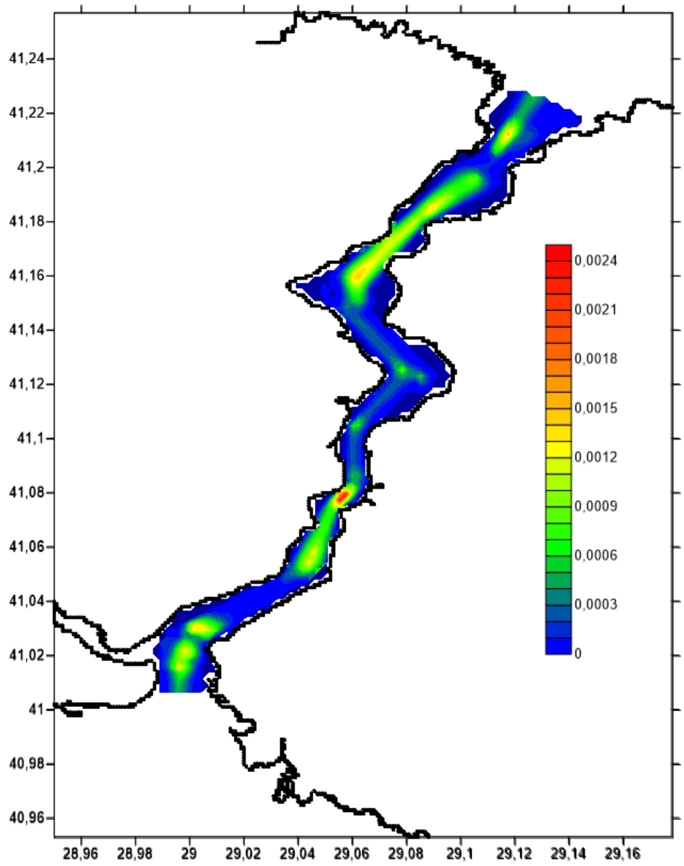

Figure 6.29. Geometric Collision Probability map for fall.

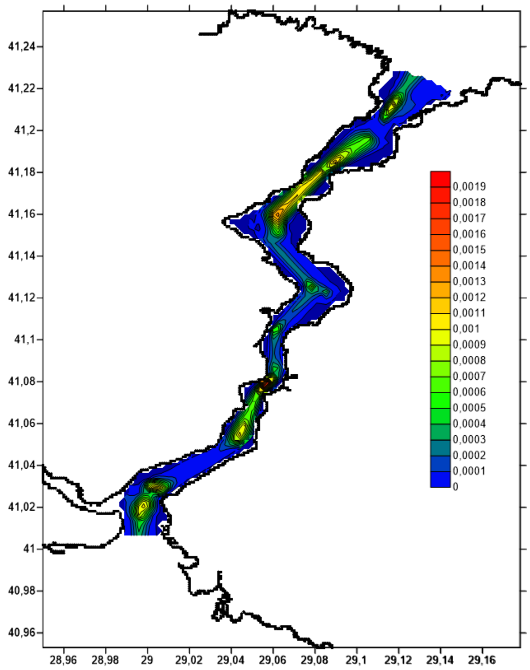

Figure 6.30. Geometric Collision Probability map of winter.

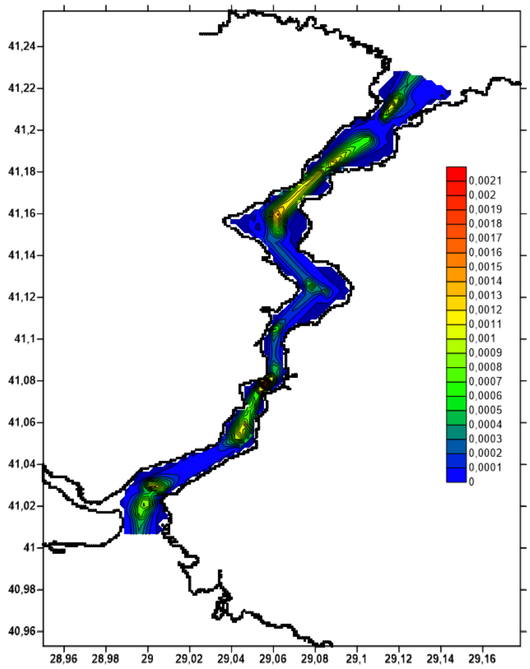

Figure 6.31. Geometric Collision Probability map of spring.

