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Economic and Environmental Performance Improvements Based on S-100 Hydrographic Information

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In this study, we empirically analyzed the impact of dynamic hydrographic information provided by the next-generation hydrographic standard S-100 on the economic efficiency of maritime transport and environmental protection. Unlike the existing S-57 standard, the S-100 standard offers dynamic hydrographic information, including real-time changes in tides, currents, and weather, which can improve the safety and efficiency of ship operations. Using the Full Mission Shipping Simulator for Mokpo–Jeju routes, we quantitatively assessed the economic effects of S-111 surface currents with the S-100 Electronic Chart Display and Information System and S-101 Electronic Navigational Charts on fuel consumption, sailing distance, and travel time, as well as the environmental benefits, such as reductions in air pollutant emissions.

1. Introduction

1.1 Research background

Vettor and Soares(1) defined that maritime trades are strictly dependent on the environmental conditions that the vessels experience during sailing. Park *et al.*(2) revealed that the International Hydrographic Organization (IHO) has established an S-100 implementation strategy and, in agreement with the International Maritime Organization (IMO), has consented to the phased mandatory adoption of S-101 ENCs and S-100 ECDIS. S-100 ECDIS, including information on S-101 ENCs and S-10X hydrographic data, will be mandatory on new ships starting from 2026 to 2029.

In line with industry trends, S-101 ENCs and S-10X hydrographic data have been developed for ships engaged in international navigation in Korea, and according to the study by Park *et al.*,(2) quality verification was conducted in actual operational environments. Additionally, a test bed has been established to verify the technology, promote international technical cooperation,

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and support the development of digital hydrographic standards and product specifications by the IHO.

The purpose of this study is to quantitatively analyze the economic and environmental benefits of using dynamic hydrographic information based on the S-100 standard, currently under development in Korea. Through this analysis, the potential impact of the S-100 standard has been evaluated. In particular, we focus on whether the introduction of the S-100 standard can enhance the operational efficiency of the maritime transport industry and contribute to sustainable environmental management.

1.2 Digital maritime information based on S-100 standard

The IHO developed the S-100 standard as a universal hydrographic data model to cater to future demands for digital products and services that can enhance the interoperability of marine information systems and integrate various marine data. While the existing S-57 standard is based on static data, the S-100 standard can process dynamic hydrographic information, including real-time updates on wave currents and weather conditions.

According to Kang *et al.*,(3) the technological advances brought about by the S-100 standard play an important role in improving the safety and efficiency of maritime transportation and enable the real-time utilization of various marine information. Table 1 lists S-100-based product standards, including products with dynamic channel information, such as S-102, S-104, and S-111.

1.3 Literature review

Various maritime international organizations, including the IHO, expect the S-100 environment to help reduce marine accidents and lower carbon emissions. However, quantitative studies that measure or predict its effects are still lacking.

Table 1
Product specifications based on S-100.

S-10X number	Product specification
S-100	IHO Universal Hydrographic Data Model
S-101	Electronic Navigational Chart (ENC)
S-102	Bathymetric Surface
S-104	Water Level Information for Surface Navigation
S-111	Surface Currents
S-121	Maritime Limits and Boundaries
S-122	Marine Protected Areas
S-123	Marine Radio Services
S-124	Navigational Warnings
S-125	Marine Navigational Services
S-126	Marine Physical Environment
S-127	Marine Traffic Management
S-128	Catalogue of Nautical Products
S-129	Under Keel Clearance Management

In 2024, Park *et al.*(2) proposed new routes available to passenger ferries operating in South Korea, verifying reduced voyage times. Their findings indicate that if shipping companies apply the seven alternative and improved routes suggested in this study, based on next-generation hydrographic information, there could be an annual fuel cost savings of approximately 1 billion won from a long-term perspective.

Choi *et al.*(4) equipped an S-100 ECDIS prototype with a ship behavior prediction algorithm to forecast ship movement as a rudder is used during navigation. They predicted the ship's position at intervals from 10 to 60 s in the future. Through user satisfaction surveys, they assessed how the S-100 ECDIS and ship behavior prediction model can reduce accidents.

