Fuel Saving in Coastal Areas
– a Case Study of the Oslo Fjord

Abstract
Fossil fuels such as marine diesel oil (MDO) account for a significant part of the shipping industry's total operating costs and have a certain negative impact on the environment. Maritime transport emits around 1000 million tonnes of CO_2 annually and is responsible for about 2.5% of global greenhouse gas emissions. To focus on fuel saving is therefore important for both economic and environmental reasons. It is indicative that ship owners are now using weather routeing to save fuel and reduce emissions, particularly for long passages. In coastal areas, navigation is limited by traffic rules. This study examines whether fuel consumption can be reduced with current routeing in confined coastal areas, in this case a relatively short voyage in the Oslo Fjord, Norway. An advanced bridge simulator is used, where different current fields from a high-resolution ocean model are implemented. The results reveal that if the voyage is conducted on a typical field with following currents, instead of a typical counter current field, the travel time will be reduced by 12% for a typical vessel with speed through water set to 16.7 knots. On following currents, the vessel speed can be reduced to 15.7 knots and the voyage is completed within the same time as if no currents are present. This implies approximately a 15% reduction in fuel consumption for the vessel tested. The results also reveal that fuel consumption can be reduced if the vessel is operated within most favourable or least unfavourable currents inside the main traffic lanes.

Keywords
Weather routeing · Fuel saving · Air Emissions · Ship operation · Currents in coastal areas · Experiments · Confined coastal areas

1 Introduction

Today, 70-90 per cent of goods are transported by sea (Stopford 2009; IMO 2014; UNCTAD 2016). Even though maritime transportation is generally considered environmentally friendly compared with other transportation types (Dalsøren et al. 2009), fuel is an essential cost in shipping operations and fuel combustion results in air emissions that have a significant impact on the environment, particularly in coastal areas (Corbett et al. 2007; Oeder et al. 2015). In addition, the impact of human activities such as the burning of fossil fuels further contributes towards climate change; phenomena like increasing sea-levels and more powerful storms are indicative of the new environmental paradigm (Watson et al 1996; Bode et al 2002; IMO 2014).

Fuel consumption accounts for up to 50-60% of the overall shipping operating costs, depending on the type of ship and service (Word Shipping Council 2008). Reduced fuel consumption can therefore bring down those costs significantly and decrease marine pollution levels in relation to air emissions.

Air emissions from ships represent a significant contribution to the global human-made CO_2 equivalent greenhouse gas (GHG) emissions, combining CO_2, N_2O and CH_4 (IMO 2014). According to the International Maritime Organisation (IMO), maritime transport emits around 1000 million tonnes of CO_2 annually and is responsible for 2.5% (IMO 2014) to 4-5% (Harrould-Kollilb 2008) of total GHG emissions. By 2050, the EU aims to reduce GHG emissions by 80% and shift 50% of road freight over 300 km in Europe to other transportation modes such as waterborne transport in order to achieve a more competitive, greener and resource-efficient transport system (European Commission 2011). Moreover, the local environment is especially impacted by air emissions of particulate matter (PM), NO_x and SO_x (Endresen et al. 2003; Corbett and Köhler 2003; Eyring et al. 2005; Oeder et al. 2015). IMO has established certain emission control areas (ECA) with more stringent controls on SO_x and NO_x emissions (IMO 2014). In the Baltic and North Seas the contribution of NO_2 from shipping contributes up to 83% of the total concentration of NO_2 near the surface. The corresponding percentage for SO_2 is up to 88% (Haglund et al. 2016).

Although previous studies state that GHG emissions could be reduced by 25-75% with known measures (Buhaug et al. 2009 and references therein), there is a gap between research and implementation of energy efficient shipping (Styhre and Winnes 2013). The ports operate on a "first come, first served" basis, which in turn leads to ships normally going full speed ahead and then laying at anchor while waiting to be served (Porathe et al. 2014). Studies conducted of short sea dry bulk shipping in the North and Baltic seas reveal that some ships spent more than 40% of their time in ports and that half of this lay time was not productive (Johnsen and Styhre 2015). If the ships are to adjust their speed according to the currents and other weather conditions, the ports have to change their practice accordingly and operate on a "just in time" basis (Bichou 2013). The increased complexity and volume of ship traffic are other challenging factors, especially in coastal areas. The North Sea is a region with high dense traffic with about 3000 ships sailing its waterways at any time (Aulinger et al. 2016) and the English Channel is the world's most congested sea passage (Porathe et al. 2014)).

