Chapter 9
Tanker Design and Safety: Historical Developments and Future Trends

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Nomenclature

CAF	Cost for averting one fatality
CATS	Cost of Averting one Tonne of Spilled oil
CSR	Common structural rules
DH	Double-hull ships
DWT	Deadweight
EEDI	Energy efficiency design index
EEOI	Energy efficiency operational indicator
ESP	Enhanced program survey
ETS	European telecommunications standards
FSA	Formal safety assessment
GCAF	Gross cost of averting a fatality
GISIS	Global integrated shipping information system
IACS	International Association of Classification Societies
ICAF	Implied cost of averting a fatality
IEA	International Energy Agency
IHS	IHS Fairplay [formerly LRF (Lloyd's Register Fairplay)]
IMO	International Maritime Organization
IOPCF	International Oil Pollution Compensation Fund
IPCC	Intergovernmental Panel on Climate Change
ISM	International Safety Management Code
LMIU	Lloyd's Maritime Intelligence Unit
LOWI	Loss of watertight integrity
MARPOL	International Convention for the Prevention of Pollution from Ships

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S. Orszulik (ed.), *Environmental Technology in the Oil Industry*,
DOI 10.1007/978-3-319-24334-4_9

MEPC	Marine Environment Protection Committee
NCAF	Net cost of averting a fatality
NASF	Non-accidental structural failure
NTUA-SDL	National Technical University of Athens–Ship Design Laboratory
OILPOL	International Convention on the Prevention of Pollution of the Sea by Oil
OOI	Oil outflow index
OPA 90	Oil Pollution Act
Paris MoU	Paris Memorandum of Understanding on Port State Control
PLC	Potential loss of cargo
PLL	Potential loss of life
RBD	Risk-based design
RCO	Risk control option
SECA	Sulfur emission controlled areas
SEEMP	Ship energy efficiency management plan
SOLAS	International Convention for the Safety of Life at Sea
SFOC	Specific fuel oil consumption
STCW	International Convention on Standards of Training Certification and Watch Keeping for Seafarers
ULCC	Ultra-large crude carrier
VLCC	Very large crude carrier

1 Introduction: Tanker Design and Operation from an Environmental Perspective

The main objective of the present section of this chapter is a critical historical review of oil transportation by tankers and an assessment of their safety performance with focus on the past 25 years. It is a prime concern of the maritime industry and of governmental and regulatory authorities to continuously enhance ship safety and to reduce marine pollution related to ship incidents and accidents. Despite the introduction of a variety of safety-enhancing measures, regulations, and technologies related to the avoidance of accidents, tanker as well as marine accidents in general continue to happen, and this is not likely to change in the future. Thus, a reasonable goal for the maritime industry and relevant authorities is mitigation of the risk connected with accidents in terms of minimizing the probability of an occurrence and the associated consequences. In this respect, it is of paramount importance to critically review past accidents and assess the associated risk in terms of frequencies of the occurrence of accidents and their consequences.

The present chapter constitutes a critical review of historical developments in oil tanker design and of relevant regulations referring to the prevention of marine oil spills and the protection of the marine and the atmospheric environment. It presents a comprehensive analysis and critical review of recorded accidents of medium and large oil tankers (deadweight more than 20,000 tonnes) that occurred after the introduction of OPA 90 and up to the present. Raw casualty data were reviewed and reanalyzed to produce appropriate statistics useful for the implementation of risk-based assessment methodologies. The study includes the identification and quantification of the principal hazards that may lead to a tanker's loss of watertight integrity and consequently cause environmental damage. Finally, the chapter looks into future developments in oil tanker design and operation in the framework of risk-based design and operation.

Relevant research work started in the framework of the EU-funded project POP&C (2004–2007 [33]), in which casualty data of the Aframax class of tankers were systematically analyzed and post-processed as necessary for the application of a risk-based methodology regarding pollution prevention and control in view of tanker accidents. Further studies, beyond those of the POP&C project, were conducted in the frame of another EU-funded project SAFEDOR (2005–2009) by the Ship Design Laboratory of NTUA (NTUA-SDL), in collaboration with Germanischer Lloyd, Hamburg, namely, addressing the Suezmax, VLCC, and ULCC tankers, thus practically all large-size tankers. Based on this research, project SAFEDOR developed a Formal Safety Assessment for large tankers, which was submitted for consideration to IMO by Denmark (IMO-MEPC 58/17/2 and IMO-MEPC58/INF.2 [15, 16]). Even more, project SAFEDOR introduced the risk-based design concept to the wider maritime field and presented a variety of demonstration studies with respect to both ship design and maritime regulations [30]. Among these was the risk-based design of an innovative Aframax tanker [31]. To identify possible effects of *tanker size* on accident statistics, NTUA-SDL complemented these studies more recently by the analysis of medium-size tankers, namely, in the range 20,000–60,000 t DWT, thus, Handysize and Handymax tankers [4, 5].

The main outcome of the conducted research on accident statistics is the identification of significant qualitative historical trends of tanker accidents and of quantitative characteristics of particular tanker accidents, such as overall accidental frequencies per ship year; frequencies of each major accident category; and per tanker ship size, ship type/design and age, degree of accident severity, and oil spill tonne rates per ship year. Thus, besides the identification of important trends in the safety of oil transport by tankers, important risk elements were also quantified as necessary for the implementation of risk-based methodologies in tanker design and operation. Finally, the conducted analysis identifies heavily polluted geographic areas worldwide resulting from tanker accidents, which is of prime importance to society, the maritime industry, and governmental authorities around the world.

As per today, future developments in tanker design and operation appear to be driven more by efficiency aspects and the protection of the aerial environment issues, namely, the MARPOL regulations on the Energy Efficiency Design and Operation Indices (EEDI and EEOI), affecting a ship's speed–power characteristics in relationship to her hydrodynamic performance in calm water and in seaways (IMO-MEPC Resolution 212(63), [19]).

2 Brief History of Oil Transport by Sea: The Evolution of Tanker Design

Crude oil and petroleum products have been carried in ships since the late nineteenth century, that is, along with the first significant oil discoveries and the development of the oil industry in the early 1850s. Beginning at the very first, oil waterborne transportation was accomplished by general cargo ships carrying the oil in barrels or casks. The practice of carrying the oil in bulk mode *inside the single hull* of a ship became common practice after the introduction of the tanker ship type in 1886.[1] Tanker ship design established in that period remained virtually unchanged until shortly after World War II. Until then, the common tanker ship size varied from 10,000 to 15,000 tons DWT, with ships having a single skin construction in the cargo area, without double bottom, the engine room abaft, and multiple compartmentation with either two or three tanks across.

After World War II, rapid growth of the world economy triggered a huge demand on energy in terms of crude or refined oil products and a new oil transport pattern evolved: crude oil began being transported from distant, oil-producing areas, such as the Persian Gulf, Southeast Asia, and South America, to major markets/consumption areas, notably North America, Northern Europe, and Japan, where the crude oil was refined and redistributed as product. These long voyages set the stage for a dramatic increase in ship size, reflecting the *economy of scale* of the transport vehicles. Between 1950 and 1975, the largest tanker ship in the world grew from about 25,000 tons DWT to more than 500,000 tons DWT. The share of tanker ships in the world fleet also drastically increased over the years, reaching today about 33 % of the world tonnage.

After that period and to date, significant developments in shipbuilding technology, relevant regulations, and operational procedures were introduced, aiming at reducing the probability of accidents (frequencies), for example, by improved navigational equipment and crew training, and at mitigating the consequences in terms of oil cargo release in case of accidents, notably, the introduction of the double-hull tanker concept. Although technologically tankers of even larger capacity could have been built, reducing even further the required freight rates, the risk of marine pollution in case of such a tanker accident was considered unacceptable, as well as the constraints resulting from navigational limitations (maximum ship draft). This consideration led to freezing of the uppermost size of crude oil tankers and even the gradual withdrawal and disappearance of the ultra-large crude carrier ship type (ULCCs, with a deadweight capacity of more than 320,000 tons and up to about 500,000 tons) from the market.

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[1] The first modern times oil tanker is believed to be the *Glücksauf (Good Luck)*, built in 1886 by the Armstrong Mitchell yard in Newcastle upon Tyne for the German H. Reidemann, which was chartered by the Standard Oil Company. It was the first steam-driven, ocean-going oil tanker into which oil could be pumped directly to its internally subdivided, eight-compartment hull; she featured all the main elements of a modern tanker, such as cargo main piping and valves, operated from the main deck, vapor lines, and cofferdams, and the ability to receive ballast water when empty of cargo. She was lost in 1893 after grounding near Long Island (New York) in fog.

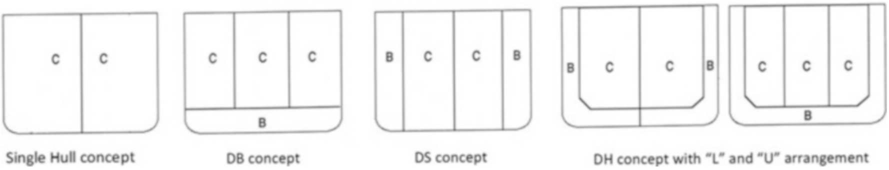

Fig. 9.1 Typical tanker hull designs. *B* ballast, *C* cargo oil

The basic generic hull configurations with respect to the internal watertight subdivision, namely, the double-hull ships and the non-double-hull ships, are sketched in Fig. 9.1:

- The double-hull (*DH*) concept is characterized by the full, all-around, double-hull concept according to MARPOL requirements currently in force.
- The non-double-hull (*non-DH*) definition includes single-hull (SH, with or without segregated ballast tanks/protectively located), double-bottom (DB), and double-sides (DS) oil tankers.

3 Marine Oil Pollution

The potential for oil released to the marine environment was recognized by the International Convention for the Prevention of Pollution of the Sea by Oil, 1954 (OILPOL 1954), but marine oil pollution had become an issue of international concern after the first major oil tanker accident in 1967 (*Torrey Canyon*). Although the major part of marine oil pollution is coming from land-based sources/operations (about 80 % according to UNESCO data, in Global Ocean Commission Summary Report 2014 [8]), a significant amount of the oil released to the sea environment is still the result of shipping and maritime activities. Among them, the most important pollutant activity is the transportation of oil by tankers, related mainly (in terms of *released amount* of oil) to tanker accidents, whereas in *terms of frequency* the most polluting activities are terminal operations of all types of ships. Tanker ship accidents, if they happen, immediately draw the attention of local governments and public media; thus, their importance is multiplied by a nonaccountable factor of significance.

3.1 Review of Major Tanker Accidents

Although ships appear by statistics to be the safest mode of transportation, marine incidents and accidents have always happened and will continue to happen. Therefore, the prime concern of ship safety is to minimize or reduce the probability of occurrence of such incidents, as well as to mitigate the serious consequences of an incident/accident.

