“This is the peer reviewed version of the following article: Valdez Banda, O.A., Kujala, P., Sapsathiarn, Y., Mokkhavas, O., Punurai, W., Suvanjumrat, C., Priyadumkol, J. A risk analysis of autonomous vessels in complex urban waterways. Developments in Maritime Technology and Engineering - Proceedings of the 5th International Conference on Maritime Technology and Engineering, MARTECH 2020, 1, pp. 283-289, which has been published in final form at https://doi.org/10.1201/9781003216582-32. This article may be used for non-commercial purposes.”

A risk analysis of autonomous vessels in complex urban waterways

O.A. Valdez Banda & P. Kujala
Aalto University, Department of Mechanical Engineering (Marine Technology), Research Group on Maritime Risk and Safety, FI-00076 Aalto, Finland.
Y. Sapsathiarn, O. Mokkhavas & W. Punarai
Mahidol University, Faculty of Engineering, Department of Civil and Environmental Engineering, Phuttamonthon Nakhon Pathom, Thailand.

C. Suvanjumrat & J. Priyadumkol
Mahidol University, Faculty of Engineering, Department of Mechanical Engineering, Phuttamonthon Nakhon Pathom, Thailand.

ABSTRACT: Autonomous vessels have become one potential alternative for the concept of urban mobility. In complex urban waterways, autonomous vessels could assist in the transporting of goods and people. The recent development of technologies enabling autonomous systems has supported the initial design of new autonomous vessels concepts. However, before these concepts are further designed and operated, it is necessary to analyze their risks to develop strategies for ensuring the safety of people and the protection of the natural environment. In this study, an initial analysis is elaborated to assess the application of autonomous vessels in Chao Phraya River in Bangkok and Larn island in eastern Thailand. The aim is to provide an initial analysis of the risks of autonomous vessels by developing an initial overview of the application of the autonomous vessels in the mentioned operational context. The capabilities of the proposed process to analyze these risks are also evaluated.

1 INTRODUCTION

The concepts of autonomous shipping and smart mobility are of high level of importance in the development of a more sustainable urban transport (Levander 2016). The recent progress in the development of technologies for developing autonomous systems has supported the planning and initial design of new concepts of autonomous vessels for urban mobility (Tannum and Ulvensoen 2019). In addition, significant efforts are currently made by ship manufacturers and technology developers for making an efficient integration of the components needed to have an autonomous vessel ready for operation (Yara 2019 and DNV GL 2019).

One critical aspect to further develop the design of new concepts and their potential sub sequential implementation is the analysis and management of the risks of the vessel operation (Valdez Banda et al. 2019). This type of analysis must support the design and operation of the autonomous vessel and the entire ecosystem where it operates. The prioritization on the analysis of the vessel and its operational ecosystem is critical because the efficiency of a smart vessel depends on efficiency design of the smart environment (operational context) (Renn 2016).

This study presents an preliminary analysis to assess the potential application of autonomous vessels in Chao Phraya River in Bangkok and Larn Island in eastern Thailand. The process for analysis is based on the process presented in Valdez Banda et al. (2019). The process aims at providing an initial coherent, transparent, and traceable safety input information for analyzing the potential implementation of autonomous vessels in complex urban waterways.

The initial results of this analysis provide an informative but yet realistic evaluation of the application of the autonomous vessels in the mentioned context. Moreover, the results provide a representation of the process capabilities to initialize the analysis and management of the risks of autonomous vessels in complex urban waterways.

2 RESEARCH BACKGROUND AND DATA

2.1 *Operational context (Chao Phraya River)*

The Chao Phraya River begins at the confluence of the Ping and Nan rivers at Nakhon Sawan in Nakhon Sawan Province. It flows south for 372 kilometres (231 mi) from the central plains to Bangkok and the Gulf of Thailand. In Chai Nat, the river then splits into the main course and the Tha Chin River, which then flows parallel to the main river and exits in the Gulf of Thailand about 35 kilometres west of Bangkok in Samut Sakhon. In the low alluvial plain which begins below the Chainat Dam, there are many small canals which split off from the main river (McCarthy 2005). These canals interact among both rivers and allow water, and in some cases, urban traffic in Bangkok area.

In Bangkok area, several ferry lines transport people every day along 31 kilometers of the Chao Phraya River. The river is one of the existing alternatives to the oversaturated urban transport system of the city. Urban water transportation in the river has had some issues with finding subsidy and heavy government regulations that have delayed the modernization of the system (Tanko and Burke 2016). Current efforts are been allocated in modernizing the ferry piers (smart piers) similar to the existing train (Skytrain) system by BTS. The modernization of the system is essential as every day more than 100 000 passengers move along the river (Statistics by MD, 2019a).

