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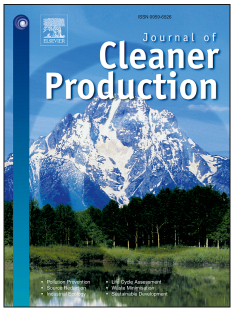

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Deterministic and stochastic carbon footprint of intermodal ferry and truck freight transport across Scandinavian routes

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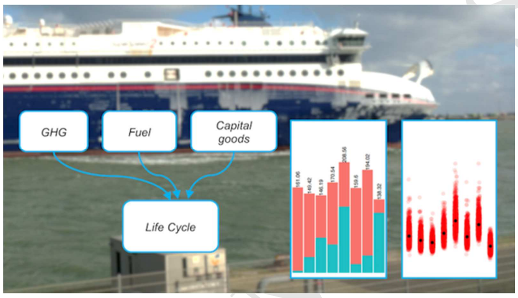
Graphical Abstract



Highlights

- The carbon savings of intermodal freight transport were investigated

- 66 intermodal truck-ferry routes in Scandinavia were analysed

- The carbon footprint of each route was calculated via Life Cycle Assessment

- Results uncertainty was quantified via comparative stochastic error propagation

- Intermodal routes with Ro-ro and LNG ferries show lower carbon footprint than truck-only routes

Abstract

Intermodal transport is the transport of cargo using one single unit by at least two different modes. Previous research suggests that intermodal transport might lead to emissions savings when traffic is shifted from high- to low-emission vehicles. This study aims to test this hypothesis by comparing intermodal truck-ferry routes and road-only routes within Scandinavia. The environmental performance of 66 routes in eight transport corridors was assessed in terms of carbon footprint using methods, databases, and software from the Life Cycle Assessment domain. To improve the robustness of the comparison between alternative routes, stochastic error propagation was applied to obtain a distribution of carbon footprint values for each route and pairwise statistical tests were performed between these distributions. Shifting freight traffic on ferries leads to emission reductions which size depends on the route, ferry type, and fuel used. Long distance routes by sea must sensibly cut road distance to allow for net emission reductions. The use of ferries transporting cargo only and of liquefied natural gas-powered ferries is highly preferable to the use of ferries carrying both cargo and passengers and of diesel ferries. The results can support the decision making of different stakeholders within the freight transport sector interested in lowering their carbon footprint.

Keywords

Sustainability, Shipping, Climate Change, Life Cycle Assessment, Uncertainty analysis

1. Introduction

The transportation sector is a major source of greenhouse gas (GHG) emissions worldwide and a substantial contributor to human-induced climate change. Transport represents almost a quarter of the GHG emissions of the European Union, of which 74% are associated to road transport while 13% are attributable to navigation and 13% to aviation (EC, 2018). In particular, freight transport via road is a major source of emissions, as heavy-duty vehicles are responsible for 6% of the total emissions of the European Union. Thus, the reduction of carbon emissions related to freight transport via road is a priority in order to comply with current political emissions reduction targets, such as the 80% GHG emissions reduction by 2050 under the Paris agreement conditions. Among the several possible solutions to this problem there are technological improvements, as the development of more efficient and near zero-emission engines, and management improvements, as reducing and optimizing transport distances and shifting the traffic from high-emission to low-emission vehicles, for example from truck to train or ship (Kreutzberger et al., 2003; Steadieseifi et al., 2014).

It is in principle possible to reduce the environmental impacts of freight transportation in Scandinavia by shifting traffic from road to sea routes, as the existing infrastructure of several ports and vessels operating between them could support this shift (Jia et al., 2017). Nowadays, freight transport in container ships over transoceanic distance allows lowering carbon emissions compared to air or road transport, despite the large absolute magnitude of the emissions associated with the international shipping industry, estimated at 2.5% of global greenhouse gas emissions (IMO, 2014). A concrete option for sea freight transport within Scandinavia is the use of roll-on/roll-off (ro-ro) vessels designed to carry wheeled cargo, such as ferries. Ferries can be dedicated to cargo transport only, passengers only, or both. The demand for this type of cargo transport is increasing in Northern Europe (Shippax, 2016). Ferries have a smaller size compared to transoceanic container ships and higher emissions per t of cargo transported. It is therefore unclear whether shifting the freight transport from trucks to ferries would reduce GHG emissions.

In this context, this study has two objectives. The first objective is to compare the carbon footprint of alternative sea-road routes and road-only routes within Scandinavia. Doing so would answer the question of whether increasing the freight transport via ferry leads to a reduction in the environmental impact related to carbon emissions. The second objective of this work is to provide quantitative estimates of the uncertainties associated with the carbon footprint of each transport route, and to investigate whether the choice between different alternatives can be made with sufficient statistical confidence. Identifying low-emission routes is interesting for different stakeholders in the transport sector from logistics operations managers in import/export companies to port and ferry operators.

Previous studies have approached similar problems in the extensive literature on multimodal freight transportation, defined as "*the transportation of goods by a sequence of at least two different modes of transportation*" (Steadieseifi et al., 2014). Intermodal transportation is a special case of multimodal transportation that uses one single unit (e.g., container) without handling the goods when changing modes. A review by Kreutzberger et al. (2003) concluded that intermodal freight transport has overall better environmental performances than unimodal road transport, and intermodal transportation has been suggested as appropriate strategy to decarbonize freight transport (Kaack et al., 2018). Similar conclusions were reached in a recent study of the CO_2 intensity of 400,000 North American road-to-rail intermodal shipments (Craig et al., 2013) and by a social-eco-efficient analysis of truck-rail-vessel gravel transportation in Taiwan (Shiau and Chuang, 2012).

Carbon emissions and their related impact on climate are a major concern in the transport sector. Currently, the most established approach to calculate a carbon footprint for a product (intended as either a *good* or a *service*) is by using the Life Cycle Assessment (LCA) modelling framework(ISO, 2018). LCA is a mainstream and widely accepted methodology for quantitative environmental assessment of products (ISO, 2006) and appears well fitted for the analysis of transport routes. LCA has been previously applied to compare freight transport options in the case of the air Swiss commercial air transport fleet (Cox et al., 2018), for road, rail, and air transportation of freight in the United States (Facanha and Horvath, 2007), for inland road and train freight transport in Belgium (Merchan et al., 2019), for modal split between road, rail and inland waterway transport in Belgium (Mostert et al., 2017), and for rail intermodal freight transport on trains in Belgium (Merchan et al., 2016). To date, no comparative LCA study on intermodal sea transport routes has yet been produced to the best of the Author's knowledge. Previous LCA studies on the topic of ferries focused on the environmental trade-offs associated with ferry retrofit (Blanco-Davis et al., 2014), ferry design (Tchertchian et al., 2013) and ferry propulsion systems (Jeong et al., 2018) rather than comparing transport by ferry with other transport modes. A problem with LCA studies is the superficial treatment of uncertainties, that can limit the decision support-role of LCA (Mendoza Beltran et al., 2018). Quantitative estimates of the uncertainties associated with results of LCA studies are seldom reported, and the vast majority of LCA studies only reports a deterministic or "static" value for each indicator of impact. In comparative LCA studies, these uncertainties might be too high to meaningfully conclude which alternative is preferred (Heijungs and Lenzen, 2014). A common option for uncertainty analysis in LCA studies is to use a stochastic approach to obtain the uncertainty distribution of the results of the LCA model, typically by performing error propagation via Monte Carlo simulation as described in (Heijungs and Lenzen, 2014) and as for example done by Niero et al. (2014). Although feasible and done in previous studies (Henriksson et al., 2015), a statistical testing to identify significant differences between the alternative distributions is lacking in most stochastic comparative LCA studies (Lesage et al., 2018).