Investigations into some tragic tanker accidents have provided in-depth knowledge and experience governing the changes in the safety regime in the past years, as well as the change in basic tanker ship hull internal configuration that is described in detail by Papanikolaou et al. [29]. Significant outcomes of some catastrophic casualties that were investigated led to improvements of the IMO regulatory framework and eventually of maritime safety and operation. In the following, some spectacular tanker casualties are listed that led to the adoption of new regulations or/and amendments of the existing ones:

- The grounding of the *Torrey Canyon*, in 1967, with 119,000 tonnes of Kuwait crude oil released off the western coast of Cornwall, England, was the first catastrophic marine pollution accident since the introduction of modern tankers. The associated accident investigations and conclusions led to the introduction of MARPOL 1973, STCW 1978, and SOLAS 1974 (fire safety provisions for tankers).
- The grounding of the *Argo Merchant* on Nantucket Shoals, off Massachusetts, USA, in 1976, with 28,000 tonnes of oil released, contributed to the development of Protocol 1978 of MARPOL.
- The grounding of *Amoco Cadiz* off the coast of Brittany in the northwest of France, in 1978, with 227,000 tonnes spillage, led to the implementation of MARPOL 1978 Protocol; it also formed also the basis for the introduction of Paris Memorandum of Understanding on Port State Control (Paris MOU).
- The grounding of the *Exxon Valdez* on Bligh Reef in Prince William Sound, Alaska, in 1989, with about 37,000 tonnes spillage, led in year 1990 to the adoption of the first major *regional agreement* for tanker operations in US waters (introduction of the double-hull tanker concept), through the Oil Pollution Act (OPA 90) in the USA in 1990.
- The *Erika* disaster, in which the ship broke in two in a severe storm in the Bay of Biscay in 1999, with about 20,000 tonnes spillage, contributed to the revision of MARPOL 73/78 (Reg. 13G), and led to an accelerated phase-out of single-hull tankers (MEPC–IMO). Furthermore, this particular accident led the European Union to the adoption of the ERIKA I- and ERIKA II-enhanced safety regulatory packages.
- Following the "*Prestige* accident" in 2002, which suffered hull damage in heavy seas off northern Spain, with 77,000 tonnes carried cargo, the European Union adopted Reg. 1726/2003, regulating the accelerated single-hull tanker phase-out, carriage of heavy-grade oils in double-hull tankers, and enhanced hull condition assessment. This regulation took effect within the EU on 21 October 2003. The IMO's Marine Environment Protection Committee (MEPC) adopted amendments to Regulation 13G and produced Regulation 13H to Annex I of MARPOL on 4 December 2003 (Resolution MEPC.111(50) [12] and Resolution MEPC.112(50) [13]).
- The "Deepwater Horizon" drilling rig explosion in 2010 (Mexican Gulf), with a spillage of about 600,000 tonnes of oil, is the largest marine accidental oil spill in the history of the petroleum industry. In contrast to spillages related to accidents of ships, which operate internationally and need to comply with international

safety regulations (IMO), the safety of offshore platforms is governed by safety codes of the petroleum industry and of the authorities certifying their proper design, construction, and operation (classification societies and governmental authorities).

3.2 Review of Major International Regulations and Recent Debates at IMO

3.2.1 MARPOL 73/78: On the Prevention of Oil Pollution from Ships

The likely pollution of the marine environment is regulated by MARPOL 73/78, the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978; it is the most important international marine environmental convention. Its objective is to minimize pollution of the seas, including dumping, oil pollution, and areal pollution by toxic exhaust gas emissions. In the course of the years, after its introduction in 1973, MARPOL underwent several amendments and improvements that contributed to today's quite satisfactory state of affairs in tanker safety, namely, in terms of recorded tanker accidents and environmental consequences (Fig. 9.2, [6]; updated frequencies after 2007 in later section).

Following a series of catastrophic single-hull tanker accidents, current MARPOL regulations (and long before US OPA 90) recognized double-hull tanker designs as the only acceptable solution for the safe carriage of oil in tanker ships. According to current MARPOL regulations, the tank arrangement of the cargo block of an oil tanker should be properly designed to provide adequate protection against accidental oil outflow, as expressed by the so-called *mean outflow parameter*. According to Resolution MEPC.122(52) [14], the mean outflow parameter, O_M, is the non-dimensionalized statistical *mean* or *expected* outflow, as percentage of ship's cargo capacity, and provides an indication of a design's overall effectiveness in limiting oil outflow.

The mean outflow equals the sum of the products of the probability of occurrence of a likely damage case and of the associated oil outflow; thus, O_M equals the mean outflow divided by the total quantity of oil onboard the vessel; the *maximum permissible mean outflow parameter* is set as a function of ship's deadweight, as follows:

$$O_M \leq 0.015\left(\text{for } C \leq 200{,}000\ \text{m}^3\right) \tag{9.1}$$

$$\begin{gathered} O_M \leq 0.012 + (0.003/200{,}000)(400{,}000 - C) \\ (\text{for}\,200{,}000\ \text{m}^3 < C < 400{,}000\ \text{m}^3) \end{gathered} \tag{9.2}$$

$$O_M \leq 0.012\left(\text{for}\,C \geq 400{,}000\ \text{m}^3\right) \tag{9.3}$$

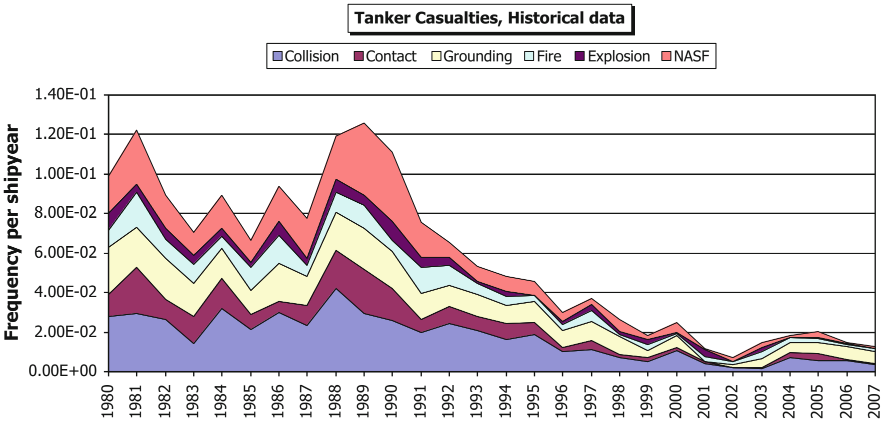

Fig. 9.2 Frequency of large tanker accidents per ship year

where C is the tanker's oil cargo capacity (in m^3). The foregoing provisions mean, essentially, that the societally accepted mean oil outflow of an oil tanker is in the range of 1.2–1.5 % of its cargo capacity. Clearly the *mean outflow parameter*, as some additional indicators expressing ship oil outflow performance (such as the *probability of zero oil outflow*, etc.), is a major design constraint of tanker design and directly affects ship cargo space compartmentation and the sizing of oil tanks.

The entire MARPOL 73/78 provisions are actually elaborated in six Annexes, as follows:

1. Annex I	Prevention of pollution by oil
2. Annex II	Control of pollution by noxious liquid substances in bulk
3. Annex III	Prevention of pollution by harmful substances carried by sea in packaged form
4. Annex IV	Pollution by sewage from ships
5. Annex V	Pollution by garbage from ships
6. Annex VI	Prevention of air pollution from ships

3.2.2 MARPOL 73/78: On the Prevention of Air Pollution by Ships

Beyond the prevention of marine pollution by oil, significant importance with respect to ship design and operation has been gained recently by ANNEX VI of MARPOL, and thus the prevention of air pollution by ships. It is today well established that human activities have a significant impact upon the levels of

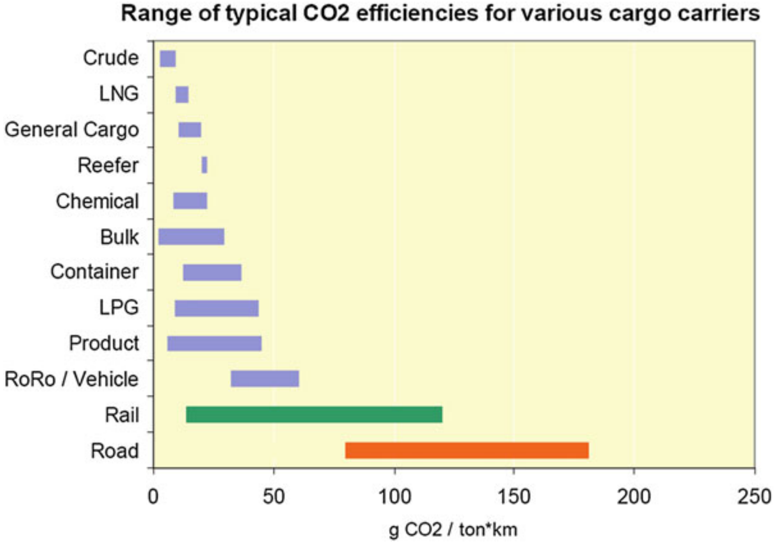

Fig. 9.3 Typical range of CO_2 efficiency of ships compared with rail and road transport [2]

greenhouse gases in the atmosphere, those gases that absorb and emit radiation within the thermal infrared range. The gases with the most important release to the atmosphere are, in descending order: water vapor, carbon dioxide (CO_2), methane, and ozone. The Intergovernmental Panel on Climate Change (IPCC) recently released a report stating that "*most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*" [36]. One of the main contributors to emissions of greenhouse gases by human activity is the burning of fossil fuels. The total CO_2 emissions from shipping (domestic and international) amount to about 3.3 % of the global emissions from fuel consumption, according to the International Energy Agency (IEA) [2] (Fig. 9.3).

Climate stabilization will require significant reductions of CO_2 emissions by 2050, and the international shipping industry needs to participate in this process. Independently of the fact that maritime transport is the most efficient mode of transport (ton-km) and the least polluting in terms of greenhouse gas emissions, current discussions and expected regulatory measures suggest the collaboration of all major stakeholders of shipbuilding and ship operations to efficiently address this complex techno-economic and highly political problem, and to call, ultimately, for the development of proper design, operational knowledge, and assessment tools for energy-efficient design and operation of ships [1]. In this respect, an energy efficiency design index (EEDI)[2] has been introduced for most types of merchant

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[2] The Energy Efficiency Design Index (EEDI) was made mandatory for *new* ships, as of 1 January 2013; this was decided at MEPC 62 (July 2011) with the adoption of amendments to MARPOL Annex VI (resolution MEPC.203(62)) and accompanied the introduction of a Ship Energy Efficiency Management Plan (SEEMP) for *all ships*.

ships, which needs to be kept below a certain limiting value that is specific to the ship type and size.