Emitted pollutants are regarded as proportional to fuel consumption, but depends on, inter alia, actual hull shape and surface roughness, loading condition and engine condition. (Endresen 2003). In any case, fuel consumption per time travelled is typically a cubic function of speed (Ronen 1982; Fagerholt et al. 2010). One response to rising fuel costs is to reduce the vessel speed (Notteboom and Vernimmen 2009).

Weather routeing has a high potential for fuel savings on specific routes (IMO 2012). Relevant information, such as current and tidal atlases, climatological and oceanographic forecasts, should be taken into account when planning a voyage (IMO 1999). By exploiting the weather and current conditions, speed made good (SMG) can be gained and thereby reduce fuel consumption, transport costs, and air emissions (Fagerholt et al. 2010). Systems for route optimization and weather routeing are therefore becoming increasingly sought after for planning and execution of a voyage.

These systems exploit the favourable currents and weather for both ocean-going and coastal ships (i.e. Padhy et al. 2008; Takashima et al. 2009; Delitala et al. 2010; Tsou 2010; Lin et al. 2013).

The effect on fuel saving using weather routeing can be considerable on longer passages (Fagerholt et al. 2010). One of the many variables that affect the ship motion is currents. In the case of following currents, speed through water (STW) can be reduced accordingly and the ship will still maintain the same speed made good (SMG) and thereby reduce fuel consumption and cost, and consequently, air emissions. However, in coastal areas navigation is constrained by rules, including the existing Traffic Separation Scheme(s) (TSS), restricted and protected areas and fishing areas, in addition to the numerous pleasure crafts, especially during summer.

This study investigates whether fuel consumption can be reduced on a relatively short voyage in the Oslo Fjord, Norway. Previous studies based on Automatic Identification System (AIS) reveal that most vessels in the Oslo Fjord can benefit more from exploiting the currents to a larger extent (Hjelmervik and Schøyen 2015). As in most fjords, both the currents and the ship traffic are headed either in or out of the fjord. The Oslo Fjord can therefore be regarded as a representative fjord in terms of navigating currents in fjords.

In order to have full control of the currents and other factors influencing the voyage, this study is conducted on an advanced ship bridge simulator in combination with an engine room simulator. High-resolution current data from a numerical model are implemented on the bridge simulator. Bridge simulators have previously been applied for testing voyage plan systems for the Baltic Sea (Porathe et al. 2014), analysis of vessel collisions (Gralak and Juszkiewicz 2010), and are becoming increasingly popular in maritime human factor research (i.e. Porathe et al. 2015; van Leeuwen 2013).

2 The Oslo Fjord

The Oslo Fjord in the south-eastern part of Norway is selected as the area of interest, since it is has the largest density of vessel traffic in Norway; previous studies also imply that the currents can be exploited more in this area (Hjelmervik and Schøyen 2015). This area has the country's highest traffic density of ferries, cargo ships, charter boats, and pleasure craft. More than 40% of the Norwegian population live less than one hour by road from the fjord. The majority of vessels operating in the fjord head either North or South.

The Oslo Fjord is approximately 150 km long and can be considered as restricted water. Its width varies from about 25 km at the mouth (~59ºN) to about 1-2 km in the inner areas. The currents in the fjords are affected not only by tides, but also by fresh water input from rivers, atmospheric pressure, local water depths, the coastline, and winds. Seasonal and daily changes -in addition to variations in depth- result in a time dependent flow pattern with vertical layers. Sills, numerous skerries, islets, and several basins at different depths, contribute to a complex flow pattern. The dominant tidal constant in this fjord is M_2 with a period of 12.4 hours, which indicates that the direction of the currents changes every 6.2 hours (Norwegian Mapping Authorities 2016). The direction is northwards during rising tide and southwards during ebb tide. The strength of the tidal currents in the fjord typically ranges from 0.5 to 2 knots (Hjelmervik et al. 2017a).

Recently, a high resolution, three-dimensional model covering the fjord has been developed (Røed et al. 2016; Hjelmervik et al. 2017a). The numerical model calculates the currents based on tidal forcing at the mouth of the fjord, fresh water inputs from the rivers, bottom topography, and atmospheric pressure, winds, air temperature, and humidity. The results generated from the numerical model are validated against observations (Hjelmervik et al. 2017b).

