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Original Article

MULTIDIMENSIONAL COST ANALYSIS OF EUROPE–ASIA CONTAINER TRANSPORT ROUTES

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Highlights:
- viability of sea, rail and intermodal transport between Europe and Asia analysed;
- DTC, inventory carrying and EC included;
- emission pricing mechanisms unable to change the balance between transport modes;
- emissions of rail transport much higher if emissions of energy production included.

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Abstract. In this article, we propose a 3-dimensional framework for evaluating the costs of transporting goods between Europe and Asia, including direct transport, time, and Environmental Costs (ECs). We estimate the costs of alternative container transport routes, including direct sea transport via the Suez Canal Route (SCR) and the Northern Sea Route (NSR); direct rail connections via the Trans-Siberian Rail (TSR) and the Belt and Road Initiative (BRI), and intermodal transport options consisting of rail and sea transport legs. When considering environmental and Inventory Carrying Costs (ICs), the NSR is viable at least seasonally, whereas rail and intermodal alternatives remain more expensive. The results provide a robust estimate of the potential of alternative transport routes and modes. The inclusion of ECs in our analysis provides valuable new information to stakeholders on how to achieve the ambitious environmental goals while also considering the economic viability of different route options in Europe–Asia container trade.

Keywords: Europe–Asia container trade, transport corridors, cost of transport, environmental impact, route selection, transport policy.

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Notations

- a – variable [kW·h per source];
- ALT – alternative, referring to alternative scenarios of ETS cost;
- b – variable [kW·h per kg];
- BRI – Belt and Road Initiative;
- CII – carbon intensity indicator;
- CO_2 – carbon dioxide;
- CO_2e – CO_2 equivalent;
- CO_2f – CO_2 emission factor;
- DTC – direct transport cost;
- EC – environmental cost;
- EEDI – energy efficiency design index;
- EEXI – energy efficiency existing ship index;
- EP – electricity production [kW·h];
- ETS – emission trading system;
- EU – European Union;
- FEU – 40-foot equivalent unit;
- FO – daily fuel oil consumption;
- GHG – greenhouse gas;
- HB – higher bound;
- HR – heat rate;
- IA – second highest ice class of the Finnish–Swedish ice class rules;
- IC – inventory carrying cost;
- IMO – International Maritime Organization;
- IMF – International Monetary Fund;
- LB – lower bound;
- LIBOR – London interbank offered rate;
- MDO – marine diesel oil;
- NECA – nitrogen oxide emission control area;

NELB – New Eurasian Land Bridge;
NGO – non-governmental organization;
NSR – Northern Sea Route;
OC – operating cost;
SCC – social cost of carbon;
SCR – Suez Canal Route;
SECA – sulphur emission control area;
SEEMP – ship energy efficiency management plan;
SFOC – specific fuel oil consumption;
TCT – total cost of transport;
TEU – 20-foot equivalent unit;
TRC – traction cost;
TSR – Trans-Siberian Railway.

1. Introduction

The landscape of Europe–Asia container trade is constantly evolving because of increasing volume being traded, changing customer demand in terms of the increasing importance of speed and reliability, the emergence of new route options, and introduction of more stringent environmental regulations.

This lays the ground for a discussion on the potential of alternative transport corridors between Europe and Asia. Currently, the main Europe–Asia container transport corridor is the sea connection through the SCR. Climate change and the gradually melting Arctic Sea ice may render the NSR a new option in the future. Currently, the open water season in the Arctic lasts around 150 days per year, but this period is likely to increase in the future. Even with its currently minor role in Europe–Asia traffic, the TSR – and most recently the Chinese-led BRI – offer land bridge options across the Eurasian continent by rail.

Since 2020, international container trade has been in unprecedented turmoil. Occupational health issues caused by the pandemic have limited the efficiency of the system, whereas changes in consumer preferences have simultaneously boosted demand, causing poor availability of containers, record low service reliability, and soaring container freight costs. The high costs combined with delays and increased transit times have directed shippers to seek alternative, mainly land-based transport options.

Traditionally, the choice of transport mode and route in container trade has relied on an evaluation of DTCs and, in some cases, the capital costs associated with the transported cargo. However, this perspective fails to internalize the external costs of transport. Considering the ambitious goals of the Paris Agreement, which has been supported by recent plans of the European Commission, for example, the costs of CO_2 emissions should be given more attention.

With global trade rapidly growing, the research on route and mode alternatives in freight transport has gained more attention. Global trade largely relies on cost-efficient maritime trade (80% of world trade volumes are by sea), in which containerization and lowered tariffs in international trade have played an important role, among others (Hummels 2007; UNCTAD 2020). Overall, seaborne trade volumes (tons) have grown remarkably over the last 2 decades by almost 95% from 2000 to 2019 and by 41% from 2010 to 2019. Contained global trade totalled 152 million TEU in 2019. Between Asia and Europe, the total volume was 24.7 million TEU, of which 17.5 million TEU was in the westbound and 7.2 million TEU was in the eastbound directions (UNCTAD 2020).

Transport operators tend to choose the route that minimizes the transportation costs (e.g., fuel costs and other operational costs) while providing quick and efficient transportation according to the customer's needs (Hao, Yue 2016). Depending on what factors are preferred, the choice of mode and/or route may differ. For example, from the perspective of time/cost in Europe–Asia trade, shipping is typically the cheapest option, but it is also the slowest mode. Air transport is the fastest option, but it is also remarkably more expensive, whereas rail transport falls in between.

Container ships trump other modes by a large margin in their carrying capacity, making shipping an extremely efficient mode of transport per transported cargo unit. Despite its increased efficiency, its cost per ton has not been reduced accordingly. Thus, the composition of transported goods has shifted toward higher valued goods, especially in westbound container trade, whereas the eastbound backhaul also includes recycled metals and other less valuable goods. The higher the value of goods, the more it invites competition between transport modes and routes (Hummels 2007).

Characteristically, external (transport) costs have often been neglected in cost calculations because they do not affect day-to-day business. The environmental aspects of transport are gaining more attention in academic and business discussions, with climate change and its mitigation are becoming more prevalent. Climate change was recognized as an urgent threat by the *Paris Agreement*, and it set a mitigation goal to limit the mean global temperature increase to below 2 centigrade, preferably below 1.5 centigrade. Here, transport is currently responsible for approximately 24% of direct CO_2 emissions (IEA 2023), which has led to various transportation GHG emission mitigation schemes by different government and NGO bodies.

