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Analysis of the Relationship between Selected Ship and Propulsion System Characteristics and the Risk of Main Engine Turbocharger Explosion

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Abstract: The scientific aim of this paper is to analyse the topicality of the turbocharger explosions and to attempt to answer the question of whether some technical characteristics of the engine can be perceived as directly connected with the risk of the turbocharger explosion. Moreover, our objective was also to calculate the turbocharger explosion probability. This article presents the results of a quantitative and qualitative analysis of 42 explosions of marine main engine turbochargers occurring between 1977 and 2022. The number of explosions was analysed, and the average and instantaneous frequencies of turbocharger explosions each year were determined. An analysis was performed of the number of explosions with respect to the age and type of ship on which the accident occurred. An analysis of the contribution of different types of main engine to the studied population of explosions was also carried out. Criteria such as the number of strokes, engine speed, type of crank-piston mechanism, cylinder arrangement, engine power per cylinder, and number of cylinders were considered. An analysis was carried out of the disasters that had occurred, considering the contribution of the various engine manufacturers. An integrated distribution of the number of turbocharger explosions by year was presented, considering the engine speed, the maximum continuous rating of the engine, and the engine design. The analysis did not indicate a significant correlation between the type of ship and the number of explosions that occurred. More than half of the analysed population of explosions (median) occurred on vessels no older than 15 years. It is highly likely that engine type does not directly affect the number of turbocharger explosions and the risk of explosions. On the other hand, it is not possible to exclude the influence of the individual characteristics of an engine built to a particular manufacturer's design on the magnitude of the risk of a turbocharger exploding during engine operation. Considering the number of ships worldwide, the probability of an explosion in a given year on a given ship is not less than 1.61×10^{-7}.

Keywords: main engine; marine propulsion; prime mover; turbocharger; explosion; fire; failure analysis

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1. Introduction

Some of the hazards [1] that occur during the operation of marine engines are fires [2] and explosions [3]. Among the engine components exposed to these phenomena are turbochargers [4], whose failures are particularly dangerous to the engine and the immediate environment [5], as they can result in fires in the ship's engine room [6], as well as injury to crew members [7] and damage to machinery [8]. The main cause of turbocharger explosions is overspeed operation [9]. This is caused by the inconsistent flow [10] of air through the compressor, which in turn is related to too little or too much fuel and the parameters of the charge exchange system [11]. A change in the amount of fuel fed depends on the quality of the engine control system and the characteristics of the engine itself [12]. In the literature on the subject, the following are listed as the root causes of failure (based on [13–15]):

- Developing turbocharger damage (undetected in the absence of periodic maintenance).
- Air hose becoming completely detached.
- Air leaks between the compressor and engine.
- Erosion and deterioration of the piston crown.
- Loss of signal to the electronic actuator for the wastegate.
- Inappropriate operation of VNT (variable nozzle turbine) control.
- Tear in the air hose.
- Restrictions in the air intake filter or pipework (excessively dirty filter, improperly performing water-wash on the turbine and compressor side and/or dry-cleaning on the turbine side).
- The wastegate or VNT mechanism has been set incorrectly.
- Worn injectors.
- Feeding the engine with fuel of improper physical and chemical parameters.
- Installing an incorrect turbo.
- Modification of turbocharger, scavenging system, fuel injection system, or control units (incl. fuel injection control maps/algorithms).
- Incorrect movement or restrictions in the VNT mechanism.

The manner in which an unsafe situation develops can vary depending on the individual root causes in a given situation [16]. For example, an explosion can be caused by overheating due to improperly functioning cooling [17]. The source of the problem may also lie in a crack in the bottom of the piston allowing oil to flow from the engine lubrication system into the combustion chamber. This situation results in a flow of lubricating oil that cools the piston in the combustion chamber during the exhaust stroke, and the oil is then further transferred through the open exhaust valve(s) into the exhaust manifold. Subsequently, the accumulated oil in the exhaust manifold ignites (spontaneously), and the fire then moves to the turbocharger, causing it to explode [18,19].

Another cause may be an unstoppable fire in the under-piston space, which in the next step results in a shortage of oxygen supplied to the cylinders because of a reduction in the amount of air due to the combustion process (fire) in the air reservoir. This, in turn, has the effect of reducing engine speed. The control system in such a situation will increase the fuel dose to compensate for the drop in power. In a situation of increased fuel and decreased oxygen, unburned fuel will enter the under-piston space and the exhaust manifold. Subsequent ignition of the large amount of accumulated fuel in the exhaust manifold can, in turn, overspeed the turbocharger and damage it (burst the device).

An analogous situation can occur with a lack of attention to the cleanliness of scavenging system components, including the cleanliness and permeability of air filters and coolers, scavenging spaces, under-piston spaces, and scavenging ports. An example of such negligence is shown in Figure 1, which shows scavenging ports with significantly reduced active cross-sections due to carbon deposits that had accumulated over a long period of time [20].

The replaced engine suffered two major failures related to turbocharger explosions on 22 September 2002 and 12 February 2003. The effects of these explosions are shown in Figures 2 and 3, respectively. Both explosions led to damage to the rotor and turbocharger body [20].

Figure 1. View of contaminated scavenging ports in the sleeve of cylinder No. 2 of the main engine of the m/v Goliath (Australian Transport Safety Bureau, 2006).

Figure 2. View of the turbocharger of the main engine of the ship m/v Goliath after the explosion on 22.09.2002 (Australian Transport Safety Bureau, 2006).

Figure 3. View of the turbocharger of the main engine of the ship m/v Goliath after the explosion on 12.02.2003 (Australian Transport Safety Bureau, 2006).

According to turbocharger manufacturers' recommendations, once the turbocharger's rotor has reached its maximum allowable speed, the engine power should be reduced. In certain situations, additional measures, such as installing an exhaust gas waste gate [9], are necessary. As a result of the accidents that have occurred to date, engine manufacturers are increasing safety requirements. For example, MAN has increased the level of security by requiring an engine shutdown activated by the main engine safety system, instead of the previously used engine slowdown, to be initiated when turbocharger overspeed is detected [11].

