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The enhanced role of canals and route choice due to disruptions in maritime operations

Thalis P.V. Zis
Department of Shipping, Cyprus University of Technology, Limassol, Cyprus

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Abstract

Purpose – This paper focusses on the aftermath of disruptions and the importance of the two largest canals (Suez and Panama), commenting on how during the pandemic the canal fees were lowered. Considering the ongoing efforts to decarbonize shipping, some of the ongoing disruptions will help reach these objectives faster.
Design/methodology/approach – Following a literature review of route choice in shipping, and a presentation of significant disruptions in recent years, the author deploys a simplified fuel consumption model and conduct case study analyses to compare different routes environmentally and economically.
Findings – The results explain why at times of low fuel prices as in 2020, canals provided discounts to entice ship operators to keep transiting these, instead of opting for longer routes. Considering the ongoing repercussions of the pandemic in supply chains, as well as the potential introduction of market-based measures in shipping, the value of transiting canals will be much higher in the coming years.
Research limitations/implications – The main limitation in this work is that the author used the publicly available information on canal tolls, for the different ship types examined.
Practical implications – The envisioned model is simple, and it can be readily used for any ship and route (port to port) combination available, if ship data are available to researchers.
Social implications – It is possible that canal tolls will increase, to account for the additional environmental benefits brought to ship operators.
Originality/value – The methodology is simple and transferable, and the author proposes several interesting research questions for follow-up work.

Keywords Disruptions, Maritime transport, Route choice, Shipping canals, Shipping decarbonization
Paper type Research paper

1. Introduction

International shipping allows low-cost transportation of goods and offers the lowest carbon intensity in freight compared to other transportation modes, in part due to economies of scale (Cullinane and Khanna, 2000). According to the fourth International Maritime Organization (IMO) greenhouse gas (GHG) emissions study, in 2018 international shipping was responsible for approximately 2.89% of the global anthropogenic emissions or about 1,076 million tonnes, indicating an increase in absolute numbers and emissions from 2012 (IMO, 2020). At the same time, maritime shipping moves approximately 80–90% of world trade with a constant annual increase of 3–5%. Two notable exceptions were 2009 with a small reduction following the recession, and 2020 where a 4.1% reduction was estimated by United Nations Conference on Trade and Development - UNCTAD (2022) due to the pandemic. The pandemic is still affecting shipping in various ways, but it is expected that world trade will eventually relapse and keeps increasing. As a result, emissions from shipping are expected to grow further.

To address this issue, the IMO has set ambitious targets in its Initial Strategy for the decarbonization of international shipping. The strategy has three main objectives: achieving a 40% reduction in the carbon intensity of emissions by 2030 (aiming for 70% by 2050) and at least 50% reduction in absolute greenhouse gas (GHG) emissions by 2050. Both targets are compared to the benchmark year of 2008. The final objective of the strategy is for shipping

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emissions to peak as soon as possible. Other voices aim for a full decarbonization, stating that the IMO targets are insufficient, for example, the US special presidential envoy for climate announced that the United States wants the IMO to push for zero shipping emissions by 2050 [1]. The European Commission has approved the European Green Deal, a set of policies with the ambition to constitute the European Union climate neutral by 2050, and achieve a 55% reduction of GHG by 2030 compared to 1990 levels. In this Deal, the proposed legislation in the “Fit for 55” package also contains regulations relevant to transportation, and maritime operations in particular. Apart from monitoring their emissions, shipping operators will also have to utilize low or zero carbon technologies, while ports will also need to invest in infrastructure upgrades to provide alternative fuels and shorepower. The EU Emissions Trading System (ETS) will also include international shipping for voyages starting or finishing in an EU port. Without doubt, the increasing environmental pressure will result in increased operating costs for maritime operations that will eventually be passed on to shippers and subsequently the consumers.

The situation is rapidly changing with new national and international policies, the rise of new technologies aiming to reduce fuel consumption and emissions, as well as unprecedented external disruptions. However, the most important disruption in recent years has been the pandemic, which severely affected global production and international trade. To understand how the pandemic has affected the operation of canals, it is important to present some basics with regard to their operation and also shed some light on what academic research has focussed on in recent years. Canals are waterway channels that connect existing lakes, rivers, canals or seas and oceans. When it comes to international shipping, the use of canals significantly cuts time and sailing distance for voyages and has allowed more port-to-port connections. Suez Canal (SC) and Panama Canal (PC) are the two most famous canals used in international shipping, as well as two of the largest infrastructure projects in history. It is estimated that 12% of global trade passes through the SC, and approximately 6% through the PC. The PC is of vital importance to the United States, as 60% of cargo passes through PC (origin or destination in the United States). The PC can accommodate between 35 and 40 sailings per day, while the SC can accommodate between 40 and 50 sailings. A typical passage duration is around 10 h for PC and 8 h for SC. Any disruption to their operation, or to a ship operator’s routing decision, will have significant impacts on the per voyage fuel consumption and emissions generation and can jeopardize the sector’s efforts to decarbonize. The paper will attempt to shade light on whether there can be lessons learnt for the maritime sector to reach its objectives with regard to decarbonization after major disruptions.

