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Freight Transport Modal Split and Environmental Performance Revisited

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Abstract

This paper revisits the comparative environmental performance of European freight transport modes. Ten years ago, we analyzed how exhaust emissions per unit of transport work compared for different modes of freight transport. In this paper we present calculations for a 2020 and a 2030 scenario. Compared to our original analysis, it seems that all modes have become significantly more environmental-friendly over the last decade, and that this development is likely to continue within the current decade. The most prominent deviation from our original study is the very high emissions from Roll-on-Roll-off shipping, which are estimated to be higher than that or the road transport alternative. Based on our analysis, we discuss future perspectives on the environmental competitiveness of transport modes.

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1 Introduction

10 years ago (Hjelle and Fridell, 2012) we argued that the environmental superiority of Short Sea Shipping (SSS) is not self-evident and conducted a comparative analysis of relevant transport mode alternatives in an intra-European setting. We concluded that SSS operations may very well deserve their "green label" when compared to alternative modes with respect to CO_2-emissions. However, we pointed out that the victory was a marginal one for Roll-on-Roll-off (RoRo) shipping operations versus truck transport, and that the victory also was highly dependent on the prevailing market situation and the resulting load factors. SSS did generally not deserve a "green label" when SO_2, NO_X and PM emissions were considered.

SSS is still considered a preferred solution in many transport policies in Europe, and is still benefiting from supporting political actions. Over the last decade, much has happened to this picture with respect to regulations and political agendas. Recent examples are the "European Green Deal" and the "Fit for 55" (European Commission, 2021b) packages within the EU, and the new stricter sulphur- and NO_X-regulations for marine fuels and vessels under the Marine Pollution (MARPOL) convention of the International Maritime Organization (IMO).

Much is also about to happen to transport technology for both land-based and maritime modes of freight transport in response to these new policies. This paper revisits the question "When is SSS transport environmentally competitive?" under current and future technological and regulatory scenarios. Answering this question is important to policy formation and the discussion of the role transport modes should play in a future reality where policy aims demand freight transport to operate under "zero emissions" or "carbon neutrality" requirements.

In the literature review below, we review the latest statistics of the market shares of European freight transport and puts this development into a context with recent technological and regulatory developments pertaining to the environmental performance of the transport modes. Although many researchers (McKinnon et al., 2015, Browne et al., 2022, McKinnon, 2023, Santén et al., 2021, Bergqvist and Monios, 2019, Holguín-Veras et al., 2021) have pointed out that mode choice within freight transport is a key part of the toolbox available to governments and businesses when trying to reduce the environmental footprint, original research on emissions per unit of transport work is scarce (Christodoulou and Woxenius, 2019). In intercontinental trades, sea transport is often the only viable option, also from an environmental perspective, but in an intra-continental (e.g. European) setting the optimal mode choice is no longer self-evident.

New data from real operations enable us to provide a new analysis of the comparative environmental performance of the transport modes, first under the current stage of development, and then in future scenarios under plausible technological and regulatory perspectives. Our analysis focuses on emissions per net mass of cargo transported. Based on this analysis we reflect upon the need for a change in the aims and tools applied in European transport policies regarding modal mix in intra-continental freight transport.

In the subsequent section we provide recent statistics and a literature review to relate our analysis to the current state of affairs regarding modal split in a European freight perspective. In section 3 we review relevant policy developments with respect to emission from transport modes. Then we move on to a presentation of the technological development in section 4, before our analytical methodology and data sources are presented in section 5. Our analysis and results are presented in section 6, before we discuss our findings (section 7) and conclude in section 8.

2 Literature review

2.1 Recent market developments and the current environmental footprint of European freight transport

Over the last decade (2010-2019), EU-27 freight transport has grown from 3036 to 3392 billion tonne-kilometres (tkm), corresponding to a growth of 11.7% (European Commission DG for Mobility and Transport, 2021). Over the same decade, the EU-27 GDP grew from 10 979 450 mEUR to 13 963 897 mEUR, corresponding to a growth of 27.2% (EUROSTAT, 2021). This means that one of the most prominent aims of sustainability policies; i.e. to decouple economic growth from freight transport resource use (European Commission, 2011a), seems to have been reached in the last decade. The same could be said for the total greenhouse gas (GHG) emission levels (all sectors) over the same period (IEA, 2020), but total GHG emissions from transport still increased by 3.5% (European Commission DG for Mobility and Transport, 2021). In the recent evaluation (European Commission, 2020b) of the effects of the 2011 White paper on transport (European Commission, 2011b), the conclusion is that the dependency on oil-based fuels has only diminished marginally from 95% in 2010 to 93% in 2018. The white paper also targeted a modal shift to sea and rail for 30% of road transports shorter than 300 km by 2030. **Feil! Fant ikke referansekilden.** shows the development of freight transport work in EU-27 over a 25-year period. Road freight remains the dominant mode of transport, constituting 1764.2 billion tkm in 2019. This corresponds to a market share of 52.0% in 2019 (Figure 2). The equivalent market share for road freight in 2010 was 51.3%, so the relative situation has almost not changed at all. The same could be said for the other freight transport modes, although sea transport seems to have