Typical design and outfitting measures for reducing CO_2 emissions are related to hull form optimization for least power (and fuel consumption), improved diesel engine combustion, improved fuel technology, etc.; last, but not least, a drastic operational measure for reducing CO_2 emissions is reduction of service speed, with major impact on a ship's competitiveness and economy, especially when the ship is in liner service (e.g., for container and passenger ships).

The energy efficiency design index (EEDI) of a ship is a measure of the ship's energy efficiency (g/t*nm) and is calculated by the following formula (see Resolution MEPC 212(63) [19]):

$$\frac{\begin{array}{c}\left(\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME\ (i)}\ SFC_{ME(i)}\right) + \left(P_{AE}\ C_{FAE} SFC_{AE}\right) + \right.\\ \left.\left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} SFC_{AE}\right) - \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{eff(i)} C_{FME} SFC_{ME}\right)\right)\end{array}}{\left(f_i \cdot f_c \cdot f_l \cdot \text{Capacity} \cdot f_w \cdot V_{ref}\right)} \tag{9.4}$$

where C_F is a nondimensional conversion factor between fuel consumption measured in grams (g) and CO_2 emission, also measured in grams (g) based on carbon content. The subscripts $_{MEi}$ and $_{AEi}$ refer to the main and auxiliary engine(s), respectively. For details in the usage of this formula, see Resolution MEPC 212(63) [19].

According to Regulation 20 of Annex VI of Chapter 4 MARPOL 73/78, the attained EEDI shall be calculated for each new ship, or any ship that has undergone a major conversion. The attained EEDI shall be verified, based on the EEDI technical file, either by the administration or by any organization duly authorized by it. According to Regulation 21 of Annex VI of Chapter 4 MARPOL 73/78, the attained EEDI shall be less than or equal to a required level, set by regulation, as follows:

$$\text{Attained EEDI} \leq \text{Required EEDI} = (1 - x)\text{Reference Line Value} \tag{9.5}$$

where x is the reduction factor specified in Table 9.1 for the required EEDI compared to the EEDI reference line.

Table 9.1 Reduction factors (in percentage) for the EEDI relative to the EEDI reference line for tankers

		Phase 0	Phase 1	Phase 2	Phase 3
Ship type	Size	1 Jan 2013–31 Dec 2014	1 Jan 2015–31 Dec 2019	1 Jan 2020–31 Dec 2024	1 Jan 2025 and onwards
Tankers	20,000 DWT and above	0	10	20	30
	4000–20,000 DWT	n/a	0–10*	0–20*	0–30*

*The reduction factor is to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size

The reference line values shall be calculated as follows:

$$\text{Reference line value} = a \times b - c$$

where a, b, and c are the parameters given in Table 9.2.

The following figures, Figs. 9.4 and 9.5, represent typical reference lines for tanker ships to be used in the assessment of EEDI according to the IMO-MEPC 62/6/4 [17].

The key measures for reducing gaseous toxic emissions from marine engines, which accompanies the reduction of fuel consumption, are as follows:

- Reduction of fuel consumption through reduction of ship's resistance and powering
- Optimization of ship's hull form leading to a reduction of the required propulsion power for specified speed (calm water performance and added resistance in seaways: *new ship buildings*)

Table 9.2 Parameters for determination of reference values for the different ship types

Ship type defined in Regulation 2 of Annex VI of Chapter 1 MARPOL 73/78	*a*	Capacity	*c*
2.25 Bulk carrier	961.79	DWT	0.477
2.26 Gas carrier	1120.00	DWT	0.456
2.27 Tanker	1218.80	DWT	0.488
2.28 Container ship	174.22	DWT	0.201
2.29 General cargo ship	107.48	DWT	0.216
2.30 Refrigerated cargo carrier	227.01	DWT	0.244
2.31 Combination carrier	1219.00	DWT	0.488

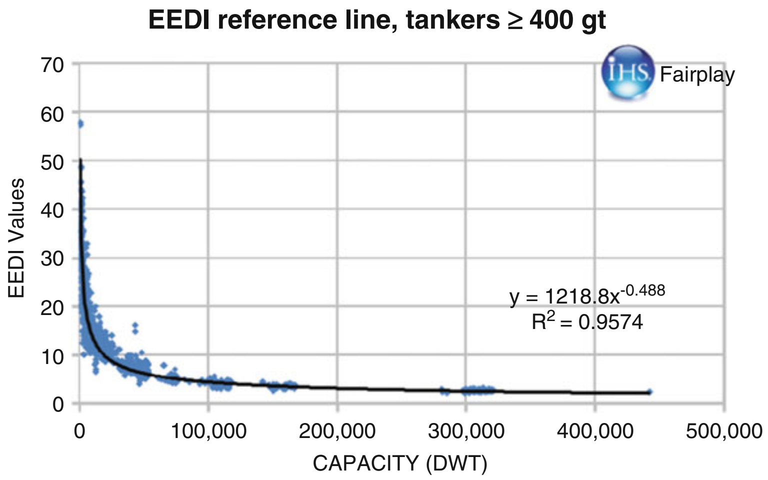

Fig. 9.4 Typical reference lines for tankers (IMO-MEPC 62/6/4) [18]

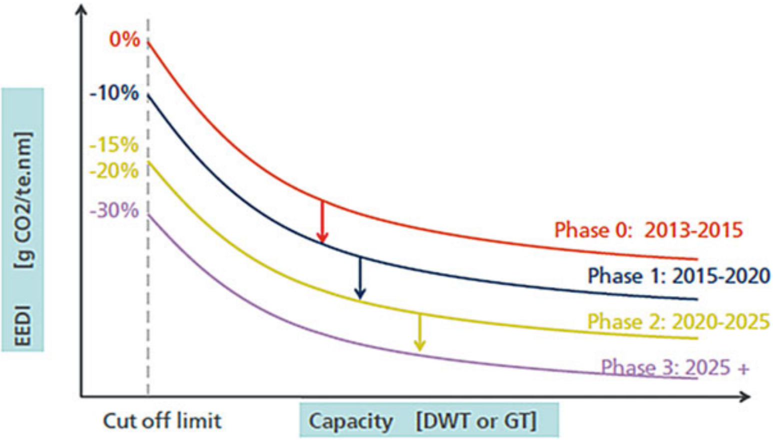

Fig. 9.5 Energy efficiency design index (EEDI) concept (Lloyd's Register, [25])

- Fitting of propulsive efficiency-enhancing devices (stern flow ducts, spoilers, controllable-pitch CPT propellers, etc., for *existing ships and to some extent new ship buildings*)
- Refitting of bulbous bow (*existing ships*)
- Optimization of operational trim (*existing ships*)
- Minimization of the amount of carried ballast water (*new buildings and existing ships*)
- Reduction of viscous resistance through special treatment of wetted surface (paints, etc.) and other innovation measures (release of air bubbles, etc.) *(mainly new ship buildings*)
- Optimization of ship routing
- Reduction of service speed (*slow steaming*)
- Improvement of marine engine technology
- Reduction of specific fuel oil consumption (SFOC)
- Reduction of toxic gas emissions
- Dual fuel consumption (heavy fuel oil, HFO; marine diesel oil, MDO; liquefied natural gas, LNG)
- Improvement of fuel quality
- Introduction of biofuels for marine engines

3.2.3 Formal Safety Assessment of Tankers (FSA)

The FSA is a structured and systematic methodology aimed at enhancing maritime safety, including the protection of life, health, marine environment, and property, by using risk analysis and cost–benefit assessment (CBA). FSA can be used as a tool to help in the evaluation of new regulations for maritime safety and protection of the marine environment or in making a comparison between existing and possibly improved regulations, with a view to achieving a balance between the various technical and operational issues, including the human element, and between maritime safety or protection of the marine environment and costs. FSA consists of five main steps:

1. Identification of hazards (a list of all relevant accident scenarios with potential causes and outcomes)
2. Assessment of risks (evaluation of risk factors)
3. Risk control options (devising regulatory measures to control and reduce the identified risks)
4. Cost–benefit assessment (determining cost-effectiveness of each risk control option)
5. Recommendations for decision making (information about the hazards, their associated risks, and the cost-effectiveness of alternative risk control options is provided)

FSA, which was originally developed as a response to the *Piper Alpha* offshore platform disaster in 1988, is now being applied routinely to the IMO rule-making process. The Guidelines for Formal Safety Assessment (FSA) for use in the IMO rule-making process were approved in 2002 (MSC/Circ.1023/MEPC/Circ.392 [21]). At its 80th session in May 2005, the MSC reviewed the report of the Joint MSC/MEPC Working Group on Formal Safety Assessment (FSA). The MSC also agreed on the establishment, when necessary, of an FSA Group of Experts (GoE) for the purpose of reviewing an FSA study if the Committee plans to use the study for making a decision on a particular issue. The MSC also agreed in principle that the proposed GoE would undertake to review FSA studies on specific subjects submitted to the organization, as directed by the Committee(s), and to prepare relevant reports for submission to the Committee(s). The structure of the group of experts was left open for future discussion, although the Committee agreed, in principle, that members participating in the expert group should have risk assessment experience, a maritime background, and knowledge and training in the application of the FSA Guidelines.

Following this, the Experts Group on Formal Safety Assessment (FSA) met in November 2012 under the chairmanship of Mr. K. Yoshida from Japan (MSC 91/WP.6 [23]). The group considered, among others, documents MEPC 58/17/2 and MEPC 58/INF.2, referring to the Formal Safety Assessment of Tankers developed by the EU-funded project SAFEDOR. The group also considered documents MSC 90/19/4 and Corr. 1 (Japan) [22], containing information on the reanalysis of the FSA study on crude oil tankers, as well as documents MSC 91/16/1 and MSC 91/INF.5 submitted to MSC 91 by Japan, providing further background information and data used for the recalculation and reanalysis. The Experts Group noted the following:

- *Regarding the differences of the values for potential loss of cargo (PLC) between those in document MEPC 58/INF.2 (Denmark-SAFEDOR) and MSC 91/INF.5 (Japan), the expert presenting the FSA pointed out that SAFEDOR* *created a database using other data sources in addition to IHS Fairplay to cross-check amounts of oil spillage and modify them as necessary, particularly those of very serious accidents. The group was satisfied with the explanation that the presented information was reliable in view of cross-checking by public domain information*

- Regarding the values for branching frequency, *the SAFEDOR study had based their estimates on databases and expert judgments*
- Regarding the cost-effectiveness of the structure-related RCOs, *the SAFEDOR FSA study used the original CATS criteria (cost of averting a tonne of oil spilt) of 60,000 USD/tonne spilled oil, while the environmental risk evaluation criteria were more recently agreed by MEPC 62*

With regard to the environmental risk evaluation criteria, the group agreed that the criteria agreed by MEPC 62, which is included in the Revised FSA Guidelines, should be used when conducting FSA studies. Further important issues of general interest noted by the GoE are the following:

- *Validity of the input data*

The group noted that the tanker FSA study developed a database using *several data sources in addition to LMIU and LRFP (IHS Fairplay)*, which might contain errors or insufficient data, while affirming the importance of transparency and availability of data. *The group expressed concern that commonly used databases sometimes do not contain oil spill information even on large-scale oil spill accidents.* In this regard, the group reaffirmed its view that databases that are accessible and contain detailed root causes are important, and that commercially available data should be examined and corrected and recommended to the Committee, that the GISIS module for that purpose should be further enhanced, and that the Committee encourage Member States to submit casualty data to GISIS.

