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Causal factors in accidents of high-speed craft and conventional ocean-going vessels

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Abstract

An analysis of 40 ocean-going commercial vessel accidents is compared with the study of a similar number of high-speed crafts (HSCs) accidents, using in both cases a methodology that highlights the sequence of events leading to the accident and identifies the associated latent or causal factors. The main objective of this study was to identify and understand the difference in the pattern of causal factors associated with HSC accidents, as compared with the more traditional ocean-going ships. From the analysis one can see that the HSC accidents are mainly related to bridge personnel and operations, where the human element is the key factor identified as being responsible for the majority of the accidents. When compared with ocean-going commercial vessels, it is clear that navigational equipment and procedures have a larger preponderance in terms of the occurrence of accidents of HSC and particular attention should be given to these issues.
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1. Introduction

In the last decade, high-speed craft (HSC) operations have become more widespread particularly in Europe as a result of a common strategy for short sea shipping. During the same period, the development of innovative hull designs and advanced propulsion technologies, together with the need for modern transportation alternatives, in response to ever-increasing highway congestion, have improved the economic viability of HSC operations. The increase of this mode of transportation leads to new safety issues with regard to these types of vessels and the waterways on which they sail. In fact, while for the traditional lower-speed ocean-going ships the pattern of risk levels is relatively well established [1], the same has still not been established for the case of HSC.

It is then not surprising that there is increased concern on the part of the authorities towards this type of ship. With the development of many new types of HSC in the 1980s and 1990s, the International Maritime Organization (IMO) decided to adopt new international regulations dealing with the special needs of this type of vessel. In 1994, IMO adopted the International Code of Safety for High-Speed Craft (HSC Code), which was developed following a revision of the Code of Safety of Dynamically Supported Craft. Also in 1994, IMO adopted a new SOLAS (Safety of Life at Sea) chapter X—Safety measures for HSC, which makes the HSC Code mandatory for HSC built on or after 1 January 1996. In 2003, the first revision of the HSC Code 2000 entered into force. The revised code remains the basic philosophy and has been used to update regulations for damage extent and survivability, fire regulations and incorporates the necessary modifications to follow the changes agreed in the Safety of Life at Sea (SOLAS) Convention [2]. More recently, IMO issued a regulation (MSC. 94 (72)) concerning the night vision equipment for HSC due to safety problems with visibility.

With the development of a structured and systematic methodology denoted as formal safety assessment (FSA) aimed at enhancing maritime safety [3,4] several studies

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have been conducted on its application to HSCs. The application of FSA made in the UK [5][1] addressed the quantified risk levels for HSC operating under the existing regulatory regime. A selection of risk-control options was developed to address these risks, and an evaluation of the costs and benefits was performed. Within the range of accident categories studied, collision was identified as the main contributor to the overall risk level. Two risk-control options, specific to the collision accident category, and an option common to all accident categories were considered in detail. Assuming effective implementation, all three options would significantly reduce risk levels, typically by at least 40%. The experience gained from this trial application of the FSA process to high-speed catamaran ferries has been reported by the UK [6]. More recently, a study was performed concerning the adequacy of the current stability and buoyancy regulation with respect to actual HSC accidents [7].

It is recognised that lessons learned from past maritime accidents are important to identify weaknesses and to avoid them in the future. There have not been a large number of accidents with HSC when one considers the total shipping activity over the period of 20 years. However, several accidents with far-reaching consequences have occurred during this period such as the Sleipner [8], Saint Malo's [9] and Sea Cat [10]. In addition to these accidents, which resulted in fatalities and environmental damages, it is also possible to learn lessons from less dramatic accidents and incidents as they also provide valuable lessons to be learnt.

The overall quantification of the risk levels existing in the maritime transportation can be estimated on the basis of accident statistics. For the conventional ocean-going commercial vessels, this risk-level quantification is not a difficult task due to the amount of accidents registered and studied throughout the years. These accident statistics allow the identification of the main type of accident for each of the vessel types [11]. Throughout the last decades, the annual rates of total losses of these ships have decreased substantially, although the gross tonnage remained almost constant [1]. In the present world fleet general cargo, bulk carriers and tankers represent the largest fleets of conventional commercial vessels.

In terms of accidents, typically, collisions, contacts and fire/explosions are the most frequent failure modes registered in the last decades in these vessels [1,12]. From the statistical point of view, there are several causes that can lead to an accident with these failure types. In relation to collision, grounding and contacts, the main causes are usually related to human failures during the operational state, while the cases of foundering are usually associated with technical failures.

[1] It must be mentioned that the UK submissions of these FSA studies of HSC were not officially accepted by IMO due to a number of errors in the analysis and therefore not recommended for decision making.

2. High-speed craft accidents

Although most people think that this type of fast transportation is recent, reality shows that the Maritime High-Speed transport has an old tradition born in 1957, when in Italy the first hydrofoil "Freccia del Sole" was built by Cantieri Rodriguez. Since then many new ship types have been developed with an emphasis on catamarans. The modern catamaran passenger ferry first appeared in Norway 30 years ago and their market demand still continues, being dominated by this hull form [13]. This increasing trend within this industry prevailed until recently. In fact, in 2001, 1200 additional passenger ferries and 100 car/passenger ferries of different types were in operation worldwide [14].

The success of this industry is a result of its economical competitiveness, which is associated with being an environmentally friendly mode of transportation [15]. In the beginning of the 1990s, there has been an exponential growth in the number of yards and catamarans design companies. However, there has been a drop in the number of new builds since 1998 mainly as a result of the raise of oil prices [16].

When one analyses the distribution of types of HSCs presented in Fig. 1, one may see that catamarans represent nearly 50% in the actual fleet, followed by hydrofoils (22%) and monohulls (19%). This percentage of catamarans can also be seen in the study performed by Zaraphonitis et al. [17] in which a HSC database was created with 353 vessels. In the same paper, the distribution of HSC accidents by each of the types is presented. This is a result of a recent work performed by the Maritime Coast Guard Agency [7] where the stability aspects of HSC accidents was analysed. For this work, a database was built based on 669 accidents in a 31-year time span (1972–2003).