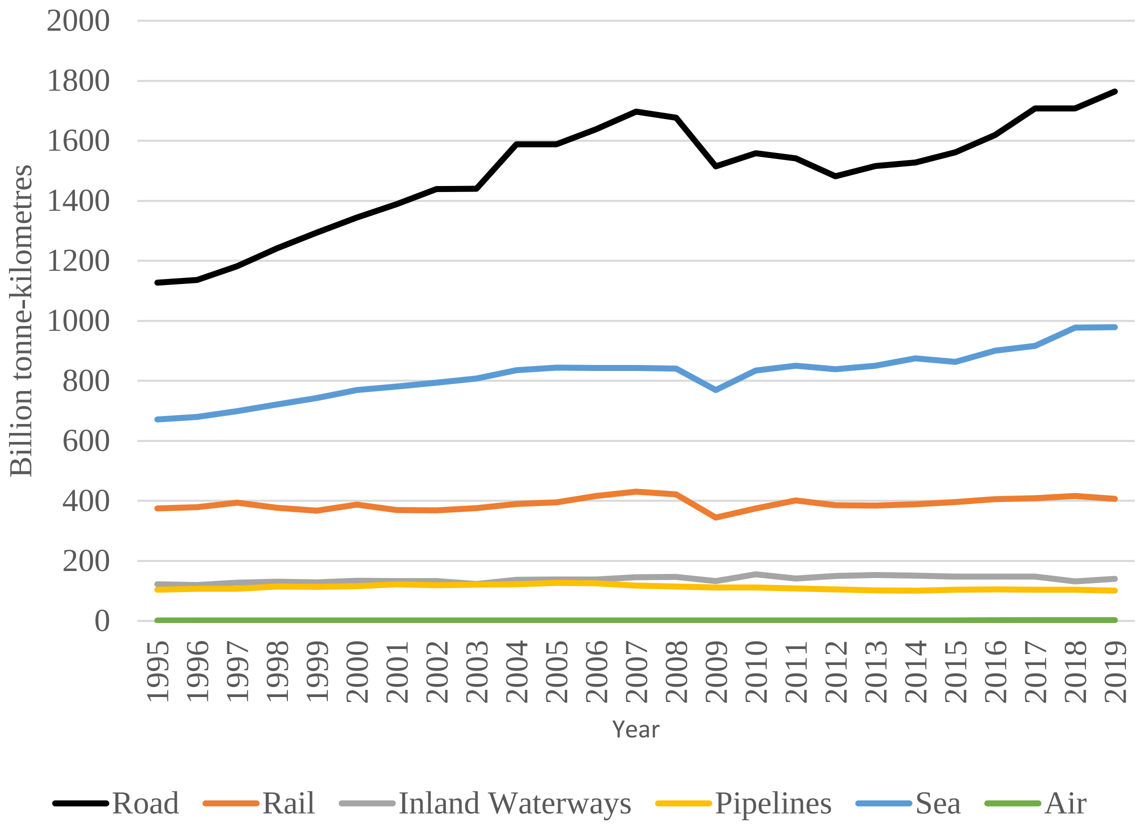

Figure 1 *Tonne-kilometres transported by mode 1995-2019 EU-27 (Source: Eurostat 2021)*

strengthened its relative position versus rail freight and inland waterways with around two percentage-points over the last decade. Although significant questions could be asked about the reliability of European transport statistics (McKinnon, 2010, Vanelslander, 2021), it seems little has happened in the first decade of the timeframe of the 2011 White paper regarding modal shift (Pinchasik et al., 2020). Modal shift is not as prominent in the toolbox of the current Green Deal policies (European Commission, 2019) of the EU as it has been in earlier policy documents, at least not explicitly. The focus is now on actions supporting the transition to low- or zero-emission technologies within each mode, and over-arching tools like different forms of "polluter pays" instruments. The tools proposed may, however, have a significant *impact* on future modal shift. For example, the planned inclusion of sea and road transport in the emissions trading regime may have a clear impact on modal split. The actual impact will be highly dependent on each mode's ability to adopt low- or zero-emission technologies, which again is dependent on technological maturity and the level and design of regulatory intervention.

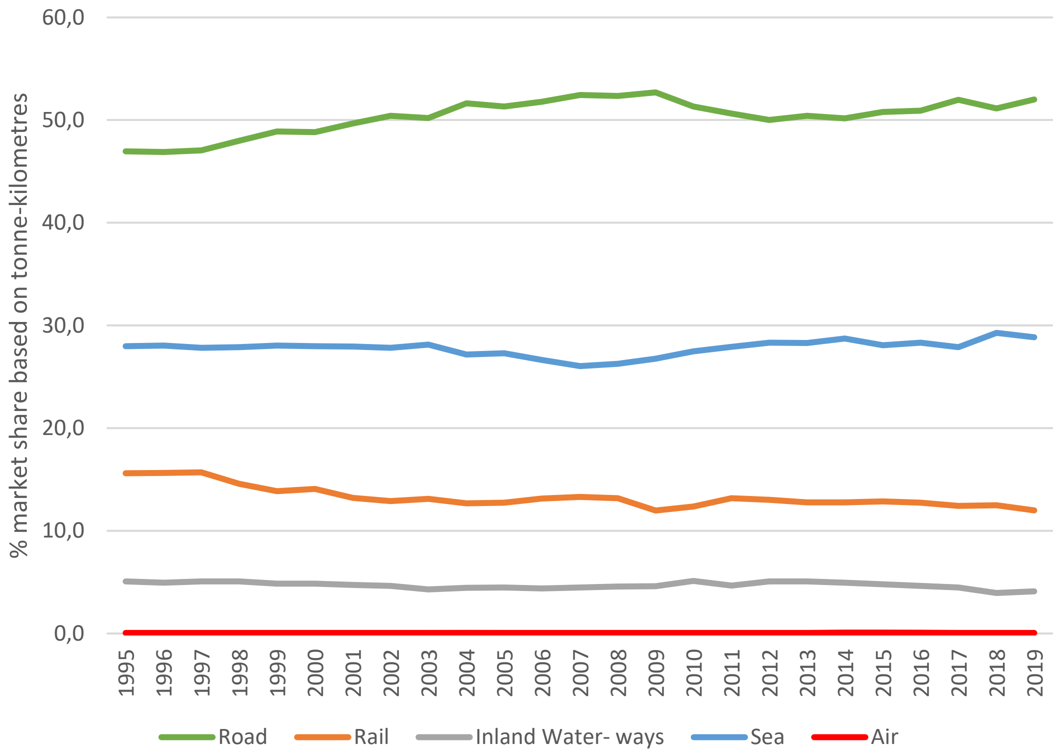

Figure 2 Modal split European (EU-27) freight transport 1995-2019 (Source: Eurostat 2021)

Understanding the comparative environmental performance of the alternative modes of freight transport is, nevertheless, essential when designing regulatory policies. Several support programs for freight modal shift have been implemented in Europe, with a varying degree of success (EU INEA, 2020, Takman and Gonzalez-Aregall, 2021). Currently, the Connecting

Europe Facility (CEF), supports freight transport actions which could be instrumental in achieving the goals of the European Green Deal.

Our aim is in this paper is to shed some light on the current performance of the main freight transport modes, how this has evolved over the last decade, - and, also to assess the likely development of the environmental footprint of the transport modes in the coming years, given what we already know about policy aims and technology development.

2.2 Empirical evidence on the comparative environmental performance of freight transport modes

Generally, there is less research to be found on the environmental performance of short sea and feeder operations, than on deep sea shipping (Christodoulou and Woxenius, 2019, Woxenius, 2015). The environmental superiority of shipping services vs. road transport has largely been seen as self-evident and thus not an interesting area to investigate further. This may be true for deep sea shipping where the economies of scale also work in favour of the maritime transport modes in terms of emissions per tkm (Cullinane and Cullinane, 2013). It is also clear that bulk shipping, even over relatively short distances, has lower emissions per unit of transport work – mainly due to the high capacity to deadweight tonnage factor, combined with energy-saving modest speeds. The interesting comparisons are, however, present in the case of smaller general cargo, container or RoRo vessels. Here the emissions per tkm might be higher if vessels travel at relatively high speed, if cargo volumes are not regular or big enough to secure a sufficient capacity utilization (Hjelle, 2014), or if the maritime route is significantly longer than the road alternative.