Summing up, this study wants to support the decision making of different stakeholders within the freight transport sector by calculating carbon footprint estimates for intermodal Scandinavian routes and studying in detail the related uncertainties.

2. Materials and methods

The modelling is performed according to LCA principles (ISO, 2018). The functional unit for the analysis is the service of *transporting 1 t cargo* over a specific route. Each route provides the same function but using a different combination of sea and road transport modes. The foreground product system compiled to quantify the impacts related to this functional unit is described in the following sections and schematized in Figure 1. The corresponding inventory tables for each foreground activity (transport corridor and route, ferries, and fuel combustion) are provided as Supporting Information (SI). Background data are from the standard library of ecoinvent v.3.4 – consequential model (Wernet et al., 2016), chosen because this prospective analysis investigates the consequences of decisions concerning marginal, near-future shifts in transport modes. The impact of the product system is quantified as carbon footprint, here intended as the global warming potential of the system measured in amount of carbon dioxide equivalents (CO_2-eq) and calculated using the IPCC (2013) life cycle impact assessment method with a timeframe of 100 years (Trenberth et al., 2007). The calculation of LCA results and the Monte Carlo simulation were performed using the *Brightway2* open source LCA software (Mutel, 2017). The statistical analysis of LCA results was conducted with the R Statistical Environment software (De La Guardia et al., 2015). All code used in this study is either available on request to the author or openly available online (Pizzol, 2019).

2.1. Geographical scope and selection of points of departure, destinations, and routes

The study investigates freight transport between Norway and continental Europe that is based on roll-on/roll-off transport of consumer goods between production sites and final warehouses. The comparative assessment covers the freight transport between three points of departure and seven destinations, for a total of eight transport corridors and 66 routes between Norway and continental Europe (Figure 2). To cover the whole range of theoretically possible routes between all locations in Norway and continental Europe is an unrealistic task and was beyond the scope of this study. Instead, a number of relevant points of departure, destinations, and routes were selected for the analysis. The routes between the points of departure and the destinations were selected based on their current relevance for the Scandinavian freight transport market. The selected routes are existing routes that are frequently used and are economically competitive for freight transport of the majority of consumer goods. This sample should allow to draw conclusions about the overall transport pattern in the geographical area under analysis.

Two points of departure for North-bound freight transport have been selected and a point of departure for South-East freight transport. Reims northeast of Paris was chosen as first point of departure for North-bound freight transport. Reims is considered a representative location in relation to freight transport coming via road from Spain, France and Belgium and then heading further to Norway. Duisburg was selected as second point of departure for North-bound freight transport. Duisburg is a key transport hub in western Germany and is representative of points of departure located in western Germany and further south, such as Italy, as freight transport coming from these areas and directed to Norway will pass through or near Duisburg. Hitra located west of Trondheim was selected as point for South-East-bound freight transport. The area surrounding Hitra provides for an important share of the Norwegian salmon production, and the choice of Hitra reflects the need to better understand the impact of the increasing export of Norwegian salmon. The choice of two points of departure located in the Northern part of continental Europe and one in Norway allows to focus on the impact of transport occurring in proximity of these markets and to exclude the impact of transport occurring in Southern Europe from the comparative analysis.

Oslo, Bergen and Larvik are some of the largest coastal Norwegian cities and were chosen as destinations for the North-bound freight transport to Norway. The largest share of Norwegian population is settled in those cities and drives the demand for transport of consumer goods. Kongsberg was selected as an example of non-coastal Norwegian city and as representative for the transport to the region of Southern Norway. The choice of destinations for South-East bound transport was made considering the rising trade in salmon between Hitra's production area and Utska on the Polish Baltic coast, and between Hitra and Saint Laurent Blangy in Northern France. Both destinations are characterized by the presence of salmon processing industries.

Due to the specific geography of Northern Europe and especially the fact that continental Europe is separated from Scandinavia by water, all selected routes except for those across the Øresund bridge are characterized by transport via sea. The selected routes use the following existing ferry connections: Ystad – Scwinoujscie, Oslo – Frederikshavn, Frederikshavn – Gothenburg, Gedser – Rostock, Oslo – Kiel, Hirtshals – Larvik, and Hirtshals – Bergen.

2.2. Life cycle inventory data of freight transport routes

Summing up from the previous section, this study considered eight transport corridors: Duisburg (DE) – Bergen (NO), Duisburg (DE) – Larvik (NO), Duisburg (DE) – Oslo (NO), Reims (FR) – Stavanger (NO), Reims (FR) – Kongsberg (NO), Reims (FR) – Oslo (NO), Hitra (NO) – Saint Laurent Blangy (FR), and Hitra (NO) – Utska (PO). The alternative routes within each corridor assume either a combination of transport by sea and transport by road, or they assume transport by road only. Table 1 reports the full list of routes including departure point and destination, corridor, company that operates the ferry, name of ferry, distance covered by sea and by road, total hours and ID used in the analysis. The distance covered by each mode of transport in each route was used to compile the life cycle inventory of the foreground system. Inventories in table format are provided in the SI (cf. *Routes_ei4.csv*).

2.3. Life cycle inventory data of truck and ferries

The two modes of transport considered in the study are ferry and truck. Goods are transported via a cargo truck, that in turn can be transported via ferry depending on the chosen route. The cargo and truck characteristics are identical in all scenarios: EURO6, refrigerated, length 17 m, total weight 32 t (load 14 t, truck 9 t, trailer 9 t). The inventory for truck was compiled using background LCI data from the standard library of ecoinvent v.3.4 – consequential model, in particular the process *transport, freight, lorry >32 metric ton, EURO6 RER*. As reported by ecoinvent, this represents *"the service of 1tkm freight transport in a lorry of the size class >32 metric tons gross vehicle weight (GVW) and Euro VI emissions class"* (ecoinvent, 2017a). The transport dataset refers to the entire transport life cycle and assumes average load factors.