It is important to undertake timely and correct maintenance of the engine, including the turbocharger [21], pistons [22], and fuel apparatus [23]. Assessing the condition of the turbocharger rotor makes it possible to detect the fact that the turbocharger is operating at overspeed. The main effects are [14] the 'orange peel' effect, inducer blade damage, partial loss of blades, burst wheels, and fatigue fractures of the blades. 'Orange peel' effect is shown in Figure 4. Such changes in surface condition when discovered during routine overhauls of the turbocharger should be used as an important symptom of turbocharger overspeed operation occurrences.

Figure 4. 'Orange peel' effect of turbocharger operation in overspeed conditions—zoomed surface of the rear side of the inducer (modified from Diesel Levante, 2017).

The scientific aim of the paper is to analyse the topicality of the turbocharger explosions and to attempt to answer the question of whether some technical characteristics of the engine can be perceived as directly connected with the risk of the turbocharger explosion. Moreover, our objective is also to calculate the turbocharger explosion probability. Such data are currently unavailable in reliability databases known to the authors, e.g., OREDA [24]. The obtained probability value can further be used in other reliability and safety analyses as a part of operational models of marine internal combustion engines.

2. Materials and Methods

This study used a methodology adapted from a previous study on the issue of improving the safety of marine engines in the context of minimising the risk of explosions in crankcases [25]. The course of the research process is shown in Figure 5. The successive steps were to firstly select a query to obtain source data, then analyse the data, and finally synthesise the results.

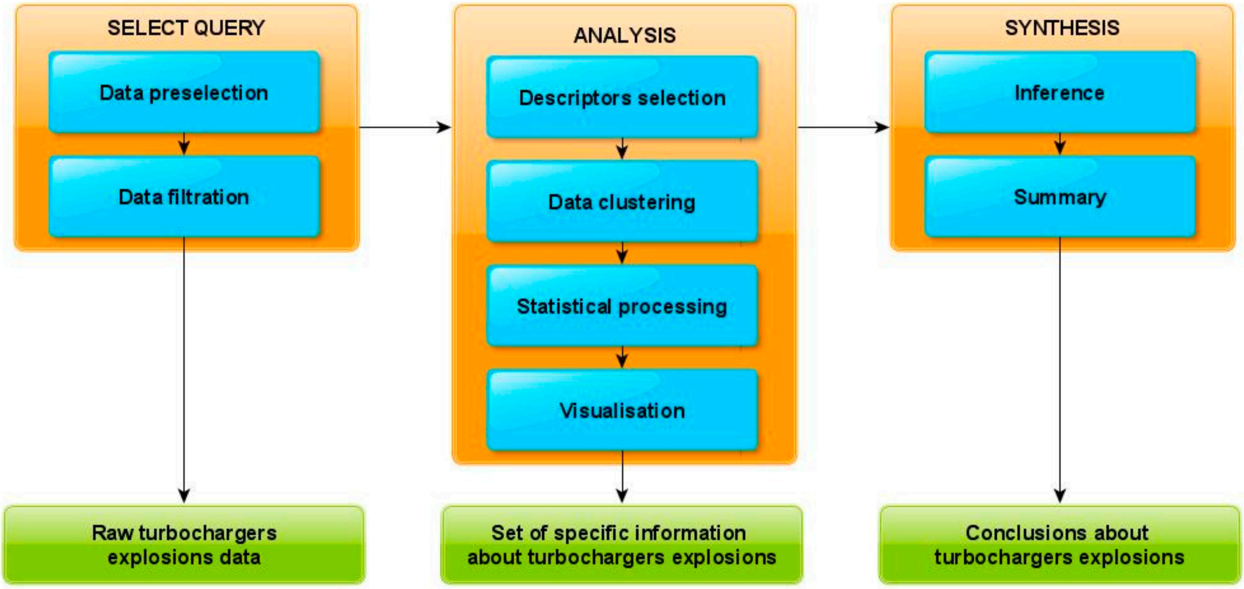

Figure 5. Methodology adopted in the study.

The aim of selecting a query was to obtain raw turbocharger explosion data. The underlying tool, in this case, was the *IHS Sea-web* platform (S&P Global Inc., New York, NY, USA). This tool provides a set of databases for casualties, fixtures, port state control, shipbuilders, shipowners, ships, real-time vessel movements, and port information in a single application. The platform provides detailed information on more than 200,000 ships of 100 GT and above and more than 240,000 marine company records. This paper relies on information contained in the Sea-web Casualty and Events database [26], which contains characteristics of maritime accidents officially reported to ship operating authorities. The authors did not find any compatible information in other databases, e.g., OREDA [24]; hence, it was used as a primary source supported by publicly available accident reports. To improve the quality of the presented information, the source data for the study were taken from the press [13,17,27], recommendations [28,29], and postaccident reports [20].

In the first stage, from more than 100,000 of all the accidents taking place on ships, incidents based on types of fire/explosions associated with casualties were preselected, which accounted for almost 90,000 events. The search area was narrowed, in the next step, using keywords including the terms 'turbo', 'turbocharger', 'turbo compressor', and 'blower', as well as 'breakdown', 'fire', and 'explosion'. Only cases related to explosions and fires of main engine turbochargers were then taken forward.

Results from all the analysed sources were merged, consolidated, and supplemented (where applicable). Thus, raw turbocharger explosion data representing a population of $n = 42$ explosions of marine main engine turbochargers taking place in the period of 1977–2022 were obtained [30].

The consequence of a ship's main engine failure is often its temporary immobilisation, and the failure may additionally lead to a fire outbreak in the engine room, which can spread throughout the entire ship. These incidents are reported to the nautical supervisory institutions and marine rescue units. Therefore, the adopted input data can be considered reliable.