This study focuses on a selected area of the fjord; details are presented in Fig. 1. As the Port of Oslo is located in the innermost part of the fjord, all vessels to and from the capital city travel through the selected area. All vessels longer than 24 metres have to apply to the Traffic Separation Scheme (TSS) established in this area. The TSS is approximately one nautical mile (1.85 km) wide and divided into northbound and southbound lanes. In this study, only northbound vessels are considered (thus only the northbound lane is of interest). Due to complex flow patterns, the currents in this area vary over short distances, also inside the TSS. Different routes inside the northbound lane are therefore examined.

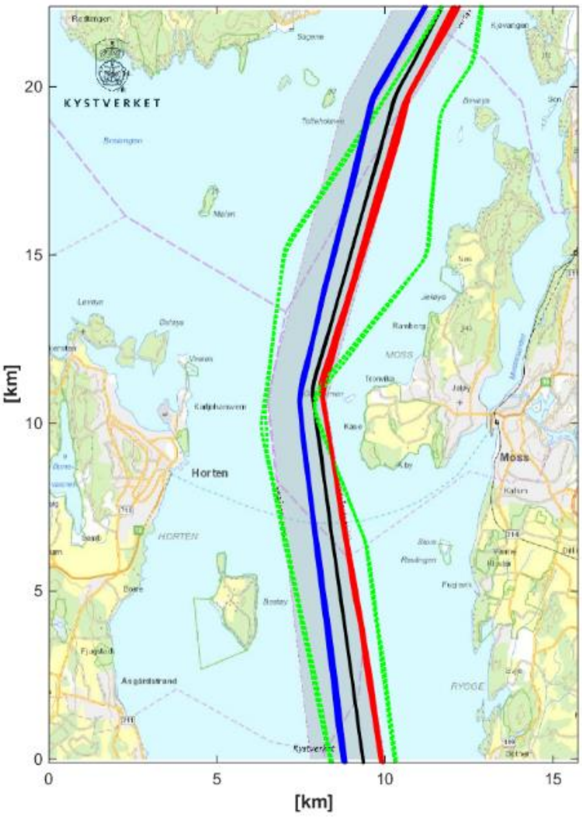


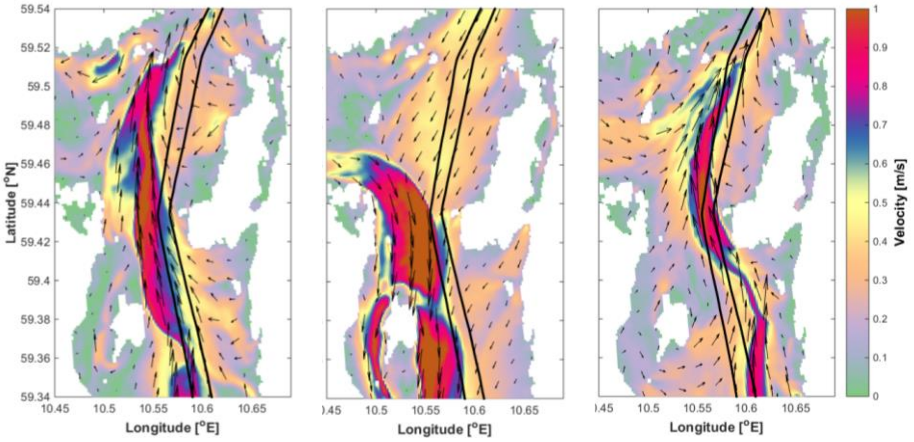
Fig. 1 The routes in the selected part of the Oslo Fjord. The TSS is indicated by the shaded area. The blue, black, and red lines indicate the western, middle, and eastern routes inside the northbound lane respectively. The TSS does not bind the routes marked by green lines. The routes are drawn on a map supplied from the Norwegian Coastal Administration.

Fig. 2 The K-Sim Navigator Bridge applied in the experiments. Photo: Svend Nordby

3 Experimental Setup

In order to have full control over the currents and other factors influencing the fuel consumption, the experiments were conducted by a full bridge team using the advanced K-Sim Navigation bridge simulator from Kongsberg Digital (Fig. 2). The K-Sim navigation system is found to comply with Class A- Standard for Certification of Maritime Simulators based on the requirements in the STCW Convention, Regulation 1/12 (DNV 2007). The simulator thereby fulfils the international standards for maritime training and allows vessels, objects, and equipment to operate and interact realistically using hydrodynamic models.