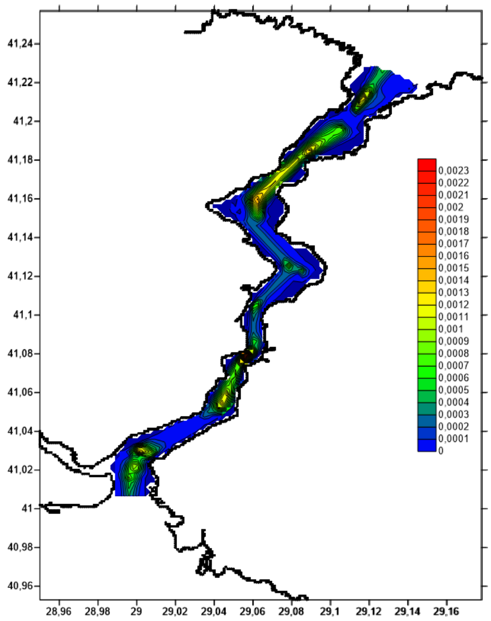

Figure 6.32. Geometric Collision Probability map of summer.

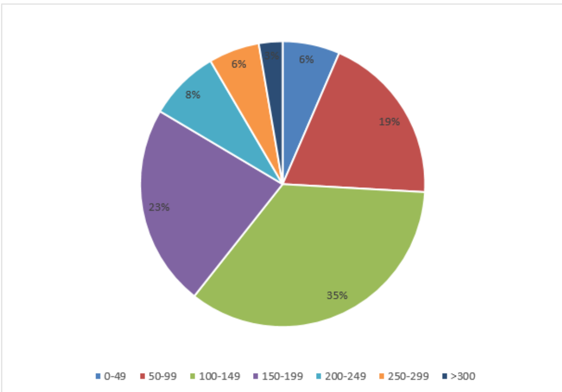

Figure 6.33. Geometric Collision Probability in Terms of LOA.

Geometric collision probability distribution of accidents in terms of LOA is given in Figure 6.32. When geometric collision probability is analyzed in terms of LOA, the most expected collision probability is observed for LOA between 100-149m. In Figure 6.33, geometric collision probability distribution along the SOI in terms of LOA is given. Since it is the narrowest point of the SOI and the most common ship type, the peak point is at Sector 5 for LOA 100-149m.

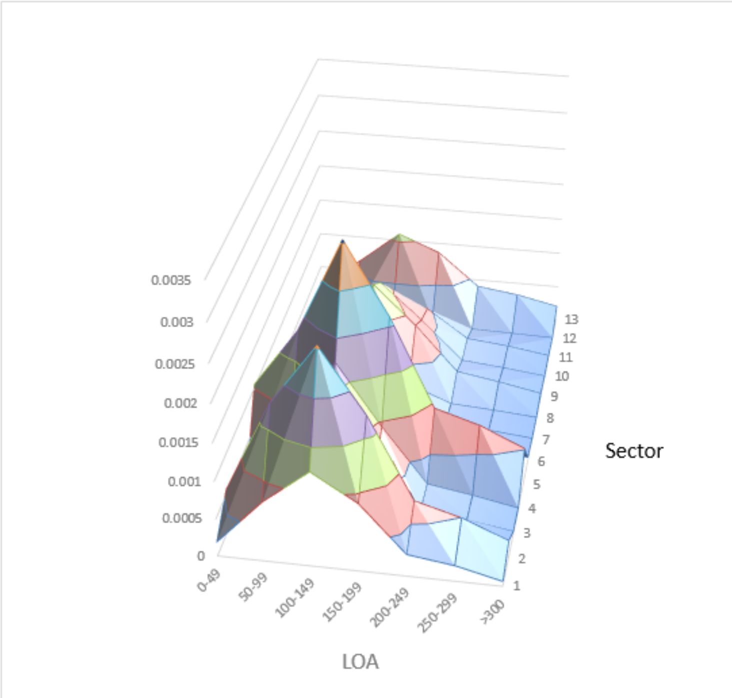

Figure 6.34. Geometric Collision Probability Distribution along the sectors in terms of LOA.

Scaled collision probability of one ship in terms of most common LOA (100m-149m) is given in Figure 6.34. As the LOA increases, collision probability increases as expected. But for the ships longer than 300, collision probability increases 6.58 times the most expected LOA.