- *Whether it is necessary to improve the FSA Guidelines, and, if so, prepare proposals for their improvement*

The group noted a concern that the calculated societal oil spill costs (SC) described in Appendix 7 of the draft Revised FSA Guidelines, if the assurance and uncertainty factor is unity, *may be too low for large spillages and it would discourage any effort of reducing potential oil spill risk*, and that these values should be reviewed, as well as GCAF and NCAF.

Also, the group reiterated its view that when analyzing historical casualty data, it should be kept in mind that safety levels might be improved by implementing safety measures and should be analyzed taking into account the virtue of today's mandatory instruments. For example, they should be careful when using casualty data of single-hull tankers.

Finally, the group generally agreed that *the tanker FSA was conducted in accordance with the Guidelines, recognizing that the FSA used the CATS criterion, which is different from the environmental risk evaluation criteria that were recently agreed by MEPC 62.*

3.2.4 Assessment Criteria: The Cost for Averting Fatalities and Spillages (CAF and CATS)

An important step of any FSA is (step 4) the cost–benefit assessment (CBA) determining the cost-effectiveness of each investigated risk control option (RCO). In the tanker FSA, a series of RCOs referring to both design changes, improvement of equipment, and operational and training measures were investigated and assessed in terms of cost-effectiveness with respect to both the potential loss of lives (PLL) of crew and the potential loss of cargo (PLC). Herein a cost for averting fatalities (CAF) of USD 3.0 million/fatality and a cost for averting of 1 tonne spillage (CATS) of USD 60,000/tonne spilled oil were considered in the tanker FSA. Based on these criteria, some investigated RCOs were found cost-effective and could be recommended for implementation.

However, both the foregoing assessment criteria are nowadays disputed; namely, considering the increase of the worldwide living standard in the past two decades, the EU project GOALDS ([9], 2010–2013) recommended recently an increase of CAF to USD 7.45 million/fatality, and this was acknowledged during the discussion of the passenger ship FSA at the Experts Group on Formal Safety Assessment MSC93/6/2 (18 November 2013 [24]).

Regarding the CATS criterion, MEPC 62 concluded after lengthy deliberations that CATS should be a *volume-dependent, nonlinear spill cost function*, in which the per tonne spillage cost should decrease when the spillage size increases, because this better accounts for the cost of actual spillages around the world (IOPCF database[3]).

Following the deliberations of a working group, MEPC 62 (2011) endorsed the consolidated database and the foregoing functions (Table 9.3), although it made clear that *FSA analysts are free to use other formulae, so long as these are well documented by the data*. MEPC 62 also decided to put the consolidated database in the public domain.

In the foregoing deliberations, an open issue remained: the determination of the so-called *assurance factor*, expressing *society's willingness to pay to prevent an oil spill instead of sustaining its damages*. For instance, an assurance factor of 2.0 means that society would rather spend two dollars to prevent an oil spill than pay one dollar in the form of spill cost if the spill occurs. A critical review of the developments leading to this CATS criterion may be found in Psaraftis [32].

Table 9.3 Nonlinear total spill cost functions, based on consolidated oil spill database (V, spill size in tonnes)

Spill dataset (IOPCF, USA, Norway)	Total spill cost (2009 US dollars)
All spills	$67{,}275\ V^{0.5893}$
$V > 0.1$ tonnes	$42{,}301\ V^{0.7233}$

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[3] Note that the most prominent *Exxon Valdez* 37,000-tonne oil spill in 1989, which led to the introduction of OPA 90, had a cleanup cost of USD 107,000/tonne (2007 dollars), whereas the cleanup cost of the *Braer* 85,000-tonne oil spill in 1993 was as low as USD 6/tonne ([32]).

3.2.5 Implementation and Enforcement of IMO Regulations

For IMO standards to be binding, they must first be ratified by a total number of member countries whose combined gross tonnage represents at least 50 % of the world's gross tonnage, a process that can be lengthy. A system of tacit acceptance has therefore been put into place, whereby if no objections are heard from a member state after a certain time period has elapsed, it is assumed they have assented to the treaty.

Regarding MARPOL 73/78, all six annexes have been ratified by the requisite number of nations; the most recent is Annex VI, which took effect in May 2005. In Europe, on 1 January 2015 maritime shipping levels are to become legally subject to new MARPOL directives because the SECA (Sulfur Emission Controlled Areas) zone is scheduled to increase in size. This larger SECA zone will include the North Sea, Scandinavia, and parts of the English Channel. This area is set to include all the international waters of the Republic of Ireland in 2020, culminating in all of Western Europe's subjection to the MARPOL directive. This decision has proven controversial for shipping and ferry operators across Europe.

4 Assessment of Tanker Safety

In the following we assess tanker safety by a statistical analysis of recorded accidents and their consequences on the marine environment.

4.1 Statistical Analysis of Tanker Accidents

A statistical analysis of tanker accidents performed for the time period 1978–2003 showed that the frequency of Aframax tanker accident occurrences presented remarkable downward trends [6]. A series of IMO regulations concerning the prevention of incidents/accidents have apparently contributed to the observed declining trends of accident rates, particularly in the post-1990s period, marked by the introduction of OPA 90 in the USA. Figure 9.6 [26] presents the navigational accident rates of Aframax tankers along with some key relevant regulations that could be held responsible for the declining trends of particular rates. Note that relevant regulations were herein presented according to their year of implementation, and it can be expected that their effect should be noticeable with some phase lag, depending on the nature of each regulation. Moreover, the significant MARPOL 73/78 is not indicated in this graph, although herein of importance, as it is falling in the pre-1978s period not studied by Mikelis et al. [26], and the same applies to the European ERIKA I, II, and III tanker safety packages and the more recent IMO-MEPC-50 provisions regarding the phaseout of single-skin tankers.

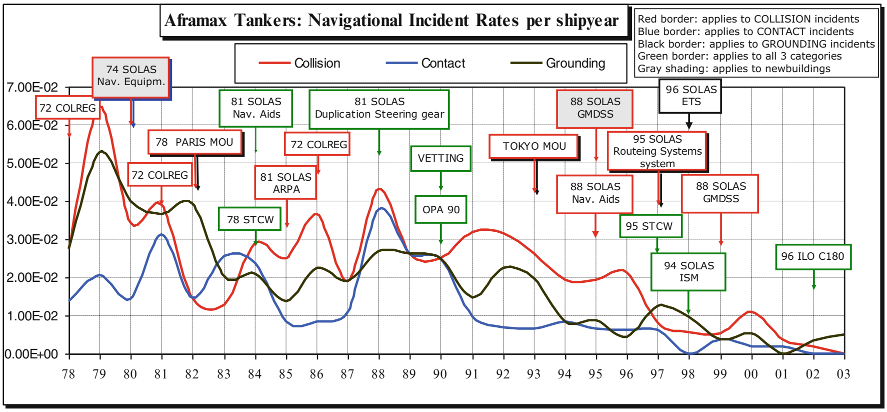


Fig. 9.6 Timeline of navigational accident rates (frequency per ship year) versus introduced international regulations, guidelines, and safety codes

4.2 *Frequencies of Serious Accidents*

The loss of a ship's watertight integrity (LOWI) by breach of a tanker's outside shell that causes release of the oil cargo to the sea is the consequence of a *serious* accident. In most, LOWI may result as a consequence of *navigational* accidents (collision, contact, and grounding), *fire/explosions*, and *structural failures*. The following accident categorization is based on the definition adopted by IMO-MSC/Circ.953 [20]:

Collision: striking or being struck by another ship (regardless of whether under way, anchored, or moored).

Stranding or grounding: being aground or hitting/touching shore or sea bottom or underwater objects (wrecks, etc.).

Contact: striking any fixed or floating object other than those included in *collisions* or *groundings*.

Fire and explosion: events are defined such that the event in question is the first initiative event reported.

Non-accidental structural failure (NASF): cases of hull damage in view of non-accidental structural failure, such as cracks and fractures, affecting ship's seaworthiness or efficiency. Damage to a vessel's rudder or rudder-adjoining parts is also considered as structural damage.

4.2.1 Employed Database Model

To conduct a risk analysis assessment, historical casualty data were extracted from the IHS Fairplay commercial casualty database and post-processed by a new purposely designed database (NTUA-SDL database) to capture/analyze the available textual information in a proper manner (using checklists, pull-down menus, etc.). Recorded raw data were then critically assessed and enhanced by other publicly available information. This procedure is considered of paramount importance for the reliability of the conducted risk analysis in the following, for these reasons:

- Commercial databases, such as IHS Fairplay or LMIU, were originally not designed for potential application in risk assessment procedures.
- Their information is to a great extent available in textual form, whereas details of importance for formal risk assessment procedures (FSA) are missing.
- In several cases, there was lack of or erratic information about principal issues for the accident analysis, namely, on the consequences of the incident or on several steps of event tree analysis (missing or erroneous spillage extent for important and well-publicized major tanker accidents).
- The data in hand were reanalyzed and post-processed in such a way to produce input to a developed global risk model. Note that all captured accidents were assigned to one of the predefined main incident categories according to the last "accidental event."

4.2.2 Sampling Plan

The following study is focused on tanker casualties that happened after the year 1990 (Table 9.4). Year 1990 is considered a landmark year because of the introduction of the double-hull tanker concept through OPA 90 in USA (in the aftermath of the catastrophic *Exxon Valdez* accident in 1989) and its tremendous effect on related regulatory developments and tanker design practice thereafter. It is believed that this period is quite representative for assessing today's situation. It is noted that previous studies on the same subject showed a significant reduction of accident occurrence in the post-1990s period, taking into consideration that a series of introduced key regulations was found to be related to the significant decrease of the frequency of tanker accidents [3].

Concerning the size of tanker ships involved in the incidents, the following DWT size segments were herein considered:

Medium oil tankers (studied period: 1990–Oct. 2009) refer to Handysize tankers (20,000–34,999 DWT) and Handymax tankers (35,000–60,000 DWT).

Large oil tankers (studied period: 1990–2011) refer to Panamax tankers (60,000–79,999 DWT), Aframax tankers (80,000–119,999 DWT), Suezmax tankers (120,000–199,999 DWT), VLCC tankers (200,000–319,999 DWT), and ULCC tankers (greater than 320,000 DWT).