Three current fields from a numerical model (Røed et al. 2016; Hjelmervik et al. 2017a) have been chosen and implemented into the navigation simulator. The surface current fields at the beginning of each run are shown in Fig. 3. The fields implemented into the simulator are three-dimensional and change with time. The first and third fields are dominated by north going currents, while the currents are south going in the second field. Note that the currents change over relatively short distances, which is typical for currents in coastal areas. In the southern part of the second field, there is a strong current shear inside the northbound lane with stronger south going currents towards the western side of the lane. Calm weather is assumed with sun, no wind, and no waves. No other ships or activities are interrupting the passage. Consequently, only the effect of the currents is considered.



a) Field 1, following current **b)** Field 2, counter current **c)** Field 3, following current

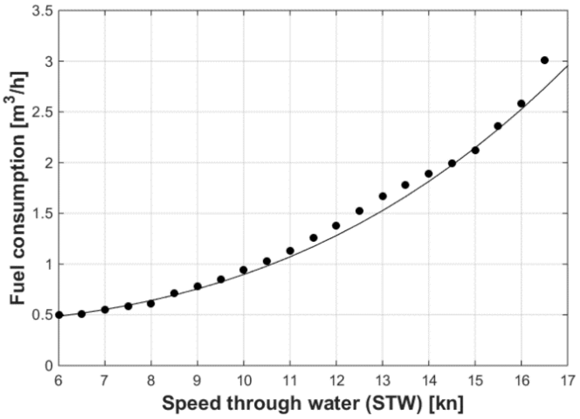
Fig. 3. The surface currents in the beginning of the three selected current fields. The colours indicate the magnitude and the arrows the direction of the currents. The solid lines mark the northbound traffic lane. The currents are retrieved from a numerical ocean model (Røed et al. 2016).

The experiment consists of ten different setups with northbound routes; one on no current, four on the first current field, three on the second current field, and two on the third current field (Table 1). The selected routes are approximately 25 km long. Both the eastern and western routes inside the northbound lane were defined in addition to two routes with no TSS restrictions. The two routes with no TSS restrictions have been chosen in order to follow the most favourable currents and avoid stronger counter currents. An Electronic Chart Display and Information System (ECDIS) was used to standardize the routes. Each setup was run twice for the sake of consistency. If the two runs diverged, more runs were performed with the same setup, and the diverging runs were deleted. Every ten seconds, the position, course made good (CMG), speed made good (SMG), heading (HDG), and speed through water (STW) were recorded.

Table 1. Experimental setup consists of 10 runs. Note the reduced speed in run 5.

ID	Current field	STW [kn]	Choice of route
1	No current	16.7	Middle route
2	Field 1, following current	16.7	Western route
3	Field 1, following current	16.7	Eastern route
4	Field 1, following current	16.7	No TSS restrictions
5	Field 1, following current	15.7	Eastern route
6	Field 2, countercurrent	16.7	Western route
7	Field 2, countercurrent	16.7	Eastern route
8	Field 2, countercurrent	16.7	No TSS restrictions
9	Field 3, following current	16.7	Western route
10	Field 3, following current	16.7	Eastern route

Fig. 4 Calculated fuel consumption (dots) for the selected vessel using the machine room simulator together with a curve which is proportional to cubic speed



An anchor handling vessel of 79 metres length overall, 5.6 metres draft, 8 991 tonnes displacement and a loading capacity of 4 743 dwt was chosen for the experiments. The vessel was fitted with a flap rudder, or Becker rudder, with a max. angle of 45 degrees. The propulsion schema was a diesel electric one, with an output of 86,109 kW (117,075 hp). It was fitted with a controllable pitch propeller (CPP) with a constant rpm of 130. Before the experiments were conducted, fuel consumption for the selected vessel was calculated using the Kongsberg Digital K-Sim Engine room simulator (see Fig. 4). As highlighted before, in accordance with Ronen (1982) and Fagerholt et al. (2010), the consumption per time travelled can be estimated by a cubic function of speed through water.

