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Eunkyu Lee
SafeTechResearch, Inc., Daejeon, South Korea.

Young-Soo Park
Division of Maritime Transportation Science, Korea Maritime and Ocean University, Busan, South Korea., youngsoo@kmou.ac.kr

Minjeong Park
Division of Maritime Transportation Science, Korea Maritime and Ocean University, Busan, South Korea.

Myoung-Ki Lee
Division of Maritime Transportation Science, Korea Maritime and Ocean University, Busan, South Korea

Eunbi Park
SafeTechResearch, Inc., Daejeon, South Korea.

See next page for additional authors

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Authors

Eunkyu Lee, Young-Soo Park, Minjeong Park, Myoung-Ki Lee, Eunbi Park, and In-Young Gong

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DEVELOPMENT OF COLLISION AVOIDANCE ALGORITHM BASED ON CONSCIOUSNESS OF SHIP OPERATOR

Eunkyu Lee[1], Young-Soo Park[2], Minjeong Park[2], Myoung-Ki Lee[2],

Eunbi Park[1], and In-Young Gong[1]

Key words: collision avoidance, PARK model, COLREGS, simulation, AIS data.

ABSTRACT

Several collision avoidance algorithms employing various methods have been developed to date. In this paper, a collision avoidance algorithm is proposed based on the potential assessment of risk (PARK) model, which is a maritime traffic risk assessment model based on the characteristics of the Korean coastal regions and the consciousness of a ship's operator. The proposed collision avoidance algorithm is intended to be used in the transition period during which autonomous and human-operated ships sail simultaneously. The algorithm avoids collisions using the PARK model that reflects the International Regulations for Preventing Collisions at Sea. Situations such as head-on, crossing, overtaking, and their combination were simulated. The performance of the collision avoidance algorithm was verified by successfully avoiding collisions while simulating a busy waterway using historical automatic identification system data.

I. INTRODUCTION

1. Background

Autonomous driving has received considerable attention from industry and academia as it is expected to influence traffic movement efficiencies over the next decade (Abdelaal & Schön, 2020). The shipping industry is also undergoing a paradigm shift towards autonomy and unmanned operations as a new industrial environment based on the 4th industrial revolution (Korea Evaluation Institute of Industrial Technology, 2018). Research on the development of autonomous ships is being actively conducted worldwide.

The International Maritime Organization (IMO) has defined Maritime Autonomous Surface Ships as ocean-going vessels that, to a varying degree, can operate independently of human interaction (IMO, 2018). The IMO is conducting a review of regulations on the operation of autonomous ships to prepare for their commercialization. There are four degrees of automation: Degree 1 is partial automation, Degrees 2 and 3 employ remote control, and Degree 4 denotes total autonomous operation. Degrees 1 and 2 correspond to manned ships and Degrees 3 and 4 to unmanned ships (IMO, 2018). Degree 4 denotes the level at which all ships at sea are replaced by unmanned ships operating completely autonomously. According to this framework, until Degree 4 is achieved, there will be a transition period when ships operated by humans and automated ships equipped with a collision avoidance algorithm sail together.

Meanwhile, as autonomous ships have been developed, studies aimed at preventing collisions have also been initiated. Collision avoidance plays an important role in reducing collision accidents at sea. Collision avoidance algorithms have been studied in several ways by many researchers since the 1970s. There are two types of algorithm for preventing collisions: those that determine collision risk, and those that determine collision avoidance behavior and timing. When determining the collision risk, input variables such as the distance to the closest point of approach (DCPA), and the time to the closest point of approach (TCPA) were used to prevent collisions; fuzzy theory, Bayesian probability, and artificial neural network models were used to measure the collision risk by different researchers with their selected methods (Hu et al., 2020; Woo & Kim, 2020; Yang et al., 2020). When determining collision avoidance behavior and timing, the measured collision risk, collision avoidance operation, and timing were determined in a way that reduced the risk. They were optimized using navigation based on the A-star search algorithm and variable space navigation methods (Liu et al., 2019; Son et al., 2009).

Paper submitted 06/03/20; revised 11/18/20; accepted 12/05/20. Corresponding Author: Young-Soo Park (e-mail: youngsoo@kmou.ac.kr)
[1] SafeTechResearch, Inc., Daejeon, South Korea.
[2] Division of Maritime Transportation Science, Korea Maritime and Ocean University, Busan, South Korea.

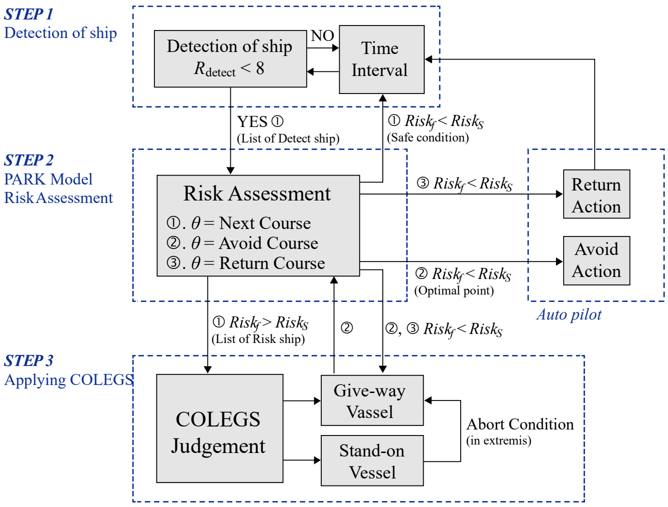

Fig. 1. Collision avoidance algorithm based on PARK model

By applying the International Regulations for Preventing Collisions at Sea (COLREGS) to the proposed collision avoidance algorithm, the risk of collision is reduced. Furthermore, by applying the same principles for collision avoidance operation to the ship operators, it was also possible to conduct an experiment using autonomous ships equipped with collision avoidance algorithms (Woerner et al., 2019).

Collision avoidance algorithms applied to autonomously operated ships can avoid collision more efficiently than humans because the algorithms make decisions based on a large amount of data that cannot be analyzed by a human being. Although these algorithms perform better than humans, there is still a preference to select human decision-making over the use of algorithms alone; this phenomenon is referred to as algorithm aversion (Dietvorst et al., 2015). This study aims to develop an algorithm that reflects the consciousness of the ship operator.

In this study, a potential assessment of risk (PARK) model based on the characteristics of the Korean coastal regions and the consciousness of ship's operators was used to develop a collision avoidance algorithm. This algorithm reflects the ship operators' viewpoint rather than being a collision avoidance algorithm that only follows the COLREGS.