In the context of the Chao Phraya river, this study focuses on the analysis of the river crossing between Siriraj Piyamaharajkarun Hospital and Thammasat University, Tha Phra Chan Campus (Tha Prachan - Wang Lang Pier). Figure 1 presents the geographical location of the area under analysis. In this area, more than 5000 people cross the river everyday (Statistics by MD, 2019a). Table 1 presents traffic statistics between Tha Prachan - Wang Lang Pier.

Table 1. Passenger and service statistics, ship dimensions on the operation between Tha Prachan - Wang Lang Pier in 2019 (MD, 2019a).

Context element	Description
Total number of passengers	1,947,523
Total number of boat trips	31,334
Average daily passengers	5,321
- Week	2,542
- Weekend	6,263
Average daily trips	86
- Week	88
- Weekend	81
Total ships in service	5
- Week	2
- Weekend	2
Fares	
- General	3.5 Bahts
- Elder	2
- Children (under 90cm)	Free
- Bicycle	6.5
Ship (ref. No SP.69)	
- Width	4.5 m
- Length	16 m
- Depth	1.2 m

The pier at Thammasart University is composed of two steel docks (size = 7.00*11.00 m and 4.00*11.00 m) with two steel bridges (size = 1.32*9.00 m and 1.54*9.00 m). The pier at Siriraj hospital has two steel docks (size = 7.00*11.00 m both) with two steel bridges (size = 1.59*7.40 m and 1.51*7.40 m) (MD, 2019a).

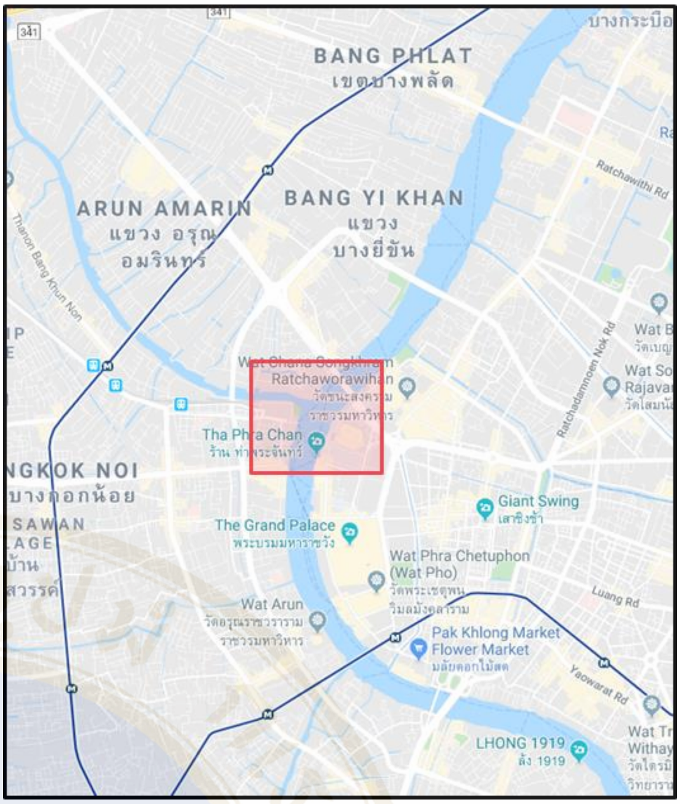

Figure 1. Graphical location of the are under analysis in Chao Phraya River (Tha Prachan - Wang Lang Pier)

2.2 *Operational context (Larn island)*

Larn Island (Koh Larn) is a small island in the eastern part of Thailand. There are 7.5 kilometers from Pattaya shore that is a famous place for sea-activities such as swimming, diving, sailing and other recreational activities. It is approximately 120 kilometers away from Bangkok. Figure 2 presents the Larn Island location. Passengers have to transit to ferry or speed boat at Balihai pier from Pattaya. There are two major piers; Naban pier and Tawaen beach pier with another one floating pier at Samae beach as shown in Figure 3. Naban pier is a traditional pier for passenger and multi-purpose cargo which is focusing on this research. There are 5.84 million passengers in 2018 at Larn Island while 2.36 million passengers are transferred to/from Naban beach pier or estimate 40 percent of the whole passenger there (MD, 2019b).