The inventories for ferries were compiled by using information from different sources, in particular a combination of primary data, literature data, data from ferry models, and background data from the standard library of ecoinvent v.3.4 – consequential model. The ferries operating in the various routes considered in this study differ in terms of size, capacity, type (ro-pax transporting both cargo and passengers, or ro-ro transporting cargo only), and fuel used (Liquefied Natural Gas (LNG) or diesel). Given the differences between the ferries under analysis, using a single dataset to model all ferries would have been too inaccurate and ferry-specific inventories were compiled. Moreover, ecoinvent does not provide data specific for ferries but only for barges or transoceanic ships. These ships have a larger capacity compared to ferries and lower fuel consumption per tkm. Thus, the available ecoinvent datasets were not considered a representative data source for fuel consumption of ferries. The fuel consumption of each ferry was thus determined using the SHIP-DESMO model (Kristensen, 2016) developed within the Danish RoRoSECA project (DTU, 2017). The model is developed from a regression analysis of primary data of hundreds of ro-ro ships operating in the Nordic area and allows to obtain fuel consumption and other output data based on relatively limited amount of input information. In particular, the data used to run the SHIP-DESMO model were taken from recent Shippax statistics (Shippax, 2016) and included: passenger capacity; actual number of passengers; lane meters occupied by rolling cargo, bus, and car and caravan respectively in percentage of total lane meters. These data are reported in Table 2 for all ferries. Average values of number of passengers (calculated as 33% of passenger capacity), percentage of lane meters occupied respectively by rolling cargo (36%), car and caravan (36%), and bus (2%), were used as input to the SHIP-DESMO model to ensure equal conditions for all ferries

The emissions per unit of fuel consumption were obtained from existing ecoinvent processes for diesel ships (ecoinvent, 2017b) and LNG ships (ecoinvent, 2017c) respectively, also reported in SI (cf. *Ferries_ei4.csv*). The total emissions per tkm were then calculated by multiplying the fuel consumption data obtained from SHIP-DESMO and the fuel-specific emission factors obtained from ecoinvent. For example, the *Superspeed2* ferry emits 0.144 kg CO_2 / tkm given the emission factor of 3.15 kg CO_2 / kg diesel and a fuel consumption of 0.0458 kg diesel / tkm.

Beyond the use stage, data referring to capital goods including the construction, maintenance, and use of port facilities was quantified for each ferry by linearly scaling background ecoinvent data for a transoceanic ship of 50000 t deadweight (ecoinvent, 2017d) according to the ferry's deadweight data reported in table 2. For example, the amount of capital goods for the *Superspeed2* ferry of 5400 t deadweight is 0.108 capital goods units / tkm.

2.4. Uncertainty analysis via error propagation (Monte Carlo simulation)

Error propagation via Monte Carlo simulation was performed to obtain estimates of the uncertainty associated with the results that depends on the uncertainty of the model parameters. This uncertainty encompasses both the inherent variability of the inventory data and measurements errors, also called epistemic uncertainty and stochastic uncertainty respectively (Clavreul et al., 2012). Values of parameter uncertainty taken directly from ecoinvent were used for background exchanges, whereas low uncertainties values were assumed for foreground exchanges, like the distance in nautical miles between two ports, as these are robust primary data. Details about variance and distribution type for each exchange are provided in the SI (cf. *Routes_ei4.csv*, *Ferries_ei4.csv*). The procedure followed was very similar to a previous study of Henriksson et al. (2015). In order to provide a level of confidence behind conclusions, the null hypothesis that different routes are associated with different environmental impacts was tested statistically. In other words, the null hypothesis tested assumed an equal impact between routes. Two approaches were used for testing the differences between paired results: a significance tests to reject the null hypothesis and an analysis of the percentage of Monte Carlo runs in which the difference between alternatives was positive, negative, or zero. As explained by Henriksson et al. (2015), the first approach is used to analyze whether the distribution of differences between alternative routes has a median that deviates significantly from zero. Instead, the second approach is used to determine how often transporting goods across a route is expected to have a lower impact than across another route (this is equivalent to the approach normally used in commercial LCA software (Goedkoop et al., 2014)).

Characterized results were calculated for each alternative with 1,000 iterations with dependent sampling. According to a recent study by Lesage P. and coworkers (Lesage et al., 2018), dependent sampling is a valid approach to stochastic comparative LCA, whereas the independent sampling approach used by most stochastic comparative LCA studies is inadequate and "*drastically overestimates the uncertainty of comparative metrics*" (Lesage et al., 2018). Dependent sampling involves two steps: in the first step, a technology matrix (Heijungs and Suh, 2002) is generated using random sampling; in the second step, results are calculated for each alternative on the same functional unit; these two steps were repeated 1,000 times. This approach allows maintaining the same error propagation simultaneously for all alternatives under analysis and avoids overestimating the total variance (Henriksson et al., 2014). Covariance was not accounted for in the current models because of inherent data and software limitations. Distributions were tested for normality using the Shapiro-Wilk test. Since normality was rejected for the large majority of distributions, differences between the impact of alternative routes within the same corridor were tested statistically using nonparametric pairwise Wilcoxon Rank Sum tests rather than using e.g. a paired t-test. Significant differences were considered as $\alpha = 0.05$ and Bonferroni correction was applied to avoid false positives (Heijungs and Kleijn, 2001).

3. Results

3.1. Deterministic carbon footprint of transport corridors

Figure 3 shows the contribution analysis of the carbon footprint of each route, i.e. the relative contribution of sea and road transport to the total carbon footprint. Values of the sea and road component of the carbon footprints of each route are provided in the SI (cf. *Static_contribution_analysis.csv*). Values reported in Figure 3 were obtained by deterministic LCA calculation (without error propagation). Figure 3 shows that different routes have different impact and the routes with lowest carbon footprint are:

- The Zeebrugge−Hirtshals route in the Duisburg (DE) – Bergen (NO) corridor, the Duisburg (DE) – Larvik (NO) corridor, the Duisburg (DE) – Oslo (NO) corridor, the Reims (FR) – Stavanger (NO) corridor, the Reims (FR) – Kongsberg (NO) corridor, and the Reims (FR) – Oslo (NO) corridor.
- The Hitra−Hirtshals route in the Hitra (NO) – Saint Laurent Blangy (FR) corridor.
- The Oslo−Frederikshavn route in the Hitra (NO) – Utska (PO) corridor.

Figure 3 also allows to identify some general trends. Within the same corridor, the route with the lowest carbon footprint always includes transport via sea. However, not all the routes including a combination of transport via sea and road are preferable to a road-only route, in terms of carbon footprint. Ro-ro vessels are a preferred option compared to ro-pax ferries. In ro-pax ferries a substantial amount of space is occupied by facilities for the transport of passengers. Since ro-ro vessels are exclusively for the transport of cargo this results in lower fuel consumption per t cargo transported, cf. the case of Valentine ferry in Table 2. Ferries fueled by LNG are a preferred option over those fueled by Diesel because of their lower emissions per t cargo transported. In particular, transport over long distances by sea in Diesel-powered ferries is not preferable over road transport in the alternatives under analysis. More specifically, results show that routes via Zeebrugge-Hirtshals are the preferred alternative in several corridors because, despite the large distance covered via sea, a ro-ro vessel is used on this route (872 km for a total of 46.99 kg CO_2-eq/t cargo). Instead, the routes via Kiel-Oslo are the worst alternative in several corridors, because of the large distance covered via diesel ferry (689 km for a total of 124.69 kg CO_2-eq/t cargo). Other routes with high impact are those via Scwinoujscie-Ystad-Svinesund because these routes cover either a larger distance via sea on diesel ferries or a larger distance via road, or both, compared to other alternative routes within the same corridors.

3.2. Stochastic carbon footprint of transport corridors and statistical analysis

Figure 4 shows the distribution of results for each route over 1,000 Monte Carlo simulations. The result of each simulation is provided in the SI together with summary statistics (cf. *MC_simulation_1000_iter.csv, MC_stats.txt*). It should be noted that mean and median values of these distribution are consistently higher than the values of Figure 3. Although not documented in the literature, this is a known issue in stochastic LCA (Mutel C., personal communication) and did not affect the ranking of alternatives.