4 Discussion and Results

The crossing time varied from run to run (see Fig. 5). The crossing time on following currents was approximately 6% less than in the reference runs with no currents and 12-13% less than with the counter currents. It is therefore advised to wait for a favourable tide if possible. Instead of reducing the crossing time, the speed can be reduced. In run 5, the speed of the vessel was 1 knot less than in the others, but due to the following currents, the crossing time was slightly shorter than in the reference runs. According to the calculated fuel consumption (Fig. 2), this implies approximately a 15% reduction in fuel consumption for the vessel tested.

There is a noticeable time difference between the eastern and the western routes inside the northbound lane on the counter-currents (see Fig. 5), which is caused by differences in SMG during the first part of the passage (see Fig. 6). As can be seen from the counter current field (Fig. 3b), the currents in the first part of the passage are approximately 0.5 m/s (1 knot) stronger in the western part than in the eastern part of the northbound lane. The SMG will therefore be more reduced if the vessel lies west instead of east in the lane. In the last part of the route, the currents are more uniform across the lane.

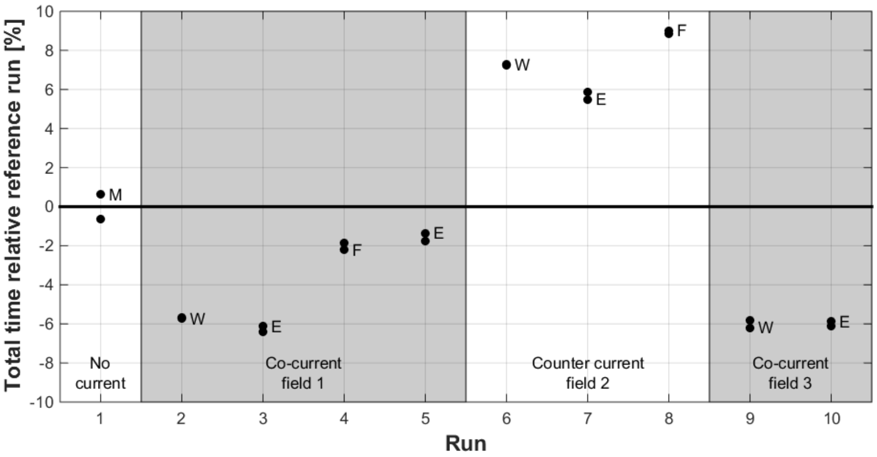


Fig. 5 Total crossing time for the 10 setups of the study. Each setup is run twice. The letter M indicates middle of lane, W and E indicate western and eastern routes inside the lane respectively, and F indicates free route with no TSS restrictions. NB. Run 4 is the one with a lower STW than the others.

In addition to the eastern and western routes inside the northbound lane, two routes not bounded by TSS restrictions were tested (green lines in Fig. 1). These “free routes” were chosen in order to follow the most favourable currents and avoid the less favourable ones. For field 1 the tested route followed the strongest following currents west of the TSS. For field 2 the tested route avoided the strongest counter current by going east of the TSS. In both cases, the length of the route was increased and thereby the crossing time did not decrease as expected when the SMG increased. Favourable currents are not always beneficial if the length of the route has to be increased in order to exploit the currents.

This study focused on northbound vessels. Similar results are expected for southbound vessels as the tidal currents change direction every 6.2 hours. In the spring, the fresh water inputs from the rivers increase due to melt water from the mountains flowing into the rivers. The lower density fresh water will accumulate near the water surface and this often results in stronger southbound and weaker northbound surface currents. During the autumn storms, the pressure in the Skagerrak outside the fjord forces water into the fjord and drags water out of the fjord. This causes sea level changes and increased current strengths. The position of the most efficient route, the favourable timing and potential fuel savings, depend therefore on both daily and seasonal changes. Detailed current forecasts are therefore crucial if currents in coastal areas are to be exploited.

In addition to currents, other weather conditions such as wind, waves and ice have a direct impact on manoeuvring the vessels. When the waves and the currents propagate in the same direction, the wavelengths increase and the wave heights decrease. The opposite would be the case when the waves and the currents propagate in opposite directions. This phenomenon could be applied to locate the currents, but can also represent a safety risk especially at the entrance of fjords when outgoing currents encounter the ocean waves or along the coastline when the coastal current encounters opposing waves (Norwegian Hydrographic Service 2017).