Although international shipping was excluded from the agreement, the discussion has been active in the maritime sector. Currently, shipping accounts for around 2.7% of global GHG emissions (IMO 2021a). The IMO has introduced the *Initial IMO Strategy on Reduction of GHG Emissions from Ships* in April 2018, which aims to reduce the carbon intensity of international shipping by 70% and annual GHG emissions by at least 50% by 2050 (compared with 2008 levels) to show support of the *Paris Agreement*. Additionally, the IMO has adopted various regulations through progressive amendments to its *International Convention for the Prevention of Pollution from Ships* (MARPOL) to control sulphur and nitrogen emissions (SECA and NECA) and increase ship energy efficiency (EEDI, EEXI, SEEMP, and CII in MARPOL Annex VI; IMO 2021b, 1973; Xing *et al.* 2021; Gilbert *et al.* 2018).

With its *European Green Deal*, the EU has put forward ambitious goals to become the 1st net-zero economic area by 2050 (EC 2021c). This goal has been enforced with the latest proposal (the so-called "Fit for 55" package) that aims to reduce net GHG emissions by at least 55% by 2030. The package includes a proposal to include maritime transport to the EU ETS. If EU ETS is enlarged to maritime transport in the proposed form, it would introduce a monetary cost per ton of CO_2 for maritime trade within EU states, and it would be applied by 50% to outside of the EU to EU (and vice versa) trade as well (EC 2021a).

In February 2022, EU ETS emission prices reached their maximum value to date at €97 per ton of CO_2. This is 3.2 times higher than the price in January 2021 (€30 per ton of CO_2). Analysts have accounted for the sharp increase as being because of the introduction of stricter environmental regulations, along with increased energy demand because of the winter period, among other factors. Estimations of the price in the near future have ranged from €60...110 per CO_2 emitted (Marcu *et al.* 2021; Nordeng *et al.* 2021; EMBER 2025).

Because of the need to comply with the increasingly stricter environmental regulations, transport operators have had to rethink their operations (route options, operational decisions, propulsion, source of energy, etc.). In shipping, slow steaming will reduce GHG emissions, but this will make faster alternatives more attractive because of the cost of inventory of goods in transit (Psaraftis, Kontovas 2010).

As of spring 2020, the global COVID-19 pandemic has increased the use of alternative transport routes (e.g., rail transport or other alternative sea routes) in Asia–Europe trade because of significant congestion and delays in container shipping throughout 2020–2021. Some shippers also opted to reroute their ships via the Cape of Good Hope to reduce idle time, despite the journey being significantly longer. This was feasible in 2020 because bunker fuel prices dropped by up to 70% during the 1st half of 2020 for some fuel grades (Ship & Bunker 2021).

It is no surprise that competition and environmental regulations have motivated research to compare transport mode alternatives, preferences of actors, and key attributes concerning the related decision-making. However, comparison is a complex task because there are a great number of attributes and variables to compare (Hummels 2007; Fries *et al.* 2010; Tavasszy *et al.* 2011).

The current article analyses the transport costs of multiple transport route combinations between Europe and Asia using a 3-dimensional framework that includes direct transport, inventory, and ECs. The purpose is twofold. The 1st aim is to analyse the viability of alternative transport routes between Europe and Asia when inventory costs and externalities are also considered. The other aim is to estimate the impact of including shipping into the EU ETS on the balance between alternative container transport routes.

The analysed route combinations include the traditional sea route through the SCR and the alternative NSR. In addition to sea routes, a land-based option via TSR is included, together with a multimodal route combining rail and sea transport. In our analysis, transport costs are estimated based on technical details, including cargo-carrying capacity, energy consumption, and price details of ships and trains. The capital costs are estimated based on the average values of containerized goods (Rodrique 2020).

Of the ECs, the current research focuses on GHG emissions, particularly on CO_2 emissions, here in view of EU ETS emission prices. The ECs of sea transportation are estimated based on the fuel consumption of ships, whereas the ECs of rail transport are estimated by combining technical data on the energy consumption of locomotives with the energy production mix and emission factors of the energy production of countries along the TSR.

The rest of the current article is organized as follows: current Section 1 – an introduction, Section 2 provides a review of the relevant literature, Section 3 describes the framework and key parameters, The results are presented in Section 4, and Section 5 discusses the results before giving a conclusion.

2. Literature review

2.1. Alternative route options in Europe–Asia container traffic

Currently, the main transport corridor in Europe–Asia trade is the maritime trade lane passing through the Suez Canal and Malacca Strait. Technically, maritime lanes are not restricted by the travel path, but because of the efficiency gained from following the great circle distance, major trade lanes around the glove have stabilized along the shortest East–West axle. The Suez Canal plays an especially important role because it allows ships to bypass the circumnavigation of the Cape of Good Hope, greatly shortening the transit time and distance and, thus, transport costs.

In addition to the SCR, there exist alternative trade corridors in Europe–Asia trade: the TSR, Chinese government-driven BRI, and the NSR, all of which attract currently marginal volumes compared with the traditional SCR (Schramm, Zhang 2019). Asia–Europe train container traffic was estimated to be 0.8...1.0 million TEU in 2020 (<5% of Europe–Asia maritime container trade), and for the NSR, international transit cargo was estimated to be 0.012 million TEU in 2019 (<0.05% of Europe–Asia maritime container trade – UNCTAD 2020; Gunnarsson, Moe 2021; Zhang 2021).

The NSR is located along the territorial waters of the Russian Arctic and is considered to have the highest potential as an alternative sea route compared with the SCR. The main advantage of the NSR is considered to be its shorter length compared with the SCR (e.g., Hamburg – Yokohama is almost 40% and Shanghai – Rotterdam 28% shorter via the NSR). This could lead to significant savings in bunkering costs and, therefore, lower transport costs (Vlček *et al.* 2019; Zeng *et al.* 2020). However, given the

Arctic and other atypical seafaring conditions of the NSR, the actual economic feasibility of the route may vary (e.g., Solakivi *et al.* 2018).

Currently, most of the traffic on the NSR is seasonal and destination traffic to and from the northern parts of Russia, especially the gas fields in the Yamal Peninsula, whereas transit traffic between Europe and Asia has been marginal. Liner shipping along the NSR is practically non-existent. Studies evaluating the potential of the NSR for commercial cargo transport have varied greatly in their methodologies, parameters, and results (Lasserre 2014; Kiiski 2017). Estimates on the navigability time of the NSR vary from a whole year (Benedyk, Peeta 2018) to 6 months (Liu, Kronbak 2010; Solvang *et al.* 2018) and from 3 to 9 months (Yangjun *et al.* 2018).

