

Decoding RoPax Ship Capsizes and Development of an ISO Ship Safety Standard

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Abstract

Marine accidents often result in significant losses of human life, environmental damage, and property destruction. Additionally, ships and offshore plants are large-scale and complex systems, making safety assessments challenging. However, the advent of onboard electronic systems has made it possible to monitor and respond more effectively. These new technologies can enhance safety levels while reducing the workload on crews. In this paper, authors analyze recent accidents involving ships with high structures above the water, such as car carriers or RoPax vessels, and propose preventive safety indicators to help prevent similar accidents from recurring.

Keywords

Ship Accident, Capsize, RoPax Ship, Profile Height, Regulatory Body, ISO Standards

1. Safety Standards for Ships and Offshore Plants

Safe operation and design require the development and adherence to design rules and standards throughout a project's engineering, design, manufacturing, and operational phases. When an accident occurs, it is crucial to conduct a thorough analysis to identify its root causes. In some cases, such analysis reveal neglected or overlooked factors that contributed to its failure.

This raises the question: How should these critical factors be addressed? To explore this issue, the authors present a summary of recent Roll-on/Roll-off (RoRo) vessel capsizes during turns and discuss the process of developing an ISO (International Standard Organization) standard for vessel safety [1].

The Titanic's sinking and the resulting loss of life in 1912 was a historic event

that led to the worldwide adoption of rules and standards aimed at preventing similar disasters. These standards include SOLAS and MARPOL. SOLAS (International Convention for the Safety of Life at Sea) was established in response to the Titanic's sinking and the large-scale loss of life that occurred in the early 20th century (see **Figure 1**).

When new ships experience major and minor maritime accidents, failure analyses may reveal areas where safety rules and standards require improvement and updates. As the reader can appreciate, this “feedback” is essential for implementing safety enhancements. To achieve these improvements, it is important to briefly review the organization and scope of existing safety rules and standards.



Figure 1. Titanic and SOLAS [2].

The second group of international rules are under MARPOL (International Convention for the Prevention of Marine Pollution from Ships), established in 1969. The Exxon Valdez crude oil spill in Alaska in March 1989, one of the largest ecological accidents in history, prompted an extension of MARPOL regulations to mandate double-hulled tankers, significantly reducing the risk of oil spill pollution.

Subsequently, the Deepwater Horizon oil spill (see **Figure 2**) occurred in April 2010, when an oil drilling facility exploded in Gulf of Mexico, USA, resulting in approximately 770 million liters of crude oil leaking over the following five months. **Figure 2** shows the oil drilling facility on fire, with four firefighting ships pumping seawater to cool down the flame. This accident led to the introduction

of additional rules and regulations aimed at preventing similar offshore accidents. In 2014, the MARPOL was further expanded to address the reduction of greenhouse gas emissions from new ships by introducing the Energy Efficiency Design Index (EEDI).



Figure 2. Explosion accident of deepwater horizon [3].

2. Cooperation between IMO and ISO for Shipbuilding and Maritime Safety Standards

Both SOLAS and MARPOL, mentioned above, are regulations under the IMO (International Maritime Organization). The shipbuilding and maritime sectors have a long history, with various organizations and safety devices supporting their development. As an international regulatory body comprising members from national governments, the IMO has the authority to prescribe and define its requirements at all levels through these delegations [4].

ISO and IEC assist the IMO in conserving resources by providing industry input and implementing IMO safety and pollution regulations. The following international standardization committees are active within the ISO and IEC:

- ISO/TC 8 Ships and marine technology;
- ISO/TC 67 Oil and gas industries including lower carbon energy;
- ISO/TC 67/SC 7 Offshore structures;
- ISO/TC 188 Small craft;
- IEC/TC 18 Electrical installations of ships and of mobile and fixed offshore units;
- IEC/TC 80 Maritime navigation and radiocommunication equipment and systems.

Ships and offshore plants are large and complex, often equipped with up to a million pieces of equipment, each governed by various standard organizations

that support the equipment manufacturing industry.