Most of the contributions in this area are based on models combined with assumptions about typical operating environments related to engine loads and resulting fuel usage. This is then combined with information about applied fuel qualities.

2.2.1 Our original study

In the comparative study that we did 10 years ago (Hjelle and Fridell, 2012), we based our calculations for short sea shipping on emission factors present in the NTM-model mostly taken from Cooper and Gustafsson (2004), NTM Working Group Goods and Logistics (2008) and NTM (2009). These factors were adjusted by us for SECA (Sulphur Emissions Control Area) and non-SECA trips. The relationship between deadweight tonnage and payload were based on factors from the Clean Shipping Project (Clean Shipping Index, 2012), and constituted a factor of 0.95 for tankers, 0.8 for container vessels and 0.5 for RoRo-ships.

The calculations for the trucks were largely based on the Artemis project (Andre, 2005), and an assumed Euro 4 engine and a 26 tonne payload capacity. For railways the emission factors were based on the values applied in the EcoTransit model at that time (Knörr, 2008), and the average electricity mix (EU 27) was also obtained from this source.

Assumed load factors are critical in an analysis like this (Monios and Bergqvist, 2017, Hjelle, 2011), and for container vessels and RoRo vessels the achieved load factor will be a combination of the utilization of the slot- or lanemeter-capacity, and the average utilization of the container or trailer. We assumed an average capacity utilization of containers and trailers to be 60%, and, achieved combined load factors of 44% for RoRo vessels, 48% for container feeder vessels, 55% for tankers, 50% for trains and 60% for trucks with trailers.

Based on the resulting emission factors presented in Table 1, we analysed the comparative emission levels in four typical intra-European transport chains: Gothenburg to Rotterdam, Helsinki to Genoa, Bremen to Le Havre, and Gothenburg to Aberdeen.

Table 1 Emission factors applied in the original analysis (Hjelle and Fridell, 2012)

	CO_2 kg/tkm	NO_x g/tkm	PM g/tkm	SO_2 g/tkm
RoRo 10' dwt SECA 1.0%	0.053	1.545	0.068	0.318
Tanker 125' dwt SECA 1.0%	0.004	0.112	0.006	0.024
Container Feeder 13' dwt SECA 1.0%	0.037	1.140	0.047	0.233
Train Electric EU27 mix	0.024	0.041	0.017	0.007
Train Diesel (EUR default)	0.043	0.740	0.020	0.001
Truck/Trailer EURO4, 19 m	0.063	0.360	0.002	0.000

We will revisit the comparative environmental performance of transport modes in this paper, focusing on recent and future technology developments in each mode of transport, but first briefly review the most relevant data sources available for this kind of analysis.

2.2.2 The EcoTransIT World model and the EN16258 standard

A much applied model for mode-comparative analysis is the EcoTransIT World model (Anthes et al., 2021), which also is compliant with the EN 16258 standard "Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services" (CEN, 2012). This standard provides necessary conversion factors and default values for energy use and GHG emissions per litre of fuel, differentiated by fuel type in both a Tank-to-Wheel (TTW) and a Well-to-Wheel / Well-to-Wake (WTW) or life-cycle perspective. However, the standard does not provide emission factors for electricity as this is highly dependent on the relevant electricity mix. Default vales for tonnage-based load factors and share of empty trips are based on a number of sources and are specified for different kinds of cargoes and carriers, ranging from 27% for volume cargo on trucks to 63% for bulk cargoes on trucks and cereals on trains. For sea-going vessels the factors are mainly based on IMO's second GHG study, but also a few newer references. Examples of default load factors for these vessels are: Dry bulk 49-60%, Tanker 48-61%, General cargo 60%, Container 70%, and RoRo 70% (Anthes et al., 2021). However, these values could be replaced by specific values in the model application whenever such are available. For maritime transport, the emission levels are based on the methodology of the third IMO GHG study (Smith et al., 2015), combined with an estimated typical ship size per trade lane and cargo type. For truck transport, emission factors are mainly based on The Handbook Emission Factors for Road Transport (Notter et al., 2019), and based on engine generation, characteristics of the road network and average cargo load.

2.2.3 Data from the IMO Data Collection system for maritime transport

The adoption of the IMO Data Collection System (DCS) in 2016 means that a comprehensive dataset is available for analysis from the first reporting period of 2019. Contrary to the data collected from the MRV system, this dataset is not openly available, but has fed into the Fourth IMO GHG Study (Faber et al., 2020). This report presents four different metrics for carbon intensity, where the Energy Efficiency Operational Indicator (EEOI) is the most interesting one in our context, because it in principle relates CO_2-emissions to transport work (in tonne-nautical miles). However, contrary to the EU MRV system, information about the actual cargo carried by the vessels is not part of the IMO DCS reporting system, due to its commercial sensitivity. The EEOI data is therefore based on a random forest regression model where UNCTAD-data (UNCTAD, 2018) on transport work by ship category is a main input factor, as it is for the EcoTransIT World model. EEOI-data for many vessel types and size classes are estimated for the time-period from 2012 to 2018. In Figure 3 we have extracted and compiled data for vessel types and sizes relevant to short sea operations. The general impression is that not much has happened with regard to the operational CO_2-efficiency of the fleet over this period of time. For all categories (container, general cargo and ro-ro) estimated emissions per gross unit of transport work is a falling function of vessel size, as could be expected due to the economies of ship size. Apart from the category pertaining to the smallest RoRo-vessels (under 5000 dwt), the emissions factors have not changed much. Still the EEOI-values for all RoRo-vessels are significantly higher than those of general cargo vessels and the container ships. It is noteworthy that the EEOI-index applies a gross cargo mass definition of transport work, i.e. including the weight of the cargo-carrying unit, and also including the repositioning of empty units (IMO MEPC, 2009).

It is also noteworthy that there may be significant variation within these categories as well. One could expect significant differences between a 400 TEU and a 900 TEU container vessel (Svindland and Hjelle, 2019), and also between a 2500 dwt and 4500 dwt general cargo vessel. Compared to the CO_2-efficiency assumed in our original calculations (Table 1), our 10 000 dwt RoRo vessel had a higher emission factor of 53 g/tkm, which is approximately 45% higher than the IMO figures for vessels between 5000 and 9999 dwt, and 73% higher than vessels between 10000 and 14999 dwt. Our 13 000 dwt containership had an emission factor of 37 g/tkm. This vessel would normally carry some 1100 TEUs. Compared to the IMO figures for container vessels our figure from Hjelle and Fridell (2012) is also significantly higher; 94% compared to the IMO category of 0-999 TEU and 255% higher than the 1000-1999 TEU category.