The proposed collision avoidance algorithm performs collision avoidance operations in a similar way to the ship operators. Therefore, it is believed that it will be compatible with other ship operators sailing in the area. The algorithm can be used until the automation level of autonomous shipping reaches Degree 4. It is expected that the performance of the algorithm will be improved continuously as the PARK model improves.

2. Related Studies

Tsou and Hsueh (2010) proposed an optimized collision avoidance model using the ant colony algorithm to select a route to avoid collision with autonomous ships. This model combines navigational practices, maritime laws/regulations, and real-time navigation information for safe and economical collision avoidance route selection. In addition, a Geographic Information System was used as a platform for navigation decision support systems.

Shih et al. (2012) proposed a collision avoidance model that provided for optimal turning and maneuvering anywhere using any type of ship. They reviewed studies related to optimal turning and ship maneuvering, and they proposed a strategy to use the nonlinear unified state-space model, in combination with another approach depending on the requirements of the situation.

Tsai et al. (2017) proposed a collision avoidance model based on the dynamic game of complete information that was played according to the COLREGS. The critical time consists of the alteration time and the physical time delay, and it is supplemented by the physical time delay.

Kang et al. (2018) developed a particle swarm optimization algorithm to reduce human error and to determine the route of the ship to prevent collisions. It was verified by performing simulations for each encounter.

Fang et al. (2019) upgraded the numerical simulation model by investigating various hydro-meteorological factors for ships with no uniform movement. Simulations were conducted under various hydro-meteorological conditions using a real-time simulator, and maneuvering indices were obtained through the Newton-Raphson method and a regression technique. The simulation model was simplified using these indices, and it was concluded that the simplified simulation model with various hydro-meteorological conditions can easily calculate the optimal rudder angle required for ship collision avoidance in heavy traffic areas.

Lee et al. (2019) developed an automatic collision avoidance and path generation algorithm for merchant vessels using a velocity potential field approach. It was based on the velocity potential of source/vortex and dipole flow theory in fluid dynamics, and it was divided into course-changing and track-keeping modes. In the course-changing mode, the source/vortex flow was created to move away from various obstacles, and in the track-keeping mode, the dipole flow field was created to enable the vessel to return to its desired course. The COLREGS were also reflected, and collision avoidance control was performed using real-time DCPA and TCPA data.

Zhao et al. (2019) improved the efficiency of the path following and collision avoidance system using a novel deep reinforcement learning algorithm. Through repeated simulation, the autonomous ship learned the safest and most economical avoidance behavior. As a result, it was confirmed that collisions were avoided by following a planned route well, ensuring COLREGS compliance, and excellent adaptation to different navigation environments.

Many of these studies have proposed a collision avoidance algorithm derived from previous studies. However, the developed algorithms only consider the end purpose of the ship without reflecting the interim sailing patterns of the ship's

Table 1. Elements affecting safety of maritime traffic in PARK model

Element	Factor
Internal element	Type Length Width Tonnage Career License Position
External elements	Crossing Side In/Out harbor Speed

operator, which are determined by the surrounding conditions. Therefore, a collision avoidance algorithm needs to be developed using input based on the perceptions of the ship operator.

II. DEVELOPMENT OF COLLISION AVOIDANCE ALGORITHM

1. Construction of collision avoidance algorithm

The collision avoidance algorithm consists of a PARK (risk assessment) model algorithm and a COLREGS application algorithm, as shown in Figure 1.

The risk measurement algorithm calculates the risk concerning other ships at the future positions of the main ship (① θ = Next Course) at regular intervals.

If the risk factor exceeds a pre-set value, the COLREGS applied algorithm selects a collision avoidance maneuver for the give-way ship and an appropriate maneuver for the stand-on ship. If the risk of collision continues because the give-way ship does not take collision avoidance action, then it is designed to select collision avoidance action for the stand-on ship.

The set interval determines the optimal avoidance point. By lowering the risk factor below a certain level, the optimal avoidance point (② θ = Avoid Course) is selected, which minimizes direction changes.

The auto pilot directs the vessel toward the best point for collision avoidance based on existing vessel headings. The risk measurement algorithm continuously calculates risk factors for the surrounding traffic during the avoidance operation.

In addition, the risk factor is calculated for the case of returning to the previous heading (③ θ = Return Course). When the risk factor is lower than a pre-set value, it determines that the avoidance maneuver is completed and the return maneuver is performed.

2. Detection of ship

The time and distance required to recognize the collision risk and to initiate avoidance action vary with the situation. It has been suggested that a range of at least eight nautical miles is needed to initiate such action (Anglo-Eastern, 2010).

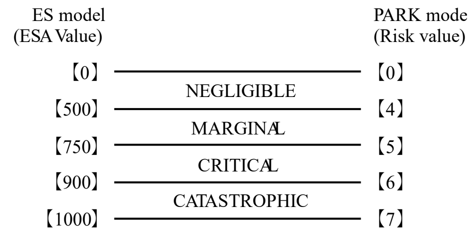

Fig. 2. Comparison of PARK model and ES model

In the open sea, the DCPA was determined to be more than one nautical mile when the target ship was detected to be more than eight nautical miles away, and the DCPA was determined to be less than one mile if the target ship was detected less than eight nautical miles away (Park and Lee, 2008).

Based on those studies, the maximum ship detection range (R_{detect}) of the collision avoidance algorithm is set to eight nautical miles.

3. Risk assessment

The PARK model is a marine traffic risk assessment model based on the characteristics of Korean coastal areas and the awareness of ship operators (Ministry of Land, Transport and Maritime Affairs, 2011).

Surveys were carried out with Korean ship operators on the types of encounter experienced between ships and the subjective risks arising from overall shipping conditions (Kim et al., 2011; Heo et al., 2012). A model based on the survey result was verified through a simulation experiment (Park et al., 2013).

The risk assessment results of the model and the Korean Vessel Traffic Service Operators (VTSO) were compared, and the comparison result suggested that the PARK model is more suitable for the risk assessment of Korean waterways than other foreign evaluation models (Nguyen, 2014). It was also confirmed that the model can be used to support the risk recognition of ship operators and VTSO decisions during the ship operations (Park et al, 2017). Table 1 shows elements affecting the safety of maritime traffic in the PARK model, categorized as internal or external elements.