In their long-term forecast, Aksenov *et al.* (2017) estimate that the North Pole will be ice-free and navigable during summer months (June–August), possibly before 2040 and probably after 2050, which would further improve the distance difference of NSR toward competing routes. However, commercial traffic would still require icebreaker assistance during winter. According to Cariou *et al.* (2021), the NSR is currently a cost-competitive alternative to the SCR or TSR for only 1.5 months during a year.

On the other hand, large and modern container ships of over 20000 TEU are efficient at sea, but additional port calls increase end-to-end transit times. Furuichi & Otsuka (2018) argue that although vessels in the NSR are smaller, the significantly shorter distance compared with the SCR makes the route viable. This is especially the case when these smaller vessels could provide faster service using the route via the Suez Canal in seasons when it is not possible to use the NSR. The NSR can be attractive when the combination of lower freight, shorter transit time, and sufficient reliability are all favourable and stable (Benedyk, Peeta 2018).

Railway transport is another possible option for containerized cargo in Europe–Asia trade. Cargo has been transported by train between Europe and Asia for a long time, but the volumes have fluctuated remarkably over the years. From 2011 onwards, the Europe–Asia rail container traffic has been increasing at a quick pace, especially between China and Europe, which has roughly doubled every year (Bucsky 2020; Pepe 2020; Chan 2018). Recent developments because of the COVID-19 pandemic have also boosted the popularity of rail freight in the Europe–Asia container trade (Pomfret 2021).

Historically, the most prominent rail corridor has been the TSR, which transverses from Europe through Russia to Vladivostok in Far East Russia. In addition to the TSR, other rail corridors are being developed under the BRI, most central being the NELB: China (Lianyungang) – Kazakhstan (Dostyk, Aktogay, Alma, Ata) – Uzbekistan (Tashkent) – Turkmenistan (Serakhs) – Iran (Tehran) – Turkey (Istanbul) –Europe. In addition to the NELB, other trade corridors under the BRI are also being developed, namely the Northern Corridor (3 alternative routes linking up to the TSR from China: the Kazakh, Mongolian, and Manchurian routes) and the Southern Corridor (through the Caspian Sea with at least one ferry leg). The Northern Corridor's route, which transits through Kazakhstan, currently holds most of the container traffic. Depending on the destination and development of infrastructure, the exact route might differ (Bucsky 2020; Schramm, Zhang 2018; Bezrukov 2018).

Available rail corridors vary in length and transit time (depending on origin and destination, 10000...13000 km), as well as in their conditions. Compared with other rail routes, the TSR is currently considered the most developed. Challenges here include technical conditions (e.g., gauge, electrification, aged infrastructure), political issues (e.g., regional instability, intercountry relations), and economic barriers (e.g., customs procedures), among others (Bezrukov 2018; Bucsky 2020; Pomfret 2021). Another major disadvantage is the limited capacity of rail freight compared with ships; a typical container train is approximately 50 FEU, whereas the largest container ships are reaching the capacity of 24000 TEU (1 FEU = 2 TEU). Additionally, the TSR is estimated as approaching its nominal capacity for cargo transport overall (Pepe 2020; Zhang, Schramm 2020; Bezrukov 2018).

Despite the limited capacity, technical issues and complex customs, the speed offered by rail transport makes it a competitive alternative for a broad range of products (Schramm, Zhang 2018). Container traffic is not limited between seaports, and for landlocked countries, train connection is also viable for goods of lower value (Lu *et al.* 2019). Railways have been deemed 2 times faster than the maritime option and 80% cheaper than air (Schramm, Zhang 2018).

2.2. Factors affecting the route and mode choice of containers

Transport mode and route choice have been studied for a long time, balancing between various criteria of transport cost and quality. In many studies, quality criteria such as reliability (Kurri *et al.* 2000) and time (Saldanha *et al.* 2009) have been found to be more important than the cost. Naturally, many of the criteria related to the quality of transportation can also be approached from the perspective of their cost impact. For example, Hummels & Schaur (2013) estimate the impact of time on the competitiveness of the product, concluding that the value of time could be as high as 2% of the price of the product per day. Because transportation often is just a part of the supply chain of the product, the frequency of the service (Kang *et al.* 2010) has also been found to be a key criterion for transportation choices.

Even though the externalities of transport – especially the environmental impact – have received a lot of attention both in the general discussion and transport research, the role of environmental issues is still found to be minor in the decision-making concerning transportation (Yang *et al.* 2018). This might be explained by the shippers' limited willingness to pay for environmentally sustainable transport (Fries *et al.* 2010) and the lack of incentives to provide such a service. Even with the key role of quality criteria being recognized, the cost criteria dominates the final decisions (Yang *et al.* 2018) and, therefore, the research associated with it. From the perspective of decision-making, the focus on cost could originate from the role of different criteria as order qualifiers and order winners. Instead of considering the quality and cost criteria as alternatives, from the perspective of decision-making, the quality criteria might act more as order qualifiers, whereas the cost criteria would be used to make the choice between the qualifying alternatives. From a research perspective, cost criteria are usually more easily measured and objectively quantified than quality.

Especially when considering the cost criteria, a lot of work focuses on the DTC, estimating the structure and level of the key cost components that – regardless of transport mode – include fuel/energy cost, capital costs, labour/manning costs, and so forth. Especially regarding shipping, much work has been done to analyse the key variables affecting the level of the major cost components and their impact on the economic viability of different transport options. Because fuel cost is a major cost in shipping and fuel consumption is highly dependent on speed, a lot of work has been done on the impact of speed on the cost of transportation (e.g., Maloni *et al.* 2013, Wang *et al.* 2013). In addition to the DTC, the in-transit inventory is often included in analyses as a trade-off (Psaraftis, Kontovas 2010). Even though the environmental impact of transportation is often discussed, it has not been included in analyses, save for some more recent work such as Ding *et al.* (2020).

Concerning Asia–Europe container transport, the traditional lens of analysis has been the SCR, which currently covers most traffic. As interest in the NSR has increased, research has focused on either the comparison of the 2 alternatives (Liu, Kronbak 2010; Yangjun *et al.* 2018) or, more recently, on combining the 2 routes in the same liner shipping network (Furuichi, Otsuka 2018; Sibul, Jin 2021).