Fang and Lin(5) conducted an economic analysis by comparing optimized routes for estimated time of arrival (ETA) and fuel oil consumption (FOC), although they did not incorporate weather conditions into their route inferences.

Lu *et al.*(6) analyzed the tracks of vessels traveling between the port of LA in the United States and the Chiba port in Japan, segmenting the route into six stages and comparing the predicted energy efficiency operational index (EEO) with the measured EEO. Their study improved Kwon's method, allowing for diverse route evaluations aimed at maximizing safety, minimizing FOC, and optimizing voyage time.

Vettor and Soares(1) conducted a simulation study on route optimization for container ships, incorporating weather information at the ETA optimization stage to evaluate FOC. Similarly, Zhao *et al.*(7) inferred optimal routes on the basis of sea current information and conducted an economic evaluation via simulation. Although this study used Pareto optimal solutions, it did not account for the navigator's view or other vessels, and the *FOC* calculation model had limitations in accuracy.

Ageliki and Nikos(8) used Matlab for a ship routing study, with wave height as the main factor in assessing safety criteria rather than sea currents or wind. Pacheco presented a method using a geographic information system (GIS) for optimal route selection, adjusting from the shortest route and implementing a wave prediction model to estimate the vessel's responses (roll, pitch, and direct motion) under various maritime conditions.

Bentin *et al.*(9) investigated the potential fuel savings of using a wind-assisted ship propulsion system within a weather routing optimization tool, comparing its effectiveness to traditional diesel propulsion systems.

Table 2 shows the routing services and decision support systems in service around the world. The environmental information currently being used by major weather routing services based on the following three numerical forecast models is provided.

(1) Global Forecast System (GFS)
- Resolution: approximately 25–50 km grid
- Advantages: It offers global predictions and is suitable for large-scale marine operations.

(2) European Centre for Medium-Range Weather Forecasts (ECMWF)
- Resolution: approximately 9–18 km grid
- Advantages: It provides high accuracy and is preferred in Europe and around the world.

Table 2
Exemplary compilation of routing service or decision support systems (Hinnenthal and Clauss(10) and Lu *et al.*(6)).

Service provider	Installed location	Service, system	Weather forecast	Route planning	Route optimization	Ship monitoring	Data recording
Aerospace and Marine International (USA)	Ashore	Weather 3000, internet service, maps displaying fleet and weather information	X				X
Finish Meteorological Institute (Finland)	Ashore	Weather and routing advice for Baltic sea	X	X			
Fleetweather (USA)	Ashore	Meteorological consultancy	X	X			X
Metworks Ltd. (UK)	Ashore	Meteorological consultancy	X	X			
Applied Weather Technology (USA)	On-board	BonVoyage system	X	X			
Euronav(UK)	On-board	seaPro, software or fully integrated bridge system	X	X			X
Germanischer Lloyd, Amarcon B.V. (Germany, Netherlands)	On-board	SRAS (Shipboard Routing Assistance System)	X	X		X	
Transas (UK)	On-board	Ship guard SSAS, software or integrated to bridge system	X	X		X	X
Norwegian met office, C-Map (Norway, Italy)	On-board	C-STAR	X	X			
US Navy (USA)	On-board	STARS	X	X	X	X	
SMART Navigation (ROK)	Ashore, On-board		X	X	X	X	X
Meteo Consult (Netherlands)	On-board	SPOS (Ship Performance Optimization System)	X	X	X	X	
Oceanweather Inc., Ocean Systems Inc. (USA)	On-board	VOSS (Vessel Optimization and Safety System)	X	X	X	X	
Weather News International, Oceanwaves (USA, Japan)	Ashore, On-board	VPS (Voyage Planning System), routing and optimization software	X	X	X		
Swedish Met and Hydrology Institute (Sweden)	Ashore, On-board	Seaware routing, routing plus and EnRoute live	X	X		X	
Deutscher Wetterdienst (Germany)	Ashore, On-board	MetMaster, Metferry, routing system, advice on demand	X	X	X		
Weather Routing Inc. (USA)	Ashore	Route advice, Dolphin navigation program combined with a web-based interactive site	X	X			

(3) Icosahedral Nonhydrostatic Model (ICON)

- Resolution: approximately 13–40 km grid
- Advantages: It is the latest model that provides global and regional predictions with various resolutions.