From the analysis and considering the size of the fleet, one can see that hovercrafts present the highest relative frequency of accidents. In fact, when a calculation of the accident frequency is performed, hovercrafts are at 0.039 accidents/ship-year, while catamarans and monohulls are at 0.012 and 0.004 accidents/ship-year, respectively. This illustrates the good safety record of the latter compared with other HSC types.

In terms of the number of accidents correlated with the periods when the vessel was built, analysis shows that the most frequent accidents occurred with vessels constructed during the period of 1980–95, while the lowest occurred after 1995. This can be seen as a reflection of the implementation of the High-Speed Code in the end of the decade, which led to more adequate design and operation of these crafts.

When a comparison between the HSC and ocean-going commercial vessels is performed, as presented in Fig. 2, one can see a substantial difference in relation to the terminal events. As expected, HSCs are more liable to collision, grounding and contact events, whereas in commercial

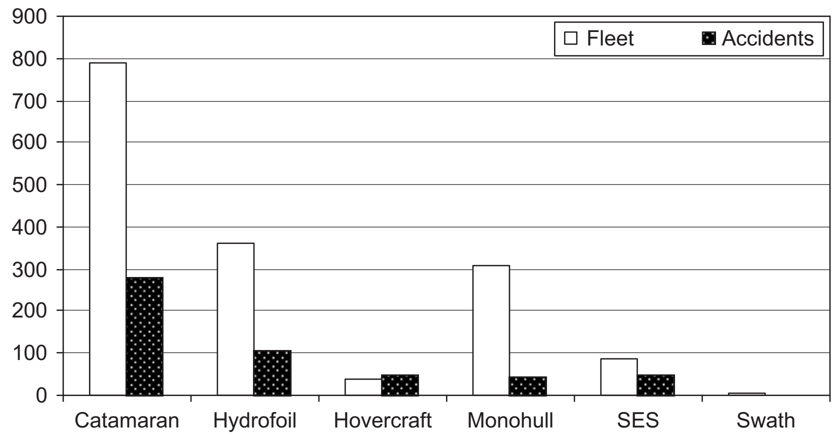

Fig. 1. Distribution of types of high-speed crafts and their accidents during the period 1972–2003 (*source*: [7]).

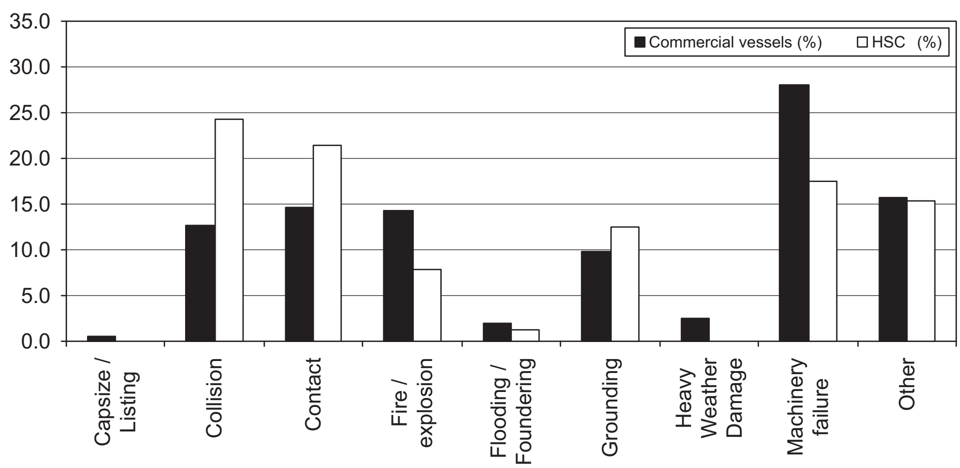

Fig. 2. Comparison of HSCs (1972–2003) and commercial vessels (1994–2004) distribution of terminal events (*source*: [7,12]).

vessels machinery failures dominate. As HSCs sail in areas with high traffic, sometimes with fishing and sailing boats, the level of exposure to these events is much higher. In fact, HSCs have frequencies of 91%, 46% and 28% higher than that of commercial vessels having collisions, contacts and groundings, respectively.

There are important findings in relation to the analysis of fatalities, when related to specific accident types. For the time span of the referred database, a frequency of 0.269 fatalities per fire and explosion, 0.253 fatalities per collision and 0.214 fatalities per grounding were found. These results show that the direct fatalities associated with each of these accident statistics are high when compared with commercial vessels. From the mentioned study performed by MCA the stability events were found to be the main contributors to the occurrence of fatalities. In fact, the major stability issues are a result of previous casualty events such as collisions (27%) and groundings (50%).

Accidents involving HSCs during the last decades are fortunately few when compared with other ship types. This can be explained by the fact that the HSCs still represent a small percentage of the ships in navigation and typically employed in short to medium routes (short sea shipping—coastal trade).

In order to have an insight about the safety issues, a systematic collection of casualty data is required, i.e., number of fatalities, types of casualties, human and technical causes for accidents, etc., followed by a detailed analysis. However, the types of accidents that one may have some information about have been summarised by RINA [18], where the importance of the human factors is highlighted, although these accidents only provided a small sample. It is therefore extremely difficult to obtain detailed information about these accidents, excluding the ones reported by the media with great emphasis. This issue was also pinpointed recently by Birmingham et al. [19].

This fact may have two main explanations: one is that there does not appear to be many organisations collecting and publishing such data on a regular basis and secondly the fact that the HSCs have a public image that, to date, shows a good safety record for both their casualties in ports and harbours. Another factor is that even the organisations that analyse, collect and maintain databases of accident data often do not make a clear distinction between HSC vessels and other conventional ones in their coding scheme. This has been partially overcome with the development of the, already referred, HSC incident database by MCA. Nevertheless, this database does not contain the particular details that lead to the accident but just the accident classification.