The PARK model estimates that the range of risk up to the level of seven, can be calculated as follows:

$$\begin{aligned}\text{Risk Value} = {} & 5.081905 + \text{Type factor} + \text{Tonnage factor} \\ & + \text{Length factor} + \text{Width factor} \\ & + \text{Career factor} + \text{License factor} \\ & + \text{Position factor} + 0.002517 \times LOA \\ & + \text{Crossing factor} + \text{Side factor} \\ & + \text{In/Out harbor factor} + \text{Speed factor} \\ & - 0.004930 \times \text{Speed difference} \\ & - 0.430710 \times \text{Distance} \qquad (1)\end{aligned}$$

The environment stress (ES) model is based on the difficulty

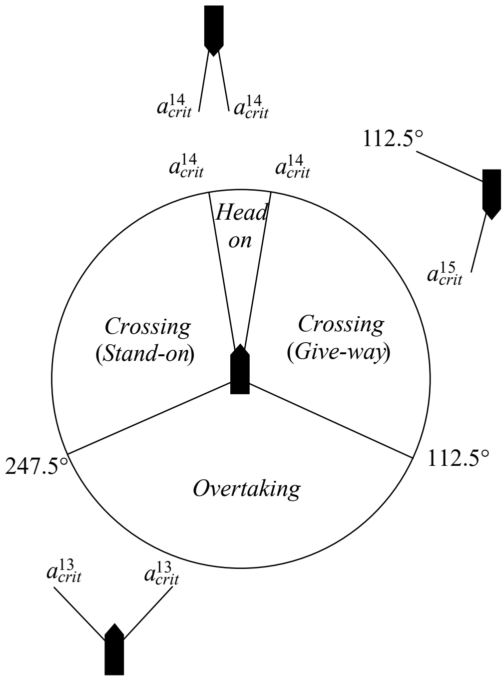

Fig. 3. Concept of Encounter situation

Table 2. Application criteria

Criteria	Applied
Maximum range for ship detection (R_{detect})	8 nautical miles
Risk assessment interval (time interval)	1.0 s
Initial risk detected ship location	4.5L
Minimum threshold range (R_{min})	6.8L
Abort condition (in extremis)	$r_{cpa} < R_{nm}$
Range for near-miss occurring (R_{nm})	1.9L
Optimal avoidance point determination interval	1° (up to ± 90°)
Avoidance risk criteria	Head-on 4.29 Overtaking 4.00 Crossing 4.11

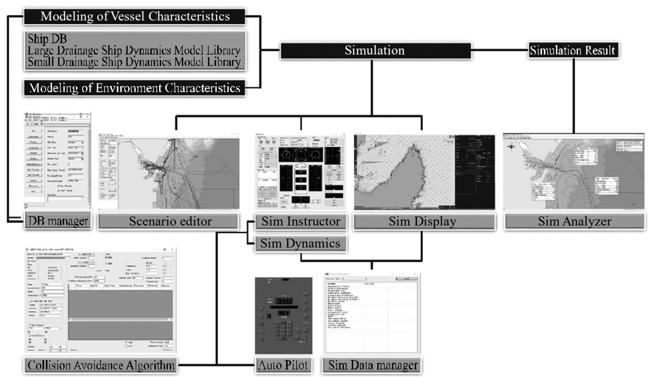

Fig. 4. Diagram of Simulator

of ship operations accompanied by restrictions of the load that are imposed on the operator by the environmental conditions surrounding the operator (Inoue, 2000). Comparing the PARK and ES models, it was determined that the PARK model is more suitable for traffic in Korean waterways than the ES model (Nguyen et al., 2015). Figure 2 shows the risk comparison of the two models.

4. Applying the COLREGS

In order to construct the collision avoidance algorithm that can perform the collision avoidance operation in a similar way to the ship operators, the rules related to the collision avoidance embodied in the COLREGS were applied to the algorithm. The COLREGS algorithm was applied only when the DCPA was within the minimum threshold range (R_{min}).

The value of R_{min} is determined by the ship domain theory. It is the minimum space surrounding a ship that should remain clear to avoid a collision. There are several studies about ship domain theory. In the current study, the domain that is defined by the consciousness of the ship operator in Korean waterways (Park et al., 2010) is used. The domain range is defined as 4.4L ahead, 3.1L astern, and 2.6L on both sides (where L is the length of the ship).
The conceptual diagram for each encounter situation is shown in Figure 3.

III. VERIFICATION OF COLLISION AVOIDANCE ALGORITHM

1. Operation environment

In order to verify the collision avoidance algorithm, the experiment was conducted with the ship handling simulator. The modular maneuvering mathematical model that expresses a complex fluid force, based on the performance of the ship inertia, the propeller, and the rudder fluid forces and their interactions, is reflected in the simulator (Yasukawa and Yoshimura, 2015). The diagram of the simulator is shown in Figure 4.

2. Application criteria

Several conditions that need to be applied to use the collision avoidance algorithm, such as the maximum ship detection range, which need to be adjusted depending on the characteristics of the ship and the surrounding traffic environment. The conditions applied in this study are shown in Table 2.

The maximum range for ship detection (R_{detect}) is related to the time taken to calculate collision avoidance action, Eight nautical miles is a suitable distance for almost all situations, but when entering the port with heavy traffic, it should be set smaller.

The risk assessment interval (time interval) is also related to the calculation time, but it is also dependent on the estimate of the expected course and speed of other shipping. If the time interval is small, a better estimate function is determined; however, the calculation time is longer.

Table 3. Details of ships used in scenarios

Type		Class (DWT)	LOA (m)	LPP (m)	B (m)	D (m)	C_B
Own ship	Tanker	5K	100	97	16.7	6.4	0.72
		10K	139	131	20.6	7.6	0.73
		15K	154	146	23.4	8.6	0.74
		20K	166	157	25.6	9.3	0.75
		30K	184	175	29.1	10.4	0.76
		50K	209	199	34.3	12.0	0.77
		70K	228	217	38.1	12.9	0.78
		90K	243	232	41.3	14.2	0.79
		100K	250	238	42.7	14.8	0.79
		150K	277	265	48.6	17.2	0.80
		300K	334	321	59.4	22.4	0.82
Other ship	Bulk	40K	198	187	30.7	11.5	0.79