2. Literature review

In this paper, the “Web of Science” (WoS) search engine was used to retrieve representative academic works dealing with issues of disruption in maritime operations, and the operation of canals. We identify three major research subjects: route choice studies considering canals, environmental benefits and disruption management.

2.1 Route choice studies

An important number of papers consider route optimization linking two ports, when an option of a canal is available. Typically, a model is constructed to estimate the total transportation costs and time for the available routes. Costs heavily depend on the fuel price and sailing speeds used at the time of the analysis. Shibasaki *et al.* (2016) examined the route choice for containerships when given the option to use the SC and competing routes via the PC or the Cape of Good Hope. The authors developed a logit model to capture the route choice decision-making procedure of operators and conducted sensitivity analyses for future scenarios that included the PC expansion. Ungo and Sabonge (2012) focussed on the impacts of the 2008 recession on traffic through the PC. The authors modelled the total transportation cost from the ship operators' perspective and concluded that with higher fuel prices, the value of using the canal increases.

Several academic works focussed on the impacts of the PC expansion that was opened in 2016 on maritime trade and the regional economies. Pagano *et al.* (2012) had focussed on the wider economic impacts on the Panamanian economy that were anticipated before the expansion was actually finished. Muirhead *et al.* (2015) considered the generation of additional traffic as larger vessels would finally be able to transit, as well as environmental ramifications of potential biological invasions due to the expansion. In the aftermath of the expansion, most studies focussed on specific case studies for niche markets and the new situation following the expansion. For instance, Shibasaki *et al.* (2018) discussed the new opportunities in the liquefied natural gas (LNG) market as bigger ships are now able to transit the canal. Moryadee and Gabriel (2017) also examined the LNG sector and on how Asian markets could now have more alternatives in their LNG imports. Other case studies considered the redistribution of container lines following the expansion (Pham *et al.*, 2018).

A noticeable trend in the last twenty years has been the comparison of traditional shipping routes with a potential Arctic Route as an alternative to the SC. The Northern Sea Route (NSR) as defined by Russia runs along the Russian Arctic coast from the Kara Sea to the Bering Strait. The NorthWest Passage (NWP) is a route through the Arctic Ocean, along the northern coast of North America and the Canadian Arctic Archipelago. It is worth noting that the NWP is not as deep and limits the vessels capable of using it. Arctic routes are typically used in the summer when they are mostly ice-free. In other cases, icebreakers can open the passage for commercial shipping. The NSR offers significantly shorter routes and has therefore attracted the interest of the industry and academia on its potential benefits. Due to climate change, the NSR is more accessible year after year, a significant environmental concern.

In terms of academic works, the NSR is usually compared with the routes using the SC, and mainly refers to the Far East Asia–Europe trade lanes. Schøyen and Bråthen (2011) examined case studies in bulk shipping between the two routes and found that a 40% reduction in total transit time can be secured via the NSR. The authors noted the issues with the reliability of the passage and concluded that the NSR should be primarily used in bulk shipping and not container shipping. Liu and Kronbak (2010) had already considered a case study of a small containership (4400 TEU) and showed that the NSR would be profitable for most scenarios compared to the SC route. The authors considered sensitivity analyses on the ice-breaking fees and fuel prices, as well as potential tolls for the use of the NSR. Tseng and Cullinane (2018) developed a fuzzy analytic hierarchy process model to examine the NSR and NWP routes. The authors surveyed several shipping companies and found that the time and cost savings of using either Arctic route are well understood and an important part of the decision process. The results showed that mostly bulk operators were interested in the Arctic routes, while container shipping operators were disinterested mainly due to political or safety concerns.

The environmental damage of ships crossing the Arctic routes has not been explored in the literature. Fuel consumption and emissions would be lowered because of the shorter distance; however, local pollutants could have a detrimental effect in the Arctic Circle as Black Carbon emissions can cause severe environmental pollution by limiting the albedo effect of arctic ice (Zis, 2015).

2.2 Environmental benefits

A recurring theme in the literature deals with the capacity of each canal. Depending on the actual sailing speed inside a canal, the booking system, and the queuing theme, models have been developed to estimate the maximum capacity of canals (Griffiths and Hassan, 1977). On environmental aspects, Lindstad *et al.* (2013) focussed on the potential cost and GHG emission reductions that would be possible through the PC expansion. De Marucci (2012) focussed on the CO_2 reductions attained through the PC expansion. Other studies focus on the quantification of exhaust emissions near a canal, similar to studies that build emission inventories on ports or coastlines. There have also been studies considering the impacts of potential new canal projects. Manh Cuong and Hung (2020) examined a Thai Canal, and Condit (2015) examined a Canal in Nicaragua.

Most of these papers do not consider the effects of prevailing weather conditions when comparing the different routes. Some routes may benefit from streams moving along with the ship, or from the fact that they are shorter and thus less prone to get caught in rough weather. In the last fifteen years, the next major environmental challenge had been the reduction of sulphur emissions from international shipping. The studies closely followed the progressively stricter sulphur limits inside and outside emission control areas (ECAs) as designated by the IMO and proposed solutions for affected ship operators. As with the decarbonization problem, the desulphurization studies also focussed on optimal paths and investments in the best technology (low sulphur fuel versus the use of scrubbers), as well as the economic impacts of the policy (Zis and Cullinane, 2020). There have been very few studies that considered the best route (using a canal or not) based on the sulphur limits of each route (Chen *et al.*, 2018). A new wave of research has started focussing on case studies to reach the IMO decarbonization goals in the short, medium and long term. Route choice is an important component in reducing both the absolute and relative emissions from shipping.