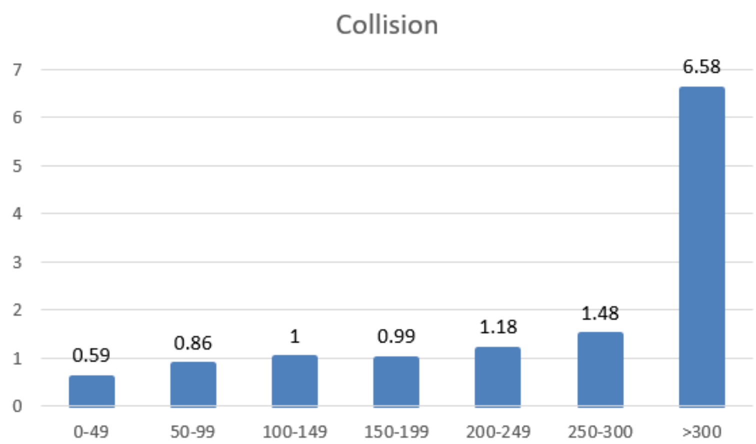

Figure 6.35. Collision Probability of ships in terms of the most common LOA.

6.5. Comparison of Results

There are two past studies for the accident probability map of the Strait. One of them is result of a physic based approach and the other one is the map of past accidents. Figure 6.34 shows the result of the physic based approach of the ships. It shows higher accident probability rate at Sariyer and Kanlica and also Bebek- Kandilli and Besiktas - Üsküdar. Figure 6.35 shows the past collision accidents from 1982 to 2003. Eminönü - Kadiköy, Üsküdar - Besiktas, Rumelihisari - Bebek- Kandilli, Kanlica - Yeniköy, Beykoz, Sariyer and north entry of the Strait has past accident records. Figure 6.23 and Figure 6.24 finds the hotspots as given in the past studies.

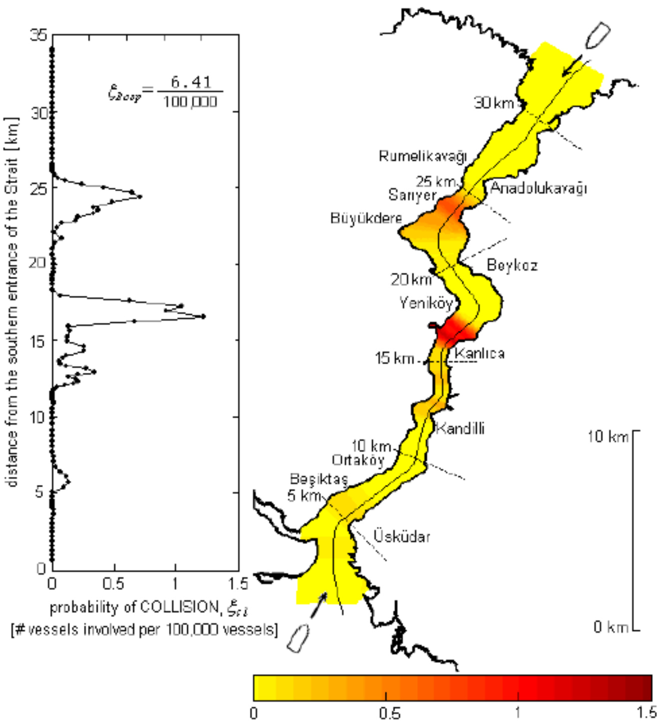

Figure 6.36. Probability of collision through the Strait of Istanbul (Otay and Ozkan 2009).

