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Uncertainty in Analytical Collision Dynamics Model Due to Assumptions in Dynamic Parameters

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ABSTRACT: The collision dynamics model is a vital part in maritime risk analysis. Different models have been introduced since Minorsky first presented collision dynamics model. Lately, increased computing capacity has led to development of more sophisticated models. Although the dynamics of ship collisions have been studied and understanding on the affecting factors is increased, there are many assumptions required to complete the analysis. The uncertainty in the dynamic parameters due to assumptions is not often considered.
In this paper a case study is conducted to show how input models for dynamic parameters affect the results of collision energy calculations and thus probability of an oil spill. The released deformation energy in collision is estimated by the means of the analytical collision dynamics model Zhang presented in his PhD thesis. The case study concerns the sea area between Helsinki and Tallinn where a crossing of two densely trafficked waterways is located. Actual traffic data is utilized to obtain realistic encounter scenarios by means of Monte Carlo simulation. Applicability of the compared assumptions is discussed based on the findings of the case study.

1 INTRODUCTION

Ship-ship collisions are rare events that potentially might have disastrous impact on the environment, human life and economics. To find effective risk mitigating measures the risk must be reliably assessed. Proper assessment of the ship-ship collision risk requires understanding on the complicated chain of events. Simplifying assumptions on certain parameters are necessary as the research in this field is not comprehensive. Especially, the important link between the encounter of the colliding vessels and the actual moment of impact contain obvious uncertainties.

In this paper a case study is conducted to compare models found in literature for dynamic parameters in collision scenario. The case study concerns collisions in which the struck vessel is an oil tanker. The traffic is simulated by means of a Monte Carlo simulation based on AIS data to obtain realistic encounter scenarios for the analyzed area. The assumptions are then applied to encounter scenario to obtain the complete impact scenario. The deformation energy released in the collision is calculated by analytic method (Zhang 1999) and the damage extents are estimated with simple formula to normalize the results of deformation energy calculations. The effects of assumptions for dynamic parameters to collision risk are discussed.

2 COLLISION RISK EVALUATION

2.1 *Concept of risk*

Risk is a product of probability p and consequences c and is expressed with (Kujala et al, 2010)

$$R = \sum p_i \cdot c_i \tag{1}$$

where i denotes certain chain of events or scenario.

2.2 *Tanker Collisions*

In case of ship-ship collisions scenario is a function of vast number of static and dynamic parameters. The parameters used in this study are listed in Table 1.

Table 1. Collision parameters used in this study.

	Description	Unit	Type
M	Mass	[kg]	Static
L	Length	[m]	Static
B	Width	[m]	Static
m_x	Added mass coefficient, surge motion	[-]	Static
m_y	Added mass coefficient, sway motion	[-]	Static
j	Added mass coefficient, rotation around centre of gravity	[-]	Static
R	Radius of ship mass inertia around centre of gravity	[m]	Static
V_x	Surge speed	[m/s]	Dynamic
V_y	Sway speed	[m/s]	Dynamic
x	x-position of centre of gravity	[m]	Static
y	y-position of centre of gravity	[m]	Static
x_c	x-position of impact point, in coordinate system ship A	[m]	Dynamic
y_c	y-position of impact point, in coordinate system ship A	[m]	Dynamic
α	collision angle	[rad]	Dynamic
μ_0	coefficient of friction	[-]	Static
e	coefficient of restitution	[-]	Static

The static parameters can be derived from AIS data, statistics and theory of ship design. Modeling of the dynamic parameters is often based on statistics of the collisions.

Ship-ship collision risk evaluation schematic is outlined in Figure 1 for the case of an oil tanker being struck vessel.

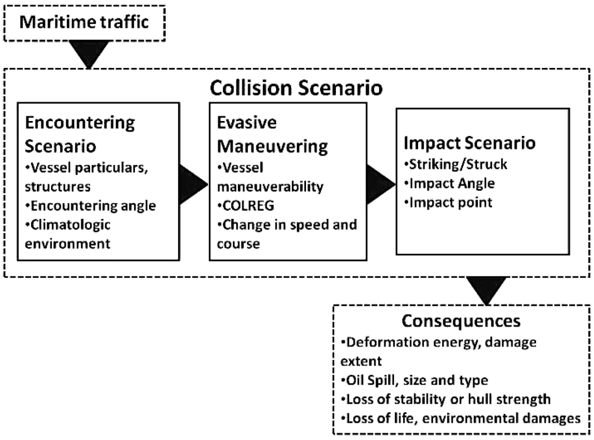

Figure 1. Tanker collision risk evaluation schematic

The first step of the risk analysis is modeling the traffic in the analyzed area. Modeling may be done via simulation of individual vessel movements as proposed by Merrick et al. (2003), van Dorp et al. (2009), Ulusçu et al. (2009) and Goerlandt & Kujala (2010) or alternatively by simulating the traffic flows as proposed by Pedersen (1995, 2010) or Montewka et al (2010). The encounter scenarios are obtained as a result of the traffic simulation. The impact scenarios may be then obtained with the models discussed in detail in Section 3.3.