The rail connection via the Eurasian land bridge has received less attention, but there is a growing interest toward the rail connection as well, caused by the emergence of the Chinese-led BRI. Some research has also considered the rail option as an alternative to maritime transport (Tavasszy *et al.* 2011). Most previous work has also focused on the transport between major hubs in Asia and Europe, where recently, Lu *et al.* (2019) have extended this perspective by considering the impact of the hinterland connection on the competitiveness of sea- and land-based alternatives.

2.3. Environmental aspects in cost analyses

The abatement cost of a negative environmental impact is increasingly affecting the selection of transport mode. For example, Psaraftis & Kontovas (2013) propose a taxonomy for estimating the costs of environmental actions and energy efficiency in transport. Their model consists of optimization criteria, market context, decision-maker, fuel price, freight rate, fuel consumption, speed (as function of cargo value), logistics (as routing), fleet size, capacity, inventory cost, emissions, and modal split.

However, the abatement cost of environmental hazards is a multifaceted problem in transport comparisons. Purely from a GHG emissions (lifetime CO_2) point of view, the marine transportation of a container is environmentally friendlier than train or other transport modes. According to measurements by Frischknecht *et al.* (2016), container-ships had an average CO_2 footprint of 15 g of CO_2e per ton-kilometre, whereas electric trains (across Europe) had a CO_2e footprint of 24 g, intercontinental aviation 989 g, and 50…60-ton heavy goods vehicles 86 g of CO_2e per ton-kilometre. Conversely, the ecological hazards vary between different routes, and comparison is not clear-cut. Additionally, environmental externalities have less significance for commercial decisions, as long as they are not internalized. Yang *et al.* (2018) compared land express trains and the traditional SCR. Their conclusion is that route selection is primarily an economical decision dependent on cost, time, and frequency.

From environmental and economic perspectives, the NSR is not very competitive for containerized cargo. According to Cariou *et al.* (2021), the NSR is a viable alternative for only a very limited period of time, and even then, it is slower than Trans-Siberian rail and exceeds CO_2 emissions of the SCR. Once the NSR is more navigable, it will be faster than the SCR. However, possible carbon tax may impact the feasibility of the NSR, especially if the SCR will have lower fees (Ding *et al.* 2020). As Liu & Kronbak (2010) note, although the NSR is shorter than the SCR, thus reducing GHGs, the increased traffic will add risk of oil spill and ballast water damage in arctic waters. Also, even when the NSR's navigability improves, the EC remains at a higher level compared with the SCR (Zhu *et al.* 2018).

3. Methodology

We analyse 4 different route configurations for container transport from Rotterdam to Shanghai, as illustrated in Figure – sea routes going either via the SCR or NSR, a direct train connection through continental Eurasia, a hypothetical multimodal option going 1st via rail connections from Rotterdam to Kirkenes in northern Norway, and via the NSR from Kirkenes to Shanghai.

As it comes to the analysed route alternatives, some key assumptions and simplifications have been made. Deep sea container transport is characteristically a liner shipping network, where container vessels make multiple port calls on a fixed round trip (e.g., Zhao *et al.* 2016) In reality, the number of port calls would have an impact on transport time and, considering that also the IC in included in the analysis, also the costs of the given route. The same would also be the case considering the rail alternatives. Assuming additional stops along the route (caused by congestion, for example) would cause an additional cost. Further, considering that especially in the NSR no infrastructure for a container port call is available, and there-

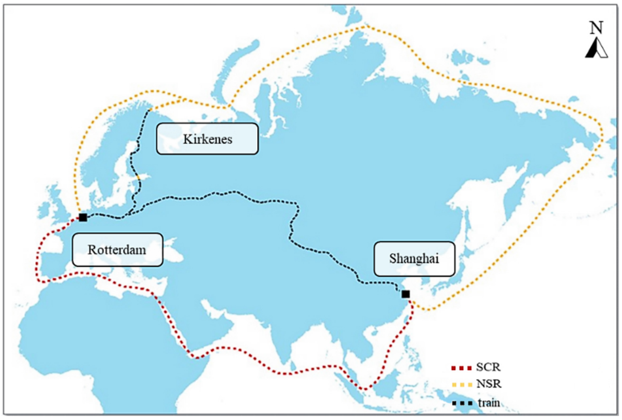

Figure. Transport routes in the study

fore it would most likely be the case that different route alternatives would have different number of port calls (e.g., Ding *et al.* 2020) we decided to limit the analysis to a direct transport between the origin and destination, excluding possible additional calls. Similar approach has recently been employed by for example Cariou *et al.* (2021). The details of the route options are provided in Table 1.

The TCT is considered to consist of 3 cost components: DTCs, ICs, and ECs. Further, the DTC is considered to include all the costs related to transport between the origin and destination.

$$TCT = DTC + IC + EC. \quad (1)$$

Because the 2 transport modes are included, their costs are calculated following the example of the literature. For the NSR, the calculations were based on the currently largest ice classed (IA) container vessel suitable for transport in the NSR: the Venta Maersk. For the SCR, the calculations were based on one of the largest containerships: the MSC Gülsun. The MSC Gülsun was the largest containership in 2019 but has now been surpassed by 3 other size classes that have added some 200 TEUs to MSC Gülsun's 23756 TEU max capacity.

As for rail transport, the calculations were based on the Alstom Prima T8 locomotive, which has an average freight load of 100 TEU (50 FEU) in Asia–Europe train transport (UTLC 2020). For reference, a container block train can carry 55 FEU in China and 75 FEU in the TSR and is usually limited to 44 FEUs in Europe. Theoretically, the locomotive could reach a maximum traction capacity of 276 TEU (138 FEU). However, because of infrastructure and clearance limitations (e.g., axle load, limited clearance, height limits, etc.), double-stacked containers or extremely long trains are not viable (Zhang, Schramm 2020). The key parameters are shown in Table 2.