With respect to the tanker subtypes/subcategories, only categories relevant to *crude oil tankers* were considered in the current investigation, namely, according to the definition of the IHS casualty database: *oil tankers*, *crude tankers*, *shuttle tankers*, *product carriers*, and *chemical/oil tankers*. It is noted that OBOs, ore/oilers, and chemical tankers (and the related accidents that may have led to maritime pollution) were excluded from the present analysis, because these ship subtypes have special design/layout and operational features that are not representative of the whole class of tankers.

4.2.3 Casualty Basic Data

The present study focuses on accidents that potentially lead to ship loss of watertight integrity (LOWI) and to accidental oil pollution; thus, only the first six (6) categories of accidents are investigated. In total, focusing on medium tankers, 722 accidents occurred in the study period, whereas for large tankers 903 accidents happened within a studied period (Table 9.4).

The listed statistics of casualty categories show quite similar results for medium and large tankers, except for the groundings and contacts (of which medium-size tankers have an increased share) and the NASF (which are more pronounced for the large tankers). This pattern may be justified by the operational profiles of the study ship types.

4.2.4 Operational Fleet at Risk

A critical review of tanker safety cannot be conducted on the basis of absolute numbers, but rather by relating the number of accidents to the relevant worldwide operating fleet of vessels. The *annual operational fleet at risk* is defined as the number of ships that is operated worldwide in the corresponding period; it was calculated by considering the monthly operation of each tanker vessel registered in the IHS database. Figure 9.7 presents the corresponding *fleet at risk of large and medium tankers* along with the annual distributions of the double-hull (DH) fleet and non-double-hull fleet.

The gradual and, after the year 1999, more rapid decrease of the share of the non-DH fleet as a consequence of the introduction of OPA 90 and later on of MARPOL 73/78 and ERIKA I and II is clearly shown.

Table 9.4 Sample of casualty data

	Medium tankers (1990–2009)		Large tankers (1990–2011)	
Casualties	Number	%	Number	%
Collision	238	33	317	35
Contact	116	16	100	11
Grounding	214	30	217	24
Fire	53	7	74	8
Explosion	31	4	36	4
NASF	70	10	159	18
Total	***722***		***903***	

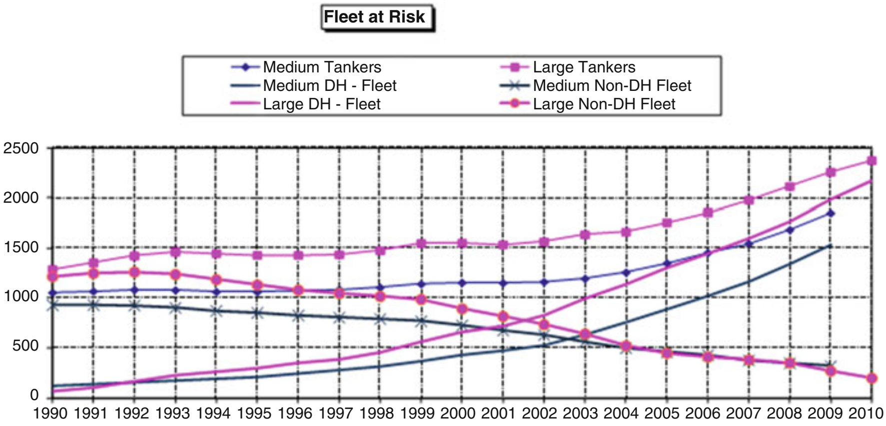


Fig. 9.7 Double-hull fleet and non-double-hull fleet

4.2.5 Frequency of Tanker Accidents Leading to LOWI

Presented accident frequencies were calculated by dividing the total annual number of registered accidents by the number of ships operating in that year (annual operational fleet at risk). Figure 9.8 presents the annual frequency of the sum of the six predefined accident categories in the post-1990 period.

The accident frequency behavior confirms a significantly decreased trend and is quite similar for both tanker sizes, with significant high peaks observed in year 1990 and progressively decreasing in the years after, presenting a significant decrease after 1999. After 1999, the DH fleet begins to show a considerable share in the overall operational fleet (Fig. 9.7), which means that the new (ship) buildings that entered the operational fleet at the year of census have had enhanced implemented formal IMO procedures, which were in compliance with stricter rules; they displayed improved design (double-hull concept) and their crew underwent enhanced training (STCW). Furthermore, the existing (non-DH) fleet at that time had to comply with a series of stricter regulations until their phaseout, so that as a consequence the overall frequency of accidents decreased.

Accident frequencies were much reduced in the past decade, namely, in the post-2000 period, compared to the preceding decade (Table 9.5). In addition, statistical values after year 2000 are almost unchanged for both tanker sizes. Serious events and oil pollution cases (which is a subset of the serious events) also present a slightly downward trend over the years.

The current study presents results of a systematic analysis of accidents pertaining to medium and large oil tankers (deadweight greater than 20,000 tonnes) and covering the period after the introduction of OPA 90, namely, 1990 to 2009 (October), continuing earlier studies of NTUA-SDL on the design and safety of tankers. Calculated values derived from the statistics must be used with caution, because available databases do not consider all accidents (problem of

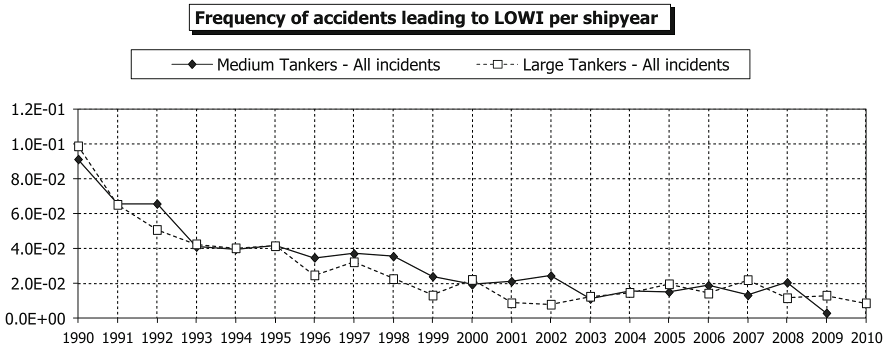


Fig. 9.8 Annual frequency of accidents potentially leading to loss of watertight integrity (LOWI)

Table 9.5 Average frequency of events

	Medium tankers	Large tankers
	1990–2008	**1990–2010**
All types of accidents	2.93E−02	2.54E−02
Serious cases	1.14E−02	9.59E−03
Cases with oil release to the sea	2.56E−03	3.21E−03
	2000–2008	**2000–2010**
All types of accidents	1.54E−02	1.37E−02
Serious cases	9.71E−03	9.46E−03
Cases with oil release to the sea	4.34E−04	2.41E−03

underreporting) and provide always a snapshot based on a certain observation period. Thus, single accidents may have a significant impact on the accident frequencies and especially on the indentified consequences. Figure 9.9 presents the frequency of accident occurrence with the confidence interval to show the uncertainty of calculated values.

The data in this chapter provide the basis for the development of a risk model for medium tankers, which complements studies for large tankers conducted earlier. Such a risk model should consider the uncertainty in the initial accident frequencies as well as in the dependent probabilities in the scenarios; this would allow considering the effect of uncertainty also in subsequent analyses, for instance, in a cost–benefit analysis of design modifications [10].

4.2.6 Navigational Accidents

Focusing on navigational accidents (collision, contact, and grounding), both main tanker sizes exhibit reduced frequencies within the studied period (Fig. 9.10). Practically, after year 1999, the annual frequency does not further decrease, but starts oscillating close to an upper limit (2.0E−02). Apart from the entrance of new construction of the DH concept, some enhanced safety regulations were introduced

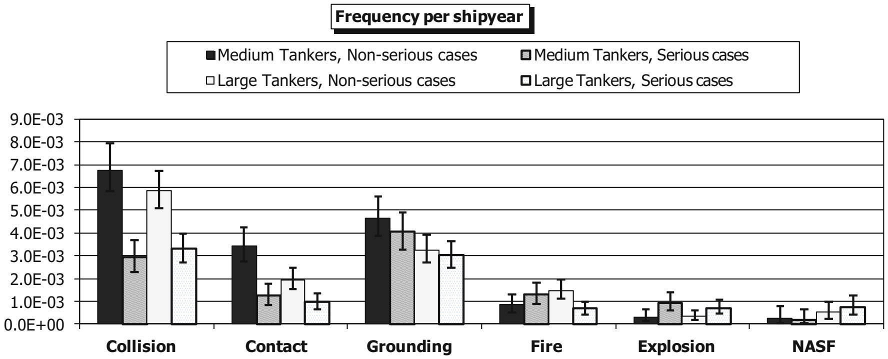


Fig. 9.9 Frequency of occurrence of main accident categories potentially leading to LOWI

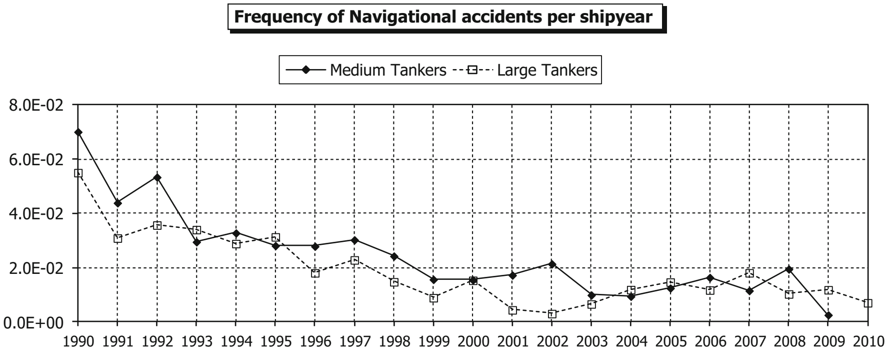


Fig. 9.10 Navigational accidents: frequency per ship year

and applied to existing (non-DH) ships as well, such as ISM Code, STCW, ETS, and SOLAS provisions on routing systems, and all these factors possibly led to the resultant frequency decrease.

Table 9.6 presents frequencies for each accident category. Collision frequencies have almost similar values and could be considered as independent of ship size. Medium and large tankers have almost the same frequency with respect to serious contact cases. Higher grounding frequencies appeared for medium tankers.

4.2.7 Fire and Explosion Accidents

A slight decreasing tendency can be observed in annual frequency during the studied period (Fig. 9.11). Especially in the second decade (after 1999), annual frequencies are confined within significantly smaller margins compared to the corresponding date of the first decade of statistical analysis. It is believed that the ISM Code has had a significant impact on the crisis management onboard ships and in the reduction of the potential of accidents of this type.