Figure 3 shows the hierarchical relationships among standards. At the base are company group standards. The next level includes national standards. They develop as companies come together and introduce national standards. Regional standards, such as those within the EU, are then established and may eventually be adopted as international standards.

In the field of shipbuilding and maritime, international standards are developed at a higher level by the International Maritime Organization (IMO). Under this framework of rules and standards, ships or offshore structures are constructed to comply with IMO SOLAS and MARPOL rules and regulations.

Initially, design drawings are reviewed, and design calculations are verified to ensure compliance with these rules and regulations. Inspections are conducted, and reports are submitted throughout the construction process, ultimately leading to the issuance of IMO SOLAS and MARAPOL compliance certificates upon the launch and commissioning of these large steel structures.

Nevertheless, errors or failures in safety-critical systems can have fatal consequences. In large systems, these issues are often exacerbated by their sheer volume and complexity, potentially jeopardizing the achievement of high-level safety objectives [5].

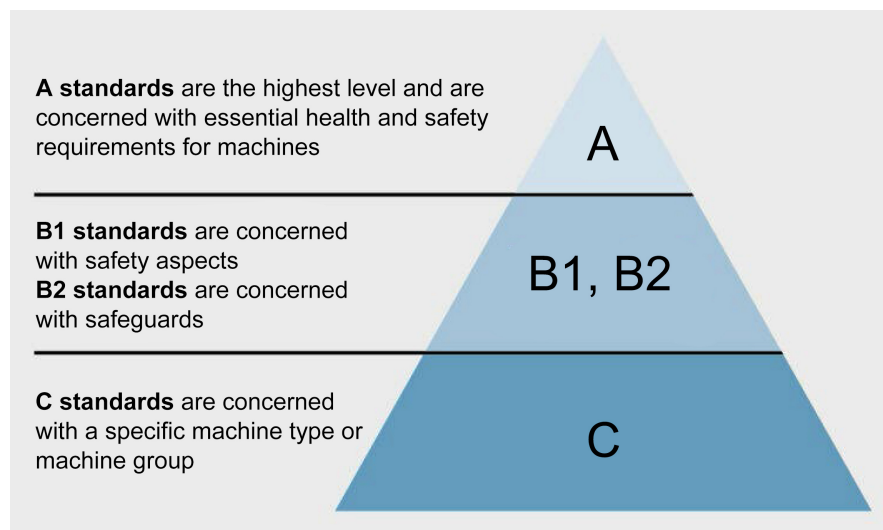


Figure 3. Organizational diagram of safety standards [6].

Figure 3 shows the hierarchy of safety standards, with sub-standards supporting various safety aspects of machinery [7] [8]. At the bottom level are safety standards for specific machines. In the context of shipbuilding and maritime standards, it is important to understand that standard layer A corresponds to IMO regulations, layer B to ISO and IEC, and layer C to standards for various equipment [9].

Figure 3 also supports the authors' approach in developing ISO standards (levels B1 and B2) to address the RoPax capsized problem during turns. RoPax vessels,

which have large roll-on/roll-off (RoRo) decks and limited passenger facilities, face unique safety challenges. Safety aspects such as the center of gravity estimation, and limits on rudder angle and corresponding heel angle during turns, are critical. These aspects are discussed in more detail in Section 3.

Figure 4 shows the IMO framework for passenger ship safety according to SOLAS 2020. The concept of “Safe Return to Port (SRtP)” is subdivided into “safety level”, “alternative design and arrangements”, “risk-based design”, and “goal-based standards”. Ship should be designed for improved survivability so that, in the event of a casualty, people can stay safely on board as the ship proceeds to port [10].

A casualty threshold needs to be defined, wherein a ship suffering a casualty below this threshold is expected to stay upright, afloat, and habitable for as long as necessary. If the casualty threshold is exceeded, the ship must remain stable and afloat for sufficiently long time (3 hours recommended) to allow safe and orderly evacuation.