The costs of maritime transport consist of fuel costs, capital costs, and OCs, as suggested by, for example, Cullinane & Khanna (1999) and Solakivi *et al.* (2018). Fuel costs are calculated following Cullinane & Khanna (1999) by multiplying the estimated daily consumption of fuel oil by the unit price per ton. Fuel prices are retrieved from Ship & Bunker (2021). The following equation is used for FO:

$$FO = Installed\ power \cdot SFOC \times Engine\ load\,(80\%) \cdot \frac{24}{1000000}, \quad (2)$$

where: *Installed power* is the installed power of the main engine power on the ship; *SFOC* is a metric used to determine the marine engine's efficiency and is listed, for example, in *Clarkson's World Fleet Register* (Clarksons Research 2025). SFOC can be calculated as the mass of fuel consumed per hour per power developed (kW). Engine load represents the power of the engine, that is, its capacity to produce power (torque output; Shahid *et al.* 2019). An engine load of 80% was chosen because it is the optimal range (80...85%) for ship engines to gain maximum efficiency.

The daily capital costs were calculated as an annuity for 20 years (the assumed economic life of the vessel), here following the recommendation of Wijnolst & Wergeland (2009) to use the LIBOR plus a margin of 1.5%. To avoid interest rate volatility, the calculations were based on a 5-year average (2016–2020) of the 12-month LIBOR rate from the Federal Reserve Bank of St. Louis (US). Furthermore, a 25% residual value was assumed for the vessel (Wijnolst, Wergeland 2009).

The daily OCs were calculated based on the size of the example vessels, which was done by using the previous results of Solakivi *et al.* (2018), here assuming the daily OCs of a container vessel using the following ratio: $\ln(OC) = 6.29 + 0.31 \cdot \ln(TEU)$, where: *OC* is cost compris-

Table 1. Summary of the studied routes

Mode	Route	Distance [km]	Transport time* [days]
Sea	Rotterdam – Shanghai Arctic	14875	18
Sea	Rotterdam – Shanghai Suez	19300	21
Rail	Rotterdam – Duisburg – Brest – Moscow – Yekaterinburg – Presnogorkovka – Astana – Druzhba – Urumqi – Lanzhou – Nanjing – Shanghai	12840	18
Intermodal	*Rail*: Rotterdam – Hannover – Berlin – Warsaw – Bialystok – Kaunas – Riga – Tallinn – Helsinki – Rovaniemi – Inari – Kirkenes	4016	6
	Sea: Kirkenes – Shanghai	11600	14
	Total	15616	20

Note: * transport time is calculated by excluding possible additional calls.

Table 2. Key parameters of chosen transport route and vehicles (Clarksons Research 2025; Alstom 2020)

	Venta Maersk	MSC Gülsun	Alstom Prima T8	Alstom Prima T8 / Venta Maersk
Route	sea	sea	rail	intermodal
Configuration	IA class container vessel	container vessel	locomotive + single FEU stacked carts	–
Fuel / energy source	MDO	MDO	electricity	MDO + electricity
TEU Capacity	3600	23756	100	–
Speed [kn]	19	21	–	–
Installed power [kW]	16080	95390	8948	–
Distance sea [km]	14875	19300	–	11600
Distance rail [km]	–	–	12840	4016
Days	18	21...27	18	20
Weight [mt] of the container (FEU) + cart	–	–	54.5	54.5

ing crew, maintenance, and insurance costs; *TEU* represents the overall capacity of the vessel. Because the studied transport routes also include the Suez Canal, the Suez Canal toll is also included. For this, the Suez Canal toll was obtained from the Suez Canal toll table (Suez Canal Authority 2025). Because container vessels practically never sail fully loaded, the daily costs for a single container were calculated by assuming an 87% fill rate, which has previously been used by, for example, Cariou *et al.* (2021).

The cost of rail transport is calculated following Gattuso & Restuccia (2014) example and is considered to consist of capital cost and depreciation of the rolling stock (locomotives and carts), the energy cost (traction), maintenance, salaries, and access charges of the rail network. The capital cost and depreciation of the rolling stock was calculated for an Alstom Prima T8 locomotive with a price of US$4.375 million (Alstom 2020) and US$50000 for the rail cart, assuming an economic life of 35 years for the locomotive and 32 years for the cart and using the same LIBOR +1.5 percentage points to account for the interest rate volatility as with the shipping costs.

The TRC was calculated by 1st estimating the transport work of the rail transport and then multiplying it by the average energy consumption of a locomotive and average price of electricity. The 40 ft containers (FEU at 32.5 tons) were assumed to be double stacked on a 22-ton railway cart (Rail Baltica 2018; UNECE 2019), bringing the gross weight of the container to 54.5 tons. This was then multiplied by the length of the rail transport(s). The energy consumption of rail transport was assumed to be 0.02 kW·h per ton-km (Klein *et al.* 2021; Ligterink *et al.* 2017), and the price of electricity was 0.1173 €/kW·h or 0.1349 US$/kW·h (Eurostat 2025). Where applicable, cost parameters are converted to US$, with an average exchange ratio of 1.15 (EUR/US$) from 2016–9/2021.

Maintenance costs were considered to be €3 (US$3.45) per train-km, because Gattuso & Restuccia (2014) estimate it to be between €2.5 and €3.5 per train-km. Salaries (US$19 per day) were calculated as distance weighted average from train drivers' mean salaries along the route, as obtained from Salary Explorer (2025). Finally, from EC (2021b), access charges of €2.338 (US$2.689 per train-km) were calculated as an average of access charges.

ICs were calculated using the previous estimates of the retail values of full container loads of different product categories presented by Rodrique (2020). Rodrique (2020) presents the high- and low-end values of commodities in 12 product categories, with a large variance ranging from US$20000 all the way up to US$2.5 million per FEU. Because it is impossible to estimate the relative share of these commodities, an average value (US$470000 per FEU) was used, resulting in an average IC of US$43.3 per day.

Even though the environmental effects of transport are numerous, in the current research, the environmental effects are considered only from the perspective of CO_2 emissions. For simplicity, the calculations were made assuming a single widely used fuel grade, MDO, with an emission factor of 3.206 g CO_2/g of fuel (IMO 2021a). The CO_2 emission estimates are based on the calculated fuel consumption (Equation (2)), which is multiplied by the fuel-specific emission factor and time in transit. Maritime transit time depends on the route-specific traversing speed.

For railways, the CO_2 emissions were calculated based on the CO_2 intensity of the EP of the countries along the route. For the EU, the CO_2 intensities were obtained from the European Environment Agency (EEA 2025), whereas for countries outside the EU, the CO_2 intensities were calculated based on the EP mix, which is calculated from the International Energy Agency data (IEA 2025) using the following formula:

$$\textit{Carbon intensity of electricity production} = \frac{\sum\left(\left(\frac{a}{b}\cdot CO_2 f\right)\cdot HR\right)}{EP}\cdot 1000. \quad (3)$$

For simplicity, the CO_2 emissions were calculated only for the largest emission sources of energy production (coal, gas, and oil), whereas other energy sources were considered CO_2 neutral. Table 3 presents the CO_2 intensities.