As the size of the grid is large, small grid data are important in ship operation because the predicted environmental information must be interpolated or averaged.

2. Research Methods

In this paper, ship control simulation was utilized to quantitatively evaluate the economic and environmental improvement effects of using S-100 dynamic hydrographic information. Considering the ships in the target sea area, each ship was modeled, the legal route was designed, and the scenario was set up by calculating dynamic hydrographic information. As the ship operates for a long time, it has set a target for ferries between Mokpo and Jeju with a long operating route to control various variables and be heavily affected by dynamic hydrographic information.

2.1 Major dynamic hydrographic information for evaluation

Factors affecting ship operation are diverse, such as human, mechanical, and environmental factors, but there are many variables to reflect all of them in the evaluation. Therefore, only environmental factors corresponding to dynamic hydrographic information were reviewed and reflected according to the purpose of the study.

According to Harbour Approach Channels Design Guidelines (2014) published by the Permanent International Association of Navigation Congress, environmental factors affecting ship operations include wind, waves, municipalities, tides, tidal and river flows, seabed ground conditions, coastal processes, and ice, as shown in Table 3.. Among these, tide, current, and river flows are the key dynamic hydrographic factors that can be reliably predicted and incorporated into navigation plan development. In this paper, surface currents and tides were selected for evaluation in order to evaluate the dynamic hydrographic information that was not evaluated in previous studies.

2.2 Target area for evaluation

Table 4 shows the results of analyzing the 1st and 2nd trading ports with the largest number of ships entering and leaving a port by sea area based on the analysis of the data from the Ministry of Oceans and Fisheries' Maritime and Port Logistics Information System (PORT-MIS), and Table 5 shows the results of analyzing the current speed, tidal current, and occurrence

Table 3
Factors affecting ship navigation.

Factors affecting ship navigation	Predictable dynamic hydrographic information	Assessment-reflected dynamic hydrographic information
Winds	–	–
Waves	–	–
Visibility	–	–
Tides	○	–
Surface currents	○	◎
Geotechnical conditions	–	–
Coastal processes	–	–
Ice	–	–

Table 4
Results of analyzing ship arrivals and departures.

Classification		Total (unit: vessels)
West Coast	1st	Incheon (29689)
	2nd	Mokpo (17324)
South Coast	1st	Busan (88015)
	2nd	Kwangyang (46797)
East Coast	1st	Ulsan (48658)
	2nd	Pohang (11180)

Source: PORT-MIS (2022.01.01–2022.12.31), https://new.portmis.go.kr

Table 5
Results of analyzing maximum flow velocity and higher high water level.

			higher high water level		
			Maximum flow velocity (knots)	Tidal difference (cm)	Date of occurrence
Port	West Coast	Incheon	1.93	953	2022.08.15.
		Mokpo	3.44	460	2022.07.16.
	South Coast	Pusan	0.8	175	2022.09.06.
		Kwang-yang	1.45	377	2022.07.15.
	East Coast	Ulsan	0.82	24	2022.09.06.
		Pohang	–	67	2022.09.06

Source: Korea Hydrographic and Oceanographic Agency Ocean Data in Grid Framework (2022.01.01–2022.12.31), http://www.khoa.go.kr/oceangrid/khoa/intro.do

date when high tide occurs by the trading port. Mokpo Port was finally selected as the target sea area by comprehensively considering ports with large changes in the number of ships entering and leaving a port and surface currents. Mokpo Port's ship arrivals and departures were confirmed to be 17324 vessels, with a maximum flow velocity of 3.44 knots and a tidal difference of 460 cm.