The shortest distance for sea transportation to Larn island is Naban pier – Balihai pier route which approximately 8.4 kilometers. The peak period is from January to May with around 27,400 persons per day moving in this route. The average passenger in 2018 was 16,000 passenger per day, approximately 378 voyages (MD, 2019b).

The overall length of Naban pier is 180 meters including with 40 meters of general-purpose yard. There is an open passenger waiting area and small parking at the hinterland. The pier has laid into the sea as “I” platform. The sea depth at the end of the pier is about 3.5 meters. The water depth and tourists demand are critical aspects for the coordination of traffic.

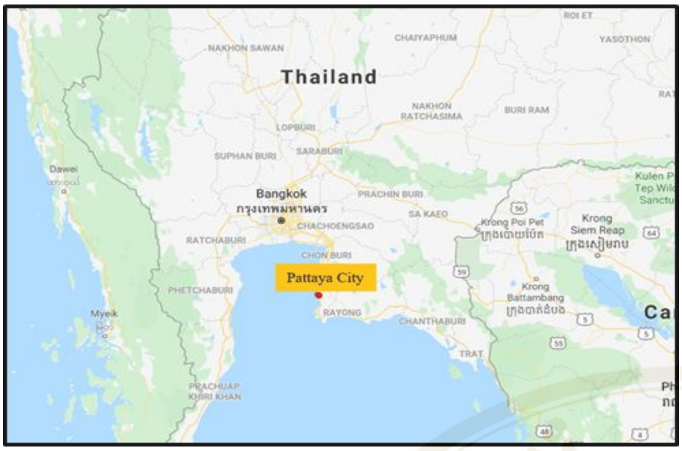

Figure 2. Larn Island geographical location

Two main types of vessels (ferry and speed boat) are utilized for passenger transport from and to the island. Ferries are operated for daily transportation with a fixed schedule (see Table 2). The service time from Balihai pier to Larn pier is 40-45 minutes depending on weather condition. Mostly, the ferries length are between 15-30 meters, width 4-10 meters and the draft is not over 3 meter. The passenger capacity is between 100-250 passengers.

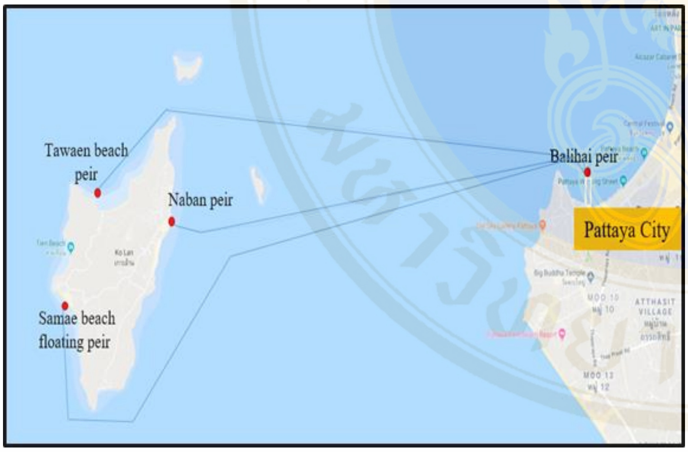

Figure 3. Naban pier and Tawaen beach piers location

Table 2. Ferry service timetable at Larn Island.

Route	Service time AM	Service Time PM
Balihai pier (Pattaya) – Naban pier (Larn island)	7, 10:00	12, 14, 15:30, 17, 18:00
Naban pier (Larn island) – Balihai pier (Pattaya)	6:30, 7:30, 9:30	12, 14, 15:30, 17, 18:00

2.3 *Hazards and accident information*

In the Context of Chao Phraya River, information about accidents and previous safety analysis are not available and therefore not included in this analysis. However, as the context of analysis is narrowed down to the potential autonomous operation of the vessel crossing from Siriraj Piyamaharajkarun Hospital to Thammasat University, Tha Phra Chan Campus, the information utilized consists of available traffic statistics in (MD, 2019b), site visits for the analysis of the operational context, interviews with maritime authorities and the analysis presented in Valdez Banda and Kannos (2018).

In the Context of Larn Island, The Nation 2019 the most relevant risks reported are:

- The falling passengers’ belongings into the sea.
- Injury onboard ferry from sea condition.
- Injury onboard speed boat from the heavy waves attached.
- Injury from the ferry transfer.
- Sinking passenger ferry from flooding
- Fire onboard the ferry
- Collision with fixed objects (rocks and buoys)

This information is complemented with the analysis to the concept of an autonomous ferry as presented in Valdez Banda and Kannos 2018. The environmental context described in Section 2.2 (DASTA 2015) is considered to adapt the described scenarios to the mentioned context.