Second part of the risk analysis is the evaluation of the consequences which begins with the estimating the released deformation energy that is absorbed by the vessel structures. Collision dynamics models to calculate the deformation energy can be divided into two groups, time domain and analytical (Wang et al 2000), based on applied calculation method. Analytical closed form methods have been proposed by Minorsky (1959), Vaughan (1977), Hutchison (1986), Hanhirova (1995), and Zhang (1999). Models based on time domain calculations are proposed by Chen (2000) and Tabri et al. (2009). In analytical models the external dynamics and internal mechanics are uncoupled while in time domain methods these are coupled.

3 COMPARISON METHODS

3.1 *Traffic simulation and encounter scenarios*

The traffic simulation is described here shortly as the simulation itself is not crucial regarding the comparison of impact models. The simulation is described in detail in (Ståhlberg, 2010)

The traffic in the analyzed area is obtained from AIS data. The data contains traffic information from the month of July 2006 in the sea area between Helsinki and Tallinn where densely trafficked waterways cross. In Figure 2 the analyzed area and the data points are presented. The four main waterways in the crossing area are named after compass quarters in form of “from-to” as shown in Figure 2. The considered waterway combinations and resulting encounter types are listed with reference numbers in Table 2.

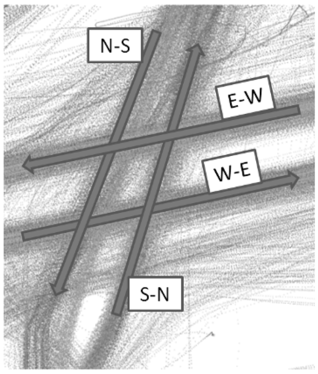

Figure 2. Plot of AIS data points in analyzed area

The AIS data is filtered to distinguish the traffic between waterways and ship types. The numbers of passages through the analyzed area per ship type are listed in Table 3. The Monte Carlo simulation flowchart starting from the filtered AIS data is shown in Figure 3. The result of the simulation is the encounter situations based on the traffic data.

Table 2. The considered waterway combinations and resulting encounter types with respective reference numbers.

Ref number	Route	Encounter type
1	N-S, E-W	Crossing
2	N-S, W-E	Crossing
3	S-N, E-W	Crossing
4	S-N, W-E	Crossing
5	W-E, E-W	Head-on
6	E-W, W-E	Head-on
7	E-W, E-W	Overtaking
8	W-E, W-E	Overtaking

Table 3. Number of passages per ship type and route.

Ship	Route			
Type	N-S	S-N	E-W	W-E
HSC	741	740	0	0
PAX	253	254	26	14
Cargo	5	4	768	742
Tanker	0	0	218	215
Other	3	3	36	35

* HSC = High Speed Craft, PAX = Passenger vessel, Cargo = Cargo vessel

The Monte Carlo simulation to create encounter scenarios is run 10000 times for those combinations of main waterways in which the tanker may be struck vessel. In the utilized data set tankers were recorded sailing only on "E-W" and "W-E" waterways. In this study the probability of a vessel involved in collision is weighted with the number of voyages in the area.

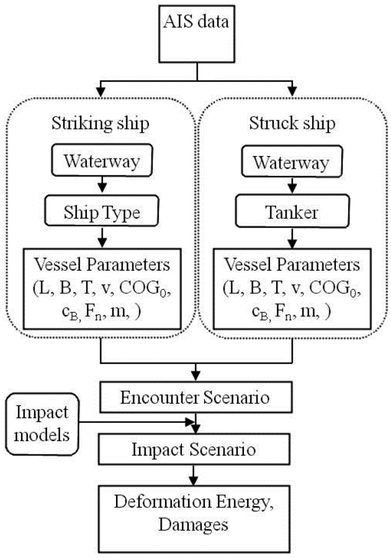

Figure 3. Flowchart of Monte Carlo simulation

3.2 *Impact scenario simulation*

With the encountering vessels' characteristics known the impact scenarios are simulated here by applying the compared models for the dynamic parameters. The models may be considered to be the "evasive maneuvering" model shown in Figure 1.

The compared assumptions are presented in Figures 4-7 and the distribution parameters are compiled into Table 4.