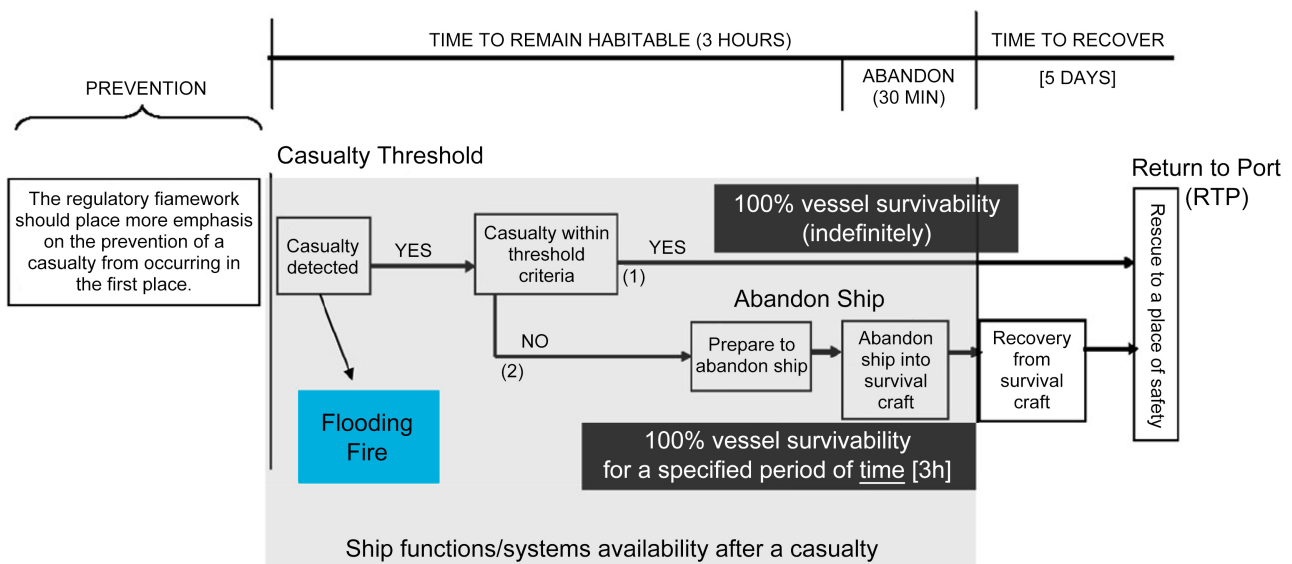


Figure 4. The IMO framework for passenger ship safety [10].

SOLAS 2020 is for damage stability, emphasizing survivability after an accident, whereas this paper is more concerned with accident prevention [11]. Prevention is the first part of **Figure 4**.

3. Risks to Ships with Large Profile Height Above the Water

To help prevent RoPax vessels from capsizing during turns, this section summarizes the results of an analysis of three recent RoPax vessel capsizes in calm seas, all of which were caused by significant heeling during turns [1]. These incidents occurred over the past decade: the MV Golden Ray in 2019 [12], the MV Hoegh Osaka in 2015 [13], and the MV Sewol ferry in 2014 [14] [15].

“On September 8, 2019, the Pure Car Carrier (PCC) Golden Ray departed from

the Colonels Island Terminal in Brunswick, Georgia, USA. The vessel speed was slightly increased to the normal transit speed of 13.3 knots. The pilot ordered the helmsman to steer to starboard, using up to 20 degrees of rudder angle. The ship then turned and began to lean sharply to port. The pilot ordered the helmsman to move the rudder to port to counteract the growing heeling, but within less than a minute, the ship inclined about 60 degrees to port side and capsized.” [12]

“On January 3, 2015, the pure car and truck carrier (PCTC) Hoegh Osaka departed the port of Southampton, UK for Bremerhaven, Germany. As it rounded the West Bramble buoy in the Solent River, it developed a significant starboard list. This list caused some cargo to shift, leading to flooding. At a 40-degree list, the ship lost steering and propulsion, eventually drifting onto the Bramble Bank.” [13]

“On April 16, 2014, the ferry MV Sewol sank while sailing from Incheon towards Jeju in South Korea. At 8:46 am, the vessel was sailing at 18 knots (33 km/h; 21 mph) at a heading of 136 degrees. The third mate ordered a course change from 135 degrees to 140 degrees. Around 8:48 am, the vessel began to heel port (left), turning quickly to the starboard (right). By around 10:30 am, after 101 minutes, the Sewol ferry was submerged, leaving only the bow section above water.” [14]

Table 1 compares the main factors involved in these RoPax ship accidents. It is believed that all these accidents occurred while turning at a fairly high speed under conditions of insufficient stability performance (GM).