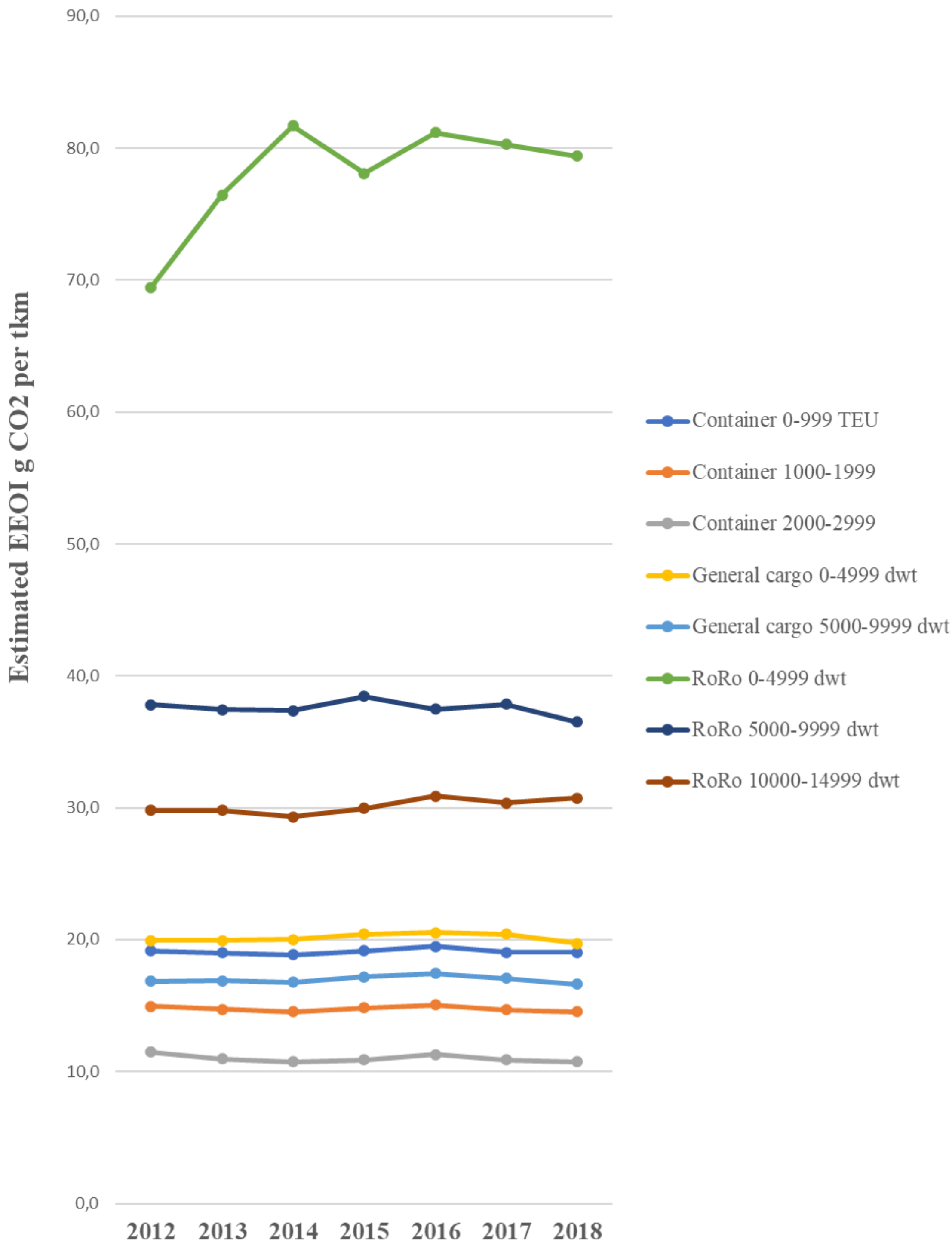

Figure 3 *Estimated EEOI for short sea-relevant vessel types and sizes. Own compilation, based on tables from the Fourth IMO GHG study (Faber et al., 2020)*

2.2.4 Data from the EU MRV system for maritime transport

Original research based on real operations, actual fuel consumption and actual transport work carried out, is rare, especially in a short-sea operations perspective. Two exemptions cold be found for smaller general cargo vessels in Hjelle (2014) and container feeder vessels in Svindland and Hjelle (2019). The new data made available from the EU MRV regime (European Commission, 2020a, European Commission, 2021a) represents an important and comprehensive contribution that could reduce the dependency on modelling approaches.

The MRV-regime was introduced from 2018, where companies shall monitor, for each of their ships, CO_2 emissions, fuel consumption and other parameters, such as distance travelled, time at sea and cargo carried on a per voyage basis. The data is included in an annual emissions report submitted to an accredited MRV verifier via the THETIS MRV database. The annual average data is transparent to anyone event at the individual ship level. However, the exact methodology applied for the calculation of transport work is not transparent in all cases. To a large extent the data reported into the MRV-system is similar to the data collected by the IMO in their DCS-system, but there are significant differences. Most prominent is the lack of transparency of the IMO system and the fact that MRV contains information on the transported cargo volumes.

The annual reports produced do not have a particular focus on short sea operations, although there is an attempt to shed some light on this market by presenting some data pertaining to ships with a short average port-to-port distance in their reported annual data.

2.2.5 The methodology for GHG efficiency of transport modes developed for the European Environment Agency

In 2020 the European Environment Agency (EEA) commissioned a report which developed a methodology for GHG efficiency estimation of transport modes (Fraunhofer, 2020). The calculations for road freight transport with HGVs is based on the same tools as applied by nations reporting GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC). The emissions for road freight vehicles are allocated to Light Duty Vehicles (LDVs) and Heavy Goods Vehicles (HGVs) by applying national data for transport activity and an average payload of 0.3t for LDVs and 12t for HGVs. The estimated EU-27 CO_2-emission figures for HGVs in this publication are 108 g/tkm (TTW) and 137 g/tkm (WTW) for 2018 on average. For highway transport the respective WTW figure is 117 g/tkm.

For maritime freight transport this methodology builds mainly on the first (2018) EU MRV-dataset. The CO_2-emission figures from this source are increased by 10% to cater for vessels smaller than 5000 GT. Other greenhouse gases are added, based on average fuel mix data from the 4th IMO GHG study, and the climate impact of black carbon is also added based on this source. Finally, WTT emission factors are added based on the fuel mix data. The calculations provided in this source are not directly relevant in a SSS context, since the EU MRV dataset includes transports to and from other continents as well. However, data for the RoRo category could probably to a large extent be assumed to be relevant for short sea. The estimated figure for this ship category is 15.7 g/CO_2e per tkm for 2018 and 53.0 g/CO_2e for 2019. This dramatic increase is noted in the report, and the authors speculate that this stems from the difficulties of estimating the right payload for this ship category, and that the figures are therefore uncertain. Christodoulou (2021) has also analysed the 2019 MRV-data for RoRo vessels, and reports 106.2 g CO_2 per tonne-nautical mile, which would equate 57.34 g CO_2 per tkm. This figure is higher than what is reported in Fraunhofer (2020), especially considering that this is representing CO_2 and not CO_2e. It is possible that the 2019 figures in Fraunhofer (2020) are based on a preliminary 2019 dataset, but this is not mentioned as an issue.