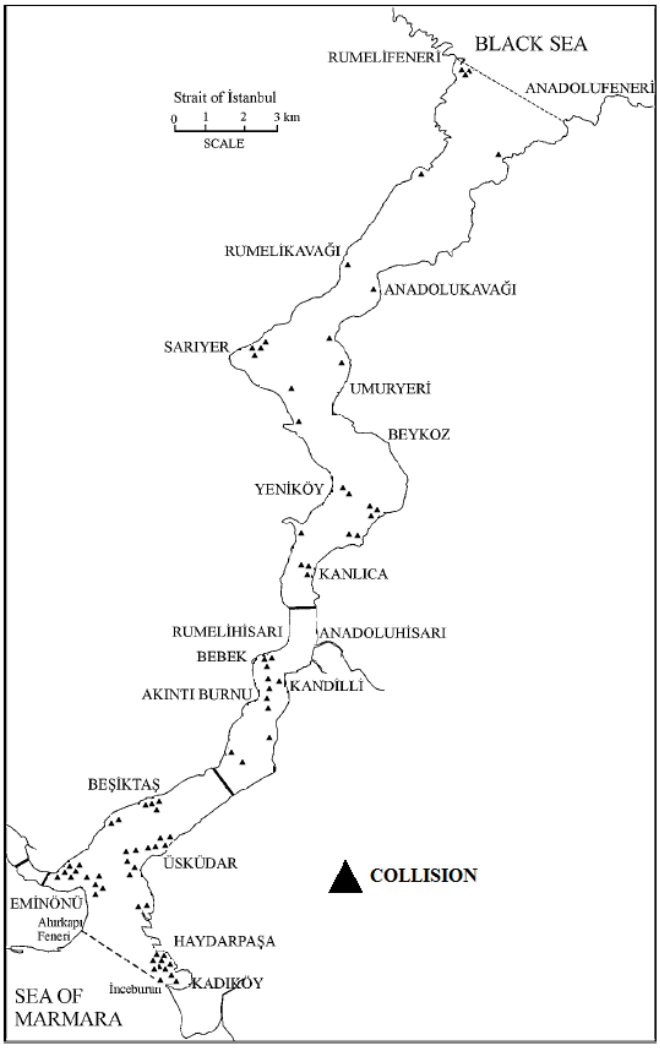

Figure 6.37. Marine accidents in the Strait of Istanbul (1982-2003) (Akten, 2004).

7. COMMENTS AND CONCLUSIONS

In this thesis, maritime traffic collision probability of the SOI is presented. A framework for the geometric collision theory is proposed, implemented and results are mapped. The mapped results show the spatial distribution of the geometric collision probability through the SOI so the captains and the stakeholders can quantify and assess the probabilities quickly. One more advantage of the mapped the collision probabilities is that, captains can decide their routes through the SOI in order to minimize the collision probability. In addition to the theories in the literature, the missing parts of the geometric collision theory is improved for the cross current and maneuver cases which are highly observed in the SOI.

This study is an application of the maritime collision theory to the congested narrow waterway. It has two main parts, one of them is the maritime traffic and the other one is the geometric collision probability modeling. Maritime traffic part contains, long term data processing and finding the traffic characteristics in the Strait of Istanbul. Geometric collision probability modeling is the usage of maritime traffic data according to collision theory.

For a realistic representation of the maritime traffic, continuous one year data is used and analyzed in terms of ship type and dimensions, SOG, COG, heading and traffic density. It is found out that north entry ships have a tendency to travel faster than other directions. Navigation patterns in terms of lateral distribution of the ships, captains decide their heading according to planned position for the next sector. Also another important finding is the transfer of goods from north to south. Cross traffic determines the ship density of the sector.

Geometric collision probability result shows the most probable accident locations. It matches with the past studies and accident locations. One more improvement is the 2 directional positioning of the geometric collision probability map. So the captains can decide their lateral position in the sector for minimizing the collision probability.

The other improvement is the modified collision diameter. The proposed collision diameter represents the cross current and maneuver cases. The overall result changed very slightly because of increases and decreases in the collision diameter. But it shows more accurate results especially at the bend locations.

According to geometric collision probability results Sector 10 is the most accident probable sector at the Strait, according to two collision diameter approach. In terms of geometric collision probability per sector per nm^2 order Sector 4 contains the most accident probable nautical miles of the Strait. The highest probability cell is observed at Sector 5. Cross traffic affects the geometric collision probability twice, first one is the collision of locals and the second one is the collision with the transit traffic. The sectors which contains double bends has the highest collision probabilities. During the maneuvers both collision diameter and the cross current effect increases. With the modified collision diameter improvements up to 70% is observed.

Also when the geometric collision probability is observed in terms of LOA, the most expected collision probability is between 100-149m which is also the most expected LOA for the SOI. For the LOA and sector distribution of the geometric collision probabilities, Sector 5 with LOA 100-149m has the highest collision probability. When the scaled collision probability of one ship in terms of most common LOA (100m-149m) is observed a big jump observed for the LOA larger than 300m.