The general impression from a visual inspection of the figure is that uncertainties are substantial and, in some cases, the large spread of results doesn’t allow to clearly prefer one alternative over another. However, a closer analysis of the pairwise differences is essential to confirm this impression in each case. Full results of the statistical testing and the results of the paired difference between routes are provided in the SI (cf. *MC_analysis_pairwise_wilcoxon.txt, MC_analysis_perc_diff.txt*). A couple of key examples are reported here for illustrative purposes. Taking as example the comparison between Route17 and Route18, there seems to be little difference between these routes from Figure 4. The distribution of the differences between the two routes has 33.5 % positive values and 66.5 % negative values, thus indicating that Route18 is generally a worse option than Route17 in terms of carbon footprint. The pairwise Wilcoxon Rank Sum test indicates a significant difference in the GWP impact of Route 17 (Mean = 136.02, Standard Deviation = 17.53) and Route 18 (Mean = 142.34, Standard Deviation = 19.64) with a Bonferroni-corrected p-value = 1.52E-12. It can with good confidence be concluded that Route 17 is a better alternative to Route 18, i.e. that the route between Duisburg - Oslo via Hirtshals-Larvik should be preferred to the route via Frederikshavn-Oslo in terms of carbon footprint. A different case is the comparison between Route64 and Route58. Again, there seems to be little or no difference between these routes from a visual inspection of Figure 4. The distribution of the differences between the Route58 and Route64 shows 52.9% positive values and 47.1% negative values, thus suggesting that Route58 might generally be a worse option than Route64 in terms of carbon footprint. However, the pairwise Wilcoxon Rank Sum test indicates no significant difference in the GWP impact of Route64 (Mean = 179.34, Standard Deviation = 23.25) and Route 58 (Mean = 179.51, Standard Deviation = 18.45) with a Bonferroni-corrected p-value = 1.00. Thus, the conclusion is that the data do not allow to identify a preferred alternative in this comparison. In general, it was observed that for all the corridors under analysis only 23 out of the 243 possible pairwise comparisons showed no or weak significance ($p > 0.00005$) (cf. *MC_analysis_pairwise_wilcoxon.txt*), and that these cases did not concern the best or worst alternatives but always middle-ranking alternatives.

4. Discussion

Summing up the results, the use of ferry can outperform road-only transport, but this depends on the route chosen. This analysis shows that ro-pax ferries have higher emission factors per tkm than trucks (cf. *SI_tables.docx*, Table S3) and therefore one condition required for intermodal routes on ro-pax ferries to outperform road-only routes is that the total transport distance is reduced. This analysis indicates then clearly that using ro-ro ferries and LNG fuelled ferries allows for substantial benefits in terms of carbon footprint reduction compared to road transport in all the scenarios under analysis.

4.1. Results in perspective

The results are not directly comparable with those of previous studies but some parallels can be made with existing literature on the topic. The study confirm the hypothesis of Kaak et al. (2018) that intermodal transport can be environmentally a better option than road-only transport. This was also the conclusion of a previous review of Kreutzberger et al. (2003), although such review didn't include studies focusing on sea routes. Sahin et al. (2014) estimated in a theoretical analysis that road transport would be economically better for distances below 200 km. This could not be confirmed by this study, but results show that the road-only route can have a lower carbon footprint than the intermodal route even in cases of distances longer than 200 km.

The validity of these results depends on the model structure and data used. Both primary and secondary data were used to build the inventories, as well as data generated from other models. When using SHIP-DESMO, average yearly values were chosen to describe the percentage of lane meters occupied. Since lane occupation varies geographically and seasonally depending on the ferry and route, this was a necessary approximation to maintain equal conditions for all ferries.

The amount of transported load can affect the fuel consumption and therefore the emissions of both trucks and ferries. For ferries, SHIP-DESMO allows calculating how load affects fuel consumption. Taken the Superspeed2 ferry as example, a 1% increase in the percentage of lane meters occupied by trailers results in a 0.06% increase in fuel consumption, while a 1% increase in the actual number of passengers results in a 0.004% increase in fuel consumption, all other parameters kept constant. However, this effect is nonlinear and a global sensitivity analysis would be needed to test the importance of each parameter using SHIP-DESMO, that is beyond of the scope of this study. Using average load factors was considered a sufficiently solid basis for comparison across alternative routes. Passenger ferries in LCA must be treated as multifunctional process as they provide two co-products: the transport of passengers and the transport of cargo. Notably, SHIP-DESMO allows choosing an allocation of the inputs and emissions of passenger ferry by lane meters occupied or by weight of passengers and cargo, or by the average of the two. In this study ferries were considered a case of combined production (Majeau-Bettez et al., 2017), meaning that the relative amounts of co-products can be varied independently (Suh et al., 2010). Thus, fuel consumption was allocated by weight to passengers and cargo, based on the rationale of physical causality. It should be noted that using allocation by lane meter would have resulted in lower emissions per t cargo transported by ferry so the choice made represents a conservative assumption. A comparison between ecoinvent and SHIP-DESMO figures for fuel consumption is provided in the SI (cf. *SI_tables.docx*, Table S1) and shows that using background data from ecoinvent to model ferries would have been inaccurate as would have underestimated the fuel consumption of ferries. It should be noted that while SHIP-DESMO is able to directly provide output data for emissions by multiplying the fuel consumption values (obtained via regression) by fixed emission factors, these are limited to six substances. The ecoinvent datasets have a higher completeness because provide fuel combustion-related emission factors for more than twenty substances and were thus considered the preferred option. A comparison between the ecoinvent and SHIP-DESMO emission factors is provided in the SI (cf. *SI_tables.docx*, Table S2) and shows a good correspondence between the factors for the exchanges in common, so using ecoinvent emission factors was considered a reasonable modelling choice. More complex approaches to estimate ships emissions exist as well, that were not considered a pragmatic option for this study, for example the use of bottom-up ship emission algorithms (Paxian et al., 2010), and the top-down disaggregation of input-output databases.

4.2 Notes on the stochastic simulation

The error propagation performed via Monte Carlo simulation is supposed to provide an idea of the uncertainties due to the data used in the model, and should not be confounded with an analysis of scenarios or of modelling assumptions, and neither is a global sensitivity analysis (Groen et al., 2017) to identify critical parameters (AzariJafari et al., 2018). While measurements of transport distances are accurate and not considered an uncertain factor, fuel consumption is a key uncertain parameter. Both ferries and trucks have different emission patterns depending on weather and traffic conditions, and the error propagation is supposed to capture quantitatively both this natural variability and measurement errors. The uncertainty associated with fuel consumption in ferries is taken from ecoinvent and modelled using a log-normal distribution with multiplicative standard deviation 1.26 for Diesel and 1.10 for LNG, that can be used to represent wide range of traffic conditions. This was considered a reasonable, pragmatic, and efficient approach compared to more resource-intensive ones such as the development of more advanced emission models for truck and ferry respectively. The use of error propagation on LCA inventories has some limitations, the major one being that the covariance between parameters is not considered, and this can lead to over or under estimation of the results' uncertainties (Groen and Heijungs, 2017). This is due to intrinsic limitations of both the database, that doesn't provide such data, and of the software, that doesn't allow performing a simulation considering the covariances. Another limitation is that uncertainty estimates for the model parameters are developed with a pedigree-matrix approach (Ciroth et al., 2016), which is a semi-quantitative method and has arguably a lower accuracy compared to using primary data to estimate confidence intervals. Very few LCA studies have attempted a statistical analysis of Monte Carlo results (Henriksson et al., 2015), and this study confirmed that this is a necessary step in order to draw robust conclusions. Despite the apparently high uncertainties associates with the results, the ex-post statistical testing of the results allowed to always identify best and worse alternatives, and only few comparisons were not statistically significative with strong confidence, thus allowing for an efficient decision support.