Table 3. Carbon intensity of EP

	Produced electricity GWh (% of production)			g CO_2 [kW·h]
	Coal	Gas	Oil	
Netherlands				390*
France				56*
Germany				350*
Poland				751*
Estonia				746*
Finland				89*
Lithuania				83*
Latvia				150*
Belarus	30 (0.1%)	38 790 (97%)	197 (0.5%)	220**
Russian federation	176787 (16%)	519149 (46%)	12010 (1%)	322**
China	4796126 (66%)	236872 (3%)	11036 (0.2%)	883**
Kazakhstan	75164 (70%)	21562 (20%)	0 (0%)	964**
kW·h per kg	6.7	10.88	8.5	
Heat rate (EIA)	0.3245	0.4362	0.3075	
kg CO_2/ kg fuel (US EPA)	2.86	1.0489	2.7183	

Notes: * data obtained from EEA (2025); ** calculated from IEA data (2025).

As for emissions, the CO_2 intensities were multiplied by the needed amount of energy to produce the needed transport work in the respective countries.

Finally, the CO_2 emissions were converted into monetary values by utilizing the concept of the SCC, which represents the economic cost caused by an additional ton of CO_2 emissions or its equivalent (Nordhaus 2017). The literature on SCC provides different monetary values because of differing methodologies, discount rates, and so forth. For the base estimate of ECs, an ETS-based estimate mimicking "realistic" conditions was formed, with costs being estimated per full effect using currently known prices.

According to the EU's "Fit for 55" legislative package (July 2021), the EU ETS is proposed to be amended to include maritime transport. Emissions for the voyage are accounted for based on the departing and arrival ports. If both ports are within the EU member state's jurisdiction, emissions occurring during the voyage are accounted for fully (100%). If either of the ports is outside the EU member state's jurisdiction, the emissions account for 50% of the emissions. For our base calculation, the modelled ships traversed directly to the destination.

In sensitivity analyses, the ships stop within EU jurisdiction areas as well (Table 5). For train transport, environmental cost estimations are applied to countries with active ETS schemes. For the EU, ECs are calculated up to the Poland–Belarus border. Belarus and Russia do not have active ETS schemes and, therefore, are unaccounted for. Calculations are then resumed from the border of Kazakhstan to Shanghai (China). For the intermodal route, the transit route stays within the EU borders and is accounted for fully up to Kirkenes (ICAP 2025a).

The carbon prices are sourced from different publicly available listings and then converted (if applicable) to US$ using the average exchange rate calculated from 2016–9/2021 (Macrotrends 2021a, 2021b; Investing.com 2025). EU ETS is calculated at a price of €60 (US$69), the Kazakh ETS at 456 KZT (US$1.2), and the Chinese ETS at 40 CNY (US$5.9) per ton of CO_2 (Lin 2021; ICAP 2025b; EMBER 2025).

4. Results

Table 4 presents the calculation results. As expected, the DTCs, including the Suez Canal tolls, are the lowest, totalling slightly over US$400 per FEU. Not surprisingly, they are followed by Arctic Sea transport (around US$540 per FEU) and intermodal transport (US$1685 per FEU). As expected, the direct cost of rail transport exceeds all others and is estimated to be around US$4000 per FEU for the journey. This alone sets rather strong limits to the modal shift between the modes and routes.

Theoretically, ICs might balance the situation because the rail connection is shorter than the seaborne route options. With an average value of a container (Rodrique 2020), the daily capital cost in transit is estimated at around US$43. Both the Arctic shipping route and the rail connection take around 18 days and result in an IC of around US$779 for a FEU container. For the Suez connection, however, the transit time was a bit longer. Assuming that a container vessel would be able to sail at its regular sailing speed without any stops along the way, the journey would take around 21 days, which would result in an IC of around US$909 per FEU.

However, this is not the case because the large container vessels rotate between multiple ports and make stops along the way. A container is expected to transit through the SCR from Shanghai to Rotterdam on average in 27 days, which would bring the IC of an average 40 FEU containers to US$1170. Finally, the intermodal op-

Table 4. TCT calculation results

		Sea (Arctic)	Sea (Suez)	Rail	Intermodal
DTC					
Maritime	fuel	281	201		219
	capital	219	151		170
	operating	42	10		32
	Suez Canal toll		46		
Rail	capital			70	23
	traction			1888	590
	depreciation			122	41
	maintenance			886	277
	salaries			346	115
	access charges			691	216
DTC Total (US$)		541	408	4002	1685
IC					
Days in transit		18	21...27	18	20
Average value US$ in FEU	470400				
IC per day	43				
IC total [US$]		779	909...1170	779	866
EC					
CO_2 per FEU [tons]		1.67	1.76	8.80	2.64
EC cost per FEU (ETS-based, direct traverse) [US$]		29	30	88	115
TCT [US$]		1349	1347...1608	4869	2665

tion would take 20 days (excluding the time spent on loading and unloading in change of the mode), resulting in an IC of US$866.

The ECs of the 2 maritime options are very close to each other. The voyage through the NSR produces CO_2 emissions of 1.67 tons per FEU container, whereas the corresponding CO_2 emissions for the SCR are around 1.76 tons. With the chosen EC pricing method, these emissions are valued at US$29 and US$30, respectively. Interestingly, the high carbon intensity of EP along rail routes produces high CO_2 emissions for rail transport. However, given that part of the voyage is unaccounted for (Belarus and Russia leg, 12% of the CO_2 emissions) and ETS schemes for the Asian transport leg (78% of CO_2 emissions) are relatively low priced compared with EU ETS, the overall ECs are lower than in the intermodal option. For the intermodal transport option, the joint CO_2 emissions of rail and sea transport are around 2.64 tons per FEU, whereas the emissions for rail transport are as high as 8.80 tons per FEU. Monetarily, these emissions correspond to ECs of US$115 and US$88, respectively. The ECs are further discussed and evaluated in our sensitivity analyses.