However, it should be remembered that in certain situations, shipowners may not disclose all the available information about accidents. This applies to situations not directly related to the disruption of other vessels or port operations and may also apply to shipowners and shipping areas assigned to less-developed countries. The quantitative indicators obtained from this analysis should thus be considered as minimum volumes, so the number, frequency, and probability of accidents of the type analysed may be much higher.

In stage two, the previously obtained raw data were processed and subjected to statistical analysis considering the following criteria:

- The number of explosions in each year of the study period and the frequency of turbocharger explosions;
- The number of explosions with respect to the type of ship and the age of the ship at the time of the explosion;
- The number of explosions with respect to the type and design of the main engine.

The third and final stage of the research was the synthesis of the obtained results, including their collation and visualisation, as well as the drawing of conclusions about the numerical indicators describing the statistical distribution of explosions of marine main engine turbochargers.

3. Results and Discussion

3.1. Number of Explosions over the Years

A summary of the number of explosions of marine main engine turbochargers in each year of operation of the world merchant fleet over a 45-year period (1977–2022) is shown in Figure 6. In the above-mentioned period, there were 18 years with 1 explosion, 9 years with 2 explosions, and 2 years with 3 explosions.

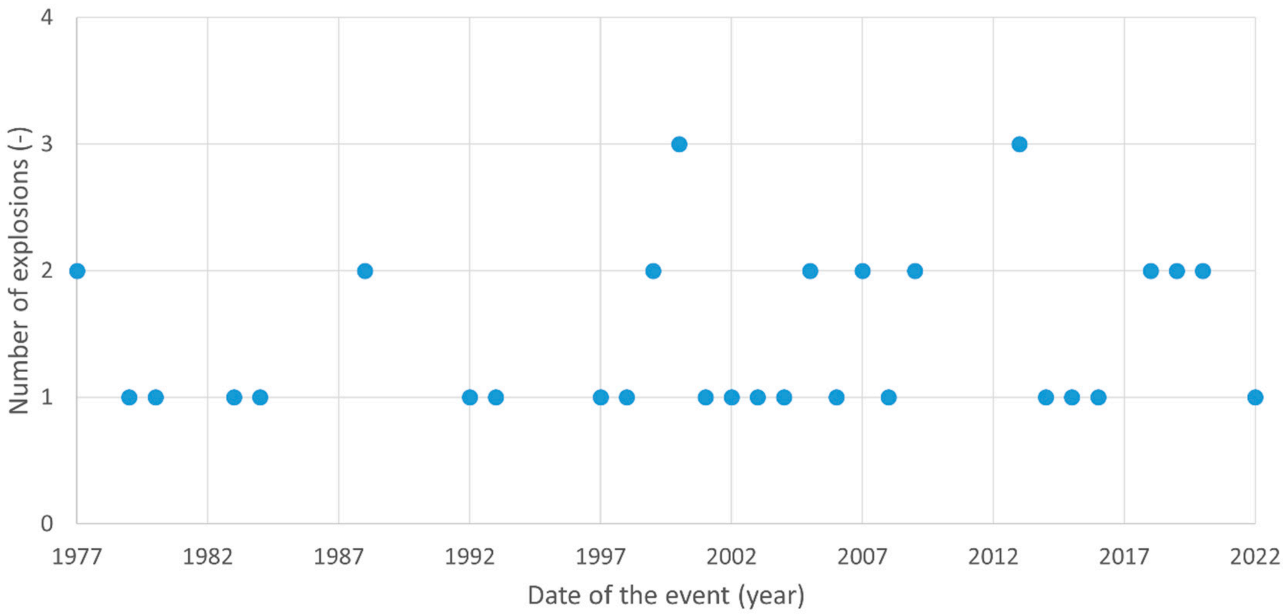

Figure 6. Number of explosions of marine main engine turbochargers in the individual years of the 1977–2022 period.

The results of the analysis for the source data used show that the frequency of turbocharger explosions per year is 0.93 explosions/year. Considering the size of the world fleet of around 58,000 merchant ships (as of 1 January 2022 [31]), this is not a large share, and assuming that the majority of the fleet is propelled by internal combustion turbocharged engines, the probability of an explosion in a given year on a given ship is not less than 1.61×10^{-7}. Taking into account that the number of ships worldwide is increasing significantly with time, the "number of turbocharger explosion per ship" can be perceived as reduced. Nevertheless, considering the number of unreported events and possibly new types of engines introduced in operation, further studies are required in the future to provide more accurate relations between the fleet size and the number of incidents.

Figure 7 shows the cumulative number of main engine turbocharger explosions. A trend line in the form of a linear model was also plotted on the graph, with the fit described by the coefficient of determination $R^2 > 0.95$. The results show that, despite the passage of 45 years, the turbocharger explosions analysed in the paper still occur, and their number is similar in each year.