In "Blind Navigator" –model there are no maneuvering actions taken to avoid the collision and thus the speeds and courses are unchanged from the encounter scenario. The collision location is assumed to be uniformly distributed along the struck vessel's length. This model is used by Van Dorp & Merrick (2009) and COWI(2008). Based on the analysis of collisions in (Cahill, 2002) and (Buzek & Holdert, 1990) it seems extremely rare that neither vessel takes any action.

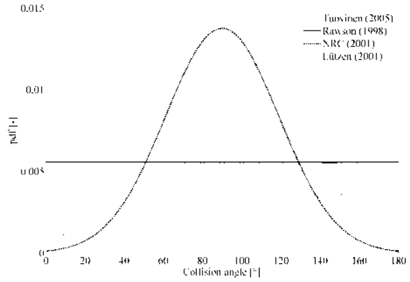

Figure 4. Input distributions for collision angle, Lützen: initial angle 90°, Brown (2002) quasi-equivalent to NRC (2001)

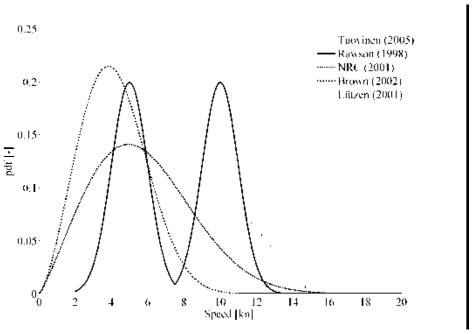

Figure 5. Input distributions for striking ship speed, Lützen with initial speed of 15 kn

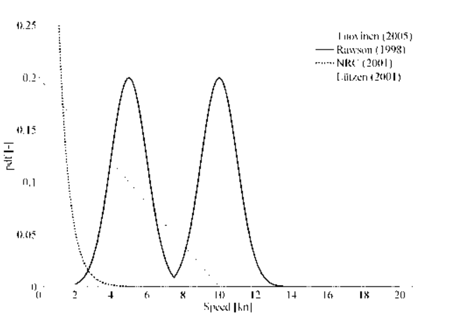

Figure 6. Input distributions for struck ship speed, Lützen with initial speed of 10 kn, Brown (2002) quasi-equivalent to NRC (2001)

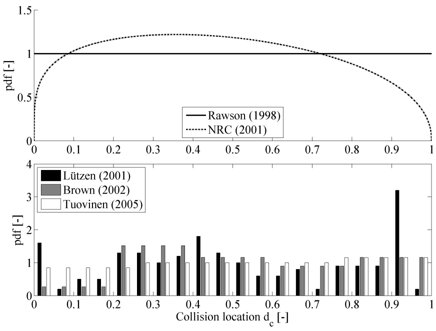

Figure 7. Input distributions for location of impact along struck ship's length, 0 = aft, 1 = fore

Table 4. Overview of impact scenario models.

Impact Model	Collision Angle, β [deg]	V_A [kn]	V_B [kn]	Impact Point, d [x/L]
Blind Navi	$\beta=\beta_0$	$V_A=V_{A0}$	$V_B=V_{B0}$	U(0,1)
Rawson (1998)	U(0,180)	bi-normal N(5,1) N(10,1) Truncated {2, 14}	idem to V_A	U(0,1)
NRC (2001)	N(90,29)	W(6.5,2.2)	E(0.584)	B(1.25,1.45) {0, 1}
Lützen (2001)	$T(0,\beta_0,180)$	$U(0,0.75V_{A0})$ $T(0.75V_{A0},V_{A0})$	$T(0,V_{B0})$	Empirical See FIG 7
Brown (2002)	N(90,29)	W(4.7,2.5)	E(0.584)	Empirical See FIG 7
Tuovinen (2005)	Empirical See FIG 4	Empirical See FIG 5	Empirical See FIG 6	Empirical See FIG 7

* Distributions are marked as follows, U=Uniform(min, max) N=Normal(μ, σ), T=Triangular(min, triangle tip, max), E=Exponential(λ), B=Beta(α, β, min, max), W=Weibull(k, λ)

Lützen's (2001) set of assumptions implies that the struck vessel is more prone to speed reduction than the striking vessel while the impact angle is triangularly distributed between 0° and 180° with the tip of the distribution at the encounter angle. The longitudinal impact location is given by empirical distribution. Although there is no explanation how the distributions for collision angle and velocities are derived these are included into the comparison because of the existing relation between encounter and impact scenarios.

Rawson et al (1998) model is based on statistics of the grounding accidents with assumption that the collision speed being similarly distributed as grounding speed. Velocities of the colliding vessel are distributed according to a double normal distribution in which the averages are described to represent the service speed, i.e. no speed reduction, and half of service speed. The same speed distribution is used for both striking and struck vessel. Collision angle and collision location are uniformly distributed between 0°…180° and along the struck vessel's length respectively.