Table 1. Summary of the RoPax vessel-accident details [1].

	Golden Ray	Hoegh Osaka	MV Sewol
Year of accident	2019	2015	2014
Built year	2017 Mipo, Korea	2000 Japan	1994 Japan, imported and modified 2013 in Korea
Profile height (above waterline)	Abt. 39.4 m (3.7 times of design draft)	Abt. 32.4 m (3.2 times of design draft)	Abt. 21.6 m (3.5 times of design draft)
Draft (design)	10.6m	10.15 m	6.2 m
Displacement	34,609 (at accident)	16,886 (DWT)	9750
GT	71,000	51,770	6800
Cause of accident	Lack of stability while turning (13.3 kt - 20 rudder angle)	Lack of stability while turning (12 kt - 10 rudder angle)	Lack of stability while turning (18 kt - 5 rudder angle)
GM	0.45 m	0.7 m	0.3 m - 0.5 m

One notable design feature of these ships is their large profile height above the waterline. Pure car carriers (PCC) and pure car and truck carriers (PCTC) often have 12 or more vehicle decks, accommodating the transport of 5000 to 6000 cars. The hull of these ships has a small block coefficient (CB) and is V-shaped near the waterline, which creates a large initial transverse GM. As a result, when cars and trucks are loaded, PCC and PCTC vessels are quite stable, with tendency to roll at a small angle of heel. These ships must comply with IMO requirements for international trade; however, unlike RoPax vessels, they are not subject to additional stability or damage stability requirements. This lack of specific international oversight highlights the need to develop an ISO standard to prevent RoPax vessels from capsizing during turns.

Typically, ship safety is assessed by calculating the ship's transverse metacenter, denoted by GM. This calculation allows for estimating the ship's transverse righting arm GZ at different heel angles, as shown in **Figure 5** for the MV Golden Ray. These calculations were performed in a post-accident analysis [12]. For small heel angles, the GZ is large, which may lead the crew to believe the ship is safe during loading, as the heel angle remains relatively small. However, observing safety regulations regarding the total area under the GZ curve, the resulting GZ curve often displays a concave region, as shown in **Figure 5**.

This concave region, in **Figure 5**, defined by an inflection point around a heel angle of 10 degrees and extending to around 50 degrees, creates a dangerous operating condition during turns. This situation can cause the vessel to list and settle at a large angle of heel (60 degrees for MV Golden Ray and 40 degrees for MV Hoegh Osaka). As a result, recently built PCCs and PCTCs are at risk of experiencing similar capsizing accidents in the future.