The proposed framework can be applied to all congested narrow waterways. Improvements can be done for the dynamic collision probability. By using real-time maritime traffic data dynamically changing collision probabilities can be calculated and mapped. But this dynamic mapping process needs a fast algorithm. With the applied methodology calculation process takes 720 hours with one year continuous maritime traffic data. Also short term future predictions for the collision probability can be done by predicting the behavior of the ship captains. Predicting near future will need a bigger database and captain behavior analyze algorithms. From the entrance pattern of the ship, navigation pattern through the SOI can be predicted and collision probability of ship can be calculated before it enters the related sector.

REFERENCES

Aarsaether, K.G., T. Moan, 2009, “Estimating Navigation Patterns from Association for Information Systems”, *Journal of Navigation*, Vol. 62, No. 04, pp. 587-607.

Akten, N., 2004, “Analysis of Shipping Casualties in the Bosphorus”, *Journal of Navigation*, Vol. 57, No. 03, pp. 345-356.

Aydogdu, Y.V., C. Yurtoren, J.S. Park, and Y.S. Park, 2012, “A Study on Local Traffic Management to Improve Marine Traffic Safety in the Istanbul Strait”, *Journal of Navigation*, Vol. 65, No. 01, pp. 99-112.

Baltic Marine Environment Protection Commission, 2012. “Baltic Marine Environment Protection Commission recommendation 33/1 - unified interpretation in relation to access to and use of Baltic Marine Environment Protection Commission Association for Information Systems”, *Helsinki Commission*, Baltic Marine Environment Protection Commission.

Bone Marrow Transplantation, 2004, “Marine Traffic Risk Assessment for Hong Kong Waters”, Report prepared for the Hong Kong Marine Department by Bone Marrow Transplantation, *Asia Pacific Limited Replimited* No. R/8152/20, Issue 1.

Braem, T.A. 1974, “A Simulation Model of Marine Traffic Flow with Particular Application to Rosario Strait Doctoral Dissertation”, University of British Columbia.

Cowi, A.S. 2008, “Risk Analysis of Sea Traffic in the Area around Bornholm”, *Kongens Lyngby*, Denmark: Cowi A.S., Report # P-65775-002.

Draper, J., and C. Bennett, 1972, “Modelling Encounter Rates in Marine Traffic Flows with Particular Application to the Dover Strait”, *Journal of Navigation*, Vol. 25, No. 03, pp. 381-382.

Fowler, T.G., E. Sørgård, 2000, "Modeling Ship Transportation Risk", *Risk Analysis*, Vol. 20, No. 2, pp. 225-244.

Fujii, Y., R. Shiobara, 1971, "The Analysis of Traffic Accidents", *Journal of Navigation*, Vol. 24, No. 04, pp. 534-543.

Fujii, Y., H. Yamanouchi, 1974, "IV-Visual Range and the Degree of Risk", *Journal of Navigation*, Vol. 27, No. 02, pp. 248-252.

Geng, B., H. Wang, J. Wang, 2009, "Probabilistic Model for Vessel-Bridge Collisions in the Three Gorges Reservoir", *Frontiers of Architecture and Civil Engineering in China*, Vol. 3, No. 3, pp. 279-285.

Gramling, R., C.J. Forsyth, G. Wooddell, 1998, "Expert Informants and Relative Risk: A Methodology for Modeling Waterways", *Risk Analysis*, Vol. 18, No. 5, pp. 557-562.

Gucma, L., E. Goryczko, 2008, "The Implementation of Oil Spill Costs Model in the Southern Baltic Sea Area to Assess the Possible Losses Due to Ships Collisions", *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 2, No. 4.

Harrald, J.R., *et al.*, 1998, "Using System Simulation to Model the Impact of Human Error in a Maritime System", *Safety Science*, Vol. 30, No. 1, pp. 235-247.

Hu, S., Q. Fang, H. Xia, and Y. Xi, 2007, Formal Safety Assessment Based on Relative Risks Model in Ship Navigation, Reliability Engineering & System Safety, Vol. 92, No. 3, pp. 369-377.

Johansson, J., E. Molitor, 2011, "Risk Assessment of the Vessel Traffic in the Kattegat Including Effects of Traffic Separation Schemes from the Skaw to the Sound-Oil Spill Accidents Relevant for the Coast of Halland".

Kornhauser, A.L., W.A. Clark, 1995, "Quantitative Forecast of Vessel Casualties Resulting from Additional Oil Tanker Traffic Through the Bosphorus", Report, Associates, *Princeton*, New Jersey.