Tuovinen (2006) compiled statistics from over 500 collisions. Statistics have been used here as presented originally, in form of empirical distributions.

Brown (2002) and NRC (2001) give quite similar distributions. Brown gives lower velocity for the striking vessel. These models both assume that striking vessel has higher velocity than struck at the moment of impact. It is noteworthy that these two models suggest much lower collision speeds than other models. Collision angle is normally distributed around right angle. In NRC model the collision location is beta distributed so that midship section is rammed at higher probability than the fore and aft of the vessel while Brown suggests empirical distribution.

Overall, the distributions Lützen suggested are the only ones taking the encounter into account in any way and other models give same distributions for dynamic parameters irrespective of encounter scenario. None of these models indicate how to determine which vessel is striking and which is struck. It is assumed here that the probabilities of vessel being striking or struck are equal for all models as no other probabilities were suggested in these models. The compared models do not have the possibility of initial sway nor yaw speeds, which in case of maneuvering is unlikely.

It can be seen in the Figures 4-7 that models, with exception of Brown and NRC, give distinctively different distributions for the dynamic parameters. Considering the struck vessel speed being lower in all the models expect Rawson it appears likely that the collision statistics from which the distributions are derived include collisions in which the struck vessel is in anchorage or in berth. Tuovinen's (2005) statistics include approximately 6% of such cases and 41% of open seas collisions. Brown (2002) states that the share is significant as in about 60% of collisions struck vessel speed is zero.

3.3 *Deformation energy calculations*

Zhang presented in his PhD thesis (Zhang, 1999) a simplified calculation method for released deformation energy in ship-ship collision. Zhang's method is based on rigid body mechanics and conservation of momentum. The method is derived based on the dynamics of two rods colliding on a frictionless surface and has three degrees of freedom. The hydrodynamic effects are considered as constant added masses. Both vessels may have initially forward and sway speeds. During the collision the rotational movements are considered as small and are neglected. After the collision both vessels are allowed to have rotational velocity. Figure 8 illustrates the impact scenario and defines the used co-ordinate systems. The formulation is not presented here due to its lengthiness.

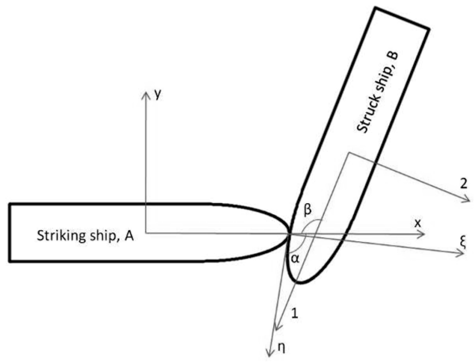

Figure 8. Impact scenario and the co-ordinate systems

3.4 *Damage calculation*

The method of damage calculation used here is presented in Goerlandt et.al. (2011). The focus in case of a tanker being a struck vessel is on the possibility that cargo oil is spilled. That requires penetration of one or more oil cargo tanks. Thus the penetration depth must exceed the double side width added with the dislocation of the inner shell when a rupture occurs. Additionally, the collision location along stuck tanker hull must be within the boundaries of the cargo tanks. Smailys & Česnauskis (2006) suggested following limits for cargo area for tankers operating in the Baltic Sea.

$$0.2L \le d \le 0.94L \quad (2)$$

where L is vessel length and d is distance of impact point from amidships along the centerline.

For the purposes of this study the simple criterion for oil cargo tank penetration is used and is expressed as critical energy, E_{cr}, with

$$E_{cr} = \begin{cases} 12.5, DWT < 5000 \\ 12.5\left(1 + \dfrac{\left(W_{ds} - 1\right)\left(\dfrac{DWT}{1000} - 5\right)}{35}\right), 5000 \le DWT \le 40000 \\ \dfrac{DWT}{2000} + 5, DWT > 40000 \end{cases} \quad (3)$$

where W_{ds} is double side width given in meters in ABS (2010) classification rules by:

$$W_{ds} = \begin{cases} 1, DWT < 10000 \\ 0.5 + \dfrac{DWT}{20000}, 10000 \le DWT \le 30000 \\ 2, DWT > 30000 \end{cases} \quad (4)$$

This criterion is obtained from a simple linear regression in the example cases discussed in (Zhang 1999, Lützen 2001, HSE 2000). It is further assumed that the effect of striking vessel bow geometry is negligible and that the energy absorbed by the striking vessel is taken into account in E_{cr}. Even though the evaluation of the critical energy is based on a very simplified model and better alternatives are available in the literature (Brown 2002, Ehlers 2008), this criterion is withheld due to its simplicity. Application of the simple criterion of (Eq. 3) affects all impact scenario models in a similar way, such that the conclusions are still valid. The actual value of E_{cr} is in this respect not essential as it is only used as a reference to better present the differences in impact models. In this study the collision consequences analysis is limited to evaluating if the deformation energy in direction normal to the struck vessel hull, E_ξ, exceeds E_{cr} that is required to breach a cargo tank, while neither the actual structural damages nor the amount of oil spilled are not considered.