3 METHODOLOGY

3.1 *The process of analysis*

The process is adapted from the original process presented in Valdez Banda et al. 2019. The process follows four steps:

- Step one (Hazard identification). It focuses on the collection of information about aspects and contextual scenarios (incl. the causes and sources of risk) which can negatively influence the safety of the system(s).
- Step two (Detailed hazard description). This step focuses on the elaboration of the detailed descriptions of the effects of the hazards, providing a comprehensive argumentation about the relevancy of the hazards and an estimation of their potential severity and type of consequences.
- Step three (Risk Control Options). The step focuses on defining of risk mitigation actions. These actions represent the initial specifications of the safety controls. Controls are set to eliminate the risk source (preventive safety controls) or mitigate the possible consequences (reactive safety controls).
- Step 4 (Identification and analysis of Unsafe control actions “UCAs”) to each safety control UCAs are identified. The UCAs represent actions that could lead to a hazardous

state in the system. Hazardous states result from inadequate controls or enforcement of the safety control (Leveson, 2011). The identification of UCAs continues with a definition of how these can occur in the design and implementation of those actions. With this definition, safety specifications are provided to manage and prevent the UCAs.

As the vessels and system operations in both study cases are currently entirely man depended, the method considers the process for transferring the human knowledge towards automation and the potential interaction between new autonomous vessels concepts and the vessels that are entirely human operated. This is done by analyzing the human role in the operational context with site visits and video recording.

4 RESULTS

4.1 *Accidents and hazards*

Chao Phraya River (Tha Prachan - Wang Lang Pier)

Table 3. Accidents and hazards in the context of the vessel operating between Tha Prachan - Wang Lang Pier in 2019.

Accident	Hazard
Collision with pier	Object detection sensor error Software incorrect design Mechanical failure Heavy weather/river/ conditions Strong currents Position reference equipment failure
Collision with moving object (e.g. another vessel)	Object detection sensor error Software incorrect design Technical failure
Collision with a fixed object (e.g. buoys, beacons, etc.)	Object detection sensor error Software incorrect design Mechanical failure Heavy weather/river/ conditions Strong currents Position reference equipment failure
Capsizing	Overloading of the vessel Shifting of weights Flooding
Fire onboard	Ignition of electrical equipment Generated by a passenger
Passenger over board	Unintended falling Intended jumping
Emergency on board and/or the pier	Person being injured Medical emergency

During the analysis of the context in site visits and video recording fundamental issues are detected. High traffic complexity, the context has not specific "rules of the road", so the operation of boats on this area is entirely dependent on the judgment and expertise of the vessel operators. Operational time, vessel speed operations vary during the entire journey. The average of trips per day is an important indicator of the expected performance of the vessel and crew on-board.

A docking operation to get on/off the vessel takes around 3-4 minutes (for a vessel with capacity of 90 passengers max.). Two persons on board and 1-3 persons on the pier control the docking, embarking and disembarking. There are not physical safety barriers focused on avoiding the falling of a person or being pressed between the vessel and the pier. Energy consumption of the operations, high speeds and passenger demands derive in full operation of the vessel capacity. Air and noise pollution is evident during the journeys and the quality of the air. Traffic diversity, there is a significant amount of different type of vessels operating in the same context (ferry and fast boats of different dimensions).

Larn Island (Naban peir – Balihai pier)

Table 4. Accidents and hazards in the context of the vessel operating between Naban peir – Balihai pier at (Pattaya- Larn Island)

Accident	Hazard
All those listed in Table 3	
Grounding	Software incorrect design Mechanical failure Position reference equipment failure Heavy weather/sea condition Strong currents

As mentioned in the report by The nation (2019), injuries happen as a combination of sea conditions and operational speeds. The process for docking in Chao Phraya river lacks of safety barriers to avoid that a person fall into the water or gets pressed between the vessel and the piers.

4.2 *Detailed hazard description*

This step provides information about the potential causal factors of the hazards, the definition of initial mitigation actions, an initial estimation of the difficulty and cost for their implementation, and the definition of the initial mitigation actions. This detailed hazard is taken from the analysis done in Valdez Banda and Kannos 2018. Table 5 presents an example of these detailed descriptions.

Table 5. Detailed description and initial mitigation actions for hazard H1 (Object detection sensor error (Valdez and Kannos 2018).