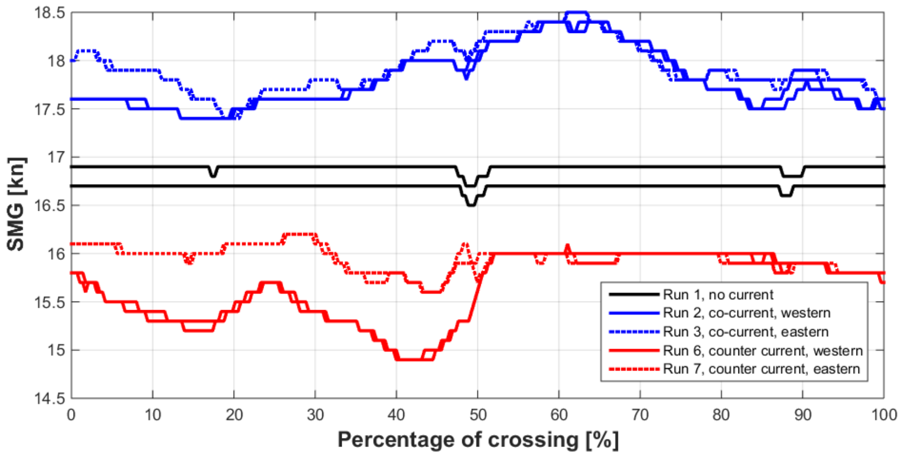


Fig. 6 Speed made good (SMG) during the crossing

5 Conclusion

Fuel consumption accounts for 50-60% of the overall maritime transports' operating costs; emissions from internal combustion engines represent a significant contribution to the degradation of the environment. Reduced fuel consumption can therefore positively impact those operating costs and bring down the respective air pollution significantly. Weather routeing has a high potential for efficiency savings, both on short and longer passages.

This study tested whether accurate and detailed current fields can be used to select the most energy efficient routes between ports in coastal areas. As the experiments were conducted using a bridge simulator, it was possible to have full control over the currents; the Oslo Fjord was selected for the conduct of these experiments. Due to the character of the currents and the movements of the vessels in the Oslo Fjord, this area is regarded representative relative to navigation on currents in fjords. It is expected that results of this study will be relevant for fjords in other areas with similar geographic characteristics.

The results of the analysis in hand are promising because they demonstrate that significant fuel and air emission savings may be achieved. An anchor handling vessel of 79 meters length over all can save up to 12-13% time if a favourable current is present instead of a counter current in the Oslo Fjord. If one knot of favourable current is present, the ship's captain may voluntarily reduce the speed from 16.7 knots to 15.7 knots resulting in a SOG of 16.7 knots, arriving at the Port of Oslo on schedule and saving approximately 15% fuel. Alternatively, a speed through water of 16.7 knots, combined with one knot favourable current instead of opposing current, would decrease the time of arrival by approximately 19 minutes. If possible, the vessels are therefore advised to time their voyage with a favourable tide and avoid counter currents. Fuel reduction of up to 15% may generate considerable economic and environmental savings.

Shipping operations in coastal areas are geographically limited. The results reveal that even the route of the vessel inside the traffic lanes has an impact on the fuel consumption, since currents in coastal areas vary over short distances. Ferries and other vessels operating with very precise timetables could thereby save fuel without changing the time of arrival.

The track of the most efficient route, the favourable timing and potential fuel savings depend on both daily and seasonal changes. Detailed current forecast are therefore crucial if currents are to be exploited in coastal areas. Actual weather can differ from predicted conditions during the voyage. The fuel savings may therefore differ from the predictions. In addition to currents, other weather conditions such as wind, waves and ice may have an impact on manoeuvring the vessels, as well as upon their fuel consumption. When the waves and the currents propagate in an opposite direction the wave height increases and thus represents a safety risk, at least for small ships. This is typically the case at the entrance of fjords and along the coastline. Wind and waves should therefore be included in further studies.

Since the routes examined in this study are relatively short (approximately 25 km), further experiments have to be conducted in order to test to what extent the results can be generalized for weather routeing in other coastal areas. Tests involving different types of vessels should also be conducted in order to estimate potential savings for the all the various vessels navigating the specific area.

In addition to the possible fuel reduction during voyages, detailed current forecasts may benefit various ship operations in connection with safe ship handling, i.e. ship-to ship rescue and recovery, dredging, and helicopter handling (Perera and Soares 2017). Quantification of possible fuel consumption effects during specified ship operations could be included in further studies.

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