4 SIMULATION RESULTS AND DISCUSSION

In this section, the results of the Monte Carlo simulations for the relative velocity, collision energy and hull breach probability are given for the impact scenario models.

4.1 *Relative velocity*

The relative velocity V_{rela} is considered as the velocity that the bow of the striking vessel is approaching the collision point at the struck vessel side. In vector form it is given with:

$$\vec{V}_{rela} = \vec{V}_A - \vec{V}_B \quad (5)$$

The released deformation energy is highly depending on the V_{rela} at the moment of impact. Relative velocities obtained from simulation for “Blind navigator” and Lützen model in selected encounter situations are presented in Figure 9. The other four models give similar results for V_{rela} irrespective of the encounter situation and thus results are presented only for waterway combination 1.

The “Blind Navigator” model is giving much higher values of V_{rela}, apart from head-on encounter, than other models as expected. There are two peaks in the result distributions of “Blind navigator” for crossing encounter situations. The lower peak represents passenger vessel cases and higher peak High Speed Crafts as striking vessel.

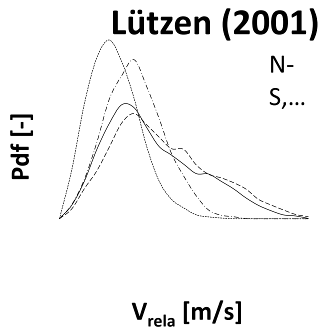

Figure 9. Simulated relative velocity distributions according to impact models in which encounter is considered

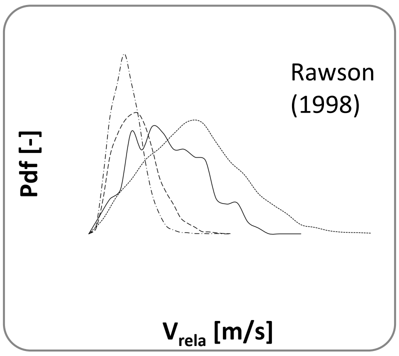

Figure 10. Simulated relative velocity distributions according to impact models in which encounter is not considered

The angle between N-S and W-E traffic flows is approximately 120° while between N-S and E-W traffic the angle is 60°. The effect of angle on relative velocity can be seen by comparing "Blind Navigator" results in Figure 9, the larger angle results in higher V_{rela}. The Lützen model appears to be relatively insensitive to variation of the encounter angle as only slight difference can be observed. This is due to the reduction of the struck vessel speed. The Lützen model gives the impact speed of the struck vessel to be on average ⅓ of the initial velocity.

The models that are derived from statistics by Rawson, NRC, Brown and Tuovinen give much more diverse results for V_{rela} than may be anticipated as the available accident data is limited and one would expect that the statistics would be practically based on the same data. It should be noted that these four model result in similar distributions for all encounter scenarios. Thus while the V_{rela} is lower in case of crossing encounter it is higher in case of overtaking compared to "Blind navigator" and Lützen models.

4.2 *Deformation energy*

In here only the transversal deformation energy E_ξ is considered because it represents the deformation energy in direction of penetration depth. The simulation results for E_ξ in each simulated encounter are normalized by dividing it with respective critical energy E_{cr}. In Figures 11-13 the cumulative distributions for normalized deformation energy $E_{\xi N}$ for each impact scenario model are presented for selected waterway combinations.

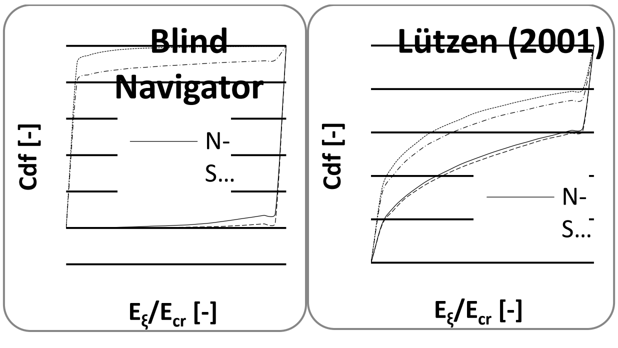

Figure 11. Simulation results of normalized deformation energy for "Blind navigator" and Lützen (2001) impact models.