2.3 Disruption management in maritime operations

Another important stream of research in maritime shipping has dealt with network resilience and the impacts of severe disruptions (Liu *et al.*, 2018). Disruptions can span from piracy incidents, cyber-resilience of ships and future autonomous vessels, to extreme weather effects (hurricanes, tsunamis) that can affect voyages or port infrastructure. Relevant to this work, we will review major disruptions in the shipping sector.

It can be argued that a disruption refers to events that are sudden and unexpected and their occurrence in time is not foretold. However, there have been major events where their date of occurrence was known and still their effects on shipping were unexpected or unresolved. For example, the impacts of Brexit are still disrupting supply chains and are still unclear. In a similar fashion, environmental regulations in shipping tend to increase fuel price volatility and require shipowners to decide whether to invest in expensive abatement technologies to counter increased fuel costs. Considering the several *ex ante* and ex-post studies on the effects of sulphur regulation (ECA in 2015, global cap in 2020), we consider this as a disruption. The global sulphur cap came in force in January 2020, and requires the use of fuel with maximum sulphur content of 0.5% down from 3.5% or use of technology with similar reductions. Concerns were raised that the policy would lead to significant increases in fuel prices and transport costs. In 2019, several ship owners started heavily investing in scrubber systems to prepare for the new limit, despite not knowing the exact repercussions of the coming policy requirement. This in turn led to additional times off-market for the retrofitting of ships, as well as concerns for fuel availability for operators that opted to use low-sulphur fuel, which could in result in fuel price increases. Interestingly, the quest of desulphurization comes in contrast with the ambitious decarbonization targets of the IMO as it has been proven in the literature that both main compliance options (scrubbers or low-sulphur fuels) are resulting in higher CO_2 emissions (Zis *et al.*, 2021). However, as was the case in 2015, the early months of 2020 saw a significant reduction in fuel prices and the disruption of the global sulphur cap was less severe than anticipated. This reduction in fuel prices can be partially at least attributed to the global disruption of COVID-19 which we will discuss briefly next.

The first notable impact of the pandemic on international shipping was the cancellations of many cruises following the “Diamond Princess” incident. A heavy outbreak onboard led to the quarantine of the ship and passengers (712 passengers and staff infected out of 3,711). The next significant distortion affected the charter market during the first half of 2020. A combined result of the global sulphur cap, the outbreak of the COVID-19 pandemic and the severe drop in fuel prices, charter rates in the liquid bulk section showed extreme increases. Several very large crude carriers (VLCC) were used as storage for fuel due to the negative oil prices, which led to extreme increases in these charter rates. Global production and international trade declined due to the initial lockdown in China and the closure of several production facilities (Cullinane and Haralambides, 2021). The ensuing lockdowns in Europe and North America also led to a reduction in import demand. In the first months of 2020, fuel prices were so low that several ship operators opted to use longer routes via the Cape of Good Hope or the Strait of Magellan to avoid the canal tolls. In May 2020, containership transits through SC fell by 32%, and an all-time low of 330 ships crossed the channel. The SC responded by reducing transit fees by 17% for all transits between May and July. In 2021, the disruptions continued with a lack of empty containers, severe reductions in turnaround time at major ports due to new guidelines for staff to avoid contagion, and record-breaking freight rates in the liner market. This perfect storm can prove critical for the Canals, as at times of low fuel prices and high transport demand (as demonstrated by the rise in freight rates) sailing speeds may increase to perform more voyages for liner shipping. Academic works examining the impact of the pandemic have started appearing in the literature, focussing on the immediate aftermath of the pandemic on shipping markets (Michail and Melas, 2020). Comparisons with the situation after the 2008 financial crisis suggest that the shipping sector is much more resilient in this crisis (Notteboom *et al.*, 2021).

Perhaps the cherry on the cake of maritime disruptions in the new decade was the event of the Ever Given ship blocking the SC for six days. Initially there were fears that the blockage could last for weeks or even months before the ship was freed. Several ships that were scheduled to transit the Canal in that period were rerouted to go around Africa. The repercussions of the blockage in prices, delivery times, as well as legal issues are a topic that has attracted a lot of media attention. The importance of alternative routes such as the NSR were also brought into public attention. The first academic works in the subject dealt with legal issues (Yizhen *et al.*, 2021).

Finally, 2022 also brought severe disruptions in supply chains and shipping following the Russian-Ukrainian conflict. The effects on the shipping industry have been both direct and indirect. Fuel prices have sky-rocketed, and freight rates have also increased. For crude oil in particular, just the insurance costs due to the risk of war have increased significantly. It is likely that the next wave of research will focus on the short and long-term impacts of this conflict. Similar research was conducted following the first sanctions to Russia following the Crimean conflict.