Kujala, *et al.*, 2009, "Analysis of the Marine Traffic Safety in the Gulf of Finland", *Reliability Engineering & System Safety*, Vol. 94, No. 8, pp. 1349-1357.

Li, H., E. Iakovou, C. Douligeris, 1996, "Strategic Planning Model for Marine Oil Transportation in the Gulf of Mexico", *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1522, pp. 108-115.

Macduff, T. 1974, "The Probability of Vessel Collisions", *Ocean Industry*, Vol. 9, No. 9.

Maimun, A., *et al.*, 2013, "Using Association for Information Systems Data for Navigational Risk Assessment in Restricted Waters", *Marine Technology and Sustainable Development: Green Innovations: Green Innovations*, Vol. 245.

Maio, D., 1991, "Port Needs Study Vessel Traffic Services Benefits", No. DOT-CG-N-01-91-1.1 Final Repo.

Martínez de Osés, F.X., N.P. Ventikos, 2003, "A Critical Assessment of Human Element Regarding Maritime Safety".

Mazaheri, A., 2009, "Probabilistic Modeling of Ship Grounding", *Helsinki University of Technology*, Vol. 1, pp. 48-56.

Meng, Q., J. Weng, S. Li, 2014, "Analysis with Automatic Identification System Data of Vessel Traffic Characteristics in the Singapore Strait", *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2426, pp. 33-43.

Merrick, J.R., R. Van Dorp, 2006, "Speaking the Truth in Maritime Risk Assessment", *Risk Analysis*, Vol. 26, No. 1, pp. 223-237.

Merrick, J.R., *et al.*, 2003, "A Traffic Density Analysis of Proposed Ferry Service

Expansion in San Francisco Bay Using a Maritime Simulation Model", *Reliability Engineering & System Safety*, Vol. 81, No. 2, pp. 119-132.

Montewka, J., T. Hinz, P. Kujala, J. Matusiak, 2010, "Probability Modelling of Vessel Collisions", *Reliability Engineering & System Safety*, Vol. 95, No. 5, pp. 573-589.

Mou, J.M., C. Van der Tak, and H. Ligteringen, 2010, "Study on Collision Avoidance in Busy Waterways by using Association for Information Systems Data", *Ocean Engineering*, Vol. 37, No. 5, 483-490.

Medical Research Council, 2010, "Constitution of Emergency Response Centers and Determination of Present Situation of Turkish Waters for Feasibility Studies", National and Regional Contingency Plans, *Specification Representative Prepared by Tubitak Marmara Research Center*, Gebze, Kocaeli.

Mulyadi, Y., E. Kobayashi, N. Wakabayashi, T. Pitana, 2014, "Development of Ship Sinking Frequency Model Over Subsea Pipeline for Madura Strait Using Association for Information Systems data", *Western Michigan University Journal of Maritime Affairs*, Vol. 13, No. 1, pp. 43-59.

Nichols, C.A.G., 1950, "Lessons From Some Collisions and Groundings at Sea", *Journal of Navigation*, Vol. 3, No. 02, pp. 166-182.

Otay, E.N., & S. Özkan, S. 2003, "Stochastic Prediction of Maritime Accidents in the Strait of Istanbul", *In Proceedings of the 3rd International Conference on Oil Spills in the Mediterranean and Black Sea Regions*, Vol. 1, pp. 92-104.

Otto, S., P.T. Pedersen, M. Samuelides, and P.C. Sames, 2002, "Elements of Risk Analysis for Collision and Grounding of a RoRo Passenger Ferry", *Marine Structures*, Vol. 15, No. 4, pp. 461-474.

Pedersen, P.T., 1995, "Collision and Grounding Mechanics", *Proceedings of Wilderness Emergency Medical Technician*, Vol. 95, No. 1995, pp. 125-157.

Proske, D., M. Curbach, 2005, "Risk to Historical Bridges Due to Ship Impact on German Inland Waterways", *Reliability Engineering and System Safety*, Vol. 90, No. 2, pp. 261-270.

Qu, X., Q. Meng, 2011, "Simulation Model for Ship Movements in Singapore Strait and Its Applications", *In Transportation Research Board 90th Annual Meeting* No. 11-0881.