Table 9.6 Frequency of collision, contact, and grounding events (full period)

	Medium tankers	Large tankers	Medium tankers	Large tankers
	All incidents		Serious cases	
Collision	9.66E−03	9.16E−03	2.92E−03	3.30E−03
Contact	4.71E−03	2.89E−03	1.26E−03	9.54E−04
Grounding	8.69E−03	6.27E−03	4.06E−03	3.01E−03

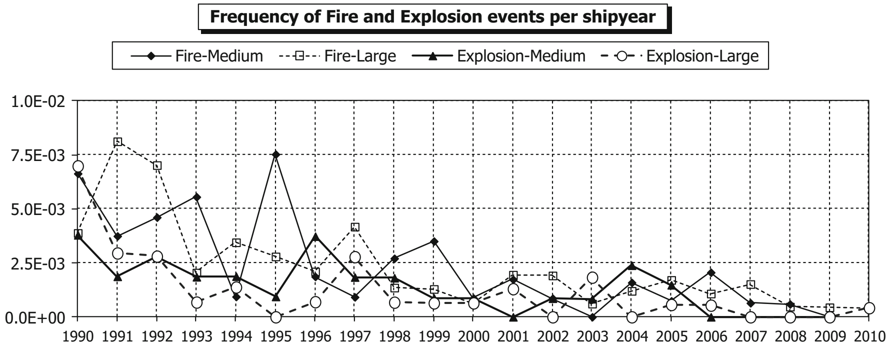


Fig. 9.11 Fire and Explosion accidents: Frequency per ship year

Table 9.7 Frequency of fire and explosion events (full period)

	Medium tankers	Large tankers	Medium tankers	Large tankers
	All incidents		Serious cases	
Fire	2.15E−03	2.14E−03	1.30E−03	6.65E−04
Explosion	1.26E−03	1.04E−03	9.34E−04	6.94E−04

Table 9.7 presents the frequencies of fire and explosion events. Considering all events, regardless of the degree of accident severity, the calculated frequencies exhibit almost the same values for both tanker sizes.

4.2.8 Non-accidental Structural Failures (NASF)

Figure 9.12 presents the annual frequency of non-accidental structural failures for both tanker sizes within the studied period. This particular accident is highly dependent on the basic hull type, namely, double-hull and non-double-hull ships; consequently, all related frequencies are herein calculated for double-hull ships only.

The diminishing frequencies, especially after year 2000, indicate improved shipbuilding technology, even though we can observe, from other statistics, that minor structural failures occur for relatively young tanker ships as a consequence of inferior shipbuilding practices [28].

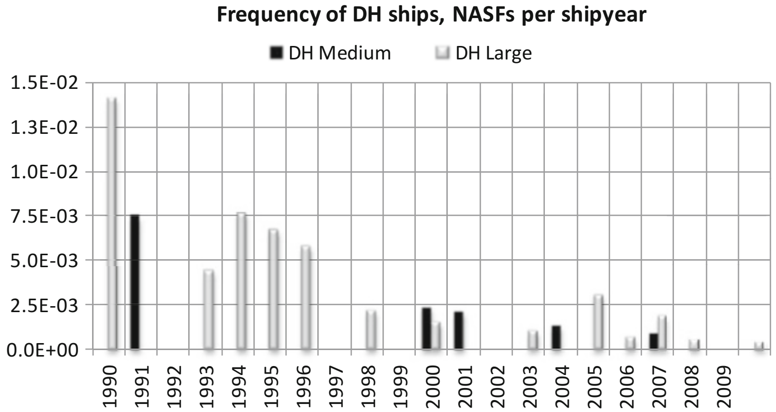


Fig. 9.12 Non-accidental structural failure: frequency per ship year

4.3 Consequences and Impact on the Marine Environment

4.3.1 Total Losses

Figure 9.13 illustrates the frequency of tanker ship total losses per accident category per tanker size, noting that there was no total loss of a ship because of a contact event.

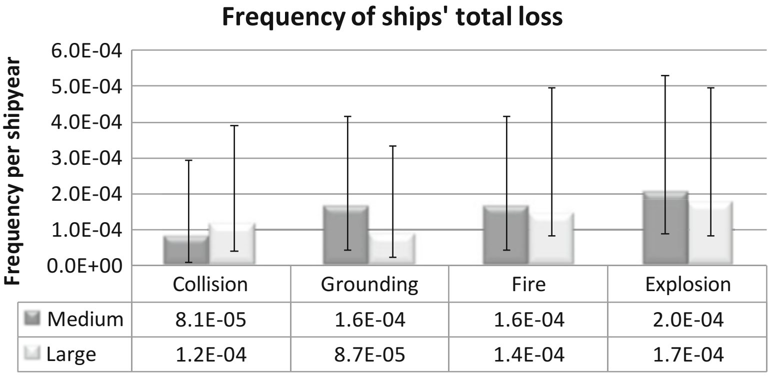
Both medium and large tankers present highest frequencies for ship total loss in explosion accidents. It must be noted that although explosion accidents have a relatively low frequency of occurrence, when they happen, the consequences are severe.

Furthermore, there was, up to now, no DH ship total loss from a *non-accidental structural failure*, which may be justified by the fact that the DH fleet is relatively new, whereas older DH ships are replaced earlier than former non-DH ships in view of the reduced life cycle of more recent new construction.

4.3.2 Marine Pollution

For the investigated tanker ship sizes, it is trivially confirmed that the larger the ship, the more severe is the environmental impact in the case of accidental loss of her watertight integrity as a consequence of the larger cargo tank sizes. Figures 9.14 and 9.15 present the oil released to the sea as a consequence of medium- and large-size oil tanker accidents during the studied time period. Note that for non-accidental structural failure, all ships independent of basic hull type (thus, both DH and non-DH ships) are included.

Year 1994 was the worst year within the studied period as related to oil release to the sea from *medium-size tankers*. Two significant accidents led to an annual



	Collision	Grounding	Fire	Explosion
▩ Medium	8.1E-05	1.6E-04	1.6E-04	2.0E-04
▢ Large	1.2E-04	8.7E-05	1.4E-04	1.7E-04

Fig. 9.13 Ship total loss: frequency per ship year

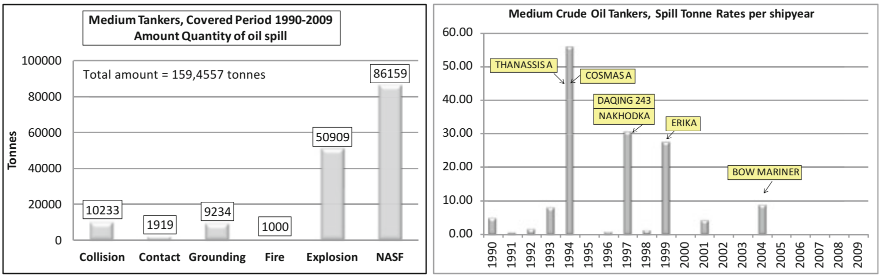


Fig. 9.14 Medium tanker marine pollution over the studied period and yearly spill tonne rate

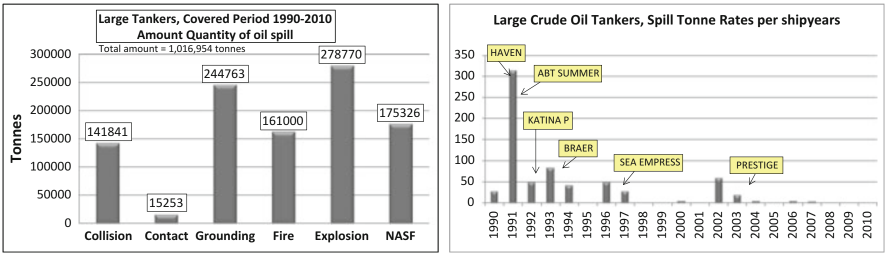


Fig. 9.15 Large tanker marine pollution over the studied period and yearly spill tonne rate

average spill tonne rate of 56 tonnes per ship year. The single-hull tanker *Thanassis A*, built in 1976, broke into two pieces during typhoon “Teresa” 700 km off Hong Kong, spilling 35,020 tonnes oil into the sea. Fifteen crewmembers were reported missing and one killed. After a tank explosion, the medium single-hull tanker *Cosmas A*, built in 1974, also broke in two 150 miles off Luzon, causing an oil release of 23,370 tonnes. Nine crewmembers were reported missing and one killed.

For *large tankers* (and *overall*), the worst year ever (up to the present) was 1991, corresponding to an average annual spill rate of 313 tonnes per ship year, mainly because of two catastrophic types of accidents related to very large crude carriers (VLCCs). The *Haven* caught fire and exploded during offloading to the Multedo floating platform, 7 miles off the coast of Genoa (Italy). The ship was originally loaded with 230,000 tons of crude oil, while the accident happened with about 144,000 tonnes of crude oil onboard; she broke into two parts and sank after burning for 3 days. About 50,000 tonnes crude oil are believed to have polluted the Mediterranean coast of Italy and France for the next 12 years; six crew members were reported killed. The *ABT Summer* sustained a deck explosion while 1287 km off the coast of Angola (Africa). The ship sank after 3 days of burning in the open sea while loaded with about 260,000 tonnes of heavy crude oil. Four crewmembers were reported missing and one person killed. As the accident occurred far from the coast, the environmental impact was limited.

4.4 World Geography of Spillage Areas

Regarding the geographic areas in which tanker accidents have occurred, the Marsden square mapping or Marsden square grid of the IHS database is used; the particular system subdivides the surface of the earth into 100 "squares" bounded by meridians and parallels at intervals of 10° (Fig. 9.16). Following this zoning system, the geographic areas with more frequent accidents are identified, independent of the accident category, namely, areas with more than 15 absolute number of accidents per ship type (red circles in Fig. 9.16) within the studied period. However, and independent of absolute accident statistics, more accurate conclusions on this subject can be drawn only by comparing the number of accidents to the operating fleet in the corresponding geographic areas.

Navigational events present a concentration of events in specific areas, whereas fire, explosion, and NASF could be considered as unrelated to geographic areas. Table 9.8 presents the most frequent areas per accident category in terms of absolute accident numbers; in Table 9.9, the areas of the most frequent oil release to the sea are presented in terms of absolute amount of oil released to the sea.

In Fig. 9.16, a Marsden grid with *green* squares presents geographic areas with the *highest numbers of navigational accidents* that occurred within studied periods (results of Table 9.8), whereas the *red* squares present areas with the *greatest amount of oil release to the sea* (results listed in Table 9.9).