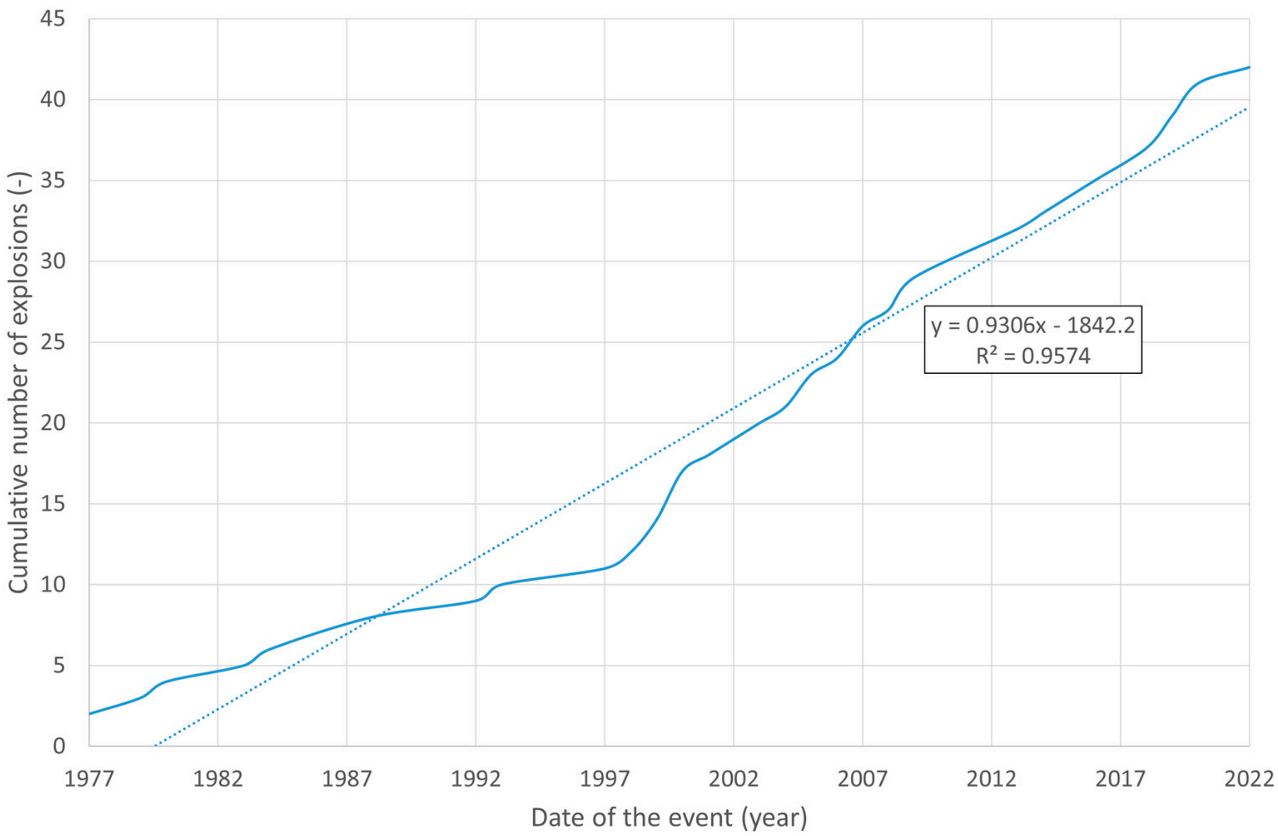

Figure 7. Cumulative number of explosions of marine main engine turbochargers in individual years for the period 1977–2022.

To more accurately assess the frequency of explosions in each year of the analysed period, the cumulative number of explosions was differentiated. The results are shown in Figure 8. The instantaneous frequency of explosions over the analysed 45-year period varies between 0.2–3 explosions/year, with the highest frequency observed in the 1997–2000 period.

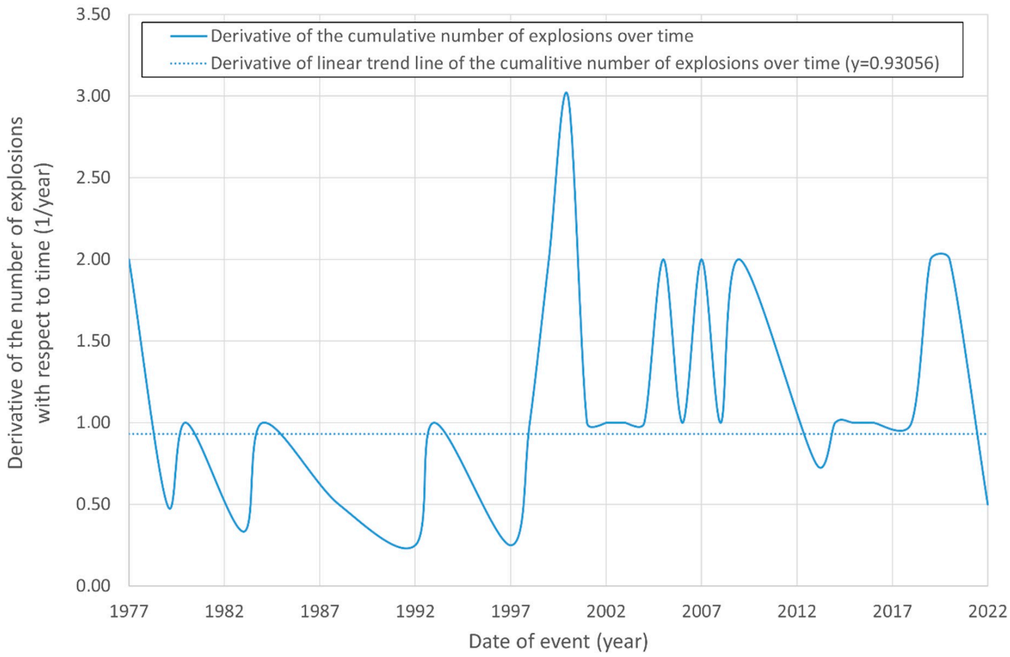

Figure 8. Instantaneous and average frequency of explosions of marine main engine turbochargers by year in the period 1977–2022.

The dotted line in Figure 8 shows the differential of the trend line of the cumulative number of explosions shown in Figure 7. This curve corresponds to the average frequency of explosions over the entire study period and is 0.93 explosions/year.

3.2. Age and Type of Ship

The recorded number of main engine turbocharger explosions as a function of the age of the ship at the time of the accident is shown in Figure 9. The youngest ship on which an explosion occurred was 2 years old, while the oldest was 35 years old. The largest number of explosions (10 events) was observed for ships that were 10 years old, accounting for about 24% of the analysed population. Half of all the observed explosions involved ships that had been in service for less than 15 years.