2.3 Target ship for evaluation

By analyzing the navigation chart of ships using Mokpo Port and the area to be evaluated, after identifying ships that regularly pass through the relevant sea area, ships that are expected to be most affected by the current were identified when the departure and destination were the same, but the route was changed by the current, or when the ship was operating. When analyzing a ship operational track, a month-long navigation chart, including the day when high tide occurred, was analyzed.

As a result of analyzing the ship's operational track for a month in July 2022, the month when the high tide occurred at Mokpo Port, it was confirmed that ferries that regularly operate between Mokpo and Jeju had the same origin and destination, but the route was partially changed as shown in Fig. 1 near Jindo Island.

In the case of ferries operating the Mokpo–Jeju route, the speed must be maintained at least 20 knots to match the operating distance (170 km) and operating time (4 h and 30 min) as shown in Table 6. However, Mokpo's surface currents exceeding 6 knots occur in maximum flood and

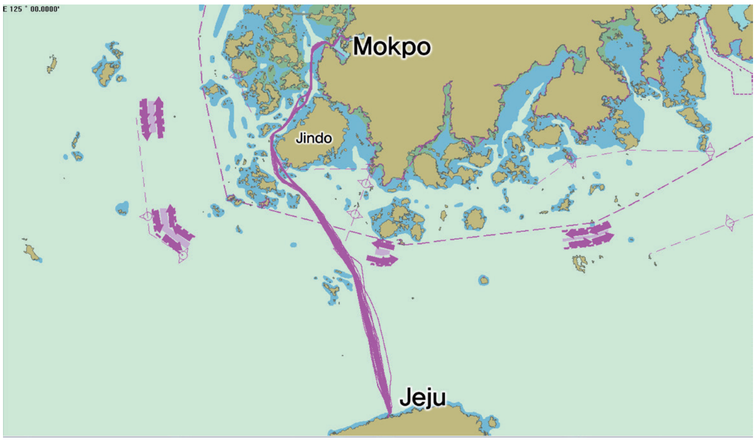

Fig. 1. (Color online) Vessel track chart for Mokpo to Jeju.

Table 6
Ferry schedule and sailing distance (Mokpo to Jeju).

Vessel	Queen Jenuvia		Queen Marry 2	
Port	Mokpo–Jeju	Jeju–Mokpo	Mokpo–Jeju	Jeju–Mokpo
Departure	01:00	13:40	09:00	17:00
Arrival	05:30	18:10	13:30	21:30
Sailing time	04:30	04:30	04:30	04:30
Sailing distance	170 km			
Target speed	20.4 knots			

maximum ebb situations, so it was judged that the dynamic hydrographic information would have a significant impact on ship operation, and passenger ships were selected as the target ships.

The ferry specifications used in the ship simulator for the evaluation are 164.0 m in full length, 25.6 m in line width, and 5.5 m in draft, and are equipped with two 13680 kW engines that can operate at a maximum of 25.0 knots.

2.4 S-111 surface currents

The Korea Hydrographic and Oceanographic Agency of the Republic of Korea has been operating stations for measuring surface currents nationwide since 1957,(11) judging that surface currents are a key factor in the operation of ships. The primary objective of this study is to compare the current S-57 ECDIS with the S-100 ECDIS in the context of ship navigation, focusing on their potential contributions to economic efficiency and environmental sustainability. First, the data on the S-111 surface currents in 2023 with 3 km resolution were analyzed to apply to the target area.

When evaluating the economic feasibility and environmental improvement effect of the Mokpo–Jeju route, the data from June 6, 2023, the day when the strongest tide occurred, were used. The current conditions before and after the peak tide were adjusted to reflect the actual operational schedule of the passenger ship. Figure 2 shows the point and flow velocity at which the highest flow rate occurred between Mokpo and Jeju. During departure from Mokpo Port under flood tide conditions, the vessel must operate at full speed (full ahead) to meet the scheduled entry time. Consequently, this case was deemed unsuitable for assessing the effects of surface currents and was excluded from the evaluation. Instead, the assessment was conducted under maximum ebb tide conditions.