4.3. Validity of the results in relation to the scope of the study

The study considered a limited set of alternative routes and was not supposed to cover exhaustively all theoretically possible corridors, routes, points of departure, and destinations between Norway and Continental Europe. The alternatives were selected in collaboration with the stakeholders of the study (one port operator in Denmark and one importer of consumer goods in Norway), based on the relevance for the stakeholders and also based on the stakeholders' primary experience with the shipping business in the region. According to the stakeholders, the alternative selected are the most realistic because are major existing routes of cargo traffic that are comparable in terms of feasibility, infrastructure, and costs.

Among the factors that could affect the long-term validity of these results is the imminent introduction of electric vessels among Nordic fleets. Small electric passenger ferries are already active in specific short routes in Norway e.g. between Helsingborg and Helsingör. Upscaling data on the electricity consumption of these small ferries to model the much bigger ferries considered in this study would lead to excessively higher uncertainties and was not considered an option. In principle, the impact of electric ferries will be closely related to the energy mix of the country where the ferry charges. This might not necessarily be a low-carbon mix depending not only on the country but also on the modelling approach (average versus marginal) used to compile the inventory for future (Mathiesen et al., 2009) or country-specific energy mixes (Menten et al., 2015).

The study has focused only on carbon emissions and their related midpoint impact, as they are a major concern in the transport sector, while other midpoint and endpoint impact categories have been disregarded (i.e. implicitly assigned a weight of zero) and possible trade-offs between impact categories have not been investigated. Another relevant impact in this case is the impact of particles. Liu and co-workers (Liu et al., 2017) show that particles emitted from ships can affect even urban air quality, and Corbett and co-workers (Corbett et al., 2007) show that mortality is indeed associated with ships emissions on a global scale. It is straightforward to calculate the life cycle impacts of particulate matter formation with available LCIA methods (van Zelm et al., 2016). However, using generic characterization factors would not allow to capture in detail the spatial differences in the impact due to particulate matter emitted over the sea by ferries and over urban and semi-urban areas by trucks respectively, so uncertainties are expected to be high and results inaccurate. A spatial assessment would be necessary e.g. using spatially explicit inventories (Humbert et al., 2011) and life cycle impact assessment archetypes (Fantke et al., 2017), that was beyond the scope of this study.

Environmental performance is only one among several factors affecting a decision on which route is preferable, and both costs and time would be important factors to consider. It was beyond the scope of this study to report on routes costs and time savings, or to find the optimal route based on multiple different factors. More advanced stochastic approaches (Demir et al., 2016) and optimization models (Bouchery and Fransoo, 2015) developed in previous studies to identify preferable intermodal transport alternatives by considering economic, social, and environmental factors could in principle be applied directly to the case here analysed.

5. Conclusions

This study compared 66 intermodal truck-ferry routes in eight transport corridors in terms of carbon footprint. The results of this study show that different routes have substantially different impact, and it is therefore possible to reduce the impact of freight transport by choosing routes with low impact. Compared to a road-only alternative, a route involving transport via ferry can indeed have a lower impact. However, the carbon saving achievable with freight transport on ferries largely depends on the route, ferry type, and fuel used respectively. Shifting the traffic on ferries must also allow to reduce substantially the distance covered via road, in order to obtain a sensible reduction in emissions. Shifting to ro-ro vessels and LNG fuelled engines are highly preferable strategies to reduce emissions. These strategies should in particular be considered for the routes where a large distance by sea has to be covered, whereas would not allow reducing substantially the total carbon footprint in routes where the distance covered by seas is small (e.g. Rødby-Øresud). It is recommended that further research in this area focuses on three issues: to model in detail how the results of this study change under different load conditions, to explore additional impact categories in particular by applying a detailed analysis of the impacts related to particulate matter, and to complement the environmental assessment with an economic assessment to investigate trade-offs between the two dimensions.

In the study, new inventories for ferries were compiled from both primary and secondary data, that can be applied directly in other studies on freight transport via sea. The results of this study can be used to support decision making for different stakeholders within the freight transport sector interested in lowering their environmental footprint, such as import-export, ferry, and port operators, and could in particular support the planning of future Scandinavian freight transport. For example, the results could be used to support the decision-making process when prioritizing investments in harbour and warehouse capacity in Scandinavia.

Disclosures

The study was developed within the research project: *Carbon footprint of transport corridors relevant for the Port of Hirtshals*, carried out at Aalborg university and funded by the Port of Hirtshals. The role of the Port of Hirtshals in the project was to select relevant transport corridors between Scandinavia and Continental Europe and alternative routes within each corridor, for the comparative analysis. The modelling and evaluation of results was carried out independently by the Author. The author declares no competing financial interest.

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Supporting information

List of files supplied as SI: *SI_tables.docx.* Additional tables comparing e.g. fuel consumption and emissions. *Routes_ei4.csv*, *Ferries_ei4.csv* Life cycle inventory for each route and ferry under analysis and for fuel combustion. *Static_contribution_analysis.csv* Values of carbon footprint via sea and road for each route respectively. *MC_simulation_1000_iter.csv* Raw results of the Monte Carlo simulation with 1,000 iterations for 66 routes. *MC_stats.txt* Summary statistics for the distribution of each of the 66 routes. *MC_analysis_pairwise_wilcoxon.txt* p.value obtained as a result of the pairwise Wilcoxon test for all routes. *MC_analysis_perc_diff.txt* Analysis of the pairwise differences of values obtained from each iteration of the Monte Carlo simulation. "BaseRoute" and "AltRoute" are the routes to be compared. "Percpos" "Percneg" "Percequ" indicate the percent of values that are positive, negative, equal, respectively this distribution. "Percscal" is calculated as median(BaseRoute) / median(BaseRoute) * 100 and is a measure of the impact of one route compared to the impact of the other.