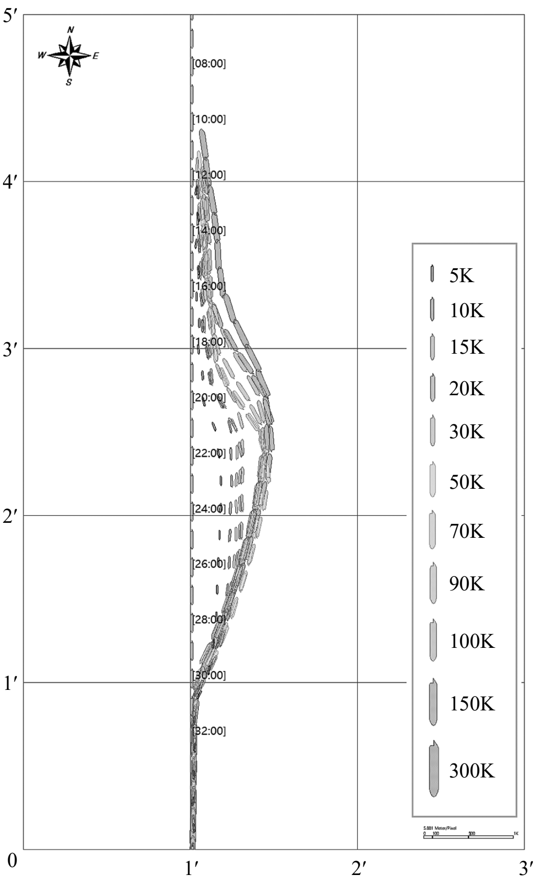

Fig. 5. Collision avoid track of head-on situation

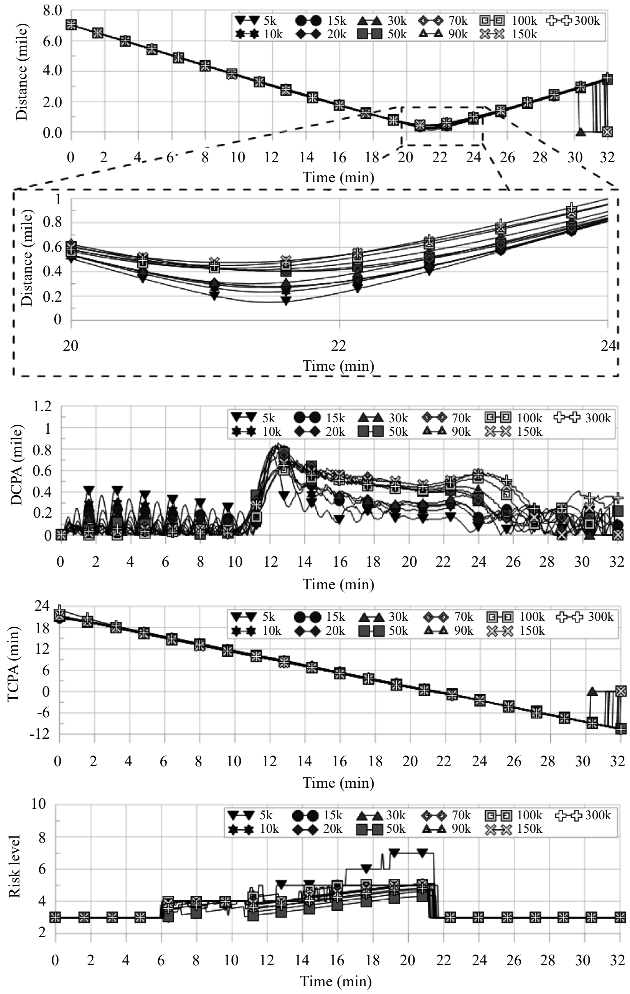

Fig. 6. Distance, DCPA, TCPA, risk changes of head-on situation

The initial risk detected ship location is the minimum distance required for the own ship to avoid a collision. As the IMO standard of advance is 4.5L, it should be longer than this.

The minimum threshold range (R_{min}) is the clear space surrounding a ship needed to avoid a collision. A large value indicates that the ship is safe. However, it should be minimized when navigating a narrow channel or passing through heavy traffic conditions.

The abort condition is the situation in which a collision is almost inevitable. Collision avoidance action must be taken even if the own ship is the stand-on vessel. The range for a near-miss occurring (R_{nm}) is used to determine the abort condition compared to DCPA of the other ship (r_{cpa}).

The optimal avoidance point determination interval is the calculated avoid option when navigating in the open sea, which might be from 5° to 10° or more.

The avoidance risk criterion is the risk level collision avoidance action that is initiated. It is determined by the risk level when the VTSO involved has sufficient time to avoid a collision (Park, 2015).

Every ship has an optimal energy efficiency operational index, so that the navigational speed may vary with the draft which is related to the weight of the ship (Shaw and Tzu, 2019). To verify the collision avoidance algorithm, 10 knots were used for the own ship, and 5~20 knots were used for the other ship in the encounter situations.