Hazard	Object detection sensor error
Hazard effect/ description	
In case of object detection sensor error, the information about objects around the vessel is not reliable and thus the vessel may not be able to navigate safely and avoid collisions with moving	

objects according to the rules of the road or collisions with fixed objects. This hazard may not affect the ship operation significantly in most cases, but in a more severe scenario, the hazard can have a negative impact on people, property, and environment. It can result in injuries, the loss of human life, severe damage or loss of property (own and others property) and environmental effects such as oil spills or other damage of a sensitive waterway or sea area.

Causal factors
- Loss of power
- Equipment malfunction
- Dirt
- Heavy rain
- Overheating
- Equipment interference
- Inappropriate maintenance
- Incorrect sensor set and/or positioning of the sensors
- Targets impossible to detect
- Corrupted readings
- Complete equipment failure

4.3 *Risk control options*

Table 6 presents the Risk Control Options for the Hazard (Object detection sensor error). The entire list of risk control options of the hazards listed in Section 4.1.

Table 6. The detailed description and initial mitigation actions for hazard H1 (Object detection sensor error (Valdez and Kannos 2018).

Hazard	Object detection sensor error

Risk Control Options (RCOs)
- Sensor system redundancy and diversity
- UPS (Uninterrupted Power Source)
- Appropriate cooling and cleaning systems
- Thorough commissioning of equipment set
- Appropriate and continuous maintenance program
- Continuing system diagnosis and proof testing
- Autonomous Integrity monitoring

4.4 *Unsafe Control Actions (UCAs)*

Table 7 presents the detected UCAs for the Risk Control Option (RCO) Sensor system redundancy and diversity. The UCAs of the listed RCOs for all hazards is presented in Valdez Banda et al. 2018.

Table 7. Unsafe Control Actions (UCAs) of the RCO "Sensor system redundancy and diversity" (Valdez and Kannos 2018).

RCO	Sensor system redundancy and diversity

Unsafe Control Actions (UCAs)

UCA 1. Sensor does not function properly and there is no other sensor available

Potential causes
- Lack of economic resources

UCA 2. Equipment chosen to provide the redundancy are not suitable

Potential causes
- Lack of economic resources
- Lack of knowledge of sensors characteristics when planning the equipment set needed

UCA 3. Sensor failure is not detected

Potential causes
- Not enough coverage with the diagnosis

UCA 4. External or common cause failures takes several equipment down at the same time

Potential causes
- Inappropriate system design
- Incorrect installation
- Incorrect usage
- Environmental conditions

5 DISCUSSION

5.1 *The process application and results*

The implementation of the process focuses on the generation of initial risk management information that can guide the design and planning of the operation of the autonomous vessel concepts.

Step one defines the main accidents that may result in damages and injuries during the operations of the autonomous vessel and its entire operational system. The hazards represent the obvious initial states of the system which endanger the mission and operation of the vessels.

Step two incorporates a justification of why the hazard analysis is relevant and the initial estimation of its severity and its consequences. Moreover, potential causal factors are also identified and analyzed in this step. These provide a systemic representation of the causes linked to different components included in the design and operation of the vessels and the entire operational ecosystem.

Step three provides specific alternatives with valuable information for further development of safety controls and the analysis of the operational context and functionality of the vessels and other components in the operational environment.

Step four goes deeper into understanding how the vessels and the ecosystem can still drift into a risky status and potentially trigger an accident.

The site visits and recorded videos provide critical information and realistic perception of the level of complexity of the current operation and the evident challenge in the inclusion of autonomous vessels in the two selected operational contexts. The complexity linked to the functionality of a muddled water traffic system in Chao Phraya River demands a strategic plan to incorporate the autonomous vessel and the other components of its smart operational ecosystem.

Clear strategic specifications for planning the design of this smart ecosystem is essential. This includes the autonomous vessels and their interaction with other manned vessels. In discussions with experts of urban waterway and sea operation in Thailand, the experts mentioned the need for a gradual inclusion of the smart vessels and systems into the operational context. Due to the system complexity, the planning and making an entire disruption the operational context seems to be a non-viable alternative. As mentioned by the experts, there is a need for (gradually) evidence of the improvement of waterway traffic and the benefits obtained by the incursion of these modern systems. This evidence allows confirming the success of the planning, design and implementation of autonomous vessels and understanding the process to successfully updated waterway operations and urban waterway mobility.