Accidents are a result of a highly complex set of coincidences leading to a chain of failures, which could, in case of most accidents, be unforeseen and unpredictable. This unpredictability is caused by a large number of direct and latent causes associated in most of the cases to the role of persons involved at different levels. It is normally stated that the major contributor to ship accidents is the human factor, commonly associated with rates up to 80%, from direct participation or, for instance, at the design stage, with the equipment and other factors only contributing with 20%. The question is therefore no longer whether a human factor is involved in an accident, but where in the chain of events the human factor is to be found and what its main characteristics are. It is in this perspective that it is necessary to analyse both the technician and operator's roles in the chain of the events as well as the compatibility between operators, technology and nature. For that purpose, in this study, the approach used was the one proposed by Kristiansen et al. [20] and Guedes Soares et al. [21], where there is a clear identification of each actor in the chain of events leading to an accident.

Therefore, 40 maritime accidents involving conventional commercial vessels were analysed with these approaches. Similar approaches were used in the analysis of HSC accidents and incidents [22]. The maritime accidents analysed complemented some of the major accidents that involved HSC, including the well-known Sleipner, Saint Malo or Sea Cat. In the case of the ocean-going commercial vessels, the criterion used was to study some of the major ship accidents including the Exxon Valdez, Estonia, and Derbyshire. The sources of the descriptions of the accidents were the Maritime Agencies (MAIB, US Coast Guard, Australian M.A., New Zealand and Canada M.A.) and official reports of major accidents mentioned above. Also, additional incidents for the HSC were analysed, with data provided by companies and port authorities in three European locations, with the objective of obtaining additional insight of some safety issues. Furthermore, in order to assess the results, the findings of all these accidents were compared with the objective of finding particular trends between them.

3. The accident modelling approach

The analysis of accidents used in this study is based on finding the chain of events that led to the accident and their associated contributory factors and causes. In this methodology, the casualty events are numbered chronologically in relation to the other identified accidental events. The objective is to have an overall picture of the sequence of events from the initiation to the final outcome since most accidents evolve, sometimes, over a considerably large time span.

These casualty events are qualified with two different attributes, namely Class and Flag State, which express certain aspects of the context when the casualty took place. The accidental events are divided into five categories, namely human error, equipment failure, hazardous materials, environmental effects (waves, wind, etc.) and other vessel or agent (VTS systems, tugs, etc.). It is important to keep in mind that accidental events are strictly related to the casualty as it is observed from initiation to the final outcome. The accidental events are normally the direct cause of the next one in the chain, and in turn they result from an earlier accidental event. The analysis process has so far concentrated on identifying the accidental events or, in other words, has given an account of *what* happened and *who/what* was involved.

These events are then categorised according to specific attributes depending on the context in which they occur since they can be associated with a specific person or system. This means that if a particular event is identified as being a human error, certain attributes are given, namely the identification of the persons involved (master, pilot, engineer, etc.), the human task affected by the error (mooring, close door, trip planning, etc.), cognitive or behaviour failure type (detection, activation, analysis, etc.) and finally substandard performance or error type (action delayed, ignored, underestimated, etc.) as presented in Table 1.

In the case of equipment events, it is necessary to establish the connection between the failure and the physical cause that triggered it. The methodology complements a series of parameters that identify the failure type and physical cause for each equipment event. The same procedure is used for the other types of accidental events.

Although these methodologies do not have the contributory factors, in terms of a specific set of parameters, they represent an important role in the accident, particularly in terms of HSC vessel accidents. These contributory factors and their influence will be discussed later. These factors can be seen as facilitators for the occurrence of certain accidental events, since they are not always present.

The choice of the relevant codes and their standardisation is an important issue because general patterns of causal factors in accidents can only be derived from statistical analysis of a large number of cases, and thus

Table 1
Human error parameters [20]

Human position	Task affected	Performance mode	Error type
Master	Mooring	Execution	Wrong timing
Helmsman	Trip planning	Observation	Inadequate action
Seaman	Look out	Interpretation	Omission
Deck crew	Set speed	Planning	Underestimated
Pilot	Set heading	Identification	Not performed
Bridge crew	Position fix	Evaluation	Delayed

accident databases need to be properly designed in accordance with the methods for accident modelling and codes for causal factors as discussed in Antão and Guedes Soares [23].

The next step is to give the diagnoses or answers as to *why* the casualty took place by identifying the conditions or actions external to the accidental event sequence that arose prior to the casualty. These basic causes or causal factors are related to how the work is organised, how the different tasks are assigned, and whether adequate tools and resources are provided by the supporting management for normal and safe operation. In fact, this structure is a consequence of the now common understanding that the root causes of accidents are a consequence of the shortcomings of persons, job conditions and management. This means that the accidental events can be explained by failures within the organisation as described by Reason [24], at different levels of influence. In these methodologies, the causal factors are related to both decision levels: Daily Operations, and Management and Resources. The first one corresponds to the onboard perspective, where the primary responsibility is from the crews, while the second is related to the onshore supporting organisation, which corresponds to a higher decision level.

As with the accidental events, the causal factors have attributed codes. For the Daily Operations, as presented in Table 2, the codes can include Supervision (inadequate work methods, inadequate work preparation, etc.), Personnel (lack of skills, lack of knowledge, etc.), Social environment, Manning, etc. In terms of the Management and Resources, one may have Operations Management (inadequate procedures and checklists, pressure to keep schedule, etc.), Personnel Management (inadequate training programme, selection/training of officers), Organisation and General Management, etc.

In Table 3, the methodology is demonstrated through the application to a HSC accident that occurred in the Port of Barcelona [25]. A summary description of the accident is presented below.

> The accident took place on the 5th of April 2001, involving an Incat 96 with less than one year of operational life. It collided with a "golondrina" (a type of port water bus that takes tourists on a tour of the harbour) crushing the aft part with the wave piercer of the Incat 96. The consequences of the accident were three people wounded and a major overhaul needed of the "golondrina". The HSC was not damaged and trials were carried out before taking on passengers.
>
> The first conclusions of the investigation pointed to a possible blackout and subsequent loss of ship control, by the ship's master, allowing sufficient time to travel the distance to the other ship. If during this time the electronic controls of the ship were turned off, the ship would be no longer under control, and this could have provoked the collision itself. According to the Port Authority representative, "*the ship was not under command for 20 seconds, probably due to a control transmission systems failure*". Unofficially it would seem that the manoeuvre flaps that these vessels have aft, have intervened in the propulsion control system. Therefore, any wrong move in an operation using the flaps, either due to technical or human causes, could well lead to a blackout. According to technicians at the Australian manufacturer, Incat, it would seem to have been a problem of design.