Most papers published on disruption management focus on post-disruption recovery, with some immediate measures including port skipping or swapping (Abioye *et al.*, 2020), rescheduling based on weather with the overall objective to minimize losses (De *et al.*, 2019). Adjustments of buffer times between port calls with speed adjustments are also a recurring subject (Mulder *et al.*, 2019). An important aspect of papers in disruption management for maritime operations is that these are rarely linked with climate and environmental policy. It has been argued that during severe disruptions, compliance with environmental regulations is more difficult and can increase operating costs. Supply chain networks can recover faster if certain environmental regulations are temporarily lifted (Zavitsas *et al.*, 2018). At the same time, ongoing discussions at the IMO are showing that a market-based measure (MBM) in the form of a carbon levy or tax on fuel is very possible. Depending on the level of that levy, speed and profit reductions are expected for ship operators (Kosmas and Acciaro, 2017). Considering that longer transit times can negatively affect shippers and result in modal shifts, it can be expected that the importance of canals will be upgraded in the near future, and the value of each crossing will be of higher importance to ship operators (fuel and time saved).

This paper will present a methodological framework that allows the comparison of toll fees, fuel costs and emissions for routes crossing a canal versus longer routes that are toll-free.

3. Methodology

We will compare the economic and environmental performance of different routes transiting a canal versus longer routes that are toll-free. To perform this exploratory analysis, it is necessary to estimate the associated fuel consumption for each voyage and thus retrieve the operational costs and associated emissions generated during each trip.

Estimating the fuel consumption of a specific voyage requires information on the vessel's technical specifications, the sailing speed during the voyage, its loading condition (ballast or laden, or partially loaded for containerships) and information on environmental factors (weather, waves, wind, streams). In microscopic studies, detailed information is required to accurately predict the necessary power demand and associated fuel consumption of a given vessel. In most macroscopic-level studies, several relaxations are used based on sea-trial data that typically are provided for each vessel. Sea-trial data provide an estimation of the fuel consumption at calm waters for a specified sailing speed. We use an intermediate approach with an activity-based methodology to estimate the fuel consumption.

A voyage can be broken down into different activity phases: sailing (cruise), manoeuvring at arrival/departure, berth hotelling, and anchorage hotelling when the ship has arrived near the port but its berth is not ready. In this paper, we will compare fuel consumption for different routes between given ports of origin and destination, and as a result, the at-berth and manoeuvring fuel consumption will not change for the different route options. Thus, we will use equations 1 and 2, adapted from Zis *et al.* (2021), to estimate fuel consumption during the cruise.

The fuel consumption FC_{cruise} (tonnes per hour) during sailing (only main engines and auxiliary engines are active) is given by equation (1):

$$FC_{cruise}(ton) = 10^{-6}(SFOC_{main} \cdot EL_{main} \cdot EP_{main} + SFOC_{aux} \cdot EL_{main} \cdot EP_{main}) \cdot \frac{D}{V_s} \quad (1)$$

where *SFOC* (g/kWh) is the specific fuel oil consumption of the machinery (main for propulsion engine, aux. for auxiliary. The *EL* (%) is the engine load at which the machinery operates. The nominal installed power of each engine is given by *EP* (kW). Finally, *D* (in Nautical Miles – NM) is the sailing distance of the route, and *Vs* (knots) is the sailing speed of the vessel. We assume a constant sailing speed in the voyage (which is an oversimplification), and we do not consider the impacts of weather or streams. To estimate the *EL* at different sailing speeds V_{S1} and V_{S2}, we use the propeller law shown in equation (2):

$$\frac{EL_{m1}}{EL_{m2}} = \left(\frac{V_{S1}}{V_{S2}}\right)^n \quad (2)$$

In calm water and for low sailing speeds, the value of the exponent *n* can be assumed to be 3, as an approximation, although higher values have been suggested for rough weather and faster sailing speeds.

The fuel cost for a voyage can be estimated by multiplying fuel consumption by an appropriate fuel price. As of 2020, maximum 0.5% sulphur content must be used for all shipping activities outside ECAs, and a 0.1% limit inside ECAs. If a ship is equipped with a scrubber, then it can use HFO of higher sulphur content (typically 3.5%) and benefit from the much lower fuel price of the scrubber.

To estimate the emissions generated per voyage, the fuel consumption of each engine should be multiplied with an appropriate emission factor that is fuel-specific. Currently, emissions are not considered as costs, but there are efforts to reduce emissions from shipping, and there are increasing calls for the introduction of market-based mechanisms to achieve this. This can include either a tax on fuel (bunker levy), or the potential inclusion of international shipping in emissions trading systems (ETS). It is also noteworthy that when ship operators choose to cross a canal, the reason is not only the reduction in overall time, but there might be other aspects offering higher utility compared to a longer route. These could be the safety offered by the crossing, the reduced emissions (which will play a bigger role in the future), the higher reliability of service and more. It is therefore difficult to only attribute route choice to a single time and cost metric. There are other operational costs associated with a specific voyages that may include staff costs, insurance costs, depreciation of cargo value, as well as the depreciation of the vessel itself. In addition, the difference in the total voyage duration from choosing a different route will have an impact on the revenue generated per unit time. However, as this estimation is beyond the scope of this paper, we will only focus on the cost comparison of fuel costs for the different routes, and a comparison of total voyage time. Considering that in the recent past there were changes in route choice that were mainly attributed to fuel price and freight rates (ship operators opting for longer routes), it is important to be able to compare cost and time for shipping routes.