The equivalent figures for container vessels and general cargo ships in 2019 are 7.7 g/CO_2e per tkm and 13.2 g/CO_2e respectively, but these categories would be heavily influenced by inter-continental trades, and are therefore less relevant in our setting.

3 Changes in the environmental regulatory framework of European freight transport

Many changes have been made to the environmental regulatory framework and policies for European freight transport over the last decade. Partly these changes are mode-specific, e.g., new regulations for maritime or road transport, and partly these are over-arching policy changes, like new political targets for GHG emissions or more concrete propositions like the expansion of the domain of the EU Emissions Trading System (ETS) to encompass the transport sector. Most of the changes are made by the EU, and implemented by member states and associate states (EEA). To some extent, the policy changes are also global, but with an impact on the European freight market.

3.1 Regulatory changes pertaining to the road freight regime

Since 1992 the EU has gradually introduced stricter emission standards for heavy goods vehicles. Two new stages have been implemented since our last analysis: the EURO V, effective since 2008, and the EURO VI from 2013. The step from EURO V to EURO VI represents a significant reduction of HC, NO_X particles (PM) (Table 2). To achieve these emission levels, a catalytic converter is necessary.

Table 2 EURO emission standards for trucks (g/kWh) (Dieselnet, 2021)

Engine standard	Implementation date	CO	HC	NOx	PM
Euro IV	2005.10	1.5	0.46	3.5	0.02
Euro V	2008.10	1.5	0.46	2.0	0.02
Euro VI	2013.01	1.5	0.13	0.40	0.01

The first regulations of CO_2-emissions from HGVs were introduced in 2019 (EU Regulation 2019/1242), but will only have an impact from 2025 when CO_2-emissions from manufacturers' fleets of new trucks must be 15% lower than the reference period (1 July 2019 to 30 June 2020). This is to be tightened further to a 30% reduction by 2030.

Beyond the direct regulations pertaining directly to HGVs, a long range of EU regulations have a more indirect impact on these emissions, such as the Energy Efficiency Directive, The Energy Taxation Directive, The Renewable Energy Directive, The Fuel Quality Directive, and the EU Emissions Trading System (European Environment Agency, 2022).

3.2 Regulatory changes for maritime transport

The regulation of maritime transport is to a lesser extent governed by regional (e.g. European) policies (Cullinane and Cullinane, 2013). The global character of the shipping industry, and the international legislation (the law of the seas; UNCLOS), means that national or regional regulations would be less efficient than global ones. Global regulations of the maritime transport industry have been administered through the IMO of the UN for many decades. Global environmental regulations have mainly been implemented under the MARPOL convention of the IMO. In the first decades this convention was mainly revolving around emissions to sea, but since Annex VI of the convention was coined in the late 1990s and implemented from 2005, much focus has been on emissions to air (IMO, 2021b). Over the last decade the most prominent new IMO regulation pertains to the reduction of sulphur emissions, as the maximum sulphur content of marine fuels was reduced to 0.5% from 2020 on a global scale, and from 2015 to 0.1% for the SECA. Ship operators/owners now have basically three options to comply with this new regulation: 1) to switch to low sulphur fuels, 2) to install sulphur cleaning systems (scrubbers), or 3) to retrofit existing ships or commission new-buildings capable of running on alternative fuels, e.g. Liquified Natural Gas (LNG) (DNV-GL, 2014). NO_X-emissions have also been regulated through the tightened allowed emission levels for new marine engines. The Tier II emission levels applies to vessels build from 2011, the more ambitions Tier III levels applies to vessels built from 2016 when operating in North American Nitrogen Emissions Control Areas (NECA), and applies to The Baltic Sea and the North Sea NECA areas for ships built from 2021. These regulations mean that ship owners/operators normally will have to go for LNG propulsion, or apply Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) technology for their new-buildings operating in these areas.

Although reducing the emissions of GHGs has been on the agenda of the IMO for several decades, the implemented regulations have been softer in this area, than for the pollutants mentioned above. The shipping sector has been exempted from the early regulations under the UNFCCC, partly because it is not easy to allocate the responsibility for emissions from international shipping to individual nations. The main action in this area from the IMO has been to introduce the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) for vessels delivered after 2013. The EEDI gradually introduces reduction factors up to 30% versus the reference line in four phases 2013-14, 2015-19, 2020-24 and after 2025. The EEDI only applies to newbuildings, but a similar tool, the Energy Efficiency Existing Ship Index (EEXI) will apply from 2023, along with a Carbon Intensity Indicator (CII) rating. With a poor (D or E) rating, shipowners must implement an approved corrective action plan as part of their SEEMP (Johnson et al., 2022).

As presented above, in 2016 the new Data Collection System (DCS) was adopted by the IMO. This means that all ships (greater than 5000 gt) must report fuel consumption data and a proxy for transport work from 2019.

In 2018 the IMO adopted a strategy on the reduction of GHG emissions from ships, following up on the Paris agreement of the UNFCCC. Here the IMO confirms its commitment to reducing GHG emissions from international shipping, and phasing them out as soon as possible, and by 2100 latest. An intermediate goal is to reduce total GHG emissions from shipping by 50% within 2050, compared to 2008 levels. Emissions per unit of transport work should be reduced by 40% within 2030. A more ambitious plan for decarbonisation, possibly 100% reduction by 2050 is promoted by several actors, and is currently under debate within the IMO system.

The EU has, for a long time, expressed its impatience with the IMO. Even though the EU also recognises the higher efficiency of global, rather than regional, regulations, several environmental regulations pertaining to the maritime transport sector has been implemented at the European level over the last decade. One example is the strict regulation on sulphur content of marine fuels burnt in European ports, which introduced a 0.1% sulphur level limit from 2010, five years prior to the equivalent MARPOL/SECA regime was introduced. In 2013 the EU also adopted a strategy for the reduction of GHG emissions from the shipping industry, comprising several steps (European Commission, 2013), where the most important one was the introduction of the MRV system, collecting data on CO_2-emissions and transport work for ships visiting EU ports.