Table 2
Basic causal factors [20]

Daily Operation	Management and Resources
Social environment	Business climate
Supervision	Organisation and general management
Manning	Operations management
Personnel	SE management
Work place conditions	Occupational health management
Physical stress	Personnel management
Inadequate tools and equipment	System acquisition
Maintenance	Design
Environmental conditions	Maintenance policy
Emergency preparedness	Emergency preparedness

The first column in Table 3 presents the timeline of the accidental events of this particular accident with an identification of the respective category (in this case, three events are equipment failures and one event is a human error). Each of these accidental events was codified according to parameters described above. In this case, the equipment failures are related to the navigation systems located on the stern of the vessel due to incorrect loading. The root causes of these failures were related to design problems, associated with an initial design error or due to a deviation from the standard/specification not detected in an earlier stage. A similar approach to the analysis was used with the remaining 80 cases.

4. Discussion of the results

Forty ocean-going commercial vessel accident cases were analysed and, although the generality of the conclusions is limited because of the sample size, they provide some indications as where to look in terms of identifying safety issues, particularly when compared with the findings of the analysis of the HSC. As described above, the analysis consisted of identifying the accidental events such as human errors, equipment failures or environmental factors and their corresponding categorisation, depending on the context. The sample of the commercial vessels is constituted by 40 accidents while the sample of HSC used in this analysis resulted from 27 cases of accidents and 14 incidents, as one can see in Fig. 3. These incidents can be seen as situations where there is no damage to the vessel, injury to the crew or to a third party. Mainly, they are related to situations involving port approach or port

Table 3
The HSC accident in the Port of Barcelona

Accidental events	Code parameters				Causal factors	
	System/human position	Location/task affected	Failure type/ performance mode	Physical cause/ error type	Daily Operations	Management and Resources
EF—control transmission system failure	Navigation	Stern	Out of range	Incorrect loading	–	Design
EF—electronic controls turn off	Navigation	Stern	Out of range	Incorrect loading	–	Design
EF—blackout	Navigation	Stern	Out of range	Incorrect loading	–	Design
HUM—vessel does not stop in time	Master	Set speed	Execution	Inadequate	Supervision	Operations Management

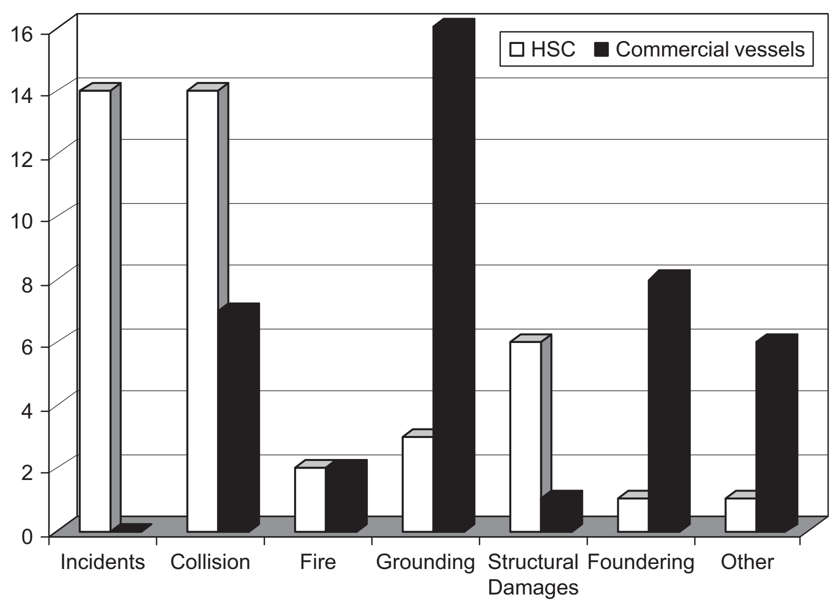

Fig. 3. Distribution of the sample of the accidents by terminal event (sample period 1991–2001; HSC—$N = 41$, commercial vessels—$N = 40$).

operations, i.e., manoeuvring, mooring, loading/unloading phases.

Of the accidents given by the HSC sample, collisions and structural damages were the most frequent ones. A large percentage of the latest is derived from contact events of the vessel with the port quay during manoeuvring or mooring operations or due to an underestimation of the weather conditions, particularly high waves for a given ship velocity. In relation to the incidents, they are mainly related to situations of near-collision and port-quay events (mooring and loading/unloading). In terms of the ocean-going commercial vessels, grounding, foundering and collisions were the most frequent.

In terms of the distribution of the types of commercial vessels, bulk carriers and tankers were the most representative of the sample. With the exception of the number of general cargo ships represented, the sample almost followed the actual distribution of the world fleet for the ship types. The objective of having a wider range of ship types was to have greater insight into safety issues since some risks are more likely to occur associated with some vessels than others due to their cargo, dimension of the vessel, length of the trade route, etc. Accidents with general cargo vessels do not have the same media impact as those that occurred with other types of vessels due to, on average, smaller dimensions and not being associated with large environmental impacts. It was therefore difficult to obtain adequate accident descriptions for these ship types, which lead to an under-representation of the sample.

Based on the application of the referred methodologies, 82 and 301 accidental events for the HSC and ocean-going commercial vessels accidents, respectively, were identified.

An immediate explanation of this substantial difference could be more easily associated with the fact that almost half of the HSC sample was constituted by incidents that have, usually, fewer accidental events associated.