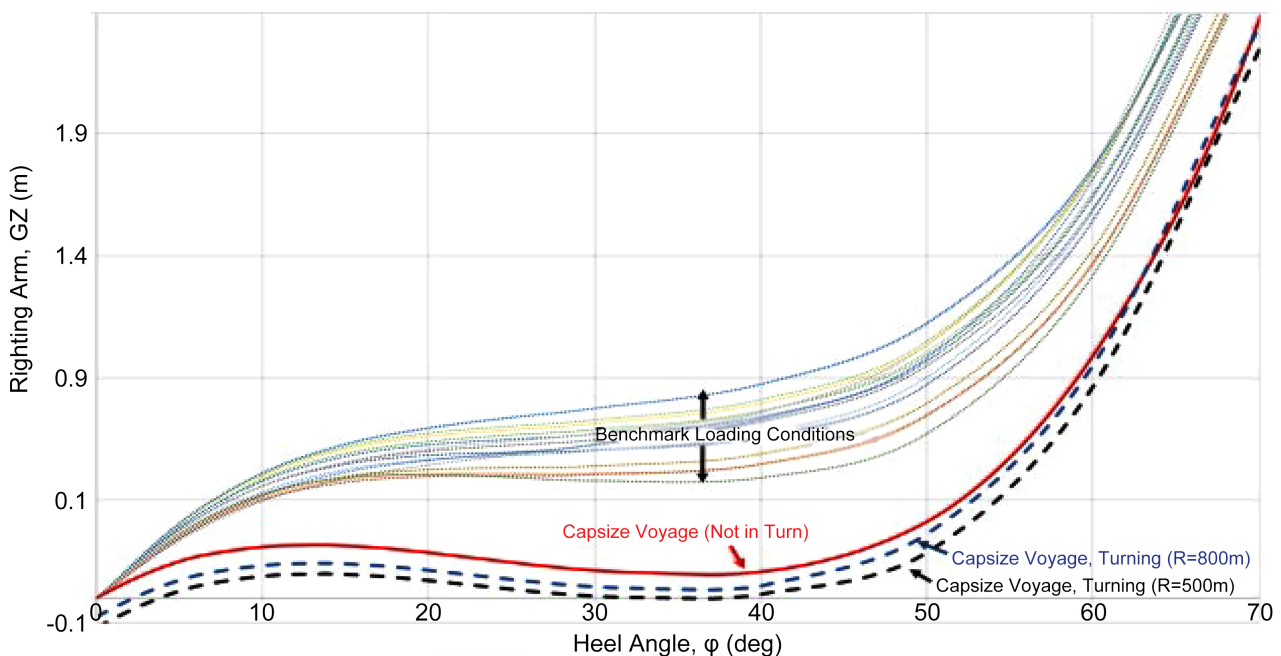


Figure 5. GZ versus heel angle for MV Golden Ray [12].

When a vessel makes a sharp turn, a heeling moment caused by centrifugal force is generated. The centrifugal force increases as turning radius (R) decreases, resulting in the righting arm GZ curves. This GZ reduction is shown in **Figure 5** for $R = 800$ m and $R = 500$ m.

The heeled deck also generates tangential force and an overturning moment acting on the lashed cargoes or tied-down vehicles. These forces and moments can break the tied-down cables, leading to a shift in the cargo. **Figure 6** shows a post-accident analysis of the MV Sewol's heel angle versus time, marking the onset of the cargo shift around 18-degree heel ($t = 8:49:25$). It should be noted that RoPax ships like the MV Sewol typically carry a wide range of cars, trucks, and busses. The trucks can be overloaded and unstable when the ship heels.