2.5 Various environmental conditions

Natural environmental conditions other than S-111 surface currents were applied by analyzing the natural environment for each target area as shown in Table 7.

2.6 Evaluation scenario

Under simulation conditions where wind speed, wave height, flow velocity, and direction change in real time, a final scenario for each target area was set up to compare the existing traditional method of S-57 ECDIS with the new S-100 ECDIS.

In the Mokpo–Jeju route evaluation, a scenario was prepared as shown in Table 8 to compare engine usage when a navigation plan was established and operated using the existing hydrographic nautical charts and S-57 and when a navigation plan was established and operated using the dynamic hydrographic information provided by S-100.

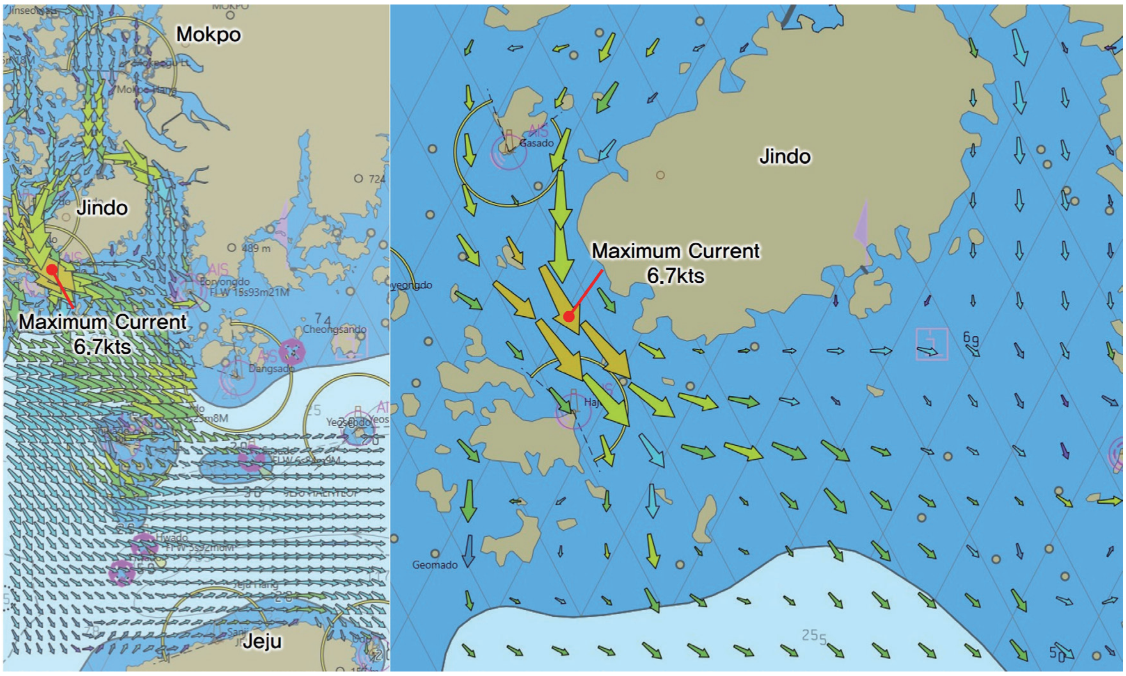

Fig. 2. (Color online) S-111 maximum surface currents.

Table 7
Criteria for setting natural environmental conditions.

Factor	Setting criterion
Wind speed	Average wind speed over the past 30 years (1993–2022)
Wind direction	Wind rose chart over the past 30 years (1993–2022)
Wave height	Average significant wave height over the past 5 years (2018–2022)
Wave direction	Applied the same as wind

Table 8
Evaluation scenario.