Fig. 4 presents the distribution of the accidental events that are mainly related to human errors. In fact, 52% of the accidental events are human-error related, which goes towards the figures usually associated with marine casualties. This high percentage of human errors onboard ships are the ones that lead the entire industry to be concerned

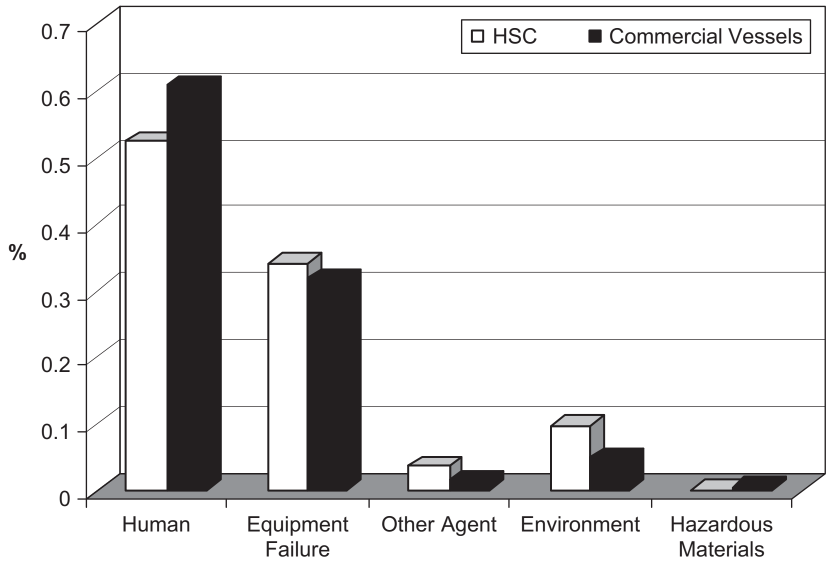

Fig. 4. Percentage for the distribution of accidental events for the sample ($N_{HSC} = 82$; $N_{CV} = 301$).

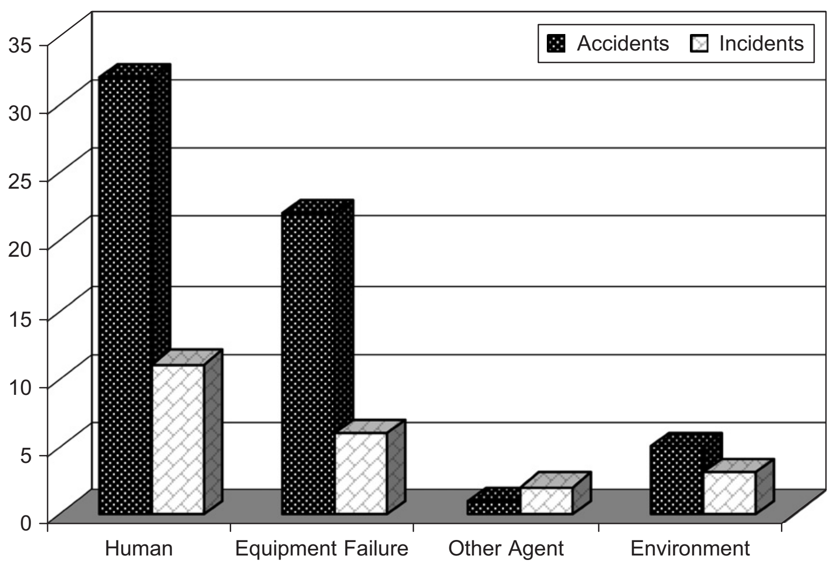

Fig. 5. Distribution of accidental events for the HSC sample ($N_{HSC} = 82$).

about the quality of the people who run the ships. These human errors are mainly related to decisions taken by the bridge crew in terms of navigational procedures as will be shown later. This trend follows the results also obtained for the commercial vessels where, in fact, it represents a high human-error percentage (60%). In terms of equipment failure accidental events, there is an agreement between the two types of ships.

However, environmental effects represent twice the frequency of HSC accidents. This is due to a frequent presence of *fog* and *wind* that leads to *unstable courses*, *significant wave heights* and the formation of *wave wash*. In fact, as referred to earlier, visibility is one of the key issues in relation to HSC accidents. Since the navigation of the ship is made primarily near the coast and at high speeds, lack of visibility substantially decreases the detection time of any object or ship and therefore the reaction time of crew is highly affected. Secondly, most of the sailing routes are not exclusive to HSC and therefore interaction with other vessels (sometimes fishing and sailing) is inevitable. One must realise that some of the busiest routes coincide with areas of large tourism particularly when these routes run in the summer.

If a comparison is performed between accidents and incidents, as presented in Figs. 5 and 6, one may see that the results are almost the same. In fact, only certain aspects of some cases lead to a slight difference in the results with a difference of less than 2% between the two. One, then, may conclude that the factors that trigger incidents are the same that trigger accidents, as expected. Particular attention

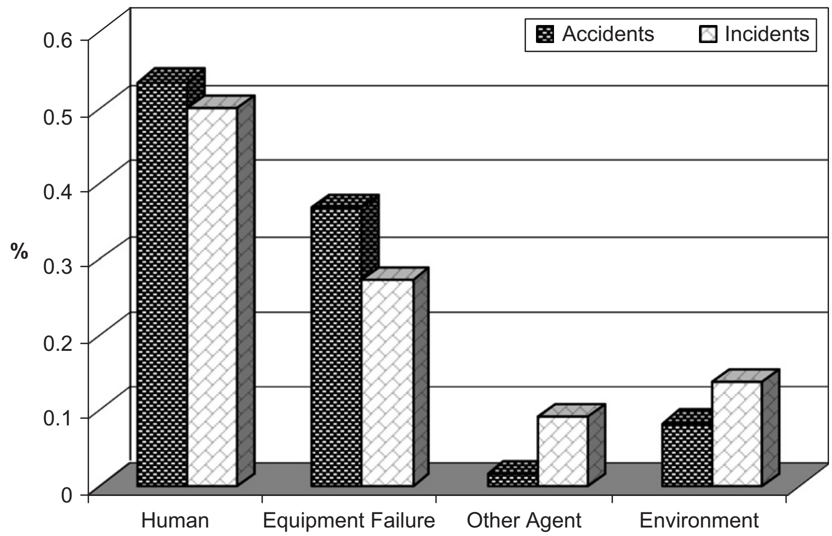

Fig. 6. Percentage of accidental events for the HSC sample ($N_{HSC} = 82$).