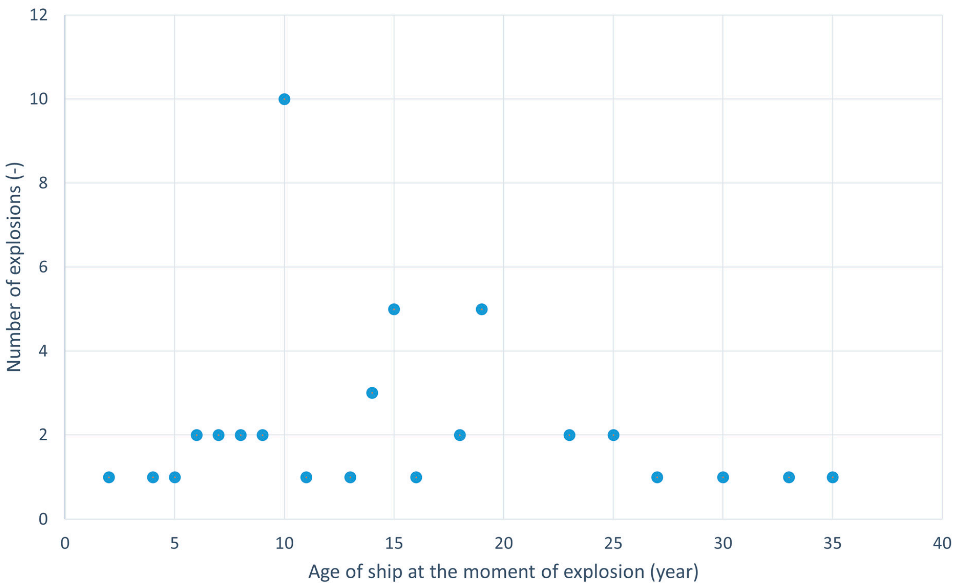

Figure 9. Number of main engine turbocharger explosions as a function of the ship's age.

The histogram of the distribution of the number of explosions in relation to the age of the ship and the empirical normal distribution curve is shown in Figure 10. In contrast, the average age of the ship is $\overline{a} = 15.21$ at the time of the explosion, while the standard deviation is $\sigma = 7.72$. We have chosen this distribution as the most "natural" and often used in analyses. Other distributions, e.g., beta, gamma, or Weibull, could be used with a potentially better fit. Nevertheless, we decided that to choose another distribution, a much higher explosion population should be analysed.

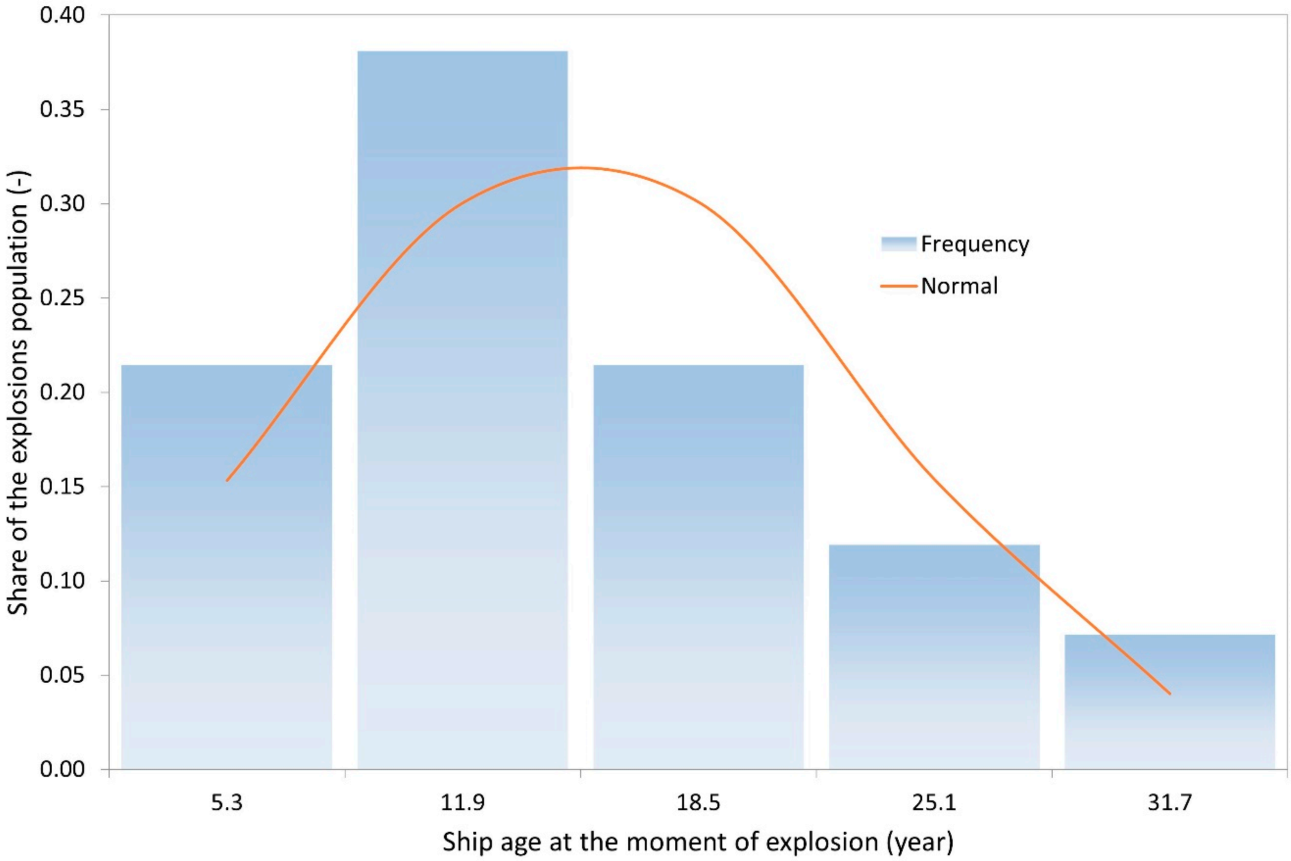

Figure 10. Number of main engine turbocharger explosions as a function of the ship's age.

Figure 11 shows the number of explosions by ship type. The largest number of explosions occurred on product tankers/ore/oil, with seven explosions, followed by passenger/Ro-Ro and general cargo ships, both with six explosions in each group. In third place, with four explosions for each group, were chemical/products tankers, container ships, and bulk carriers.