Rambøll, 2011, "Navigational Safety in the Sound between Denmark and Sweden (Øresund), risk and Cost-benefit Analysis", Virum, Denmark. The Royal Danish Administration of Navigation and Hydrography, the Danish Maritime Authority and the Swedish Maritime Administration, *Rambøll Danmark A/S*, Ref, 568125, R568125-002(1).

Papadonikolaki, G.S., Y.C. Altan, A. Stamou, E.N. Otay, G.C. Christodoulou, N.K. Copty, A. Papadopoulos, 2014, "Risk Assessment of Oil Spill Accidents", *Global Nest Journal*, Vol. 16, No. 4, pp. 743-752.

Rashad, R. 1977, "Navigation in the Gulf of Suez", *Journal of Navigation*, Vol. 30, No. 03, pp. 366-377.

Sadler, D.H. 1957, "Mathematics of Collision Avoidance at Sea", *Journal of Navigation*, Vol. 10, No. 04, pp. 306-319.

Safetec, U.K., 1999, "Identification of Marine Environmental High Risk Areas in the United Kingdom Document No". ST-8639-MI-1-Rev 01.

Sariöz, K., A. Kükner, and E. Narli, 1999, "A Real-time Ship Maneuvering Simulation Study for the Strait of Istanbul Bosporus", *Journal of Navigation*, Vol. 52, No. 03, pp. 394-410.

Silveira, P.A.M., A.P. Teixeira, and C.G. Soares, 2013, "Use of Association for Information Systems data to Characterise Marine Traffic Patterns and Ship Collision

Risk off the Coast of Portugal", *The Journal of Navigation*, Vl. 66, No. 6, pp. 879.

Tan, B., and E.N. Otay, 1999, "Modeling and Analysis of Vessel Casualties Resulting from Tanker Traffic Through Narrow Waterways", *Naval Research Logistics*, Vol. 46, No. 8, pp. 871-892.

Turkish Straits Maritime Traffic Regulation, 1998, "Traffic Regulations for the Turkish Straits and the Marmara Region", Official Gazette, October 8, 1998, Issue 23515, Regulation No: 98/11860.

Ulusçu O.S., B. Özbaş , T. Altıok , I. Or , 2009, "Risk Analysis of the Vessel Traffic in the Strait of Istanbul", *National Library of MedicineNational Institutes of Health*, Vol. 29, No. 10, pp. 1454-72.

Van Dorp, J.R., J.R. Merrick, J.R. Harrald, T.A. Mazzuchi, M. Grabowski, 2001, "A Risk Management Procedure for the Washington State Ferries", *Risk Analysis*, Vol. 21, No. 1, pp. 127-142.

Wentzel, E. and D. Lytle, 1971, "Automated Marine Traffic Advisory Systems, their Needs and Implementation", *Honeywell Marine Systems Center*, Document 2330, United States of America.

Wu, L., Y. Xu, Q. Wang, F. Wang, Z. Xu, 2017, "Mapping Global Shipping Density from Association for Information Systems Data", *Journal of Navigation*, Vol. 1, pp. 1-15.

Wylie, F.J. 1956, "The Region of Collision", *Journal of Navigation*, Vol. 9, No. 02, pp. 161-170.

Wylie, F.J. 1962, "Mathematics and the Collision Regulations", *Journal of Navigation*, Vol. 15, No. 01, pp. 104-112.

Yazici, M.A., E.N. Otay, 2009, "A Navigation Safety Support Model for the Strait of

Istanbul", *Journal of Navigation*, Vol. 62, No. 04, pp. 609-630.

Ylitalo, J., 2010, "Modelling Marine Accident Frequency Doctoral dissertation", Aalto University.

Yurtoren, C., Y.V. Aydogdu, and C. Atasoy, 2014, "Izmit Körfezi Deniz Trafik Akisinin Analizi", I. National Vessel Traffic Services Conference, 8-9 December.

Zaman, M.B., E. Kobayashi, N. Wakabayashi, S. Khanfir, T. Pitana, A. Maimun, 2014, "Fuzzy Failure Mode and Effects Analysis Model for Risk Evaluation of Ship Collisions in the Malacca Strait: Based on Association for Information Systems Data", *Journal of Simulation*, Vol. 8, No. 1, pp. 91-104.

Zhanghao, Xiaoyingjie, and Yangxiaojun, Association for Information Systems-Based Analysis of Ships' Routeing System, 2010, "The 2nd International Conference on Computer and Automation Engineering 2010", page Web 30 December 2016.