With all the included cost components combined, it would seem that the cheapest transport option for an individual container transport would be through the SCR, with an estimated cost of US$1347 per FEU. The transport cost through the NSR is around a similar cost. Assuming a theoretical direct connection between origin and destination, the cost of transport through the SCR would equal the cost of the NSR. This, however, does not hold in reality because the container vessels rotate through multiple ports, increasing the transport time and, thus, the ICs, OCs and capital costs, increasing the cost of transport to US$1608 per container, making the NSR the cheapest option for an individual container. The 2 options with rail legs were found to be more expensive, as anticipated. The estimated total cost of the multimodal option is estimated to be US$2665, which is almost double (98%) that of the NSR and around 66% more than the SCR. The total cost of the rail option was estimated to be around US$4870, which exceeds the cost of the NSR option by approximately 261% and the SCR option by 203%.

Our sensitivity analyses do not change the overall efficiency ranking of the different route options. The share of the EC of TCT overall, however, does increase. In the base scenario and ALT–ETS scenario, the EC's portion of TCT is 2...4%. ALT–LB is 4...7%, and in the costliest, ALT–HB, the share of EC increases up to 13% of TCT (range 8–13%). Table 5 provides the results of the different pricing schemes and the overall TCT cost range.

Unsurprisingly, evaluating the ECs by changing the maritime routes to include an intra-EU stop increases the overall ECs (ALT–ETS). For the Arctic route, the ship departs from Rotterdam and has a transit stop at Kirkenes because Norway is part of the ETS system and this port is also used for the intermodal route.

For the Suez route, the modelled ship, the MSC Gülsun, stops at Algeciras (Spain) as per the MSC "Swan" line's route plan (MSC 2025). By adding these stops, the EC of the NSR increases by 22% and for the SCR 12%, that is,

Table 5. Sensitivity analysis of ECs

EC sensitivity analysis	Sea (Arctic)	Sea (Suez) I	Sea (Suez) II	Rail	Intermodal
Interim sum (DTC + IC)	1320	1317	1578	4781	2550
ALT–ETS: ETS-based (Intra/Extra-EU stops) [US$ per FEU]	35	34	34	88	115
ALT–LB: fixed LB (US$40/ton of CO_2) [US$ per FEU]	67	70	70	352	106
ALT–HB: fixed HB (US$80/ton of CO_2) [US$ per FEU]	133	141	141	704	211
TCT sensitivity range [US$]	1355…1454	1351…1457	1612…1718	4869…5485	2656…2761

Notes: Sea (Suez) I → transport time 21 days; Sea (Suez) II → transport time 27 days.

by US$6 and US$4 per FEU, respectively. Here, although the EU transit leg is relatively short, its weight of EC overall in ALT–ETS is noticeable: 36% for the NSR and 22% for the SCR. Changes in overall costs might steer operators/shipowners to rethink their port calls and liner routes in the future to optimize their ECs. For rail transport portions, changing the routes in ALT–ETS does not change the ECs because the EU part of the transport leg is already fully accounted for.

For train transportation, in the EC estimations, there is a gap in the ETS coverages because Belarus and Russia do not have an active ETS scheme or one being planned, according to ICAP (2025a, 2025b). This unaccounted leg is 12% of the total emissions of the train route's voyage, and calculating it with the EU ETS pricing (US$69), this would correspond to US$72 per FEU. Using the EU ETS pricing, train transportation would pay the highest EC compensation overall, passing the intermodal option, in the ALT–ETS. Additionally, although the Kazakh and Chinese transport leg (2.4 tons of CO_2 and 4.5 tons of CO_2, respectively) are responsible for most (78%) of the CO_2 emissions of the train voyage, their ETS schemes pricing is relatively low compared with the EU one. Therefore, the overall EC compensation for the rail route is relatively low (34% of train EC) in the ETS-based scenario. If the Chinese and Kazakh legs were evaluated using a similar price level to the EU ETS, the share of train transport's EC of TCT would increase from 2% to 10% in the base scenario.

According to Lin (2021), the Chinese ETS is expected to increase in the future, with ETS prices increasing to 100 CNY per ton of CO_2 (US$15) in 2026–2027 and up to 300 CNY (US$45) in 2030 from the current level of 40 CNY (US$6) per ton CO_2. This would further increase the rail routes' ECs in the future. However, even at 100 CNY/ton (US$15), the EC of train transport would increase only by US$30 from US$88 to US$128 under the current ETS schemes, which would be lower than the ECs in the fixed-price scenarios (ALT–LB and ALT–HB).

As a comparison to the base scenario and ALT–ETS, ALT–LB and HB apply a fixed CO_2 cost throughout the voyage, and the EC performance of the route depends on its total CO_2 intensity. ALT–LB uses a fixed US$40 and ALT–HB a fixed US$80, here representing the LB and HB prices, respectively (World Bank Group 2019). Under this pricing, the EC per FEU cost of the train route would increase from 4 to 8 times compared with the base scenario, and for the maritime routes, the ECs would increase from 2 to 4 times per FEU overall. For the intermodal option, the LB price yields similar results to the base scenario, and HB pricing would almost double the ECs.

Our sensitivity analyses have the least effect on the intermodal route because ECs are covered throughout the voyage already in the base scenario. In ETS-based scenarios (base and ALT–ETS), the rail leg traverses fully within the EU and is accounted for at a 100% ETS rate, and the maritime leg's CO_2 emissions are accounted at 50% of the EU ETS rate. In the fixed-price alternatives, the ECs are higher, mainly because of the uniform application of ETS pricing. Compared with other modes, the intermodal option has slightly higher total CO_2 emissions than the sea route alternatives but significantly less than the train route.

5. Conclusions and discussion

The purpose of the present research was to explore the economic viability of the different transport routes between Europe and Asia when inventory carrying is included and the externalities of GHG emissions are internalized. More precisely, transportation between Rotterdam and Shanghai was chosen for the comparison. The results concerning the DTCs and ICs are, as expected, in line with previous research. Sea transport, especially through the SCR, was found to be the most cost effective, whereas the costs of intermodal and direct rail transport were considerably higher. Including the ICs in the equation switched the balance between the SCR and NSR when the longer transit time associated with the rotation of the large container vessels was considered. The balance between the 2 options should be interpreted with caution. Even though the NSR might theoretically be more cost effective in some circumstances, this might still be a special case because many –perhaps optimistic – assumptions were made. The transit time is considerably short because the vessel was assumed to be able to use the service speed throughout transit. In reality, the window of open water in the NSR is limited, and the vessels must navigate through ice-clogged waters during most of the year. Therefore, the real sailing speeds on the NSR are considerably lower. Hence, the vessels are forced to use ice-breaking assistance throughout most of the year. If these costs were included in the calculation, the cost balance would turn considerably to the advantage of the SCR. As anticipated, the rail and intermodal alternatives were found to be significantly more expensive than the sea-based alternatives. This result can partly be explained by the fact that an average value of a container was used, thereby reducing the value of time. Especially for the most valued, time-sensitive goods, rail transport is – and will be – a viable alternative, e.g., Zhang & Schramm 2020). This has been demonstrated during the ongoing COVID-19 pandemic because the demand for rail transport of containerized cargo has increased significantly while the timeliness of container sea transport has plummeted (e.g., Pomfret 2021).