In order to determine whether the number of explosions on individual ship types was due to the share of individual ship types in the total fleet or whether the number of explosions was significantly related to the ship type (for reasons such as specific operating procedures, the method of handling, the time, location, frequency and method of manoeuvring, or other factors), a Pearson correlation coefficient was calculated between the average percentage of the most common ships in the world fleet [32] and the share of individual ship types in the explosion population analysed. The assumed averages of the share of each ship type are shown in Appendix A in Table A1. The Pearson correlation coefficient value obtained is 0.79, indicating a relatively high correlation. Thus, it can be concluded that the type of ship and the associated mode of operation has no direct relationship with the frequency of explosions. In other words, turbocharger explosions have a similar probability of occurring on ships of any type.

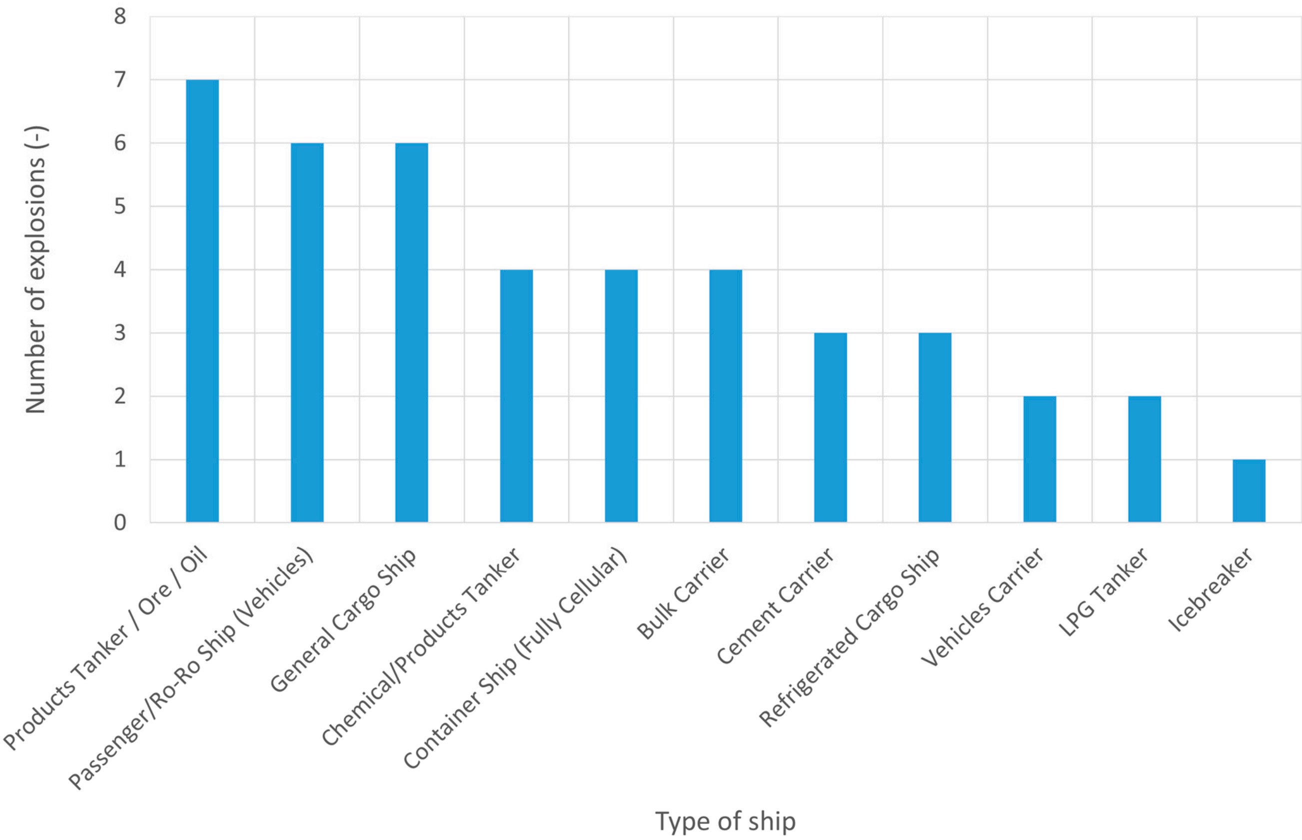

Figure 11. Number of main engine turbocharger explosions as a function of the ship's type.

3.3. Number of Explosions by Engine Type

The final step in the analysis was to determine the proportion of each main engine characteristic in the study population. For this purpose, the engines were divided based on the following characteristics:

- Duty cycle (2-stroke engine vs. 4-stroke engine);
- Construction of the crank-piston mechanism (trunk piston engine vs. crosshead engine);
- Engine speed (low-speed engine vs. medium-speed engine vs. high-speed engine);
- Cylinder layout (in-line engine vs. vee engine);
- Power per cylinder (medium-power engine vs. high-power engine vs. very high-power engine);
- Number of cylinders.

The results of the analysis are shown in Figure 12. Accidents tended to occur with 2-stroke (74%), crosshead (71%), low-speed (76%), and in-line (88%) engines. Most of the explosions occurred on engines with high and very high cylinder power (67% in total) and also tended to occur with a cylinder count of 6–8 (76%).

The distribution of the number of explosions by engine rating, maximum continuous rating, and engine design is shown in Figure 13. The chart shows that 73% of all explosions involve engines simultaneously meeting the condition of rated speed <300 rpm and maximum continuous rating of the engine below 20 MW.