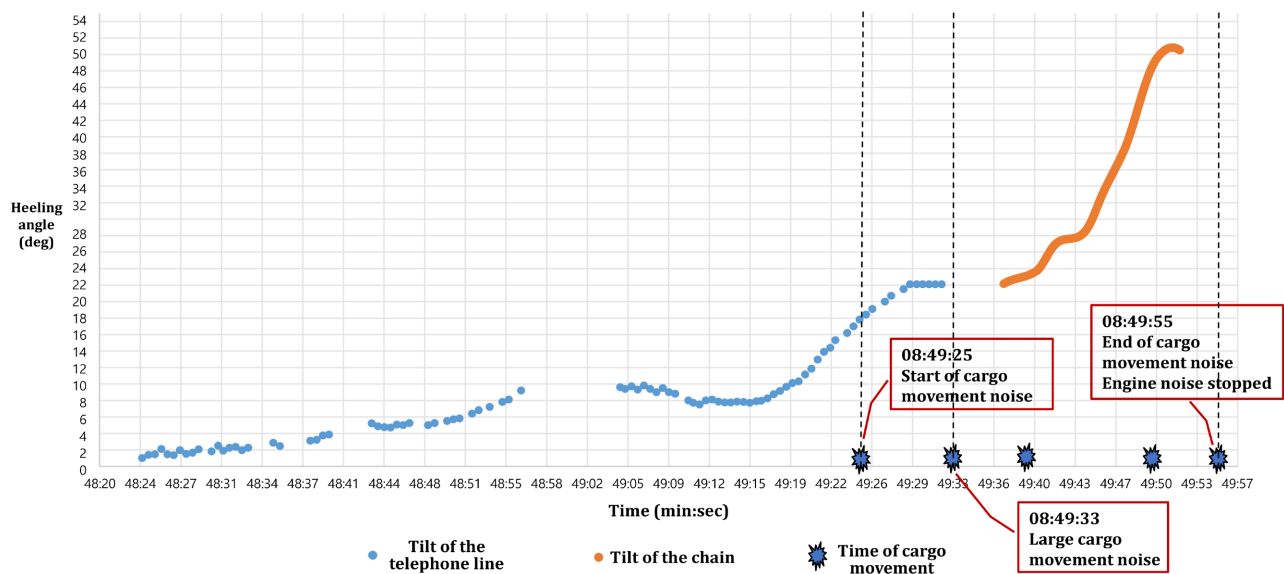


Figure 6. Change of heeling angle and time stamps of cargo movement noise during the MV Sewol ferry accident [16].

4. Possible Methods to Prevent Recurring RoPax Capsize

The MV Sewol's capsizes is similar to earlier RoPax accidents recorded between 1965 and 1982. During this 17-year period, the classification society Det Norske Veritas (DNV) identified 341 RoRo casualties, including 217 classified as "serious" and 36 as "total loss" incidents [17]. The most common causes of the 217 serious incidents were collisions (24%), machinery damage (17%), grounding (17%), cargo shifts and operational errors (16%), and fires and explosions (14%). Among the 36 total loss casualties, the most common cause was shifts and operational faults (43%); collision (25%) and fires and explosions (18%).

Figure 7 shows the changes in ship heel angle during turning. After the rudder is turned, the ship experiences an initial inward heel caused by rudder force, followed by a larger outward heel due to centrifugal force. As previously noted, the ships in **Table 1** have a low stability margin (GZ in **Figure 5**), creating a dangerous situation when they experience a large heel angle θ_{max} occurring at the beginning of a turn.

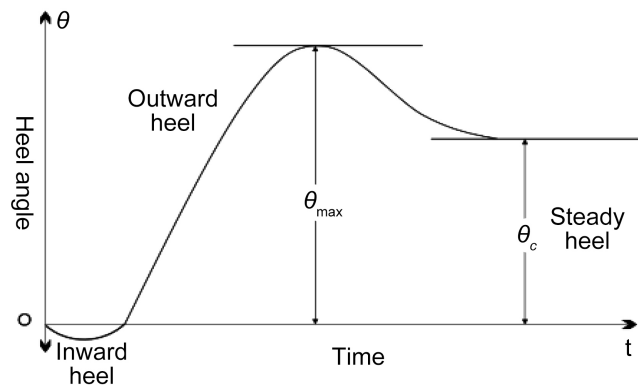


Figure 7. Heel angle versus time during ship turning.

The International Code on Intact Stability (ISC), adopted by the IMO in 2008, includes a rule that limits the heel angle to 10 degrees. MARIN of the Netherlands has proposed limiting the maximum heel angle during turns to 15 degrees [18]. Similarly, in 2012, the Italian classification society RINA proposed a maximum outward heel angle of 15 degrees and a steady-state 10 degrees.

The rationale for limiting the heel angle to 15 degrees is based on the fact that at a heeling angle of 18 degrees (Figure 6), cargo loaded without safety devices begin to slide. The authors recommend that the SOLAS limit for the “steady” heel angle be extended to also limit the maximum heel angle θ_{max} (refer Figure 7) during the “transient” period of a ship’s turn.

To provide a framework for addressing the identified problems and preventing capsizes during turns, the authors organized the design and operation parameters of the RoPax capsizes into four sequences, as shown in Figure 8.