Item		Detail
Vessel type		Passenger ship
Route		Mokpo–Jeju (170 km)
Actual time of departure (ATD)		01:00
Estimated time of arrival (ETA)		05:30
Case B1		S-57
Case B2		S-100
Current		Applied tidal currents before and after, including the maximum ebb current
Wind	Speed	3.6 m/s
	Direction	N
Wave	Height	0.2 m
	Direction	N

The starting and ending points of the Mokpo–Jeju route are from the Mokpo port pilot station to the Jeju port pilot station. The operating regulations existing in the relevant section, such as actual navigation, were checked and reflected when establishing the navigation plan.

There is a speed limit section between the Mokpo port ferry and the Jeju port ferry pier in accordance with the "Details of Port Facility Operation Regulations" and "Notification on Safety of Navigation in the Sea Near Mokpo," and the operation of the section is set to comply with the speed limit. For simulation evaluation, the operating routes applied to the Full Mission Shipping Simulator (FMSS) are shown in Fig. 3.

3. Economic and Environmental Performance Evaluations

3.1 Economic evaluation

FOC was calculated by analyzing engine usage after conducting Case B1 and Case B2 simulations to evaluate the economic improvement effect of providing dynamic hydrographic information when the navigation distance is the same on the Mokpo–Jeju route and the expected arrival time is set.

$$P \times SFOC = FOC \tag{1}$$

In Eq. (1), the engine usage (P) of the ship has a deep correlation with *FOC*, and the estimated *FOC* according to the engine usage can be calculated. *FOC* was calculated by applying

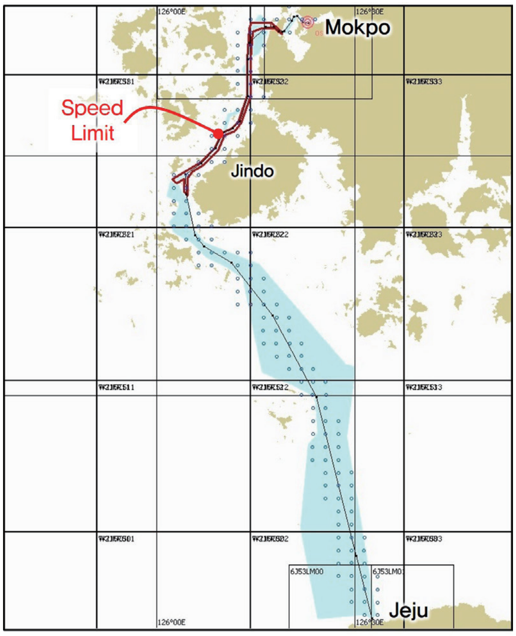

Fig. 3. (Color online) Mokpo to Jeju route plan with S-111 surface currents.

177 g/kWh, the specific fuel oil consumption (*SFOC*) of the 5-8S46MC-C8 engine, which is a product similar to the engine specifications of the target ship among MAN B&W's engines. Table 9 shows the results of calculating the *FOC* per hour of the target ship by applying the calculation formula.

As a result of the evaluation of the Mokpo–Jeju route, the Case B1 vessel operator using S-57 was operating at full speed after departure from Mokpo Port to meet the arrival time of the Jeju port ferry, and entered the port by lowering the engine below half-speed about 13 km before the Jeju port ferry. The total sailing time was 4 h and 24 min, the average revolutions per minute (RPM) was 102.3, and the estimated *FOC* according to the *FOC* calculation formula was 13.02 tons.

In the case of Case B2, where ship operators used S-100, unlike Case B1, which maintained full-speed sailing after departure, it was possible to predict changes in the speed of the ship based on flow rate and direction by referring to real-time surface current data provided by S-111. Consequently, the vessel was able to adjust its RPM according to the ETA and reach the Jeju Port pilot station as planned.

The total navigation time of Case B2 was analyzed as 4 h and 26 min, the average RPM was 100.3, and the expected *FOC* was analyzed as 11.12 tons, indicating that *FOC* during operation was reduced by about 14.6% using S-100 dynamic hydrographic information.