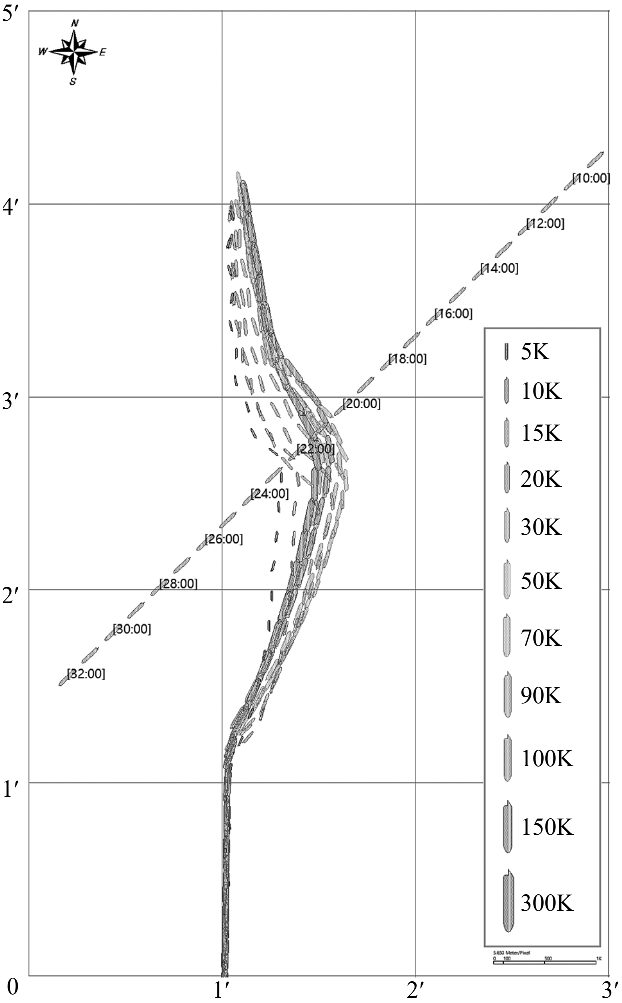

Fig. 7. Collision avoid track of crossing situation

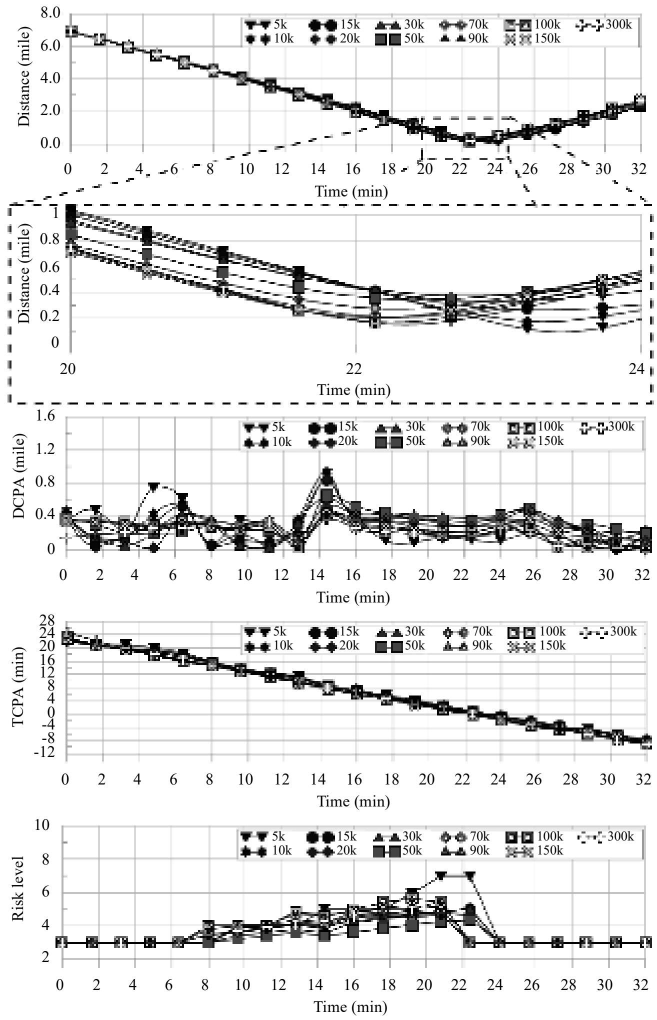

Fig. 8. Distance, DCPA, TCPA, risk changes of crossing situation

3. Application and result of collision avoidance algorithm

To verify the collision avoidance algorithm, a total of five types of ship encounter scenarios, head-on, crossing, overtaking, their combination, and an actual sea area environment were constructed for the experiment. The specifications of the own ship and the other ship are shown in Table 3.

A tanker, which has a greater risk than other types of ship, was selected as the own ship, and 11 tankers were modeled by size to check the relationship between the maneuverability and collision avoidance behavior. In the case of other ships, a single ship was modeled in this study because collision avoidance behavior is mainly affected by encounter situations with other ships rather than the ship type and size.

3.1 Head-on situation

When two ships meet in a head-on encounter, the COLREGS dictate that the ships should pass each other port-to-port. In the scenario in which the main ship does not perform the avoidance operation, the initial position of the other ships is set to collision. Figure 5 shows the simulated track in the head-on situation for each target ship referred to in Table 3.

Figure 6 show the distance, DCPA, TCPA, and risk level changes according to the simulated elapsed time for the other ship in Table 3.

As the collision avoidance operation was performed, the DCPA began to increase after approximately 10 min, and the DCPA was at its minimum from 21 to 22 min after the start of the operation, depending on the size of the own ship in Table 3. It was confirmed that the DCPA decreased to a certain level by gradually performing a return operation over time.

The minimum separation distance was determined to be approximately 0.15–0.48 miles. This means that the algorithm ensured that all own ships had a minimum separation distance of 2.6L

3.2 Crossing situation

When two ships' tracks cross each other, the own ship should maneuver as a stand-on ship or a give-way ship depending on the relative positions of the two ships. The scenario is set to maneuver only the give-way ship. Figure 7 shows the

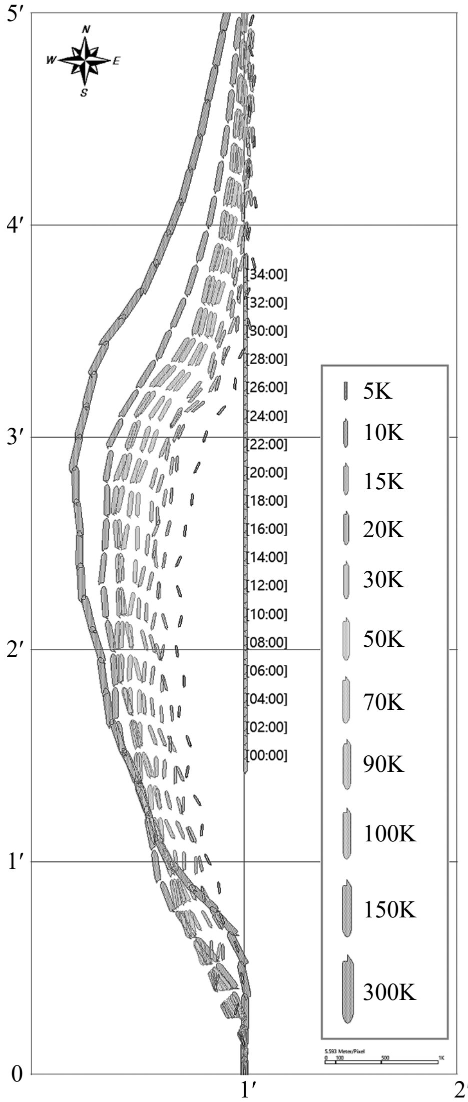

Fig. 9. Collision avoid track of overtaking situation

Table 4. Complex situation scenario configuration

	Situation	Initial course
Own ship	Own ship	000°
Other ship A	Overtaking	000°
Other ship B	Head-on	180°
Other ship C	Crossing	225°