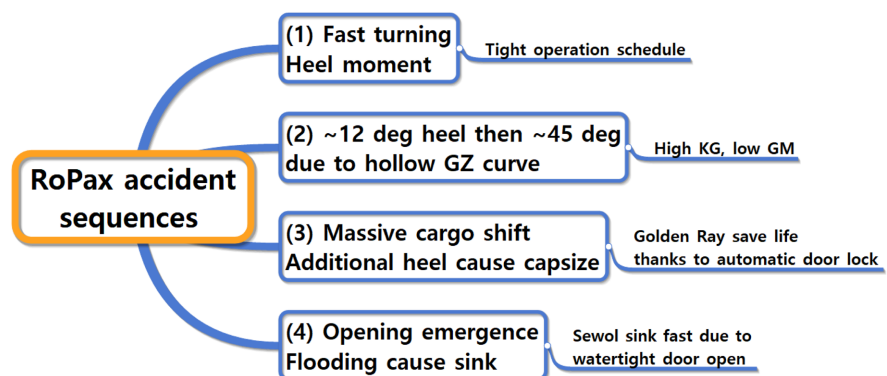


Figure 8. RoPax accident sequences when turning.

The capsize of a RoPax ship involves several interconnected design and operational factors. However, these factors are not fully addressed by current IMO rules. It is crucial for the naval architects to prioritize the goal of designing a safe RoPax ship, rather than relying solely on IMO and national marine safety organizations to impose loading and operational restrictions on current and future RoPax ships. Achieving an adequate stability margin is essential for the safe operation of RoPax

vessels. To prevent the recurrence of RoPax capsizes during turns, new rule development should focus on three key points:

- 1) Precisely determine the ship's center of gravity KG when fully loaded.
- 2) Adopt navigation systems that limit the ship's angle of heel by controlling the centrifugal force during turns.
- 3) Calculate stability assuming a 100% filling level for liquid cargo.

A number of possible methods to improve RoPax safety during turns are summarized in **Table 2**. These methods form the basis for the author's developing an ISO standard aimed at reducing RoPax ship capsizing during turns. The proposed methods are listed alongside the sequence numbers shown in **Figure 8**.

Table 2. Possible methods to improve RoPax safety when turning.

No	Possible method	Detail method	Lifecycle stage	#In Figure 8
1	Calculate up to 100% filling level for liquid cargo tank to estimate KG accurate	Modify stability calculation (estimation) software	Design	(2)
2	Measure KG after cargo loading rather than estimate	2.1 Measure cargo weight while loading 2.2 Use IMACS (integrated monitoring, alarm, and control system) to get same result of inclining test	Operation - Cargo loading	(2)
3	Limit heeling angle when turning	Unsecured cargo start to slide at 18 deg of heel	Operation - Voyage	(3)

5. Discussion and Conclusions

This paper has discussed the ISO (International Organization for Standardization) standards for ship safety, which rely on collaboration among organizations like the IMO, ISO, and IEC. It is evident from the discussion that as the number of newly built RoPax ships with large profile height increases, the likelihood of RoPax ship accidents during turns will also rise.

The analysis of recent RoPax capsizing accidents identified several issues contributing to these incidents. The authors believe that the solution is the development of an ISO standard, following the framework shown in **Figure 3** and **Figure 4**. This standard would introduce safety measures, including the estimation of the center of gravity KG and the implementation of safeguards, such as limits on rudder angle and corresponding heel angle during turns. However, ships and offshore plants are complex and large systems operating in rough seas, so the proposed ISO standards need to comprehensively address safe design, operation and training.

Officer and crew training also need to address these issues. From a broader perspective, there is a gap between the rapid development of technology and industry

and the establishment of a safety culture [19].

The shipbuilding and marine industry have evolved from Europe to United States, Japan, and then to Korea and China. However, the pace of technological and industrial development has outstripped the establishment of safety culture, creating a gap between the two [20].

Safety technology is advancing rapidly in the Far East, and new types of ships and offshore plants are emerging. However, the development of a safety culture is still in its early stage, which increases the risk of similar accidents recurring. Until a robust safety culture is established, the authors hope that active participation from the marine insurance industry can help mitigate these risks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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