4. Case study

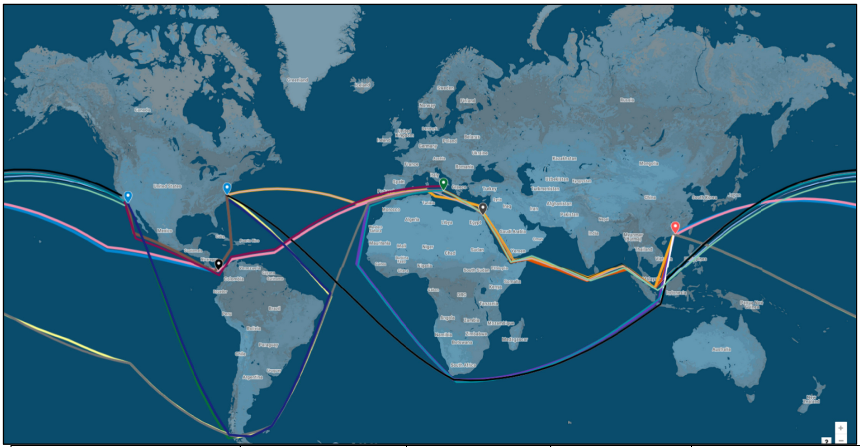
4.1 Necessary data

To conduct our analysis, it is necessary to retrieve the following data. Information on the different available routes (origin and destination ports, total sailing distance), technical specifications of the ships examined to estimate fuel consumption (installed engine power, carrying capacity), the cost of using each canal, and information on the fuel price used and revenue generated per trip.

We consider different services linking Far East Asia with Europe, Far East Asia with the US East Coast and transpacific services that link Far East Asia with the US West Coast. The ports in our case study consider the port of Norfolk (Virginia), the port of Gioia Tauro (Italy), the port of Hong Kong and the port of Los Angeles (California). The different routes and key information are shown in Figure 1.

There can be different routes linking the origin and destination ports, where the ship operator can cross a canal, or choose a longer route. The sailing distances for the different routes have been calculated using GIS software and verified through two different online tools that estimate sailing distances between different ports. The sailing distances (in NM) are shown in Figure 1 for all possible combinations (crossing the SC, the PC, sailing around Africa, sailing through the Strait of Magellan). We show this information for illustrative purposes, as certain routes would not be realistic. For example, sailing from Norfolk to Los Angeles is possible via the Cape Route, but that would add more than 7,000 NM compared to the other "free" alternative of sailing through the Strait of Magellan.

For the examined voyages, only the ports of Norfolk and Los Angeles are inside an ECA. This means that within 200NM of these two ports the ships must use fuel of maximum 0.1% content. In previous works in the literature, there were optimization approaches to limit the total sailing distance within the ECA (sail longer outside an ECA to reduce fuel costs), or to differentiate speed (faster outside ECAs, slower inside). However, the potential for speed optimization has been diminished following the global sulphur cap (Zis *et al.*, 2021). To avoid



Origin – Destination	Via Suez	Via Panama Canal	Around Africa	Around S. America
Hong Kong – Norfolk	12120 (orange)	11234 (blue)	13790 (white)	17631 (yellow)
Hong Kong – Gioia Tauro	7670 (red)	14840 (salmon)	13280 (purple)	18138 (grey)
Gioia Tauro – Los Angeles	13857 (turquoise)	8438 (maroon)	13315 (teal)	13470 (green)
Norfolk – Los Angeles	18293 (light blue)	4776 (brown)	19950 (black)	12729 (navy)

Source(s): Own calculation verified through online services (searoutes.com, sea-distances.org), figure by authors

Figure 1.
The examined routes for the four ports (Norfolk, Los Angeles, Gioia Tauro, Hong Kong) and their associated sailing distances per route

unnecessary complexities, we assume that the sailing speed will not change inside and outside ECAs, but a different fuel price is used for these legs.

4.2 The examined ships

We consider five representative ships of different sizes and types to analyse the different routes. These ships and their key technical characteristics are shown in Table 1:

Table 1.
The examined ships, their technical specifications, and their estimated fuel consumption at their current average sailing speeds

Ship ID	Ship type	Capacity	Year built	Design speed (knots)	FC design (tpd)	EPmain (kW)	EPaux (kW)	Speed in 2021–22 (knots)	Estimated FC (tpd)
Ship A	Containership	3,200 TEU	2002	21.6	110	28,880	6,840	17	62.88
Ship B	Containership)	5,090 TEU	2007	24.3	142	41,130	7,190	15.4	48.24
Ship C	Containership	10,081 TEU	2016	22	127.4	32,490	13,200	16.6	64.07
Ship D	Containership	13,386 TEU	2014	24	248.4	72,240	21,000	16.4	105.80
Ship E	Liquid bulk carrier	100,899 dwt	2005	15.2	64	15,820	4,620	11.9	36.29
Ship F	Ultra Large Crude Carrier	299,999 dwt	2008	16	104.5	29,340	3,675	11.4	45.44

Source(s): Table by authors

The technical specification data were retrieved from Clarkson's World Fleet Register, and the estimated FC was calculated using the methodology presented earlier. We can observe that the actual sailing speeds are much lower than their design speeds.