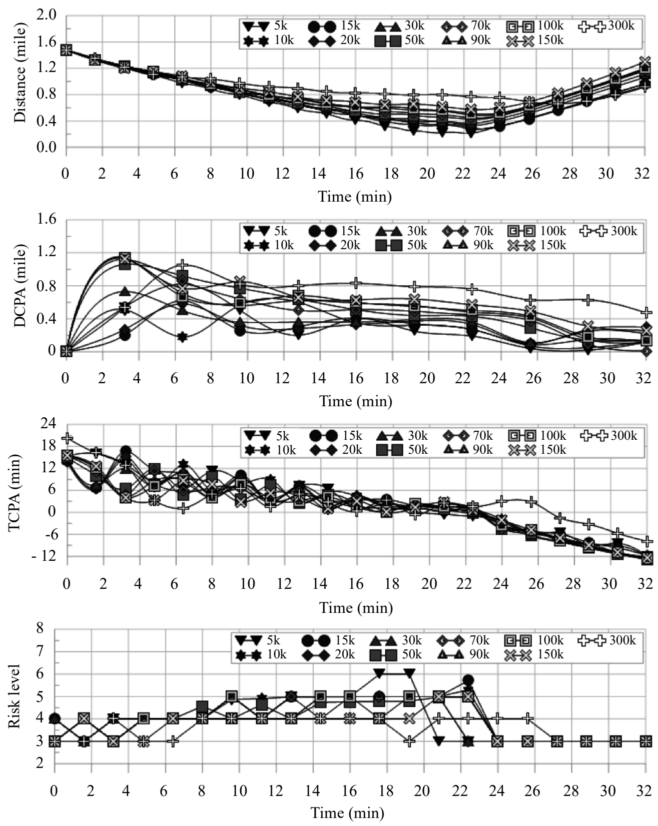

Fig. 10. Distance, DCPA, TCPA, risk changes of overtaking situation

simulation track for each target ship in the crossing situation, and Figure 8 shows the distance, DCPA, TCPA, and risk level changes depending on the elapsed simulation time for the other ship.

As the collision avoidance operation was performed, the DCPA began to increase after approximately 13 min, and the DCPA was at its minimum from 22 to 24 min after the start of the operation, depending on the size of the own ship in Table 3. It was confirmed that the DCPA decreased to a certain level by gradually performing a return operation over time.

The minimum separation distance was determined to be approximately 0.10–0.15 miles. Thus, the algorithm ensured that all own ships had a minimum separation distance of 0.8L.

3.3 Overtaking situation

When one ship overtakes another, there is no rule to decide the directions that the overtaking and overtaken ships must take, and it is safe to overtake in any direction in the open sea.

Generally, however, starboard side steering is preferred when the overtaking ship performs forward steering or engine reverse steering to avoid obstacles ahead. There is a risk of driving the overtaken ship to the left of the route in a narrow sea channel when the overtaking ship passes on the starboard side; therefore, in the current study, port side overtaking was used to determine the collision avoidance algorithm. Figure 9 shows the simulation track for each target ship in the overtaking situation, and Figure 10 shows the distance, DCPA, TCPA, and risk level changes according to the elapsed simulation time for the other ship in Table 3.

3.4 Complex Situation

Simulation scenarios in which the COLREGS are applied in complex ways are shown in Table 4.

Figure 11 shows the simulation track for each target ship in the complex situation, and Figures 12–15 show the distance,