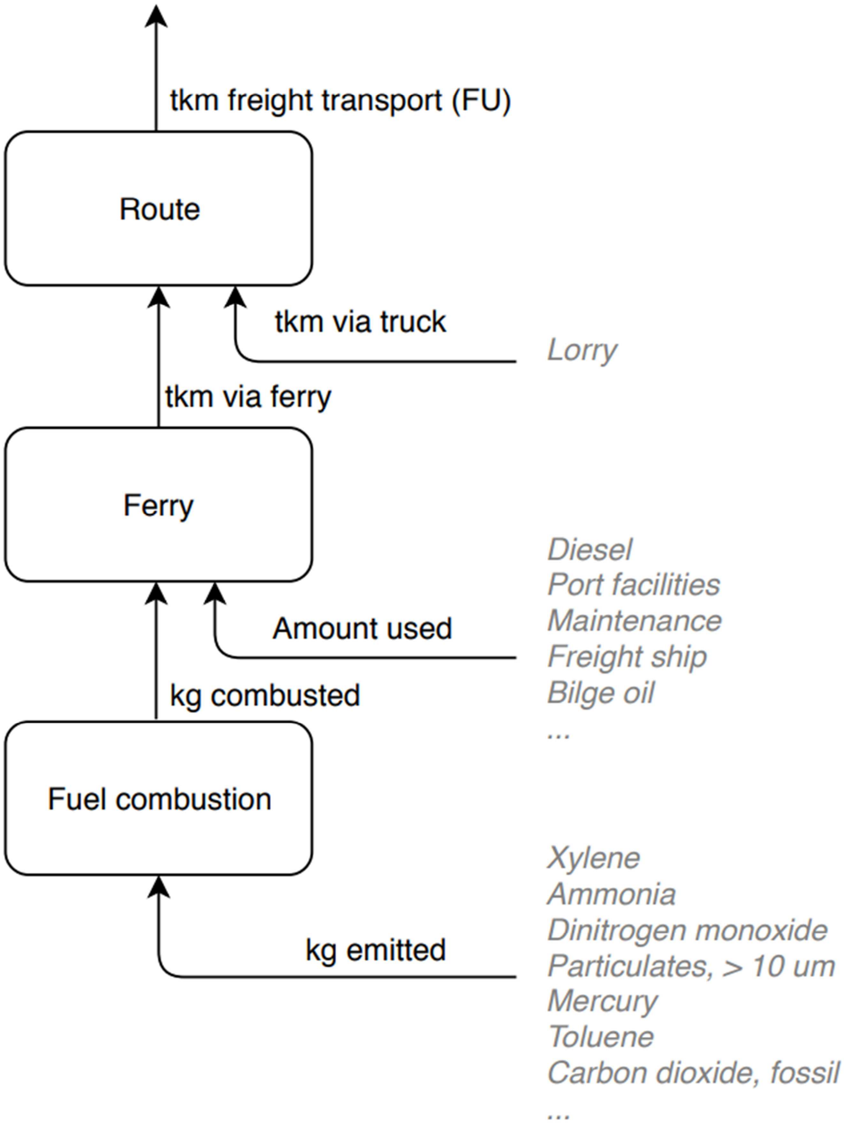

Figure 1. Structure of the product system under analysis. Boxes indicate activities in the foreground system. Arrows indicate exchanges. Grey text in italics indicates background activities from the ecoinvent v.3.4 database, consequential Unit model. FU = functional unit.

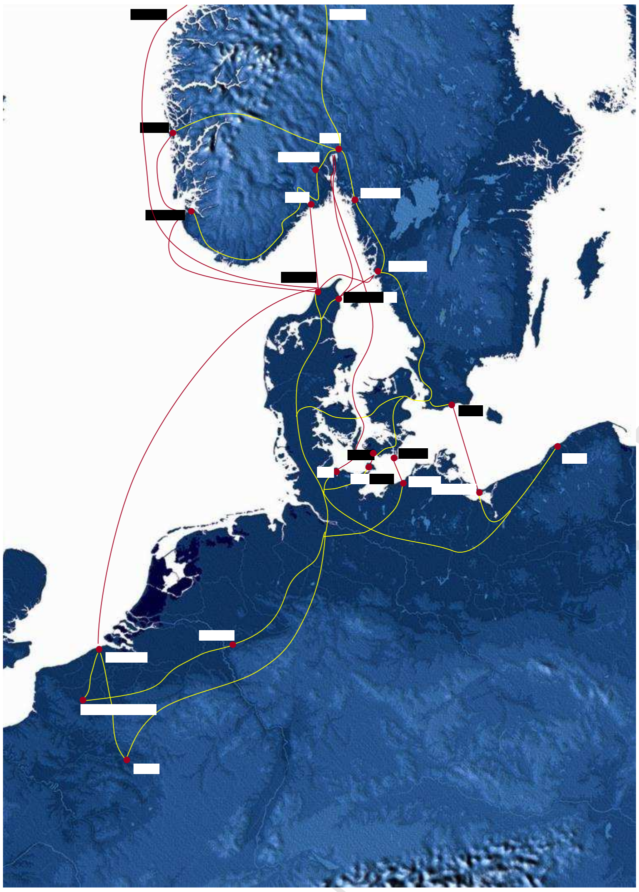

Figure 2. Map of the area under analysis between Norway and continental Europe. The red dots indicate points of departure and destinations. Yellow lines represent transport via road. Red lines represent transport via sea.