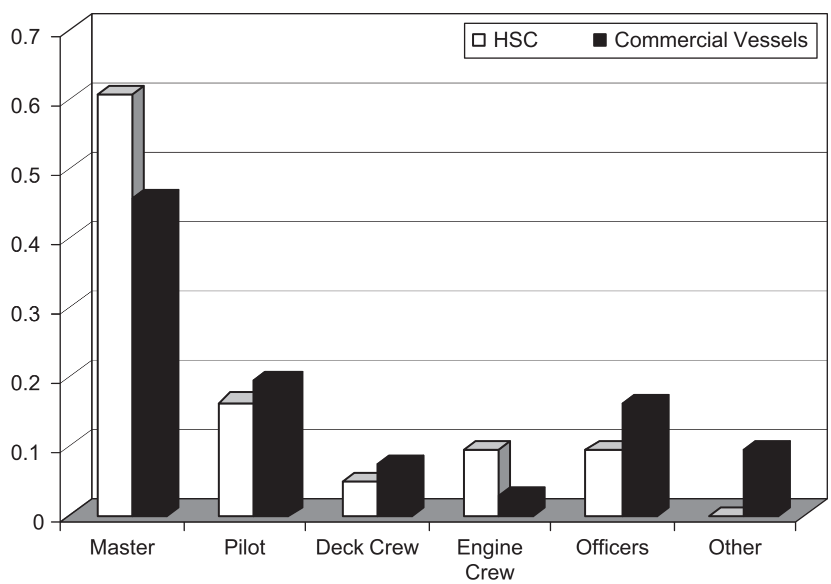

Fig. 7. Percentage of human accidental events from the analysis of all accidents/incidents ($N_{HSC} = 43$; $N_{CV} = 183$).

should be given to the role of environmental issues in terms of the incident cases. As mentioned above, these events are related to situations of near collisions and port-quay events and in these cases visibility, wave and tide (particularly within port areas) conditions were revealed to have a particular influence in these situations.

With these results, it is not surprising that the master of the crafts involved in the accidents is responsible for more than half of the human error in HSC, as shown in Fig. 7. In fact, the value is 15% higher than in commercial vessels. This result can be explained by the fact that in HSC vessels the bridge crew usually is small (two persons) with the master of the vessel taking full control during navigation, which is usually for a few hours. In commercial vessels, the shift of the bridge crew is mandatory as stated by the STCW 95, which leads to human errors being more distributed throughout the crew on board. Also, with commercial vessels, the number of tasks that the crew is involved in is higher than in HSC, which is mainly related with navigation. Petkov et al. [26] provide an example of an analysis of an accident in which the various tasks at a bridge have been examined to determine the nature of the human errors produced.

In the sample, the engine crew is also more involved in HSC accidents with a proportion of 3 to 1 with the particularity that any human error that leads to the loss of propulsion or electrical power typically leads to a large consequence of events, such as collisions and groundings. These loss of power situations are usually associated with inadequate performance of the engine maintenance task, as presented in Fig. 8.

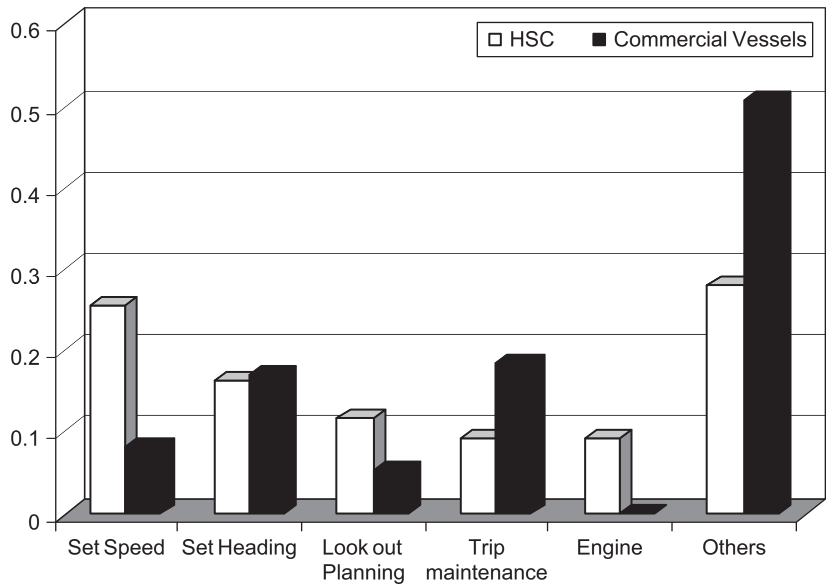

Fig. 8. Percentage of the main human task affected from the analysis of all accidents/incidents ($N_{HSC} = 43$; $N_{CV} = 183$).

The same figure shows the distribution of the human task affected, where one can see that the majority of these tasks are related to navigation and bridge operations, where *set speed* is the most frequent in the case of HSC. In fact, 65% of the human task failures in HSC vessel are bridge tasks, where 11 accidents had the description of *high speed* as one of the main causes. The set of *other* tasks includes tasks such as *ship handling* (5%) and *mooring procedures* (5%), etc. The influence of high speed is also reflected in the occurrence of situations of wave wash formation, which is responsible, in recent years, for several fatalities due to the capsizing of small boats or to their crew to fall overboard, as was the case of "Purdy" in 1999 [27].

The creation of long period waves is highly dependent on the speed of vessels, sometimes around 40 knots, and it is emphasised when they occur in shallow waters near the coastline. This risk has been already discussed by Dand et al. [28] and Whittaker et al. [29], where the shoaling of the waves is often considered a risk for people bathing or sailing in small boats. The waves can also create substantial environmental impact on the beaches due to bottom erosion. This is also related to the route chosen by the HSC operators since they work on tight schedules and therefore they look for the faster route rather than the one that potentially minimises these effects. Few companies perform adequate studies of the wave wash formation of their ship particularly during the port approach. Although there are regulations, in terms of speed restrictions, set by local port authorities, this speed can, in many cases, still be exceeded. Since the wash occurrence is dependent on the speed and water depth, mitigation relates to the study of these effects and relates to establishing adjustments to the speed and on choosing one appropriate route to the port approach that minimises the final outcome. The potential cost–benefits of such improvement have already been subject to recent studies [30].

For commercial vessels, the high frequencies are related to tasks like *set heading* (16%), *trip planning* (19%) and *position fix* (10%) in comparison with the *set speed* (26%) in the HSC. Due to the complexity of tasks that crews of these sets of vessels can perform onboard, it is not surprising that the number of *other* tasks have almost 50%, which includes tasks such as *ship handling* (6%), *evacuation* (3.3%), *towing* (3.3%), etc.