Over the last decade, the first steps towards a regulatory regime for maritime transport GHG emissions have been made – both by the IMO and the EU. The next step would be to apply this information in an efficient emissions-reducing policy. This is a more controversial issue. The EU intends to include shipping emissions into the EU ETS system (Directive 2018/410). The planned implementation was from 2023, but the process has been delayed. It is likely that this will be implemented gradually from 2024, and that a high share of the revenues will be reserved for a fund supporting investments in green and resilient technologies. This move is also supported by the FuelEU Maritime-initiative which requires ships to gradually reduce the GHG intensity of onboard energy by 2% in 2025, increasing to 75% in 2050 compared to a 2020 baseline (European Commission, 2021c). The proposed revised “Energy Taxation Directive” (European Commission, 2021e) may also impose a tax on marine fuels sold in the EEA from 2023, and, equally, the “Regulation on the deployment of alternative fuels infrastructure” (European Commission, 2021b), may secure that shoreside electricity and LNG fuel is available in all TEN-T EEA ports by 2030 and 2025 respectively.

4 Technological development and environmental performance

4.1 Technological development for road freight and environmental performance

As a result of the tightened regulations of emissions from European truck engines described above, average fleet emissions of CO and NO_X have dropped by more than 70% over the last decade, and are expected to drop further as the new emission standards dominate the fleet. However, the gains in fuel efficiency are very moderate, only 5% for the German HGV fleet. This means that the CO_2-emissions per vehicle kilometre from HGVs have only dropped marginally in the same period, and not enough to compensate for the increase in traffic volumes (Figure 4). The projected CO_2-emissions from HGVs for 2025 in Germany is expected to drop by 7% versus 2020-levels, which probably is due to the phasing-in of alternative fuels, and the industry preparing for new fleet regulations (INFRAS, 2021).

Manufacturers of HGVs are now preparing for a future where zero TTW-emissions are required, but where there also needs to be intermediate technologies that significantly reduces GHG emissions (Nelles, 2019, Krajnik et al., 2021). In the shortest term there may be some room for efficiency gains for traditional diesel powertrains, but electrified powertrains will probably soon dominate the shorter transport distances (e.g., in urban distribution). For long-haul road freight, the future technology choices are not so clear. It might involve green or blue hydrogen, various bio-fuels and/or battery-electric solutions (DNV, 2021b, IEA, 2021). The technological maturity of the different powertrains is not the only factor that will impact the trajectory of a greening road freight, the availability of supporting infrastructures and the supply chain capacity of green fuels are also very important (Ovrum et al., 2022). If the future is based on electricity, both available charging infrastructure, grid capacity and the development of green electricity production is crucial (Plötz et al., 2019, Gustafsson et al., 2021). Also, the total cost of ownership of electric HGVs needs to be competitive to ICE-based ones. Currently, mainly prototypes or limited editions of HGVs with a range suitable for distribution transports are available, and the cost of ownership necessitates government subsidies to make them competitive versus traditional ICE vehicles. However, experiences from the rapidly developing battery-electric bus-market suggest that the total cost of ownership may be comparable within a 5-year perspective for HGVs with a range similar to the E-bus fleet (Thorne et al., 2021). The capital costs will likely remain higher for some time, but this may be compensated by lower operational costs. IEA (IEA, 2021) predicts that there will be more than 100 medium electric freight truck models, and more than 50 heavy electric freight truck models available by 2023. With the necessary incentive schemes in place, combined with private sector ambitions of the cargo-owner (e.g., Ikea, Amazon) and logistics service provider (e.g. DHL, FedEx) sides, it seems that electric truck technology is set for a take-off within this century. The uptake of this new technology is, however, going to be very different in different parts of the world. DNV (Eriksen et al., 2021) predicts that the market share of electric commercial vehicle sales in Europe in 2030 will be higher than 60%, only surpassed by China, which is expected to achieve a 70%. The predicted World average is less than 30% by 2030 in the DNV most likely scenario.

4.2 Technological development for sea freight and environmental performance

Describing the environmental effects of the recent technological developments for ships is more complicated for vessels than for trucks, as the variety of vessels in the world fleet is much greater than that of road freight vehicles. Above, we have described the regulations pertaining to the sulphur content of marine fuels, the NOx-code and the EEDI. The sulphur regulations have had an immediate impact on emission-levels, but the NOx-code and the EEDI only has a gradual impact as they pertain only to new-buildings. With a typical economic life of a merchant fleet vessel of more than 30 years, the full effect of these regulations will not be seen within the decade. The 2018 and 2019 MRV-data indicate little change in the reported energy efficiency of containerships, bulk carriers, and oil and gas tankers over one year (European Commission, 2021d).