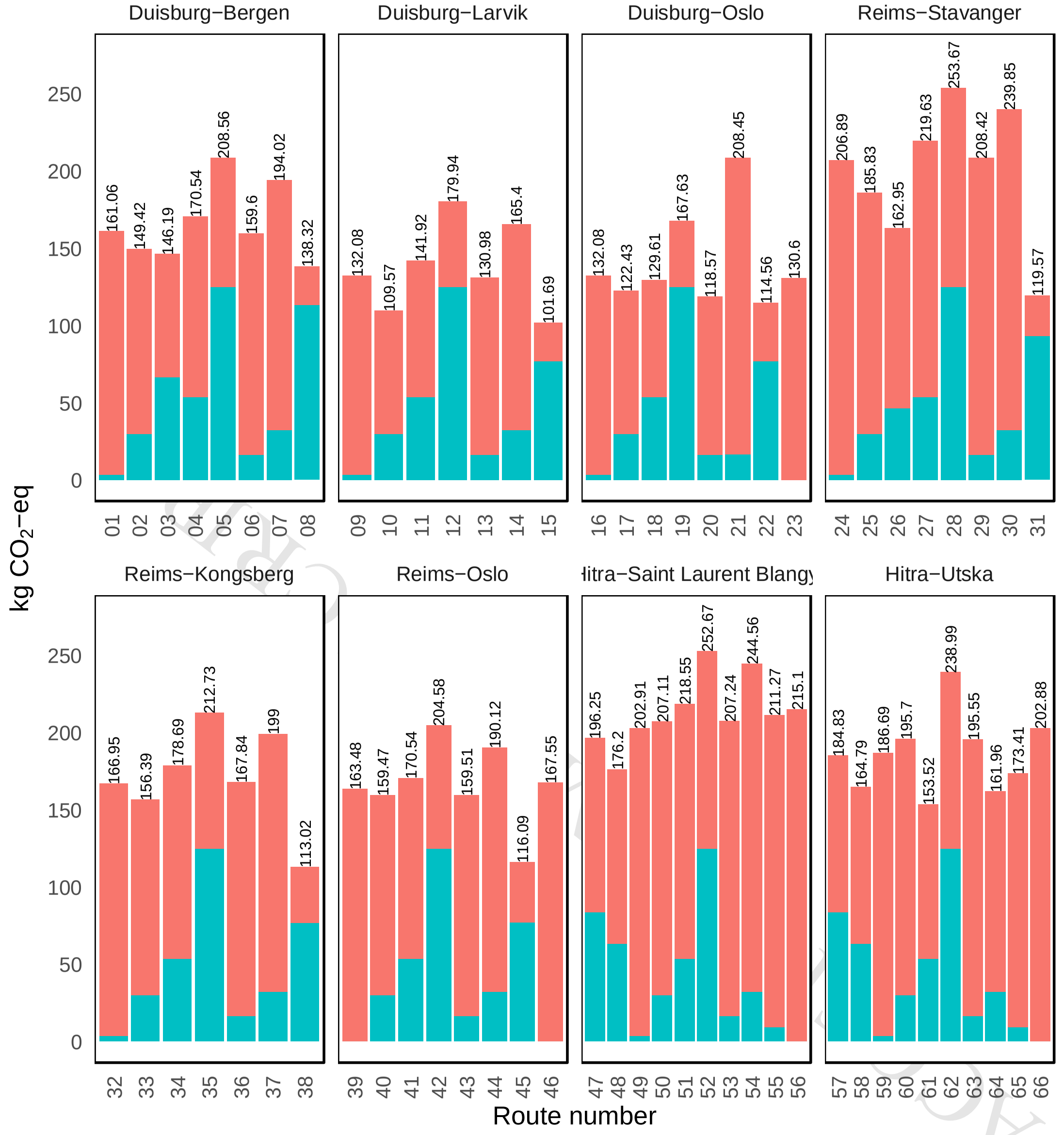

Figure 3. Contribution analysis for the carbon footprint of 66 transport routes within eight transport corridors in the Nordic region. Blue colour indicates transport via ferry. Red colour indicates transport via truck. Values are in kilograms of Carbon Dioxide equivalents (“CO_2-eq”) per t cargo transported.

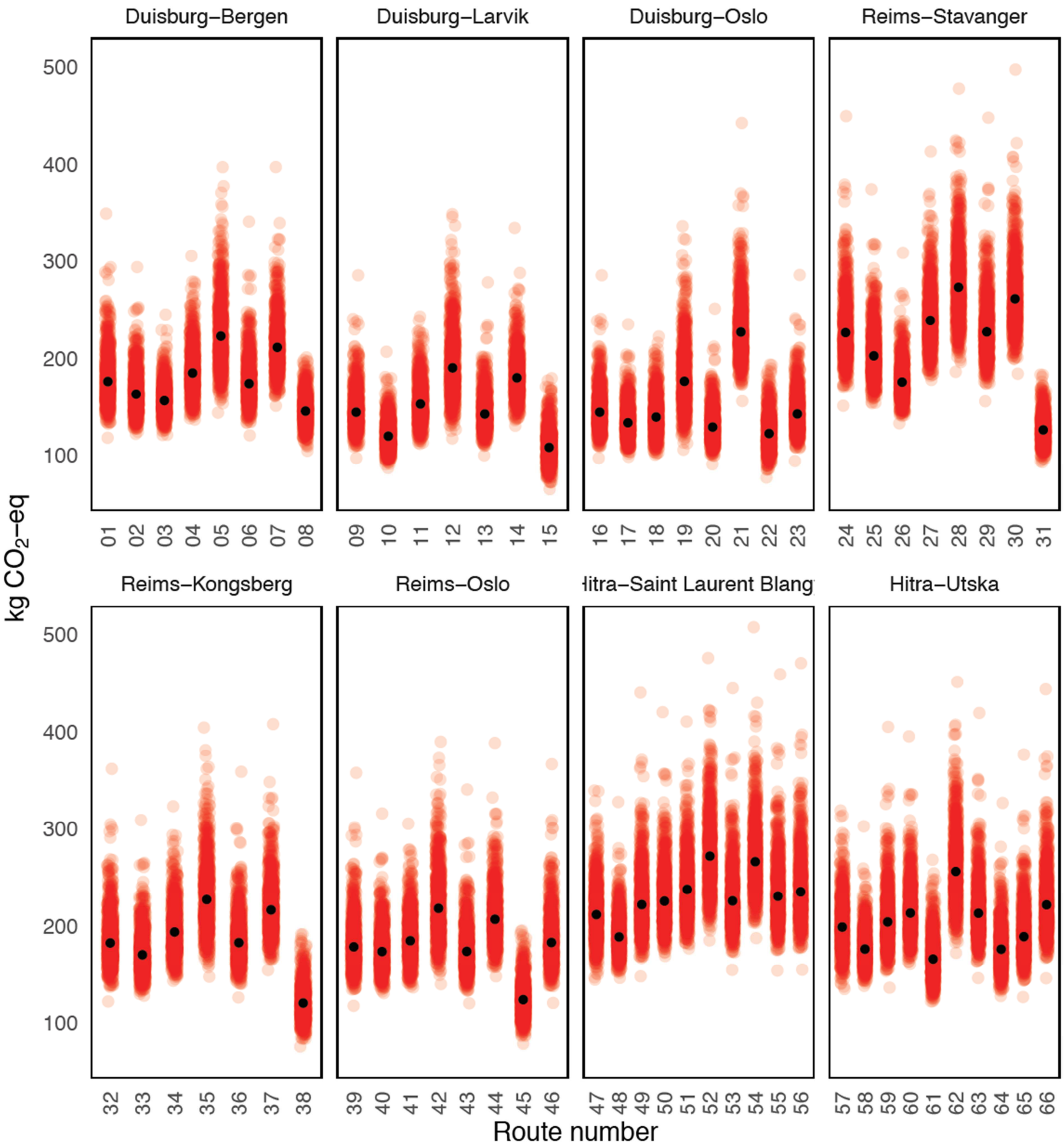

Figure 4. Results of the Monte Carlo simulation for the carbon footprint of 66 transport routes within eight transport corridors in the Nordic region. Red dots indicate the result of each of the 1,000 simulations. The black dots indicate the median of each distribution. Values are in kilograms of Carbon Dioxide equivalents ("CO_2-eq") per t cargo transported.

Table 1. Routes included in the study

From - To	Via	By	Ferry	Sea distance (km)	Road distance (km)	hours	ID
Duisburg - Bergen	via Rødby-Øresund	Scandlines	Deutschland	19	1,740	40.5	Route01
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	1,321	35.7	Route02
	via Hirtshals-Bergen	Fjord Line	Stavangerfjord	533	881	42.1	Route03
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	1,291	40.85	Route04
	via Kiel-Oslo	Color Line	Color Fantasy	689	926	36.35	Route05
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	1,582	49.95	Route06
	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	1,785	46	Route07
	via Zeebrugge-Hirtshals-Bergen	CLdN/Fjord Line	Valentine/Stavangerfjord	1,406	275	54.45	Route08
Duisburg - Larvik	via Rødby-Øresund	Scandlines	Deutschland	19	1,420	35.2	Route09
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	881	29.35	Route10
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	975	35.55	Route11
	via Kiel-Oslo	Color Line	Color Fantasy	689	610	31.05	Route12
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	1,266	34.65	Route13