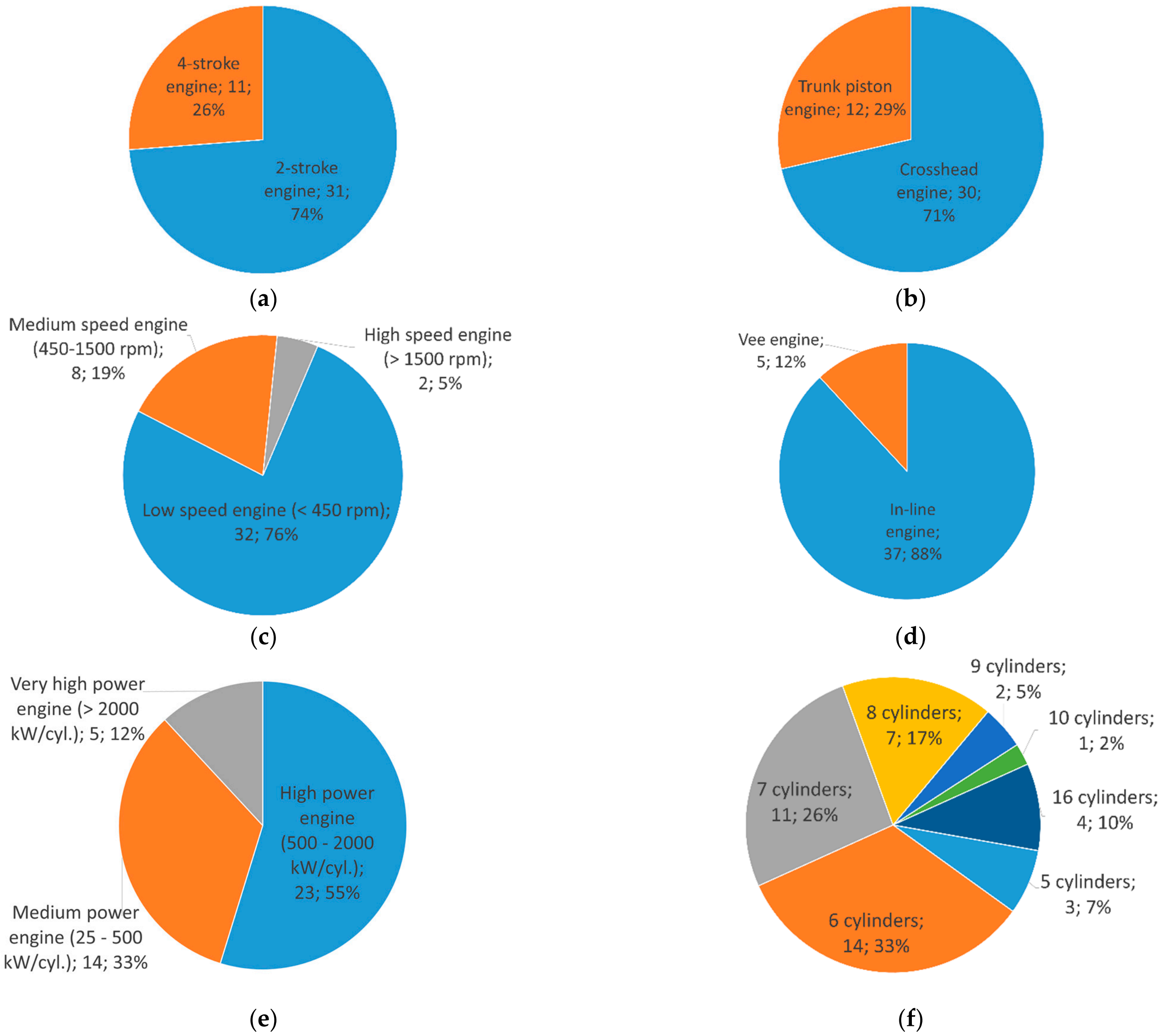

Figure 12. Number of main engine turbocharger explosions as a function of the engine type: (**a**) number of strokes; (**b**) crank-slider mechanism type; (**c**) engine speed; (**d**) cylinder layout; (**e**) engine power; (**f**) number of cylinders.

The results are consistent with the types and market share of the main engines used in large cargo ships. The lack of accurate market statistics prevented quantitative verification of this observation. Thus, it can be assumed that the type of engine does not directly affect the number of turbocharger explosions, and the risk of explosions applies to both two-stroke and four-stroke engines of any type.

The above results, however, raised the question that if turbocharger explosions are equally likely on all types of engines, then is there a combination of features associated with a particular engine design that may correlate with an increase in the contribution of a particular type of engine to the total number of turbocharger explosions? The share in the analysed population of engines by machine design is shown in Figure 14. The share shows that the risk of explosion applies to main engines from all major manufacturers. A total of 31% of the explosions in the accident population studied occurred on Mitsubishi-designed engines, 26% on Sulzer/Wärtsilä engines, 21% on MAN/B&W engines, and 7% involved MaK engines. So, 85% of all explosions took place on engines made to the design (under license) of the major companies that produce marine main engines.