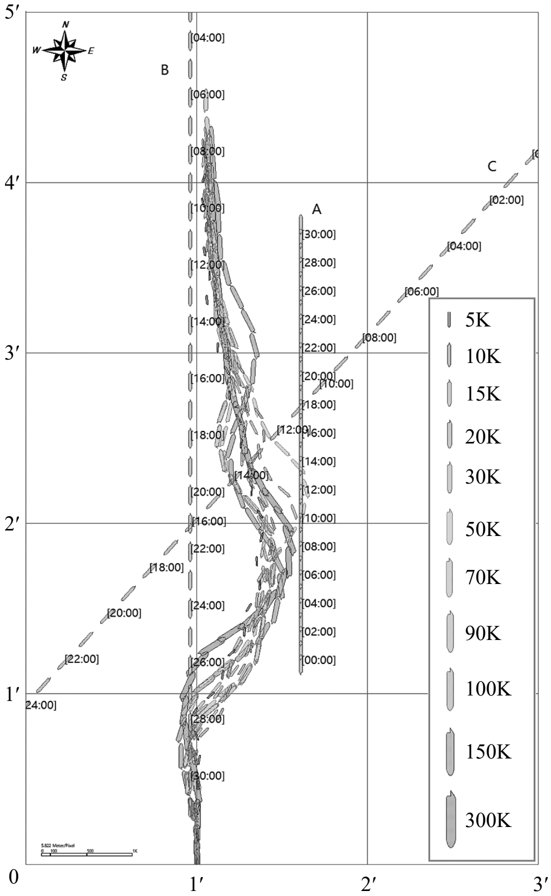

Fig. 11. Collision avoid track of complex situation

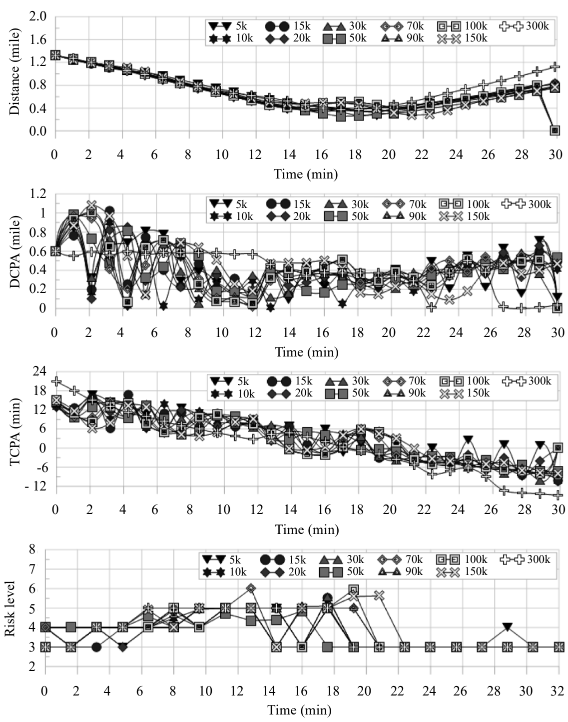

Fig. 12. Distance, DCPA, TCPA, risk changes of complex situation – Ship A

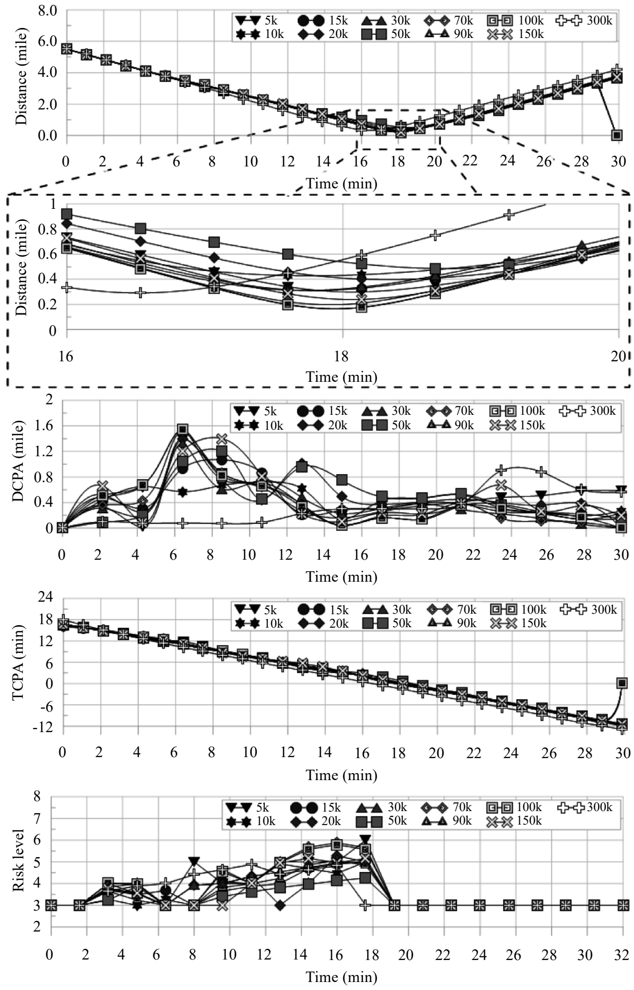

Fig. 13. Distance, DCPA, TCPA, risk changes of complex situation – Ship B

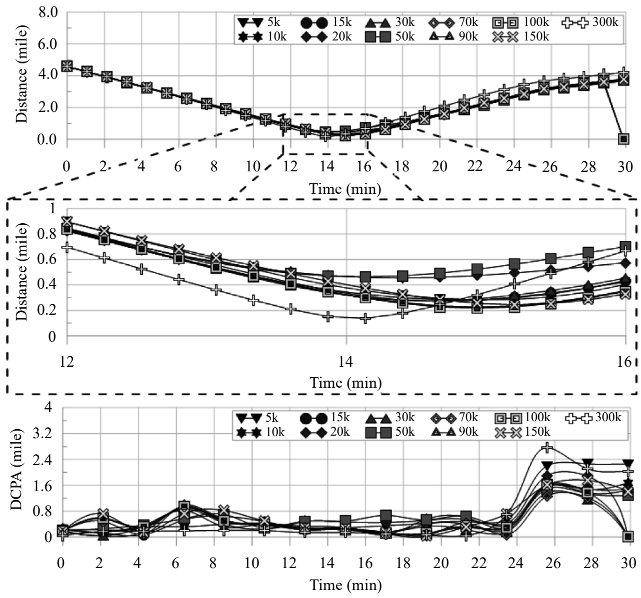

Fig. 14. Distance, DCPA changes of complex situation – Ship C

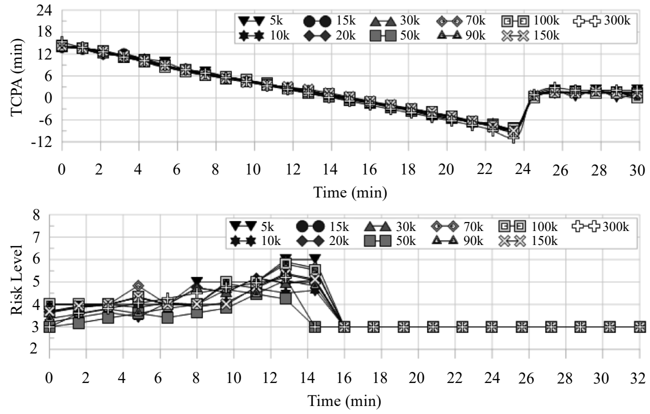

Fig. 15. TCPA, risk changes of complex situation – Ship C

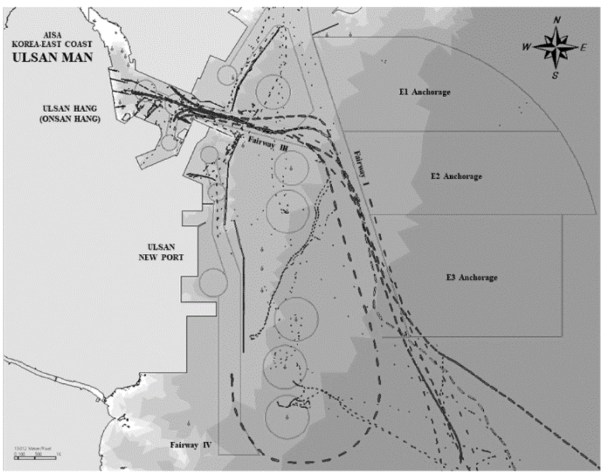

Fig. 16. Result of real maritime traffic collision avoidance simulation

DCPA, TCPA, and risk level changes depending on the elapsed simulation time for the other ships: A (Figure 12), B (Figure 13), and C (Figures 14 and 15).

At the beginning of the simulation, the DCPA of the other ship A was 0.6 miles, and it was possible to navigate with a separation distance of approximately 3.3L or more; however, it was confirmed that the DCPA was decreased by the course change to the starboard side that was performed to avoid the other ships B and C. The closest distance after 16–22 min was expected to be approximately 1.6L (0.3 to 0.4 miles) depending on the size of the own ship.

The closest to the B ship was 0.15~0.5 miles (0.8L) after 16–20 min, and the closest to the C ship was 0.15–0.45 miles (0.8L) after 12–16 min.

3.5 Experiments real maritime traffic condition (using past AIS Data)

The simulation of the actual maritime traffic environment was performed for the Ulsan Port, which is known as the largest industrial support port in Korea, where more than 80% of processed cargo is liquid cargo. The narrowest fairway in Ulsan Port, Fairway No. 3, was used in the model.

To model the maritime traffic environment, historical automatic identification system (AIS) data were used; it consisted of the highest volume of maritime traffic during seven days in 2019. Among these seven days, traffic conditions between 08:00 and 09:00 h were modeled representing the highest maritime traffic congestion time of Fairway No. 3.

Maritime traffic congestion is an indicator that expresses the actual maritime traffic as a percentage of the maritime traffic capacity of a fairway, and it is often used as a simple congestion status indicator.

The own ship was selected as a 50,000 dwt class tanker that passes through Fairway No. 3. As a result, a total of six ships approached within the distance (R_{nm}) where a near-miss occurred, but they all arrived at their destination without collision. There were 56 vessels in the vicinity, and the simulation was performed for 60 min. Figure 16 shows the simulation result.

IV. CONCLUSIONS

In this study, collision avoidance algorithms were developed, applied, and validated based on the characteristics of the Korean coastal region and the consciousness of the ship operators.