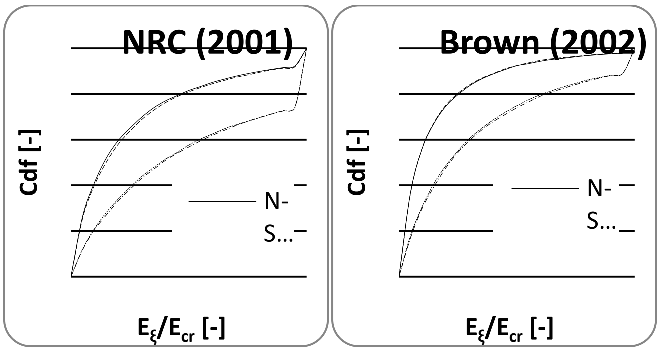

Figure 12. Simulation results of normalized deformation energy for "Blind navigator" and Lützen (2001) impact models.

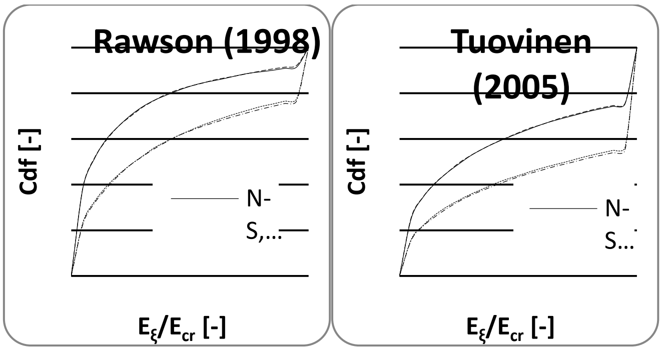

Figure 13. Simulated relative velocity distributions according to impact models in which encounter is considered

In "Blind Navigator" and Lützen models V_{rela} and impact angle are dominating factors in normalized E_ξ as seen in figure 11 when comparing results of crossing encounters with head-on and overtaking encounters. For head-on encounters normalized E_ξ is little higher than for overtaking but much lower than in crossing encountering. This is because even if V_{rela} is high the deformation energy is mostly released in η-direction along the struck vessel side.

The vessels sailing on W-E and E-W waterways are often on round trip to Gulf of Finland and thus the vessels are recorded in most cases on both waterways. Furthermore the loading condition was assumed to be fully laden for all vessels. For these reasons the vessel mass distributions are equivalent.

The same applies for N-S and S-N waterways except that the vessels are sailing between Helsinki and Tallinn. Additionally, the vessel masses on latter waterway pair are much lower than that of the prior. The differences in the vessel masses are resulting in differences between waterway combinations in the Figures 12, 13 as the distributions of V_{rela} are equivalent for all encounter scenarios in these models.

In figures 14, 15 the normalized cumulative distributions are compiled into same graph for crossing encounter and head-on encounter respectively with E_{cr} marked with vertical line.

From Figures 14, 15 similar observations as from Figures 11-13 can be made. The four models derived from statistics each result in higher $E_{\xi N}$ in head-on encounter than crossing while the opposite occurs for the "Blind navigator" and Lützen models. The same is valid for overtaking as was shown in Figures 12, 13.

4.3 *Probability of oil cargo tank penetration*

The oil cargo tank is penetrated when $E_{\xi N}$ is greater than 1 and the impact location is within tank limits given by Equation 2. The number of simulated impact scenarios in which the impact location is outside tank limits are listed in Table 5.

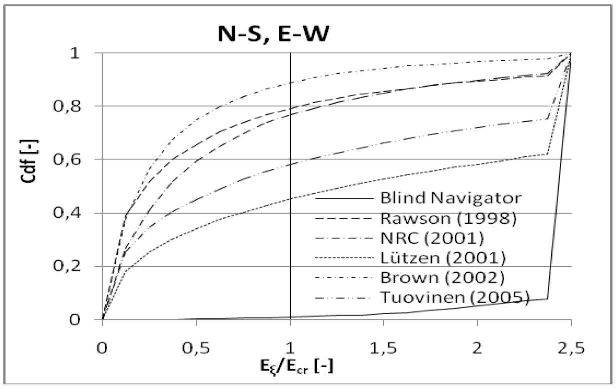

Figure 14. Simulated transversal deformation energy relative to critical energy in crossing encounter.

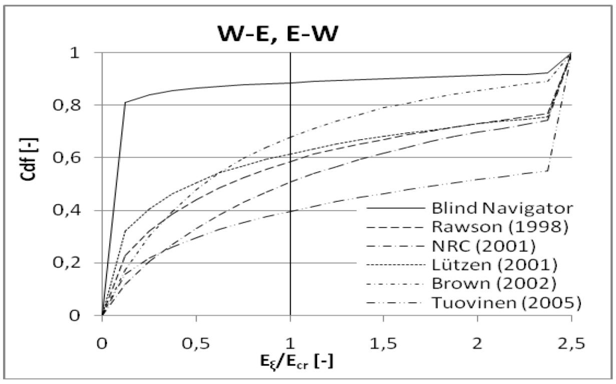

Figure 15. Simulated transversal deformation energy relative to critical energy in head-on encounter.