It is also relevant to notice that the navigation system is the one more involved in accidental events for HSC (Fig. 9). In fact, there are two main differences between these types of vessels, which are *Navigation* and *Structure*. The navigation system in the HSCs causes five times more accidents and incidents than in ocean-going commercial vessels. One may then conclude that these systems were not very reliable, but this could be an erroneous conclusion. The distribution of accidental events only emphasises that the navigation systems are very "sensitive", which means that their failures usually lead to incidents or accidents, as expected.

The hull of commercial vessels is subjected to 23% of the equipment failures, but in HSCs it only represents 7%. This result can be explained by the fact that ocean-going commercial vessels often have more open ocean trade routes, leading to failures when these vessels encounter heavy weather conditions. In fact, the study of a large number of accidents induced by heavy weather has shown that they are more frequent in areas where the average steepness of sea states is higher [31].

In the case of HSCs, damage is also associated with heavy weather conditions since most of the vessels are made of a light material like aluminium resulting in structural damage even in medium-size waves. Although there are navigational restrictions, under the High-Speed Craft Code, in terms of the limit of significant wave height under which ships can operate, these restrictions can be

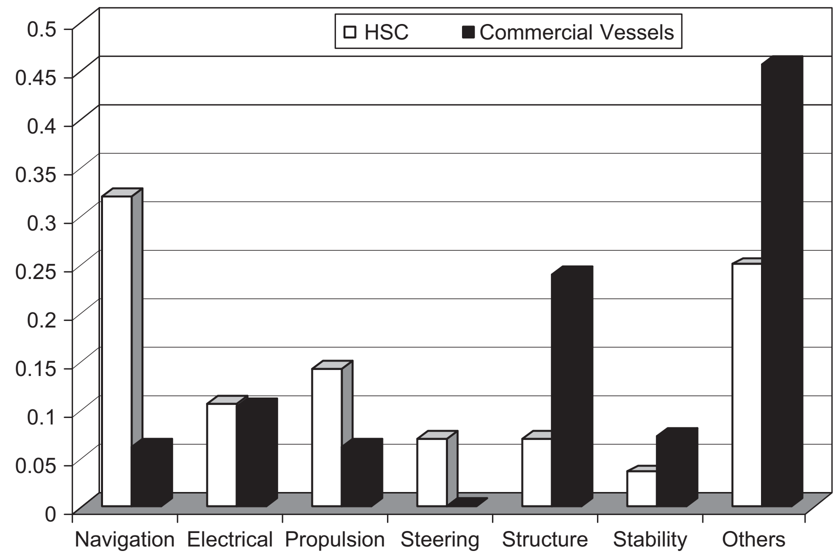

Fig. 9. Percentage of the main equipment failure events from the analysis of all accidents/incidents ($N_{HSC} = 28$; $N_{CV} = 96$).

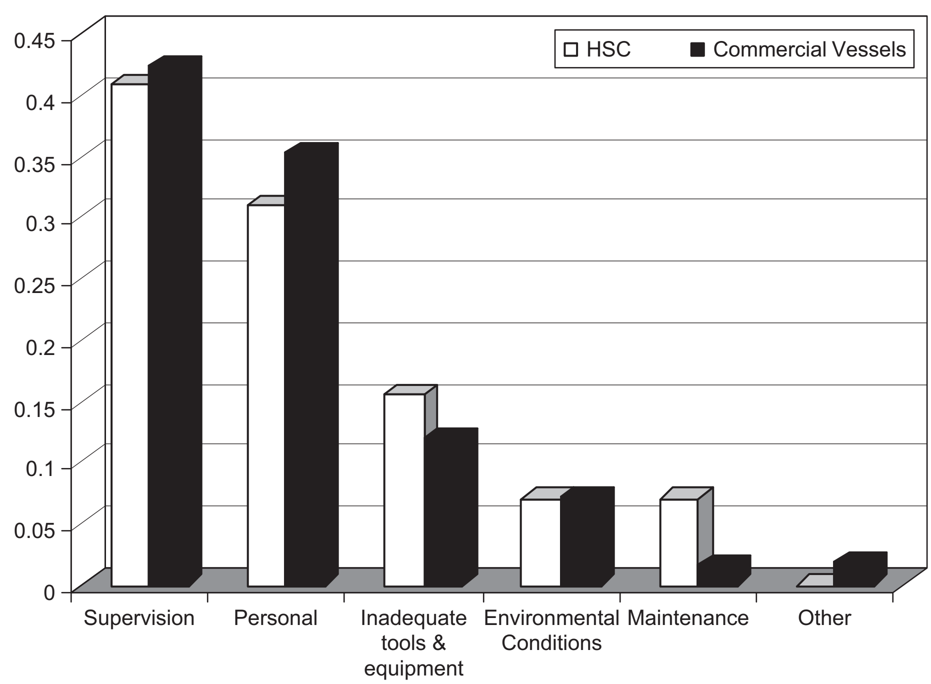

Fig. 10. Percentage of Daily Operation basic causes from the analysis of all accidents/incidents ($N_{HSC} = 72$; $N_{CV} = 273$).

seen as a ‘‘two-sided coin’’. On one side, in a very competitive business, there is the need to keep tight schedules and not affect the image of companies as a suitable and reliable mode of transport. On the other side, these particular ship types are very sensitive to rough sea conditions, such as wave length, directional spreading, crossed seas, etc., due to the difficulties in the ships behaviour, but also with respect to passenger comfort. It is necessary that companies take a safe approach to the situation and comply, in practice and at all times with established regulations, since their disregard for them can have far-reaching consequences in terms of accidents.

Besides bad weather conditions, structural damage of HSCs is also associated with berthing procedures. In some cases, the interaction of different ships at port, such as while the HSC is moored, is sufficient to lead to a hard contact with the quayside. This occurs in some ports because there is not a clear division between HSCs and commercial vessels, and also there is no specific quay for the HSCs.