	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	1,469	40.7	Route14
	via Zeebrugge-Hirtshals-Larvik	CLdN/Color Line	Valentine/Superspeed 2	1,033	275	39.7	Route15
Duisburg - Oslo	via Puttgarden-Rødby-Svinesund	Scandlines	Deutschland	19	1,420	32.2	Route16
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	1,023	30.8	Route17
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	839	34.1	Route18
	via Kiel-Oslo	Color Line	Color Fantasy	689	474	29.6	Route19
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	1,129	32.35	Route20
	via Scwinoujscie-Ystad-Svinesund	POL Ferries	Mazovia	172	1,326	38	Route21
	via Zeebrugge-Hirtshals-Larvik	CLdN/Color Line	Valentine/Superspeed 2	1,033	417	41.15	Route22
	via "storebælt" & "øresund"	No company	No ferry	0	1,442	33.25	Route23
Reims - Stavanger	via Rødby-Øresund	Scandlines	Deutschland	19	2,246	68.15	Route24
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	1,723	41.45	Route25
	via Hirtshals-Stavanger	Fjord Line	Bergensfjord	370	1,290	43.45	Route26
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	1,833	48.8	Route27
	via Kiel-Oslo	Color Line	Color Fantasy	689	1,424	53.7	Route28
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	2,121	57.8	Route29

	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	2,291	63.55	Route30
	via Zeebrugge-Hirtshals-Stavanger	CLdN/Fjord Line	Valentine/Bergensfjord	1,243	292	66.2	Route31
Reims - Kongsberg	via Rødby-Øresund	Scandlines	Deutschland	19	1,805	50.65	Route32
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	1,398	36	Route33
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	1,381	41.25	Route34
	via Kiel-Oslo	Color Line	Color Fantasy	689	972	46.15	Route35
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	1,673	40.35	Route36
	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	1,840	57	Route37
	via Zeebrugge-Hirtshals-Larvik	CLdN/Color Line	Valentine/Superspeed 2	1,033	400	58.75	Route38
Reims - Oslo	via Puttgarden-Rødby-Svinesund	Scandlines	Deutschland	19	1,805	48.15	Route39
	via Hirtshals-Larvik	Color Line	Superspeed 2	161	1,432	36.65	Route40
	via Frederikshavn-Oslo	Stena Line	Stena Saga	289	1,291	40.55	Route41
	via Kiel-Oslo	Color Line	Color Fantasy	689	882	45.45	Route42
	via Frederikshavn-Gøteborg	Stena Line	Stena Jutlandica	87	1,581	38.8	Route43
	via Scwinoujscie-Ystad-Svinesund	POL Ferries	Mazovia	172	1,742	54.05	Route44
	via Zeebrugge-Hirtshals-Larvik	CLdN/Color Line	Valentine/Superspeed 2	1,033	434	59.4	Route45

	via "storebælt" & "øresund"	No company	No ferry	0	1,850	50.7	Route46
Hitra - Saint Laurent Blangy	via Hitra-Hirtshals (D)	Color Line	Valentine s	1,002	1,247	58.35	Route47
	via Hitra-Hirtshals (L)	Color Line	Valentine s LNG	1,002	1,247	58.35	Route48
	via Rødby-Puttgarden	Scandlines	Deutschland	19	2,202	50.95	Route49
	via Larvik-Hirtshals	Color Line	Superspeed 2	161	1,958	49	Route50
	via Oslo-Frederikshavn	Stena Line	Stena Saga	289	1,821	46.3	Route51
	via Oslo-Kiel	Color Line	Color Fantasy	689	1,413	49.1	Route52
	via Gøteborg-Frederikshavn	Stena Line	Stena Jutlandica	87	2,108	51	Route53
	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	2,343	57	Route54
	via Gedser-Rostock	Scandlines	Berlin	48	2,233	53.65	Route55
	via Øresund-Storebælt	No company	No ferry	0	2,375	51.25	Route56
Hitra - Utska	via Hitra-Hirtshals (D)	No company*	Assumed as Valentine s	1,002	1,121	52	Route57
	via Hitra-Hirtshals (L)	No company	Assumed as Valentine s LNG	1,002	1,121	52	Route58

	via Rødby-Puttgarden	Scandlines	Deutschland	19	2,023	38.95	Route59
	via Larvik-Hirtshals	Color Line	Superspeed 2	161	1,832	42.65	Route60
	via Oslo-Frederikshavn	Stena Line	Stena Saga	289	1,103	39.3	Route61
	via Oslo-Kiel	Color Line	Color Fantasy	689	1,262	38.1	Route62
	via Gøteborg-Frederikshavn	Stena Line	Stena Jutlandica	87	1,979	44	Route63
	via Ystad-Scwinoujscie	POL Ferries	Mazovia	172	1,431	37.8	Route64
	via Gedser-Rostock	Scandlines	Berlin	48	1,815	39.65	Route65
	via Øresund-Storebælt	No company	No ferry	0	2,240	48.35	Route66

** The ferry is not operational yet but is expected to become operational in the near future.*

Table 2. Ferries included in the study.

Shipping line	From	To	Vessel name	Fuel	Distance (km)	Passengers capacity[1]	Actual passengers per trip[1]	Lane meters occupied by cars (%)[1]	Lane meters occupied by bus (%)[1]	Lane meters occupied by trailers (%)[1]	Deadweight (t)[2]	Fuel Consumption (kg/tkm)	Fuel Consumption (MJ/tkm)
Color Line	Hirtshals	Larvik	Superspeed 2	Diesel	161	1,928	573	41	2	36	5,400	0.0458	1.955
Color Line	Hirtshals	Kristiansand	Superspeed 1	Diesel	133	2,315	831	41	2	36	5,400	0.0454	1.938
Color Line	Kiel	Oslo	Color Fantasy	Diesel	689	2,770	1,624	41	2	36	6,133	0.0448	1.915
Fjord Line	Hirtshals	Stavanger	Stavangerfjord	LNG	370	1,390	526	41	2	36	3,900	0.0367	1.818
Fjord Line	Hirtshals	Bergen	Bergensfjord	LNG	533	1,390	526	41	2	36	3,900	0.0367	1.818
Stena Line	Frederikshavn	Oslo	Stena Saga	Diesel	289	1,700	712	41	2	36	3,898	0.0460	1.964
Stena Line	Frederikshavn	Gothenburg	Stena Jutlandica	Diesel	87	1,006	349	41	2	36	6,559	0.0464	1.968
POL Ferries	Scwinoujscie	Ystad	Mazovia	Diesel	172	1,000	130	41	2	36	6,124	0.0465	1.972
Scandlines	Puttgarden	Rødby	Deutschland	Diesel	19	1,056	189	41	2	36	2,904	0.0465	1.974
Scandlines	Gedser	Rostock	Berlin	Diesel	48	1,055	229	41	2	36	4,835	0.0465	1.974
CLdN	Zeebrugge	Hirtshals	Valentine	Diesel	872	0	0	0	0	80	9,729	0.0133	0.567
-	Hitra	Hirtshals	Valentine s*	Diesel	1,002	0	0	0	0	50	7,251	0.0206	0.878
-	Hitra	Hirtshals	Valentine s* LNG	LNG	1,002	0	0	0	0	50	7,251	0.0186	0.928

*[1]Shippax (2016); [2]www.marinetraffic.com (2017); * s = smaller version*

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