Table 5. Number of simulated collision scenarios of total 10000 simulations in which collision location is outside cargo tank limits given by Eq 2.

Blind Navi	Rawson (1998)	NCR (2001)	Lützen (2001)	Brown (2002)	Tuovinen (2005)
2626	2602	1700	1772	1223	2449

In Table 6 the numbers of simulated collisions resulting in an oil spill per impact model are presented. The same is visualized in Figure 13.

Table 6. Number of simulated collision scenarios in which oil cargo tank penetration occurs of total 10000 simulations.

Ref No*	Blind Navi	Rawson (1998)	NCR (2001)	Lützen (2001)	Brown (2002)	Tuovinen (2005)
1	7283	1581	1889	4695	926	3153
2	7379	1612	1955	4671	930	3002
3	7335	1648	1930	4743	982	3169
4	7321	1629	1934	4557	977	3033
5	604	3230	4146	3232	2901	4705
6	563	3098	4089	3054	2794	4550
7	105	3121	4107	2842	2738	4551
8	43	3192	4142	2940	2841	4591

* See Table 2 for explanation of Reference numbers

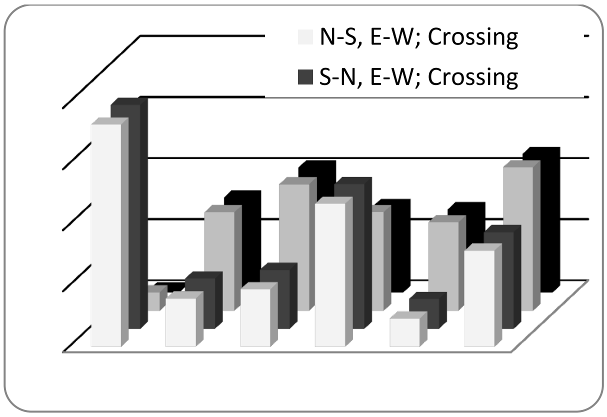

Figure 13. Number of simulated collision scenarios in which oil cargo tank penetration occurs of total 10000 simulations

Taking the collision location into account does change the results but very little. The differences between the models remain obvious. The collision following crossing encounter results in an oil spill in three out of four cases according to “Blind navigator” model. Brown’s model suggest that oil spill would occur only once in ten collisions.

5 CONCLUSIONS

In this paper a number of proposed models for impact scenarios from literature have been applied to the output of a maritime traffic simulation model to create impact scenarios. The released deformation energy is calculated with an analytical collision dynamics model for each impact scenario. Based on the obtained deformation energy the cargo tank penetration probability is estimated. The simulation results for relative velocity, transversal deformation energy and oil cargo tank penetration are compared between different impact scenario models.

The results of this case study indicate that the models give a widely varying average hull breach probability. In particular, the uncertainty on cargo tank breach probabilities dependence of initial encountering is significant, which is an important factor in the analysis of oil spill risk in specific location i.e. crossing or merging of waterways.

The distributions of collision energy for models based on statistics depend almost solely on the striking vessel mass instead of the actual encounter scenario. In the statistics that the models are based on there are no collisions where a high speed craft is involved. Further it is reasonable to assume that these statistics include collisions, in which the struck vessel is in anchorage, leading to underestimation in struck vessel speed at the moment of impact in collisions occurring at open seas.

None of the statistics is broken up for cases in different sea areas nor is the encountering related with the collision. These lacking in data are partly due to the limited number of collision cases available, lack of transparency and unsatisfactory reporting standards.

It is very likely that the statistical models are grossly underestimating the effect of encounter speed for both vessels in the area concerned in this case study. This leads to the conclusion that the understanding of the conditions of ship collision in a risk modeling framework is very limited at present.

The proposed models for impact scenarios are moreover burdened with some inherent conceptual limitations. The most significant limitation is the unsatisfactory modeling of evasive maneuvering, which links the initial encounter situation to the impact scenario. The results clearly indicates that especially the parameters which navigators have a possibility to affect in evasive maneuvering, i.e. vessel speed and collision angle, play a determining role in the evaluation of the consequences. Further research on this matter is needed.

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REFERENCES

American Bureau of Shipping (ABS). 2010. Rules for Building and Classing Steel Vessels. *American Bureau of Shipping.* Houston, USA.

Brown A.J. 2002. Collision scenarios and probabilistic collision damage. *Marine Structures*, 15(4-5):335-364.