5 Risk-Based Design of Tankers

Risk-based ship design (RBD) is a relatively new scientific and engineering field of growing interest to researchers, engineers, and professionals from various disciplines related to ship design, construction, operation, and regulation. Applications of risk-based approaches in the maritime industry started in the early 1960s with the

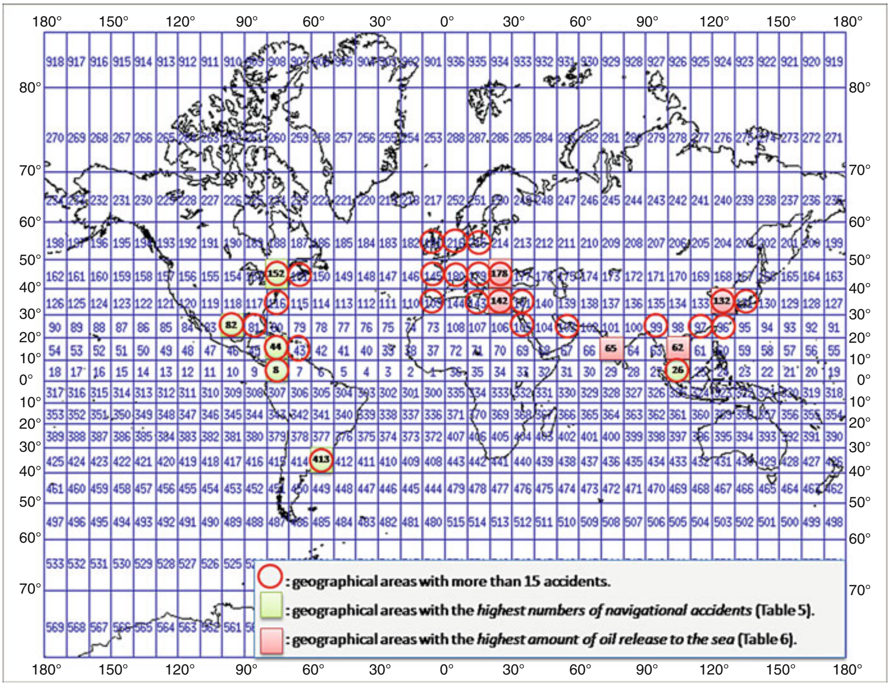


Fig. 9.16 Geography of medium (*1990–Oct. 2009*) and large (*1990–2011*) crude oil tanker accidents

Table 9.8 Marsden grid of geographic areas with highest numbers of accidents occurred within studied periods

	Medium tankers (1990–Oct. 2009)	Large tankers (1990–2011)
Collision	26	26
Contact	152	8 and 82
Grounding	152 and 413	82 and 44

Table 9.9 Marsden grid of geographic areas with greatest amount of oil release to the sea within studied period

	Medium tankers	Large tankers
Collisions	62 and 142	178 and 26
Contact	62 and 564	132
Grounding	132 and 178	65

introduction of the concept of probabilistic ship damage stability. In the following years, they were widely applied within the offshore sector and are now being adapted and utilized more and more within the ship technology and shipping sector.

The main motivation to use risk-based approaches is twofold: to implement a novel ship design that is considered safe but, for some formal reason related to current regulations, cannot be approved today, and/or to rationally optimize an existing design with respect to safety, without compromising on efficiency and performance, noting here that safety is not a design constraint but rather one aim of a multi-objective design procedure.

RBD was introduced to the maritime field by the EU-funded project SAFEDOR (Design, Operation, and Regulation for Safety [34]), an integrated project under the sixth framework program of the European Commission (see Papanikolaou [30]). The project started in February 2005 and was completed in April 2009. Under the coordination of Germanischer Lloyd, 52 European organizations, representing all stakeholders of the European maritime industry, took part in this important R&D project that prepared and submitted a variety of FSA studies and other regulatory procedures for consideration to IMO.

As part of the SAFEDOR project, a team of RTD project members developed an innovative Aframax tanker design of enhanced efficiency and safety [31]. The developed risk-based design procedure was later on extended by NTUA-SDL and Germanischer Lloyd to include more objectives representing ship's efficiency (such as EEDI and cost of transport) in the frame of a holistic approach to ship design. This approach led to an innovative tanker design concept, namely, the BEST design concept (Better Economics with Safer Tankers) [35]. Some characteristic results of this research are briefly reproduced next.

The developed design approach integrates hull form, hull layout, and hull structure optimization. Assessment tools that were developed using the NAPA software system (www.napa.fi [27]) were linked to the optimization environment of the FRIENDSHIP–Framework (FFW; www.friendship-systems.com) [7]. A general flowchart of the optimization is presented in Fig. 9.17. The optimization loop comprises the generation of models and the assessment of each design variant according to the selected objective functions.

A parametric model was created for each main part of the design problem: the hull, the layout, and the structure, with the latter the most time consuming to establish. This model included information about the main particulars of the vessel, plate distribution, and stiffener arrangement of primary and secondary members, tank arrangement, and load definitions. The parametric model was realized by providing the principal structural design as a POSEIDON template database that delivered a complete structural model by combining it with the main structural design parameters. Figure 9.18 shows the POSEIDON model, which is then used to check compliance with the International Association of Classification Societies (IACS) Common Structural Rules (CSR) hull structure requirements.

Results

The optimization process started with a so-called design of experiments (DoE), which enables the exploration of the design space in such a way that each design parameter was varied between the allowed minimum and maximum values (see Harries et al. [11]). About 2000 design variants were generated and all the design parameters were systematically varied. Plots of primary and secondary design parameters (e.g., length between perpendiculars, beam, draft, double hull width

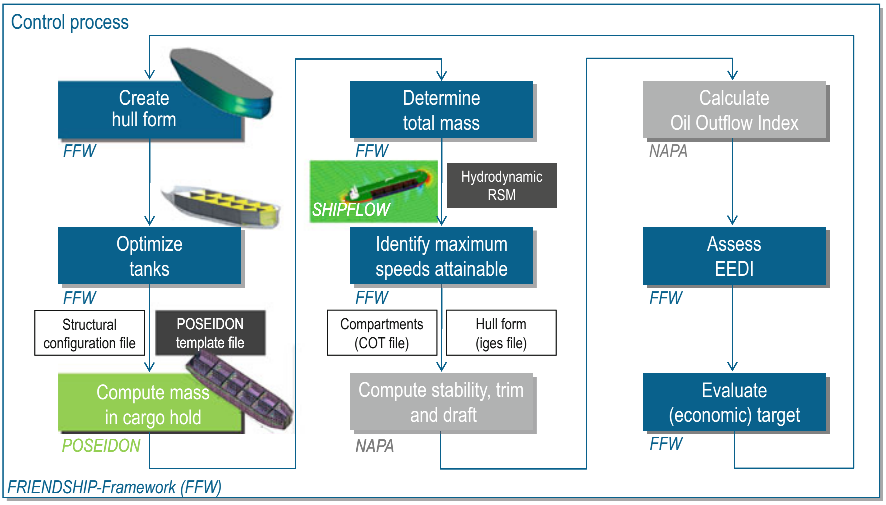


Fig. 9.17 Flowchart of innovative tanker design optimization

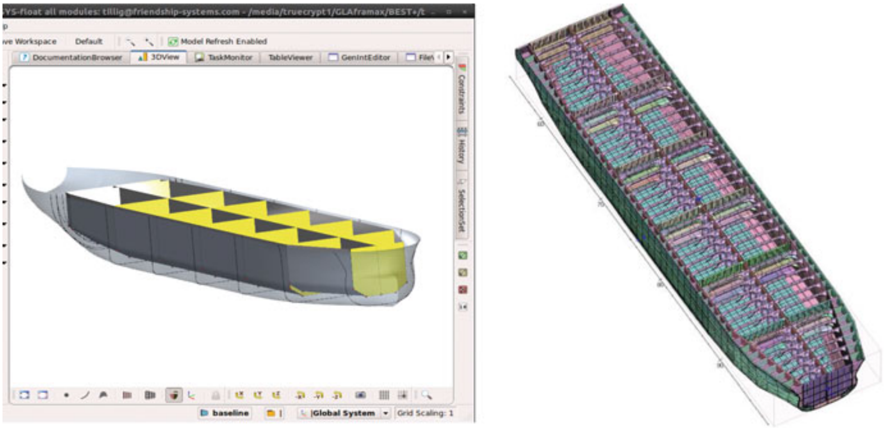


Fig. 9.18 Parametric models for hull layout created within Friendship-Framwork (FFW) (*left*) and hull structure created by POSEIDON (*right*)

and height) versus design targets (e.g., speeds at different drafts, EEDI, cargo capacity, oil outflow index) were used to visually identify design trends and to refine the design focus for the next round of DoE. The final DoE delivered about 400 design variants and design targets (cargo volume, oil outflow index, EEDI, and cost of transport) presented again in scatter plots to identify the optimum design variants (see Fig. 9.19, which shows selected scatter plots including the Pareto fronts).

The final DoE was used to identify the most promising design variants for the next level of optimization, which was conducted to fine-tune the design with a

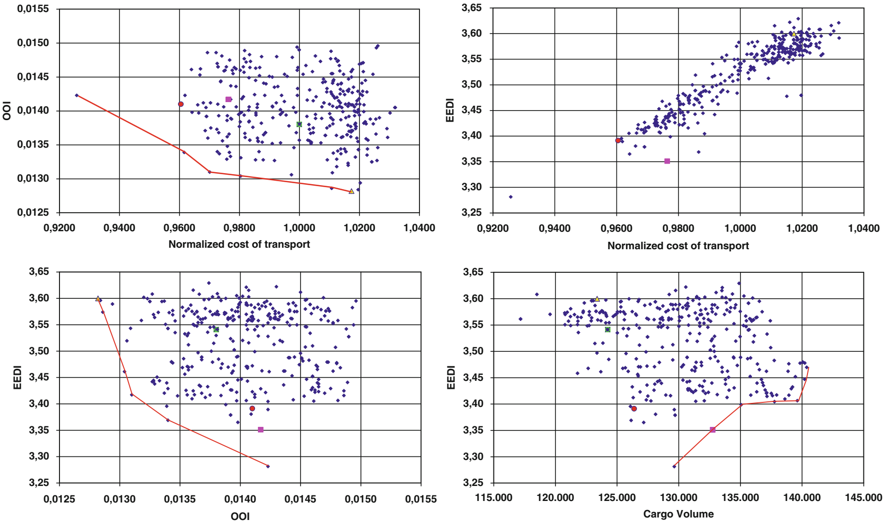


Fig. 9.19 Selected scatter plots of vessel key particulars and design targets

particular focus on hydrodynamic improvement to increase attained ship speed. Cost of transport (the ratio of annual total costs to annual cargo transported) was used to guide the optimization in the final stages (see Fig. 9.20). In Fig. 9.20, the cost of transport has been normalized by the respective value of the reference design. The reference design is an existing Aframax oil tanker design, developed and built before the Common Structural Rules (CSR) entered into force, and it is considered to be a very good design in terms of cargo capacity and oil outflow index. The Pareto front of optimum designs is clearly visible, and the best designs in terms of oil outflow index (OOI), EEDI, and cost of transport are labeled explicitly. It can be seen that the best design in terms of EEDI is a large DWT design; this is because the EEDI favors larger vessels. On the other hand, the best design in terms of oil outflow index is a small DWT design with higher cost of transport, which is the result of the larger double-hull clearances for this design variant.