4.3 Basic cost toll information

The tolls are a significant source of income for the public authorities managing the two canals. The pricing system is different for each canal but relatively straightforward. The SC tariff is a function of ship size, ship type and condition (ballast or laden). The authorities are using a progressive system where the cost is calculated in SDR (Special Drawing rights – currently equivalent to $0.69918) per SCNT (Suez Canal net tonnage). This is decreasing as the SCNT increases (Suez Canal Authority, 2021), with lower tariffs for ballast legs. For most ship types, the tariff is the same, with a slightly higher tariff for LPG carriers, dry bulk carriers, chemical and other liquid bulk carriers, and other special type vessels. Over the years, the tariffs at Suez have remained relatively stable, and always as a function of SCNT. There were typically no discounts provided by the Suez Canal Authority to any ships (for example loyalty schemes); however, there is a 25% discount for LNG vessels transiting the canal for both the ballast and laden legs.

For the PC, the tariff is also a function of the ship type, size, and loading condition, but there are significantly many more factors affecting the final toll per ship transiting the canal (Panama Canal Authority, 2020). The tariff is given in USD per Panama Canal Universal Measurement System (PCUMS), and it is lower for ballast ships. The PCUMS is a measure of the space of cargo transported by the vessel and is approximately 2.832 m3. For containerships, one TEU is roughly equivalent to 13 PCMUS. The tariff structure in the PC has changed significantly over the years. Since 1914, when the canal was opened, vessels used to pay tolls in a breakeven fashion. The PCMUS was introduced in 1994 and following the end of 1999 when the canal was transferred back to the Republic of Panama, the authorities moved towards a model aiming for client satisfaction, reliability and profitability. In 2005, toll fees for containerships were calculated as a function of TEU (maximum capacity and actual carrying capacity). A similar policy was applied for passenger carrying vessels from 2007. For the next few years, the pricing policy remained relatively stable, but from 2016 onwards, a new reformulation for containerships was used to also consider the impacts of the expanded canal allowing the transit of larger vessels. According to this, a fixed tariff per TEU maximum capacity is envisioned for vessels under and over 6,000 TEUs (60 and 50$/TEU respectively), and an additional cost per transported TEU is envisioned for carrying under 3,500 TEUs, between 6 and 9,000 TEUs, and above 9,000 TEUs (30, 40, and 35$/TEU respectively). Significant discounts on the loaded containers were offered for ships that would perform a return voyage within 28 days to attract more users. In addition, empty TEUs carried in the northbound leg (typically laden) would not be considered in the determination of the percentage utilization of the vessel.

The case studies in the following sections will concern illustrative examples for ships, based on the current tariffs for different containerships and liquid bulk carriers as published by the canal authorities. For PC, the toll fee is a function of the actual number of containers carried; we assume that in ballast the transported TEUs are at 10% of maximum capacity, and in laden at 90%. The tolls for PC are under the assumption that there is no rebate (due to loyalty or return trip within 28 days), to facilitate comparisons on a baseline case. We note that the toll fee for each ship and each canal is independent of the prevailing fuel price. Perhaps in the future, a dynamic pricing mechanism for the canal tolls can be examined. There are additional costs that are associated with transiting the canal, including the fuel consumption during the passage. These can include tug-assistance fees, security surcharges, fees for line handlers, commissions and other insurance costs. These cost elements also vary with the ship size. For illustrative purposes we note for Panama Canal, these costs (excluding fuel during transit) can amount to an extra 10–20% of the toll price we have retrieved from the websites of the authorities.

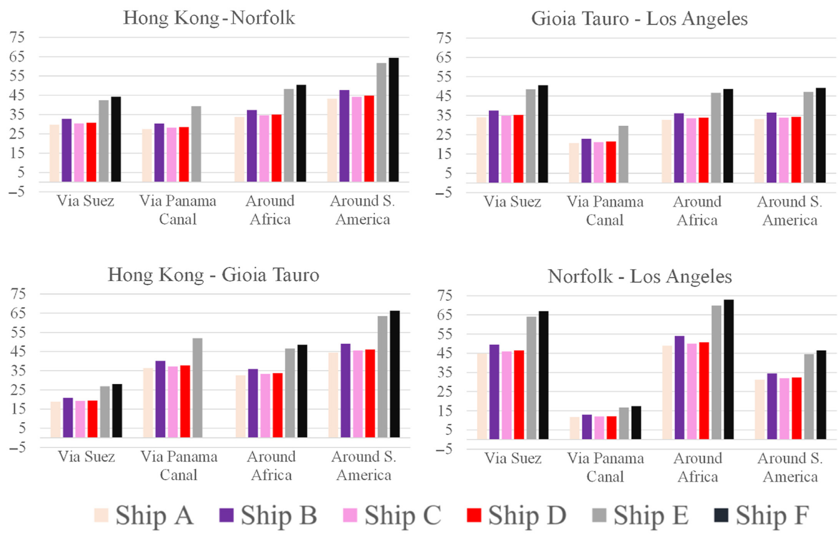
4.4 Comparison of alternative routes

4.4.1 Voyage duration. Figure 2 shows the voyage duration for all possible combinations of ships and routes, under the assumption that each ship is sailing at its average sailing speed.