In order to verify the developed algorithm, 11 ships were with sizes ranging from 5,000 dwt to 300,000 dwt were modeled. The COLREGS were applied, and collisions were avoided in head-on, crossing, overtaking, and complex situations.

In addition, a simulation was conducted which showed that collisions could be avoided, even in a situation involving ship traffic in a real waterway using historical AIS data. Other ships approached at a distance less than the distance (R_{nm}) where a near-miss occurred. This algorithm needs to be optimized by studies applying it in areas involving heavy traffic and narrow waterways, such as a busy port.

In this study, the collision avoidance algorithm was developed by selecting the own ship as a tanker. However, the risk of the PARK model depends on internal factors relating to the type of own ship. This algorithm therefore needs to be studied for various types of ship.

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REFERENCES

Abdelaal, M. and S. Schön (2020). Predictive path following and collision avoidance of autonomous connected vehicles. Algorithms 13(3), 52.

Anglo-Eastern (2010). Guideline for Collision Avoidance, Anglo-Eastern Ship Management; Hongkong

Dietvorst, B. J., J. P. Simmons and C. Massey (2015). Algorithm aversion:

People erroneously avoid algorithms after seeing them err. Journal of Experimental Psychology: General 144(1), 114.

Fang, M. C., K. Y. Tsai and C. C. Fang (2019). The effect of hydro-meteorology on ship collision avoidance in heavy traffic areas with a simplified simulation model. Journal of Marine Science and Technology 27(3), 235-245.

Heo, T. Y., Y. S. Park and J. S. Kim (2012). A study on the development of marine traffic risk model for mariners. Journal of Korean Society of Transportation 30(5), 91-100.

Hu, Y., X. Meng, Q. Zhang and G. K. Park (2020). A real-time collision avoidance system for autonomous surface vessel using fuzzy logic. IEEE Access 8, 108835-108846.

IMO (2018). Framework for the regulatory scoping exercise, MSC 99/WP.9

Inoue, K. (2000). Evaluation method of ship-handling difficulty for navigation in restricted and congested waterways. The Journal of Navigation 53(1), 167-180.

Kang, Y. T., W. J. Chen, D. Q. Zhu, J. H. Wang and Q. M. Xie (2018). Collision avoidance path planning for ships by particle swarm optimization. Journal of Marine Science and Technology 26(6), 777-786.

Korea Evaluation Institute of Industrial Technology (2018). KEIT PD Issue report April 18-4, 58-75.

Kim, J. S., Y. S. Park, T. Y. Heo, J. Y. Jeong and J. S. Park (2011). A study on the development of basic model for marine traffic assessment considering the encounter type between vessels. Journal of the Korean Society of Marine Environment & Safety 17(3), 227-233.

Lee, M. C., C. Y. Nieh, H. C. Kuo and J. C. Huang (2019). An automatic collision avoidance and route generating algorithm for ships based on field model. Journal of Marine Science and Technology 27(2), 101-113.

Liu, C., Q. Mao, X. Chu and S. Xie (2019). An improved A-star algorithm considering water current, traffic separation and berthing for vessel path planning. Applied Sciences 9(6), 1057.

Ministry of Land, Transport and Maritime Affairs (2011). Maritime traffic safety assessment model technology development. Final Report.

Nguyen, X. T. (2014). A study on the development of real time supporting system (RTSS) for VTS officers. Korea Maritime and Ocean University, PhD. Dissertation, 60-65.

Nguyen, T. X., Y. S. Park, M. V. Smith, V. Aydogdu and C. H. Jung (2015). A comparison of ES and PARK maritime traffic risk assessment models in a Korean waterway. Journal of the Korean Society of Marine Environment & Safety 21(3), 246-252.

Park, Y. S., J. Y. Jeong and J. S. Kim (2010). A study on the minimum safety distance between navigation vessels based on vessel operator's safety consciousness. Journal of the Korean Society of Marine Environment & Safety 16(4), 401-406.

Park, S. W. (2015). A basic study on guideline to proper control time on each ship's encounter situation. Korea Maritime and Ocean University (Doctoral dissertation, Master thesis).

Park, Y., J. Park, D. Shin, M. Lee and S. Park (2017). Application of potential assessment of risk (PARK) model in Korea waterways. Journal of International Maritime Safety, Environmental Affairs and Shipping 1(1), 1-10.

Park, Y. S., J. S. Kim and V. Aydogdu (2013). A study on the development the maritime safety assessment model in Korea waterway. Journal of Korean Navigation and Port Research 37(6), 567-574.

Park, Y. S. and Y. S. Lee (2008). Development of efficient training materials through risk assessment by types of vessel encounters using training ships. Journal of Korean Navigation and Port Research 32(2), 103-108.

Shaw, H. J. and F. M. Tzu (2019). The strategy of energy saving for smart shipping. Advances in Technology Innovation 4(3), 165.

Shih, C. H., P. H. Huang, S. Yamamura and C. Y. Chen (2012). Design optimal control of ship maneuver patterns for collision avoidance: a review. Journal of Marine Science and Technology 20(2), 111-121.

Son, N. S., Y. Furukawa, S. Y. Kim and K. Kijima (2009). Study on the collision avoidance algorithm against multiple traffic ships using changeable action space searching method. Journal of the Korean Society for Marine Environmental Engineering 12(1), 15-22.

Tsai, C. C., J. R. Chang and C. L. Chen (2017). Maneuverability - based critical time for preventing close-quarters situations. Journal of Marine Science and Technology 25(3), 249-258.

Tsou, M. C. and C. K. Hsueh (2010). The study of ship collision avoidance route planning by ant colony algorithm. Journal of Marine Science and Technology 18(5), 746-756.

Woerner, K., M. R. Benjamin, M. Novitzky and J. J. Leonard (2019). Quantifying protocol evaluation for autonomous collision avoidance. Autonomous Robots 43(4), 967-991.

Woo, J. and N. Kim (2020). Collision avoidance for an unmanned surface vehicle using deep reinforcement learning. Ocean Engineering, 199, 107001.

Yang, L., Z. Xing and T. Shi (2020). Risk assessment of ship navigation collision in inland waterway transportation system based on Bayesian method. MS&E 780(6), 062018.

Yasukawa, H. and Y. Yoshimura (2015). Introduction of MMG standard method for ship maneuvering predictions. Journal of Marine Science and Technology 20(1), 37-52.

Zhao, L., M. I. Roh and S. J. Lee (2019). Control method for path following and collision avoidance of autonomous ship based on deep reinforcement learning. Journal of Marine Science and Technology 27(4), 293-310.