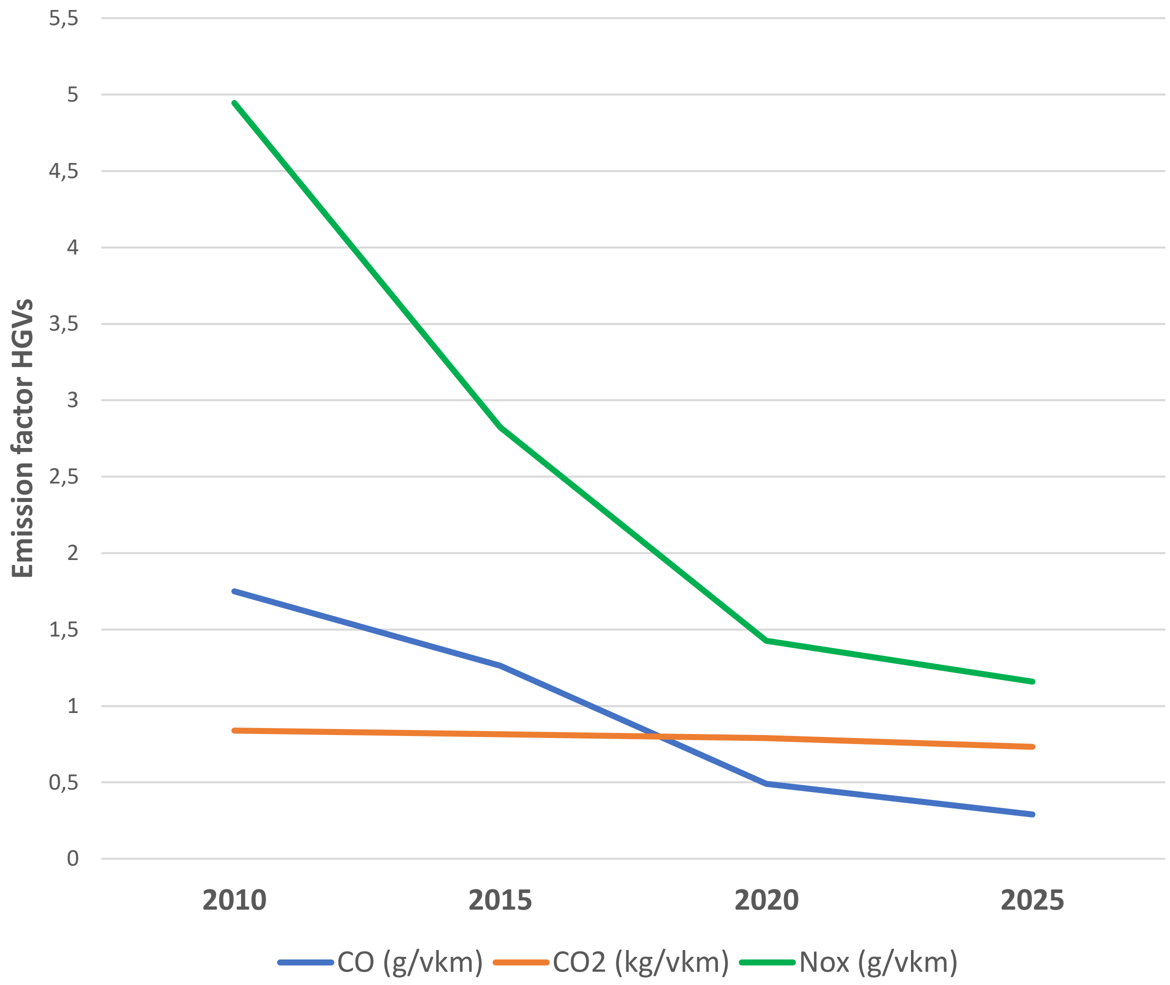

Figure 4 Emissions from HGVs Germany 2010 to 2025 (INFRAS, 2021)

In the Fourth IMO GHG Study (Faber et al., 2020) the changes in EIV (Estimated Index Value – a proxy for EEDI) from 2012 to 2018 is estimated by ship type. The reductions in energy use over this time-span is between 0.5% and 4.0% for bulk carriers, between 0.1% and 16.2% for container vessels and between 0.1% and 7.5% for oil tankers. It is noteworthy that these efficiency gains could not easily be attributed to the tightening of the EEDI-requirements, because this is an operational indicator, which would also be heavily influenced by e.g., average operating speed. The same source also estimates changes in the total emissions of pollutants over the same period from international shipping. Apart from a significant growth in CH_4 – emissions (methane), the change in the other emission types is moderate. The significant growth (more than 150%) in methane emissions is linked to two factors: an increase in the use of LNG as a fuel and a shift of engine types for LNG-propelled ships.

Despite the fact that some sulphur-content regulations were introduced during this period (the regional SECA-regulations and the EU port directive), the emissions of SO_X increased by 5.5%. This may be attributed to the fact that the average sulphur content of HFO increased over the period and to a general increase in total fuel consumption. This increase outweighed the gains from a significant increase in the use of low-sulphur fuels like MDO and LNG. However, the new global sulphur regulation from 2020 (IMO 2020) has changed this situation dramatically. This regulation is expected to have reduced global SO_X-emissions by 77% (IMO, 2021a).

The same counter-intuitive effect could be seen for NO_X-emissions (Faber et al., 2020). One might expect that ships build according to the Tier II and Tier III levels of the NO_X-code would contribute to a lower level of NO_X-emissions, but these actually increased by 1.2% from 2012 to 2018. The increase is, however, lower than the increase in total fuel consumption (5.6%), which might mean that the NO_X-code regulations have had some impact.

In the short term the IMO 2020-regulations will lead to an increase in carbon emissions, because the use of scrubbers is a process that require additional use of energy (Eriksen et al., 2021). DNV expects that an estimated doubling of world GDP by 2050, would outweigh the expected efficiency gains from supply chain optimization, digitalization, sensors and smart algorithms. Their most probable scenario is based on an expected growth of maritime transport work of 28% from 2019 to 2035. Electrification is expected to play a significantly smaller role for international shipping than for road transport, and is mainly going to play a role in short sea shipping, but also for energy use in ports. Today maritime fuels are almost all based on fossil oil. By 2050, DNV expects the mix to be 42% zero-carbon fuels and 39% natural gas by 2050. The low-carbon fuels will probably be a mix of ammonia, hydrogen and other electro-based fuels (Eriksen et al., 2021). The role of the different fuel types is highly dependent on how fast sustainable energy supply chains could develop. This is illustrated by 24 very different scenarios developed by DNV in a recent report (Ovrum et al., 2022). Here the estimated share of fossil fuels in 2050 lies between zero and 40% depending on policies, technology development and investments made in both energy supply chains and vessels with alternative fuel technologies.

More than 5% of the current fleet and about a third of ships on order are now able to run on alternative fuels (Ovrum et al., 2022). The alternative fuels in the order-book are mainly LNG and batteries. The battery-electric solutions are reserved for the short-sea segment of the fleet. LNG and LPG are not carbon-neutral, and biofuels are far more expensive and not yet widely available. DNV does not expect the carbon-neutral fuels to play an important role for deep-sea shipping until the late 2030s. For short-sea shipping, however, hydrogen is already introduced in a few cases based on ICEs, and may in the coming years also be based on fuel-cell technology. A scaled commercialization of hydrogen as a marine fuel, even in the short-sea market, is not expected to happen until after 2030 (DNV, 2021a), probably via hydrogen carriers like ammonia (Bouckaert et al., 2021). It seems that the technology readiness level of methanol is currently higher than for ammonia and hydrogen (Ovrum et al., 2022). Short sea shipping is expected by DNV to be instrumental for maturing hydrogen technology in the years to come.

5 Methods and data

The analysis performed in our original study has been updated here with data available for 2020 as well as with an outlook up to 2030. The new method covers new data sources as well as the changes in performance over the years. We have modelled the efficiency of different vehicles and vessels with respect to emissions of CO_2 per unit of transport work measured in tonne-km. The analysis does not take into account upstream emissions from fuel production, and therefore represents a TTW-perspective. We have modelled the total emissions of CO_2 and some air pollutants for a set of assumed transport cases in Europe.

5.1 Calculations for the 2020 scenario

The key data sources for our calculations are summarized in Figure 5. For road traffic the NTM model has been updated with recent data from the HBEFA model (Notter et al., 2022) which is a detailed model used for calculating emissions from road traffic used by many countries for annual reporting of emissions. In NTM the data is complemented by assumed cargo load factors using net cargo as basis. We have made our analysis for a “Truck with trailer 30-40t” using B7 diesel (diesel with 7% biofuel) and emission class Euro VI which is the most common class operating in Europe today. As load factor we have used 44 % on mass basis for the truck.

In lack of good European data on average net cargo on trailers, and transport of empty trailers, we have calculated this factor based on Norwegian Maritime transport statistics for international traffic for 2021 (Statistics Norway, 2022). This source gives an average mass of unaccompanied trailers of 11.0 tons when the share of empty trailers is accounted for. An average payload capacity of 25 tons per trailer, then yields a load factor of 44%. This results in CO_2 emissions per transport work of 59.7 g/tkm.