As referred to earlier, the role of the contributory factors as facilitators of accidents is not usually emphasised. In the case of HSC, the environmental conditions have a substantial influence on human tasks in terms of *detection*

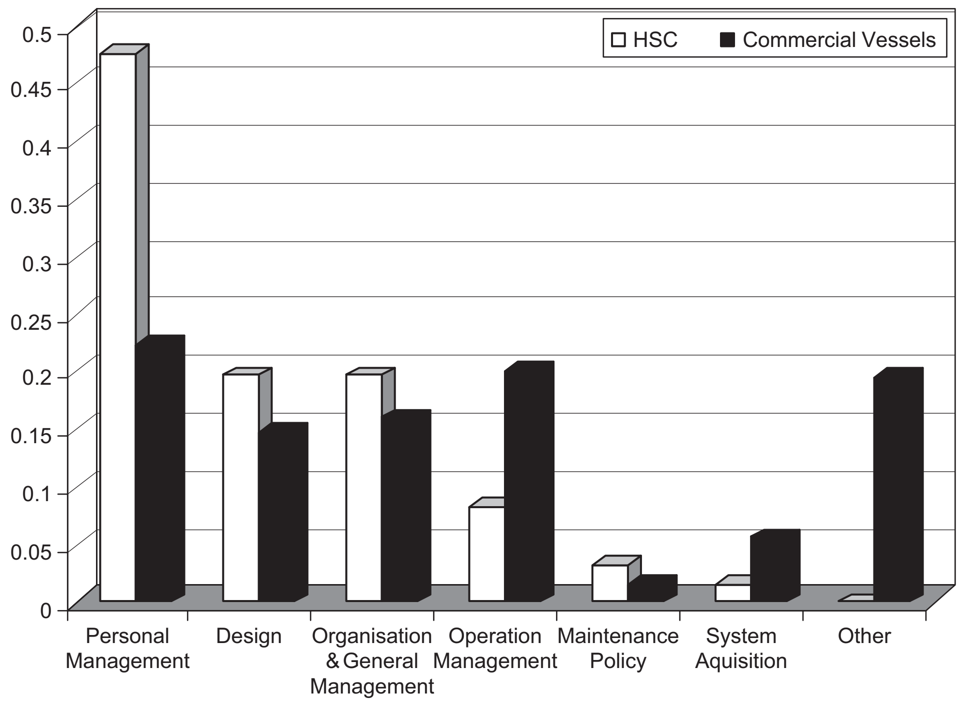

Fig. 11. Percentage of operation management basic causes from the analysis of all accidents/incidents ($N_{HSC} = 61$; $N_{CV} = 250$).

and *activation*. This is due to their impairment as a result of lack of visibility (fog and night navigation). Although there are specific regulations with regard to adequate lighting equipment onboard, the high speed of the vessel leaves less time and space for adequate reaction of the crew.

When HSC human-error types and performance modes are analysed, one can see that improper activations are the most frequent ones. Although the activation performance mode, which relates to the execution mode, is the most frequent (42%), the majority is related to the cognitive level, such as *decision making* (21%), *detection* (21%) or *observation* (2.5%). These results are not substantially different from the ones obtained on the commercial vessel and they stress the importance of highly skilled and trained crews, particularly in terms of navigation operations. Similarly, in terms of equipment *failure types* and *physical causes*, the results show that *out of range* (54%) and *incorrect loading* (40%) are the most frequent.

Figs. 10 and 11 present the frequencies for the *daily operations* and *management and resources* causal factors, respectively. One can see that there is a very similar trend between the different types of vessels. In the first case, one can see that the problems with *supervision* (40%) and *personnel* (31%) causal factors are the most frequent resulting in 71% of all HSC accidents. This concentration on *personnel* causal factors can be explained by the fact that even if the physical conditions are perfect, things can go wrong depending on how operators use the available resources and how they interpret the information. Perfect and accurate information can be neglected, misunderstood or otherwise not used properly and activities can be omitted, faulty or poorly timed. Errors like these have less to do with the physical environment, but can be attributed to the crew, their characteristics and qualities.

For Management and Resources causal factors, *personnel management* (47%) and *design* (20%) causal factors result in an overall frequency of 67% for the HSC and 37% for commercial vessels. The first one is mainly related to problems with inadequate training, inadequate knowledge of the bridge crew, lack of adequate work preparation and adequate procedures. This trend can be explained by the importance of having the right people with the right skills and training, and are assigned to the navigation procedures particularly in the HSCs. The importance of human element in this case is even more emphasised and therefore adequate organisation support should be provided.

5. Conclusions

In this study, an analysis of low-speed ocean-going commercial vessel accidents has been presented using a methodology that identified the events leading to the accident and the associated causal factors. The findings of this analysis were compared with similar results obtained from a number of HSC accidents. An analysis of a total of 81 accidents was made, 41 of which involved HSC accidents and incidents. From the analysis one could see that the HSC accidents and incidents are mainly related to bridge personnel and bridge operations, where the human element is the key responsible factor in the majority of the accidents. When compared with ocean-going vessels, it is clear that navigational equipment and procedures have a larger preponderance in the occurrence of accidents of HSC. In many cases, the optimisation of the route by the bridge crew, conducting route changes, combined with adverse weather conditions like winds or strong waves, can lead to grounding events.

It was found that in terms of tasks affected by human performance *set speed* was the most frequent. Also, weather conditions, particularly the lack of visibility (mainly fog situations), play an important role as one of the main contributory factors in the collisions on busy routes. From the results of both causal factors, it was concluded that problems with adequate training, adequate knowledge, work preparation and adequate procedures are the points to be concentrated on from the objective of reducing the frequency of HSC incidents and accidents.

On the basis of the results obtained in the present study, some recommendations can be suggested. The separation of traffic routes between commercial vessels, sailing boats and HSC, especially near ports, would allow for a substantial decrease in the probability of collisions. Special attention should be given to sailing in fog, where visibility is highly reduced, with the implementation of an adequate speed limit.

Crews must have an adequate insight into the hydrodynamic effects of their vessel, particularly in the formation of wave wash during port approach phases. This can lead, in many cases, to a limitation on the operational speed normally used. This can only be achieved if the HSC operators understand that there is a problem associated with ship speed in some particular situations and if, therefore, they implement strict policies complemented by adequate crew training.

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