From an environmental perspective, the current research evaluated the transport-related CO_2 emissions and their social costs using the current ETS scheme-based pricing method while including maritime transport into the EU ETS, as proposed by the EC (2021b). With the addition of maritime transport into the EU ETS scheme, CO_2 emissions can be covered and accounted for throughout the whole voyage, depending on the port calls. Additionally, sensitivity analysis applying a fixed rate of CO_2 cost to the route options was calculated. The share (weight) of ECs of the TCT ranged from 2% to 4% in the base scenario and 2% to 13% in our sensitivity analyses.

Under existing ETS schemes, train transport is not covered in its entirety. Approximately 12% (1.05 ton of CO_2) is currently unaccounted for (the Belarus and Russia transport leg). It might also be noteworthy that most of the estimated train CO_2 emissions occur outside the EU (90%), where there is no ETS scheme, or the ETS scheme's price is relatively low, thus keeping the share (weight) of the ECs of the total costs low in the base scenario (2% of total costs of transport). For comparison, evaluating the Asian leg with existing ETS schemes, here using EU ETS prices, would increase the share of the train route's ECs of the TCT to 10%. However, in China, where most train transport-related CO_2 emissions occur, the pricing of CO_2 is expected to increase in the future. An increase in emission costs will better compensate for CO_2 emissions, but on the other hand, it will also decrease the feasibility of transporting for all routes.

Additionally, on the maritime side, because of how the EU ETS is proposed to be calculated, even though the intra-EU leg is relatively short, its share of the total EC is noticeable. In the ALT–ETS, which included intra- and extra-EU port calls, the share of intra-EU in the EC was 22% for the SCR and 36% for the NSR. Thus, the inclusion of ETS and increases in the total transport costs might steer operators/shipowners to reconsider their shipping routes to minimize their costs in the future. Similarly, for train transport, additional costs might decrease the feasibility of the transport route, all factors considered.

In the fixed pricing scenario, the ECs increase by 2…4x for the sea routes and 4…8x for the train routes. The intermodal option is affected the least by this change because the ECs are accounted for more comprehensively in the base scenario because of the route choice. The fixed pricing results imply that the current ETS scheme price level could be higher because using the World Bank's (World Bank Group 2019) LB estimate in the calculations produces at least 2x higher EC compensations than that the current schemes do. This also implies that from the perspective of the environment, it is important to cover the entirety of the transport voyage.

With alternative pricing or more comprehensive ETS schemes (or other GHG abatement methods), the share of ECs could increase to 10…15% of the TCT, hence holding more significant weight in the shippers'/operators' decision-making. The IMF has, for example, proposed an international carbon price floor with a pricing scheme of US$25, US$50, and US$75 per ton of CO_2 emitted based on the size of the economy (low-income emerging market, high-income emerging market, and advanced economy, respectively) that would achieve similar weight that our fixed HB (US$80 per ton of CO_2 emitted) scenario results in (share of ECs of TCT 8…13% – Parry *et al.* 2021).

Because both the EU and IMO are taking measures to reduce the environmental impact of shipping, the current article takes part in a timely discussion of the effects of climate change–motivated regulation. Here, it seems internalizing the externalities of shipping does not seem to have any major impact on the economic viability of different transport alternatives. Even with the current rather high prices of CO_2, maritime transport would seem to be clearly the most cost-effective alternative for Europe–Asia container trade. The results underline the importance of including the emissions of energy production in any analysis.

Even though electric rail transport has low local emissions, their emissions depend on EP still mainly dependent on fossil fuels. As long as this is the case, the environmental friendliness of rail transport can be questioned. Also, even though the results of our analysis show that the balance between the transport modes is not affected, they also indicate the cross-elasticity between these transport modes. Introducing stricter regulations on one transport mode improves the competitiveness of the alternative modes. With the current EP mix along the route, rail transport has significantly higher CO_2 emissions per container compared with maritime alternatives. However, rail transport is not penalized in a manner similar to maritime transport. For environmental policy to be effective, all transport modes should be treated equally to prevent adverse selection.

The current research has both managerial and policy implications. For the shippers and shipping companies, this article has presented an estimate of economic viability and cost competitiveness of different transport alternatives while also including the cost of inventory and emerging ECs. With these estimates, firms can make more educated decisions regarding their transport. For policymakers, the results underline the importance of securing a level field for different alternatives because both regionally and modally limited regulations have the potential to distort the market between competing modes, leading to suboptimal results, especially from an environmental perspective.

Naturally, the current research is not without limitations. The cost of GHG abatement has increased rapidly; for example, the price of one EU ETS emission right has more than quadrupled in less than 2 years. This makes estimates of abatement costs difficult to make. Also, our estimates on emissions and inventory costs are based on averages, which do not consider more sophisticated technical nuances between individual locations, goods categories, and so forth. In considering the value of the container, analysing the value of containerized cargo would increase the understanding of what the true elasticity of demand between the competing modes and routes really is.

Further, our analysis is a simplification in a sense that the configuration of the liner shipping or rail transport system would in reality have an impact on the real cost levels of the analysed route alternatives. A natural expansion for further research would be to analyse how increasing or decreasing the number of calls along the routes would impact the cost balance between the routes.

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Author contributions

Tomi Solakivi, *Tuomas Kiiski* and *Aleksi Paimander* conceived the study and were responsible for the design and development of the data analysis.

Tomi Solakivi and *Aleksi Paimander* were responsible for data collection and analysis.

Tomi Solakivi and *Aleksi Paimander* were responsible for data interpretation.

Tomi Solakivi, *Tuomas Kiiski*, *Aleksi Paimander* and *Vesa Kilpi* wrote the 1st draft of the article.

Jarmo Malmsten was responsible for graphical illustrations.

Lauri Ojala was responsible for supervision of the work, funding and finalizing the article.

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