We notice that transiting a canal can result in a significant reduction in voyage time compared to the shortest toll-free alternative. For example, for the Norfolk–Los Angeles case the voyage duration through PC is 70% shorter than when crossing the Strait of Magellan. Similarly, in the Hong Kong to Gioia Tauro route, using the SC can result in a 50% shorter voyage in duration. The time savings are very important, and these would be higher at times of a good market condition. For example, in the first decade of the 21st century and before the 2008 recession, containerships would often sail at speeds above 23 knots. In such cases, the fuel and time savings offered by canal crossing would be significantly higher. However, at times of low market conditions, or severe disruptions, some operators would select longer routes not crossing the canals. In these cases, time savings are not as important, and the extra fuel consumption can be offset from the toll difference. The next section considers fuel consumption for the same case study.

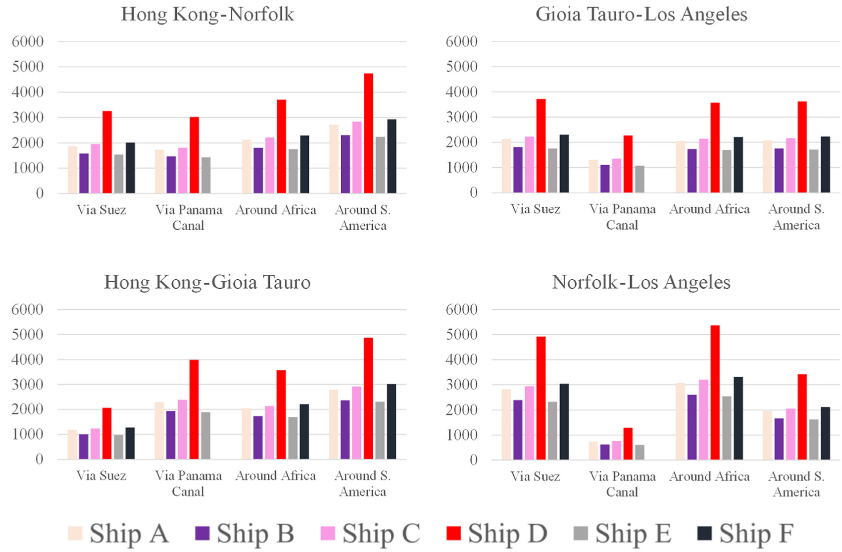
4.4.2 Fuel consumption. Figure 3 presents the fuel consumption for each ship and route assuming that each ship is using its average speed in 2021. The results are shown for a one-way leg.

Figure 3 shows that for each port-to-port connection, a similar performance is followed by each vessel. Clearly, the containerships are consuming the most fuel as these are still the largest and faster ships. The highest savings are observed for routes where transiting a canal significantly reduces sailing distance, particularly for the Norfolk–Los Angeles routes (via Panama), and Hong Kong – Gioia Tauro (via Suez). As stated earlier, selecting a toll-free longer route has only been evidenced during very low market conditions, or when major



Source(s): Figure by authors

Figure 2.
Voyage duration in days for each ship and route combination, assuming each ship sails at its average speed



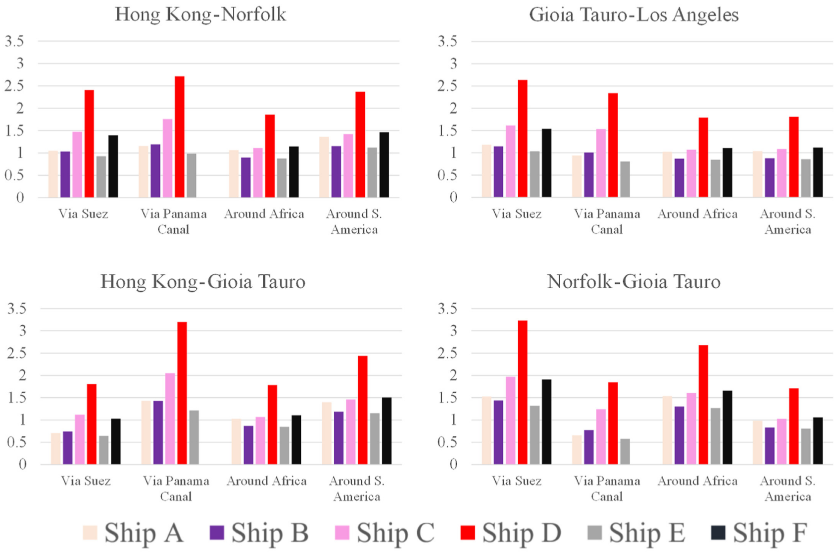
Source(s): Figure by authors

Figure 3.
Fuel consumption (tonnes of fuel) for each ship and one-way route

disruptions are forcing the operator to do so. In the first case, fuel consumption will be lower and the fuel saving difference will be lower than what is shown in Figure 3, as the ships would sail at significantly reduced speeds. However, in case of a disruption (for example a Canal blockage), the ship operator would have to minimize the total time lost, and thus speed up during the larger route, resulting in significantly higher fuel consumption and associated emissions. Considering that in the future emissions will need to be internalized (either through a carbon tax, or ETS), disruptions in major canals will have a detrimental effect on the decarbonization efforts. Next, we will try to contrast fuel consumption differences between routes, and include the toll fees in the calculation.