As a result of the evaluation of the Mokpo–Jeju route, the Case B1 vessel operator using S-57 was operating at full speed after departure from Mokpo Port to meet the arrival time. Table 10 shows the summary of Case B1 and Case B2 evaluation results, and a *FOC* map on the flight route was prepared using the engine usage recorded every second as shown in Fig. 4.

Table 9
Hourly *FOC* based on RPM.

RPM	kW	MCR* (%)	*FOC* (g)
128	13680	100.00	2421360
116	10521	76.91	1862293
105	7905	57.79	1399219
90	5035	36.81	891271
77	3213	23.49	568779
60	1573	11.50	278442
52	1060	7.75	187666
38	439	3.21	77645
25	139	1.02	24645
11	18	0.13	3232
0	–	0.00	–

*MCR: Maximum Continuous Rating

Table 10
Comparison of evaluation results based on S-57 and S-100 usage.

Category	Case B1	Case B2
	S-57	S-100
Vessel	Passenger ship	Passenger ship
Dynamic hydrographic information	–	S-111
Sailing distance	170 km	170 km
Sailing time	04 h 24 m	04 h 26 m
Average RPM	102.3	100.3
Average speed	STW 19.4 knots SOG* 20.7 knots	STW 19.0 knots SOG 20.5 knots
FOC	13.02 tons	11.12 tons
Vessel	Passenger ship	Passenger ship
Dynamic hydrographic information	–	S-111
Sailing distance	170km	170km

*SOG: Speed over ground; STW: Speed through water

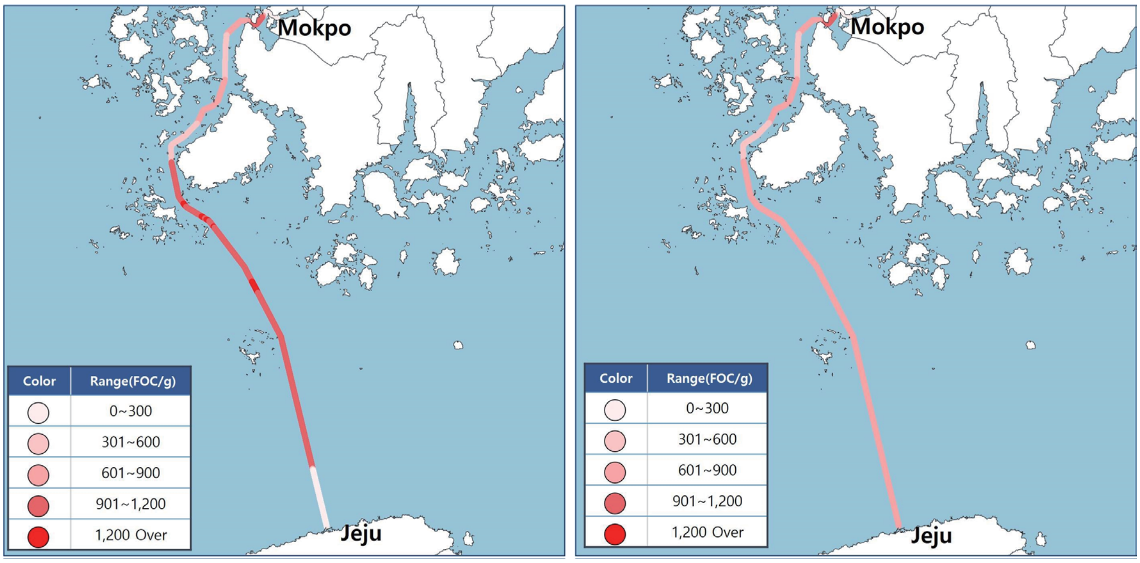

Fig. 4. (Color online) *FOC* map.

3.2 Environmental evaluation

Using the *FOC* derived from the economic evaluation of the Mokpo–Jeju route, we quantitatively evaluated the effect of improving air pollution when using S-100.

$$FOC \times EF = EA \tag{2}$$

In Eq. (2), *FOC* is fuel oil consumption, *EF* is emission factor, and *EA* is emission amount. The emission amounts of air pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), and methane (CH_4), were calculated using Eq. (2) as proposed by the IMO.