The gradual transformation of urban waterway mobility in Thailand has started with the planning of smart piers in Chao Phraya River. These aim to support the process for embarking and disembarking of the vessels and provide specific safety controllers that prevent accidents in the pier. The information on the analysis of the accident “Emergency on the pier” provides useful information to support and guide the design of the pier.

Finally, the potential incursion of autonomous vessels in the specific operational context introduced in this study can significantly support and boost the development of a more sustainable ecosystem for urban waterways. In the next years, the strategic tasks for developing such ecosystem will entirely influence the development of the maritime traffic and maritime industry in Thailand and the rest of the world (The Nation, 2019). Every country will develop a specific approach based on traffic demands and the operational characteristics linked to it (ferry and fast boats of different dimensions).

The overall and general analysis presented in this study represent only an initial reference for the development of this analysis. The study is limited to the scarce information of accidents and incidents, the initial discussions with experts, video recording and site visits of the operational context and the information obtained in the study by Valdez Banda and Kannos (2018). This represents the need for continuing/completing the risk analysis in the initial planning phase of the specific vessels and service concepts.

6 CONCLUSION

This study presents an initial risk analysis process for the planning of new concepts of autonomous vessels for urban mobility in two specific operational contexts of urban mobility. The process supports the generation of specific information to guide the design of the new concepts and evaluate the critical aspects for the inclusion of smart vessels in complex urban waterways. The provided controls and critical aspects detected in the analysis can represent the basis of the initial risk management strategy of the autonomous vessels and its operating ecosystem.

The implementation of the process represents an initial useful alternative for analyzing hazards and proposing safety controls with a systemic approach that covers the operational context of the autonomous vessel. The process should continue with the extraction of relevant information to plan, design and construct the autonomous vessel and its entire operational system.

This study and the potential extension of the application of the presented process must be complemented with the incursion of new data such as accident data and statistics of the selected operational context and the discussion of the concepts with the stakeholders that are responsible for the management of safety of the vessels and their operational ecosystem.

ACKNOWLEDGMENTS

The work presented in this study was carried out as part of the “Reliability and Safety Engineering and Technology for large maritime systems” (RESET). RESET is partially supported by the European Union’s Horizon 2020 Research and Innovation Programme RISE under grant agreement no. 730888 (RESET).

REFERENCES

Designated Areas for Sustainable Tourism Administratio (DASTA), 2015. The Study and design of port development project for Koh Larn tourism (Final report).

DNV GL, 2019. The Revolt concept. A new inspirational ship concept. Available at. https://www.dnvgl.com/technology-innovation/revolt/index.html

Levander O., 2016. Ship intelligence – a new era in shipping. Smart Sh. Technol., London. RINA; 2016, p. 25–32.

Leveson, N. 2011. Engineering a Safer World: Systems Thinking Applied to Safety. MIT Press.

McCarthy J., 2005. From Bangkok to Korat – Elephants". Surveying and exploring in Siam.

MD (Marine Department of Thailand, Bangkok office). 2019a. Summary report of ferry motorbike passanger in Chao Phraya River. Report No. 2562

MD (Marine Department of Thailand, Pattaya office). 2019 b. The statistics report of Pattaya passenger to Larn Island.

Renn O., 2016. Keynote lecture in the 4th European STAMP Workshop and Conference 2016 in Zurich.

Tanko M. and Burke M.I., 2016. Transport innovations and their effect on cities: the emergence ofurban linear ferries worldwide. World Conference on Transport Research - WCTR 2016 Shanghai. 10-15 July 2016.

Tannum M.S. and Ulvensoen J.H., 2019. Urban mobility at sea and on waterways in Norway. Journal of Physics: Conference Series Vol 1357 P. 012018, October 2019.

The Nation 2019. Ferries charge up smog battle. Article from 13.02.2019. Available at https://www.nationthailand.com/Corporate/30364085

Valdez Banda, O.A. and Kannos, S. 2018. Hazards analysis process for autonomous vessels. ÄLYVESI (Samart City Ferries) project report. July 2018 (https://www.aboamare.fi/Results).

Valdez Banda O.A., Kannos S., Goerlandt, F., Van Gelder P.H.A.J.M., Bergström M., Kujala P. 2019. A systemic hazard analysis and management process for the concept design phase of an autonomous vessel. Reliability Engineering & System Safety, Volume 191, November 2019, 106584.

YARA, 2019. YARA Birkeland (unmanned vessel concept) project. Available at https://www.ship-technology.com/projects/yara-birkeland-autonomous-container-vessel/