Buzek, F.J. & Holdert H.M.C. (1990). Collision Cases Judgements and Diagrams, *Lloyd's of London Press Ltd*.

Cahill, R.A. 2002. Collisions and their causes, third ed. *The Nautical Institute*, London.

Chen, D. 2000. Simplified Collision Model (SIMCOL). M.Sc. thesis. *Virginia Tech*, Blacksburg, USA.

COWI for the Danish Maritime Authority. (2008). Risk Analysis of Sea Traffic in the Area around Bornholm, *COWI report no*. P-65775-002, January 2008.

Ehlers, S. Broekhuijsen, J. Alos H.S. Biehl F. Tabri K. 2008. Simulating the collision response of ship side structures: A failure criteria benchmark study. *International Shipbuilding Progress*, 55:127-144.

Goerlandt, F. & Kujala, P. 2010. Traffic simulation based collision probability modeling. *Reliability Engineering and System Safety*, doi:10.1016/j.ress.2010.09.003

Goerlandt F, Ståhlberg K, Kujala P. 2011. Comparative study of input models for collision risk evaluation. *Ocean Engineering – manuscript under review*.

Hanhirova, K. 1995. External Collision Model, Safety of Passenger/RoRo Vessels, *Helsinki University of Technology, Ship Laboratory*

Health and Safety Executive (HSE). 2000. Collision resistance of ship-shaped structures to side impact, *Health and Safety Executive*, London, United Kingdom, ISBN 0-7176-1997-4

Hutchison, B.L. 1986. Barge Collisions, Rammings and Groundings – an Engineering Assessment of the Potential for Damage to Radioactive Material Transport Casks, Technical Report SAND85-7165 TTC-05212

Kujala, P. Hänninen, M. Arola, T. Ylitalo, J. 2009. Analysis of the marine traffic safety in the Gulf of Finland. *Reliability Engineering and System Safety*, 94(8):1349-1357.

Lützen, M. 2001. Ship collision damage. *PhD thesis, Technical University of Denmark*.

Merrick, J.R.W. van Dorp, J.R. Harrald, J. Mazzuchi, T. Spahn, J. Grabowski, M. 2003. A systems approach to managing oil transportation risk in Prince William Sound. *Systems Engineering*, 3(3):128-142.

Minorsky, V.U. (1959), An Analysis of Ship Collisions with Reference to Protection of Nuclear Power Plants, *Journal of Ship Research*, October 1959.

Montewka, J. Hinz, T. Kujala, P. Matusiak, J. 2010. Probability modeling of vessel collision. *Reliability Engineering and System Safety*, 95(5):573-589.

National Research Council (NRC), 2001. Environmental Performance of Tanker Designs in Collision and Grounding, *Special Report 259, The National Academies Press*.

Pedersen, P.T. 1995. Collision and grounding mechanics. *The Danish society of Naval Architects and Marine Engineers* 125-157.

Pedersen, P.T. 2010. Review and application of ship collision and grounding analysis procedures. *Marine Structures*, 23(3):241-262.

Rawson, C. Crake, K. Brown, A. 1998. Assessing the environmental performance of tankers in accidental grounding and collision, *SNAME Transactions* 106:41-58.

Smailys, V. & Česnauskis, M. 2006. Estimation of expected cargo oil outflow from tanker involved in casualty. *Transport* – 2006, vol 21, No 4, p. 293-300.

Ståhlberg, K. 2010. Estimating deformation energy in ship-ship collisions with stochastic modeling, *M.Sc. Thesis, Aalto University, School of Science and Technology*, Espoo, Finland

Tabri, K. Varsta, P. Matusiak, J. 2009. Numerical and experimental motion simulations of non-symmetric ship collisions. *Journal of Marine Science and Technology*, 15(1):87-101.

Tuovinen, J. 2005. Statistical analysis of ship collisions. *M.Sc. thesis. Helsinki University of Technology*, Espoo, Finland.

Ulusçu, Ö.S. Özbaş, B. Altiok, T. Or, İ. 2009. Risk analysis of the vessel traffic in the strait of Istanbul. *Risk Analysis*, 29(10):1454-1472.

van Dorp, J.R. & Merrick, J.R.W. 2009. On a risk management analysis of oil spill risk using maritime transportation system simulation. *Annals of Operations Research*, doi: 10.1007/s10479-009-0678-1.

Vaughan, H. (1977). Damage to Ships Due to Collision and Grounding, *DNV Technical Report* No. 77-345.

Wang, G. Spencer, J. Chen, Y. (2001). Assessment of a Ship's Performance in Accidents, *Journal of Marine Structures*, 15:313-333.

Zhang, S. 1999. The mechanics of ship collisions. *PhD thesis, Technical University of Denmark*