The design with the lowest cost of transport was used as a starting point for the final hydrodynamic optimization. This local hydrodynamic optimization, utilizing a deterministic search strategy, was undertaken only for the aft body, focusing on the quality of the wake field as an objective. The aft body was allowed to change such that the impact on the cargo tanks previously established in the global optimization was negligible.

The resulting optimal design (Fig. 9.21) and main particulars (Table 9.10) are characterized by the following aspects:

- The hull and cargo oil tank layout is conventional with a uniform tank length distribution and a mostly constant double-hull width and double-bottom height. Note that when optimizing the same tanker for *minimum oil outflow* only, thus considering only environmental aspects, then the tank length of the forward

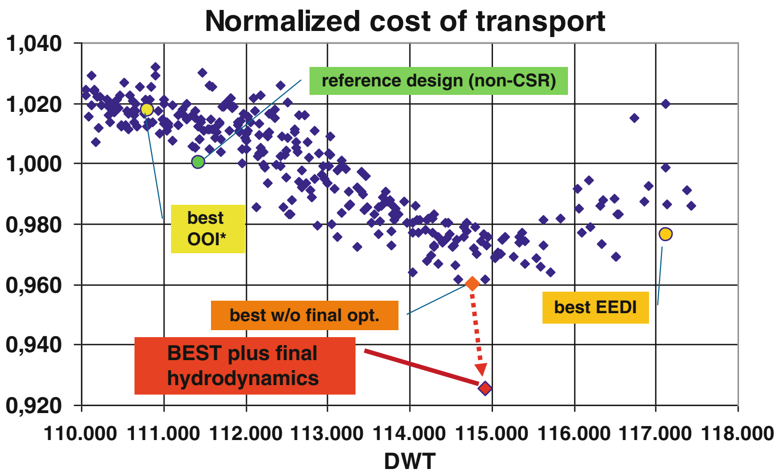


Fig. 9.20 Cost of transport for design variants

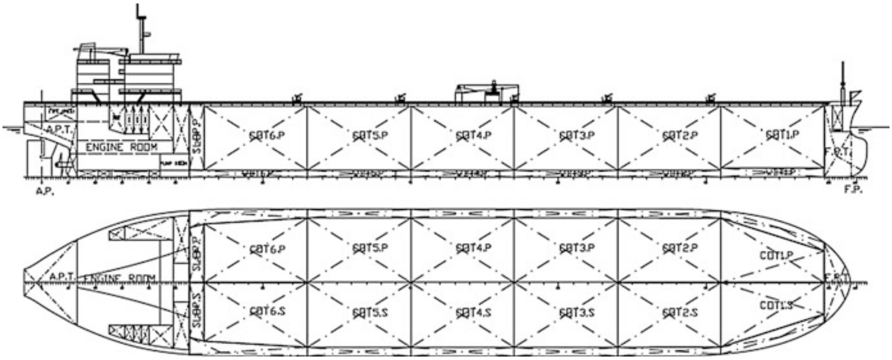


Fig. 9.21 General arrangement of Better Economics with Safer Tankers (BEST) design

Table 9.10 Main particulars of BEST design

DWT	114,923	t	Double bottom height	2.1	m
Cargo volume	129,644	m^3	DB height in COT1	2.75	m
Loa	250.0	m	Double hull width	2.65	m
Beam	44.0	m	Oil outflow index	0.0142	
Depth	21.5	m	Speed at scantling draft	15.3	kn
Design draft	13.7	m	Speed at design draft	15.6	kn
Block coefficient	0.85		Speed at ballast draft	16.8	kn
			EEDI	3.281	g CO2/(t*nm)

tanks was reduced, whereas the tanks placed more astern tended to have greater lengths and cargo capacity.

- (See Papanikolaou [31]).
- The double hull width is larger than compared to similar designs to facilitate low oil outflow in accidental conditions. The raised double-bottom height in the cargo oil tank no. 1 area also reduces oil outflow in accidents. To ensure structural continuity, an inclined inner bottom is located over two frames in cargo oil tank no. 2.
- Slop, fuel, and ballast tank capacities have been kept similar to existing designs. Only the marine gas oil (MGO) tank capacity was increased, to 700 t, to enable longer voyages inside the emission control area (ECA).
- The large cargo volume was realized, with main dimensions being constrained by port facilities, by providing a greater depth than found on similar designs. The relatively large block coefficient, defined at scantling draft, also contributes to the large cargo capacity of this design.
- The installed power was limited to the power available from a typical Aframax oil tanker engine, a MAN 6S60-MC, and the speed performance of the hull was optimized for scantling draft, design draft, and ballast draft. The speed power curves with 95 % confidence intervals are shown in Fig. 9.22, documenting the high speed potential of the optimized hull form. In this figure, a sea margin of 10 % has been included. The speed was determined for three drafts simultaneously, that is, scantling, design, and ballast, and the final hull form was the one considered to be optimal for all three drafts.

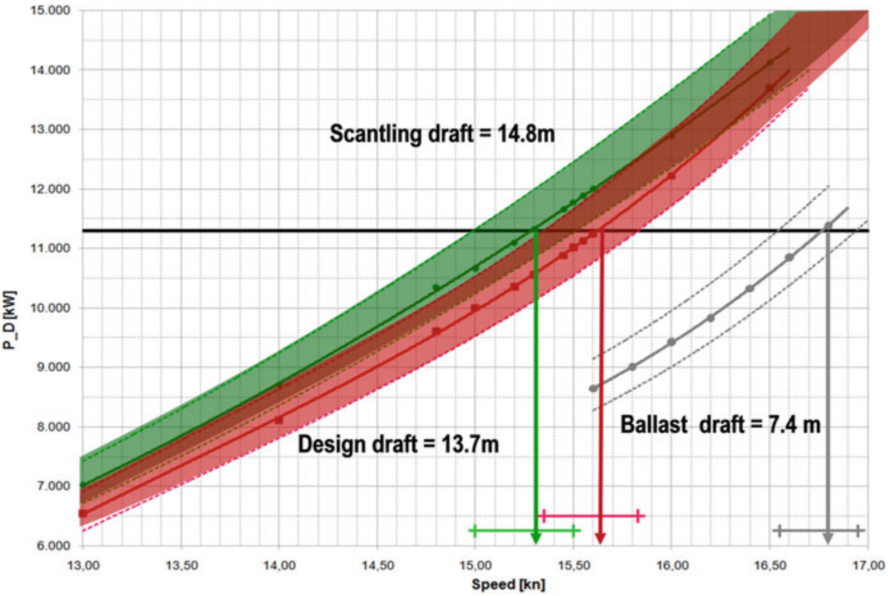


Fig. 9.22 Speed–power curves with 95 % confidence intervals. A sea margin of 10 % has been integrated into the curves

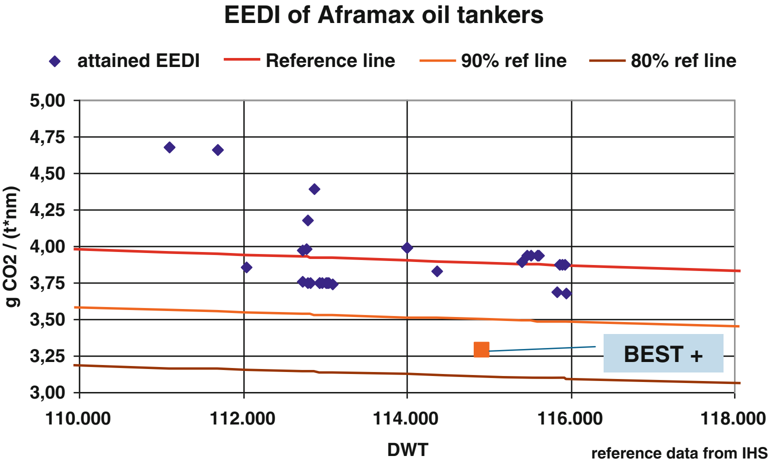


Fig. 9.23 Energy efficiency design index (EEDI) of optimal design compared to similar designs

The EEDI criterion is a mandatory new building standard, as of 1 January 2013, and greatly influences current and future ship designs of all ship types. With the first reduction of the EEDI requirement, 10 % becoming effective for vessels being contracted on or after 1 January 2015 (see Regulation 21 of revised MARPOL Annex VI), current new buildings will be facing stiff competition in less than 10 years from now. Therefore, the target for the new design was to have an attained EEDI of less than 90 % of the current reference line value to ensure competitiveness after the first reduction of the EEDI requirement will have entered into force. The resulting optimum design features a 16 % lower EEDI than required by the reference line (see Fig. 9.23).

6 Summary: Epilogue

The present chapter presented a critical review of historical developments in oil tanker design and of relevant regulations referring to the prevention of marine oil spills and the protection of the marine and the aerial environment; it showed the main results of a comprehensive analysis and critical review of recorded accidents of medium- and large-size oil tankers (deadweight greater than 20,000 tonnes), which occurred after the introduction of OPA 90 and until today. It shows that the frequency of tanker accidents significantly decreased over the years; accidental pollution rates, however, did not follow the same pattern of significant decrease, because rates are determined by the "catastrophic" type of accidents, which continued to happen from time to time. Finally, the chapter considered future developments in oil tanker design and operation in the frame of risk-based design and operation, targeting tankers of enhanced efficiency and safety within a holistic approach to ship design and operation.

Future regulatory developments in relationship to tanker design, operation, and safety, after the concluding discussion of the SAFEDOR tanker FSA by the Group of Experts at IMO (2012) and the conclusion of discussions at IMO-MEPC about the estimation of the cost for averting 1 tonne spilled oil (CATS), are not expected to be on the IMO agenda. However, past experience has taught us that this situation will rapidly change with the next catastrophic type of pollution accident near a coastline. ULCCs, representing an incredibly high risk in case of an accident, seem to be withdrawing from the world market anyway, while the limited lifespan of recent tanker ship buildings calls for an increased pace of replacement of old tonnage. All these factors may let us hope that the catastrophic type of pollution of the marine environment by tanker accidents will be gradually reduced in the future.

Future ship design developments approach highly competitive oil tanker design concepts by use of advanced multi-objective optimization frameworks, which integrate hull form, hull layout, and hull structure assessment to facilitate evaluation of many design variants. This knowhow was applied to design an Aframax oil tanker targeting Caribbean trades, and the resulting design is safer, greener, and smarter at the same time. The oil outflow index is 9 % lower than required by MAPROL, the EEDI is 16 % lower than the current reference line, and the cost of transport is 7 % lower compared to a reference design. Taken together, the new design concept demonstrates that better economics and higher safety can be realized in one design.

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