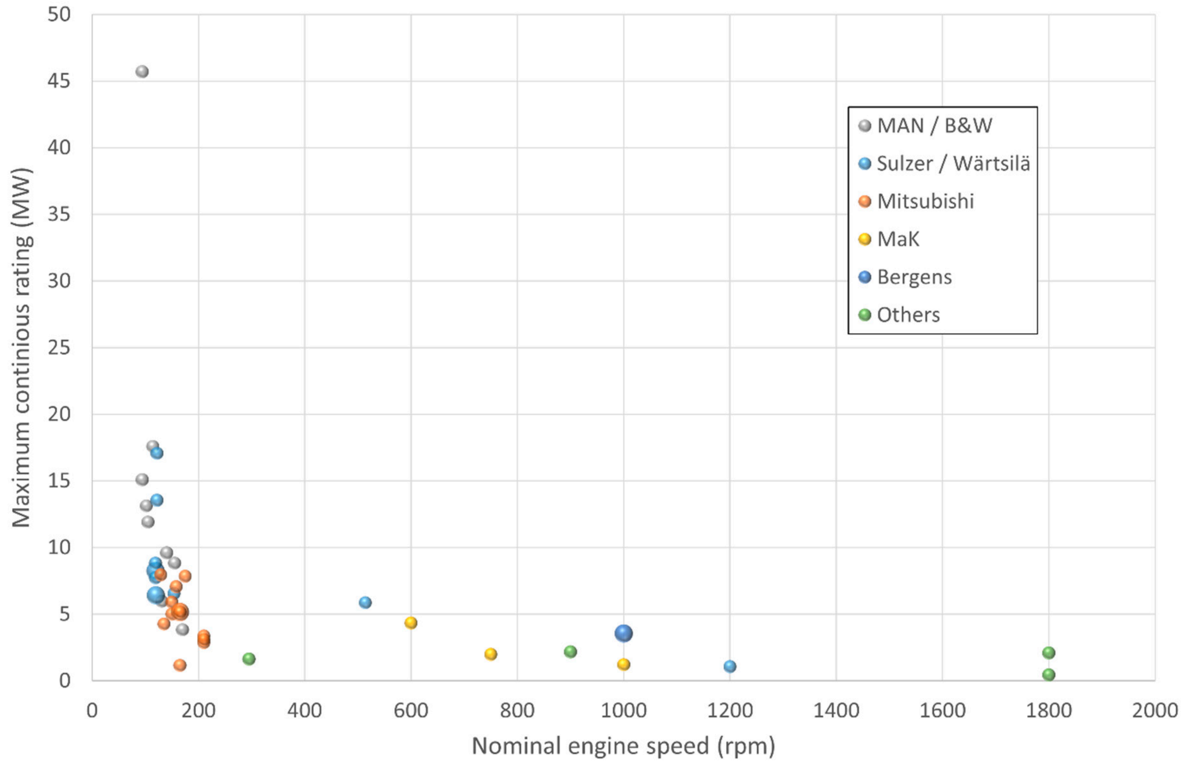

Figure 13. Distribution of main engine turbocharger explosions in the relation to engine nominal speed, maximum continuous power, and the engine's design.

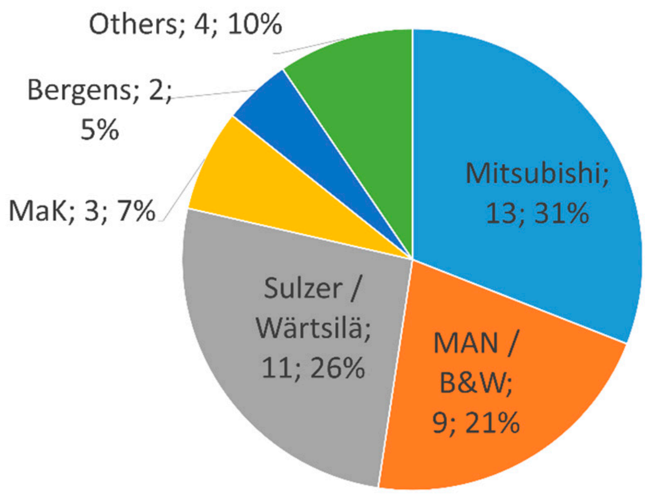

Figure 14. Number of main engine turbocharger explosions as a function of the engine's design.

In order to determine whether the number of explosions on particular designs of main engines was due to the share of particular engine types in the entire fleet or whether the number of explosions was significantly related to specific engine designs (a particular combination of engine features), a Pearson correlation coefficient was calculated between the percentage of the most common engines in the world fleet and the share of particular engine designs in the analysed population of explosions. Due to the lack of data on the share of individual engine designs in the global marine main engine market, data from Wärtsilä [33] for 2012 were adopted. The data thus correspond roughly to the third quartile of the analysed period of the ships' operation.

The assumed volumes of the share of each engine design are shown in Appendix A in Table A2. The obtained Pearson correlation coefficients were −0.66 for 2-stroke engines and 0.09 for 4-stroke engines, indicating a low negative correlation for 2-stroke engines and no correlation for 4-stroke engines. The results thus testify to the potential impact of the individual characteristics of an engine built to a given design on the magnitude of the risk of a turbocharger exploding during the use of that engine.

4. Conclusions

The frequency of explosions of main engine turbochargers has remained constant throughout the study period, averaging 0.93 explosions/year. Despite the passage of years, the intensity of accidents of this type has not changed and is approximately constant. Considering the number of ships worldwide, the probability of an explosion in a given year on a given ship is at least 1.61×10^{-7}.

More than half of the analysed population of explosions (median) occurred on vessels no older than 15 years, and the arithmetic mean age of vessels in the analysed population was 15.21 years.

The analysis did not indicate a significant correlation between the type of ship and the number of explosions on ships. On the other hand, due to the potentially very serious consequences of a ship fire resulting from a turbocharger explosion on all the above-mentioned types of ships, especially tankers, passenger ships, and Ro-Ro, it is advisable to continuously improve ships' engine room fire safety procedures.

It is highly likely that engine type does not directly affect the number of turbocharger explosions, and the risk of explosions applies to both two-stroke and four-stroke engines of any type. In total, 85% of all explosions occurred on engines made to the design (under license) of the major manufacturers of marine main engines. The influence of the individual characteristics of an engine built to a particular design on the magnitude of the risk of a turbocharger exploding during use of that engine cannot be fully ruled out. Nevertheless, the Mitsubishi design is related to 31% of explosions, while the market share of Mitsubishi is only 2%, so further analyses should be commenced to point out if this high share of explosion is a result of wrongly selected turbochargers for a given engine or other reasons, e.g., operational faults or fuel oil preparation in these engines.

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Appendix A

Table A1. Average share of ship types in the global fleet from 1977 to 2022 (UNCTAD, 2022).

Ship Type	Share of the World Fleet Averaged for 1977–2022 (%)
Oil tankers (%)	33.88
Bulk carriers (%)	38.14
General cargo (%)	8.91
Container ships (%)	10.00
Other types of ships (%)	9.07

Table A2. Average share of engine design among main ship engines in the world fleet in 2012–2013 (Wärtsilä, 2012, research in China 2022).

Engine Design	Average Share of 2-Stroke Engine Market	Average Share of 4-Stroke Engine Market
MAN B&W	80	23
Wärtsilä/Sulzer	18	47
Mitsubishi	2	0
MaK	0	5
Others	0	25

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