The review was based on the commonly used heavy fuel oil (HFO) among the air pollutant emissions by fuel presented in the IMO GHG Study 2020 Table 53.(12) The emission of air pollutants generated per ton of HFO is shown in Table 11. For emissions presented as a range, such as NO_x, SO_x, and PM, the median value was calculated by applying it to the relational expression Eq. (2).

As a result of the calculation, we found that air pollutant emissions were more effectively reduced when a navigation plan was established using dynamic S-100 hydrographic information than when a navigation plan was established on the basis of S-57, as shown in Table 12.

The amount of air pollutant emissions is generally proportional to FOC. It can be seen that Case B1, which has advanced exclusively from outside the speed limit area, discharged more air pollutants than Case B2. Therefore, it is expected that the S-100-based navigation plan will improve not only the economic feasibility on the route but also the environment by reducing air pollutant emissions.

Table 11
Emission of air pollutants generated per ton of HFO.

Fuel	Pollutant	Emission factor
HFO	CO_2	3114
	NO_x	75.9–78.61
	SO_x	44.63–50.83
	PM	6.96–7.53
	CH_4	0.05

Table 12
Comparison of air pollutant emissions.

Pollutant	Case B1 (S-57)	Case B2 (S-100)
CO_2	40.54	34.64
NO_x	1.006	0.859
SO_x	0.621	0.531
PM	0.094	0.081
CH_4	0.00065	0.00056

4. Conclusion

The major issues of the global maritime industry since 2020 are eco-friendliness and decarbonization. IMO has promoted several measures to improve vessel efficiency and reduce *FOC* and emissions.

In this study, it is expected that up to 14.6% of fuel reduction will be possible as a result of planning a route using hydrographic information that can be used directly by ship operators in the S-100 ECDIS and verifying it using an FMSS-scale simulator. Since the consumption of ship fuel means the emission of environmental pollutants, environmental pollution will also be reduced as much as the fuel is reduced.

Most accidents are recorded in coastal or congested areas,(13,14) sometimes due to a lack of maneuverability,(15) resulting in grounding or collisions.(1) The information provided by S-57 ECDIS to ships is ENCs with a limited update cycle and a conservatively produced depth information. Sailors still have to review and plan many books and paper charts at the back-bridge stage when making navigation plans. The S-100 ECDIS and S-10X hydrographic information provide real-time environmental information and high-precision data with high resolution to support the safe operation of ships. As the completeness of the S-100 standard and product specification of digital hydrographic information increases, the importance of marine GIS software used for data production also increases. In recent years, as many studies on the quality evaluation of marine GIS software have been conducted, the quality of marine data is expected to increase.(16)

It is also possible to avoid dangerous situations or take countermeasures in advance by exchanging information between ships. Grounding and collision accidents, which account for the majority of marine accidents, are expected to significantly decrease from 2029, when the S-100 ECDIS mandate is fully applied.

5. Future Work

We conducted an analysis of the impact of S-100 hydrographic information on the ship's operating environment. In Park *et al.*'s study,(2) the S-104 tidal information for navigation was used to explore the alternative routes of passenger ships to simulate the operating distance and fuel reduction effect. In this study, the S-111 surface currents were used to simulate the effect of reducing fuel and carbon emissions by moving the same operating section with the ship's lower engine power than usual.

It is judged that the economic and environmental performance improvements due to S-100 hydrographic information have been sufficiently verified through simulation. While conducting preparatory work for this study, we carried out a case study on route optimization using S-111 information for a ferry traveling between land and islands. As a result, we received a response that the ship's ETA and ETD, which we calculated, were within the range that sailors could accept. In the next study, we plan to present guidelines by optimizing the ship's speed, RPM, and rudder control systems similar to those used in car navigation systems. We plan to measure how economically effective it is when operating according to the guidelines.

Acknowledgments

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