4.4.3 Fuel costs and tolls. Figure 4 presents the total costs (fuel and toll fees where applicable) when the ships are laden. We consider the 2021 average fuel price of $500 per tonne of fuel with a 0.5% sulphur content.

We observe that for most cases, the total transportation costs are more expensive when using a canal. For higher fuel prices, the cost difference would be shorter. Using a lower fuel price as experienced in the first months of 2020 (where HFO was below 150 per tonne), the cost difference changes dramatically and makes the toll-free options much cheaper. This can explain in part the decision of several ship operators during that period to choose the toll-free alternatives, and the decision of SC to offer a discount for a three-month period. The analysis has assumed that the ships would sail at their predetermined speed no matter which route they are choosing. This relaxation can be realistic when it comes to tankers, but for liner shipping this would not be the case. A cheaper toll-free route could enable the ship operators to increase their sailing speed to obtain a comparable voyage duration. This will also have significant ramifications in the decarbonization of shipping. Depending on who will be paying for emissions in the future, sailing faster and opting for a longer route may not be an option. Canal authorities will understand that the value offered to ship operators when crossing their canal will increase. If ship operators currently select canal routes due to time savings, higher safety, and reduced fuel costs, adding a significant cost reduction in the form of lower emissions, may prompt canal authorities to increase their tolls. There is definitely



Source(s): Figure by authors

Figure 4.
Total cost comparison (tolls and fuel cost) for each ship and one-way route

room for toll fee optimization problems, and we should remember that if Canals are operating at their maximum capacity, toll fees will have to be increased due to a simple supply and demand issue. As the canals will not be further expanded anytime soon, there is also more attention given to Arctic routes as potential alternatives, which may have further negative environmental impacts. In the ongoing discussions at the IMO, there are several concerns raised by shipping companies that decarbonization may come at a price that will make their operations no longer economically sustainable.

5. Concluding remarks

This paper presented a methodology that allows the economic and environmental comparison of routes transiting a canal versus a toll-free alternative. A concise critical review of academic research on maritime transportation and the impacts of the two major canals was presented, and the main research themes were identified. Our quantitative analysis aimed to shed some light on how the pandemic led to a reduction of toll fees in the SC. It was shown that due to the very low fuel prices experienced in 2020, a ship operator could justify opting a longer detour instead of using a Canal, particularly when the transport demand was lowered. In the first half of 2021, a very different picture is seen, with extremely high freight rates, while also fuel prices have started increasing. These facts will restore the need of ship operators to transit through the major canals. We can therefore expect further increases in the toll fees in the coming years, which will require consideration also at the climate policy level, as this will affect the sector’s efforts to decarbonize.

As the attention of the shipping sector returns to its environmental issues, the importance of canals will be even more evident. Ships need to reduce their carbon emissions significantly if we are to reach the ambitious targets of the IMO. Our results clearly showed the reductions in fuel consumption when transiting a canal, and how a very low fuel price can jeopardize the traffic throughput through the canals. However, our analysis has some limitations mainly due to the lack of real-world data related to the actual toll fees paid to canals, and potential discounts offered for multiple transits to participating ship operators. It should be reiterated that the costs presented in our paper are the highest possible with the current tariffs, and in reality, these costs would be lower. We have only presented representative and illustrative ship types and voyages, but it would be a very interesting for further research to consider all ships currently transiting the canals in a longer time period.

Further analysis is required to compare the impacts of different MBMs on the route choice option of ship operators, considering more voyages and ship types. In summary, we consider that the following research questions could interest the academic community focussing on maritime disruptions and the operation of canals:

(1) Expansion of this analysis to include all voyages transiting canals

(2) Optimization of canal toll fees following new environmental standards

(3) Lifecycle estimate of environmental benefits through the use of major canals

(4) Impacts of current wars on maritime supply chain resilience and optimal routing

(5) Methodologies to isolate effects of major disruptions on fuel prices, freight rates, and capacity

Additional research could examine the optimal toll level following the polluter pays principle for ship operators, considering different voyages and ship types. When 1 tonne of fuel is burned it releases approximately 3.028–3.114 tonnes of CO_2 depending on the fuel type. If an MBM in the form of either a bunker levy/carbon tax, or inclusion to an ETS was used, the actual cost difference or each route and ship would change significantly. As all these costs will eventually be passed on to shippers and the consumer, there is an additional risk of reduced transportation volumes and modal shifts towards other modes (where possible). It is therefore imperative that the impacts of climate policy on route choice and the operation of canals be further explored. MBM would constitute any crossing that saves sailing distance more desirable for ship operators. However, as major disruptions on supply chains caused by wars, energy crises, inflation and pandemics keep on arising, more research is required to shed light on their impacts on shipping. A key challenge for researchers is to dissect the effects of disruptions and propose contingency plans for the affected stakeholders (shipping companies, ports, shippers and the society).

Notes

1. https://lloydslist.maritimeintelligence.informa.com/LL1136527/US-will-push-IMO-to-adopt-target-of-absolute-zero-emissions-by-2050

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Corresponding author
Thalis P.V. Zis can be contacted at: thalis.zis@cut.ac.cy