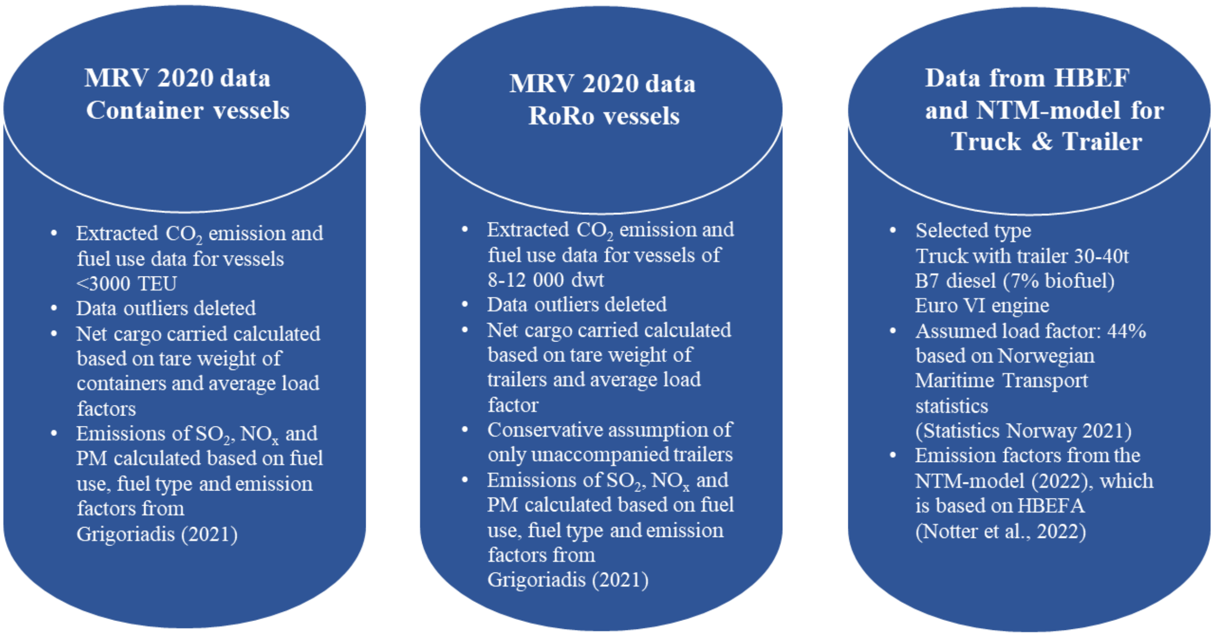

Figure 5. Key data sources applied in our calculations

For the ships we have used the MRV data for 2020 (EMSA-THETIS-MRV, 2022). This data set contains, as mentioned, information on CO_2 emissions and transported cargo. We use as examples two ships: a RoRo ship of around 10 000 dwt and a typical container feeder. For the RoRo ships we have used the MRV data for this category for ships in the range 8 000 – 12 000 dwt and disregarded a few unreasonable datapoints. The latter are usually associated with low operating times in the area during the year. The median value in the raw data from MRV yields

52.5 g CO_2/tkm for these RoRo ships. However, the cargo definition in MRV uses gross cargo, as is common for shipping, and thus includes the weight of cargo carriers, trucks etc. As discussed above the purpose of this study is to allocate emissions down to the actual cargo transported and we thus attempt to assess the fraction of the cargo mass, as reported in MRV, that is actual transported cargo. The instructions on cargo for RoRo ships when reporting to MRV is to use either actual cargo mass, unit mass times the number of units, or unit mass per lanemeter times occupied lanemeters. It is not public information which method and data are applied for each ship. For our assessment we have made the conservative assumption that the cargo is dominated by unaccompanied trailers of about 13m that have a tara weight of 6 tonnes and a cargo capacity of 25 tonnes. For load factor we have used 44% (Statistics Norway, 2022) as for the truck and this includes repositioning of empty trailers. With these assumptions the calculated emission of CO_2 per transport work (with net cargo mass) becomes 81.1 g CO_2/tkm.

For the container feeder we have used MRV data for container ships up to 3000 TEU capacity. The median CO_2 emission per transport work is 20.1 g CO_2 per tonne (gross) – km. Also, for container ships the cargo is reported as gross weight to MRV. The cargo mass in MRV for container ships can be calculated as the actual mass (including the weight of the containers themselves) or as a default TEU-weight times the number of containers. The default weights are stated as 12 tonne per TEU for a loaded container and 2 tonne per TEU for empties. It is not clear from the MRV database which method each ship has used. Assuming 10 tonnes of cargo in loaded containers, and a weight of 2 tonnes per TEU for the actual container we can calculate a net emission factor. We have assumed that 17.2% of the containers are empties, based on statistics of containers handled in main European ports (Eurostat, 2022). This gives a net emission factor of 24.9 g CO_2/tonne-km.

For the other emissions calculated (NO_X, PM, SO_2) the emissions for the truck are obtained from NTM-calc (Network for Transport Measures, 2022). For the ships we have used emission factors from Grigoriadis (2021), assuming that both ships use slow-speed engines and are of NO_X Tier II. Further, within SECAs the ships are assumed to use marine gasoil with a sulphur content of 0.1% and outside SECAs residual oil with a fuel sulphur content of 0.5% (see Table 3).

Table 3 Emission factors applied in our analysis (Grigoriadis et al., 2021, Network for Transport Measures, 2022)

Emission factors (g/kg fuel)	NO_X Tier II	NO_X Tier III	PM	SO_2
Ship in ECA	57.8	10.2	1.11	1.83
Ship Outside ECA	57.8	10.2	2.20	9.16
Truck/trailer	1.44[4]		0.049	0.019

5.2 Calculations for the 2030 scenario

For the assessment of emissions in 2030 we have made certain assumptions. For trucks we have assumed a 30% reduction in emissions per transport work in line with the stated EC target (EU, 2019). For ships we have assumed that shipping will be included in the ETS and that the EU Marine fuel directive are in place. This is assumed to give an increased efficiency of 8% (EC, 2021). Further, the decided CII and EEDI regulations will lead to more fuel-efficient ships in 2030. The EEDI regulations require new container and RoRo ships of the size analyzed here

[4] Euro VI NO_X standard for the truck

to be about 30% more energy efficient compared to the baseline (from 2008) from 2022 and 2025, respectively. Further, the CII regulations limits the emissions of CO_2 in relation to transport work allowed for all ship types. The limits are strengthened by 11% by 2026 in relation to 2019 and future requirements are expected to be more stringent. By assuming a certain ship replacement rate we conclude that a typical RoRo ship will be about 22% more fuel efficient in 2030 compared with 2020 due to the CII and EEDI regulations. The corresponding value for a typical container ship is 39%. For emissions of air pollutants, we assume that the emissions for the truck will be proportionally reduced to the CO_2 emissions. For the ships we assumed NO_X Tier III standard within the NECAs (the Baltic and North Seas).

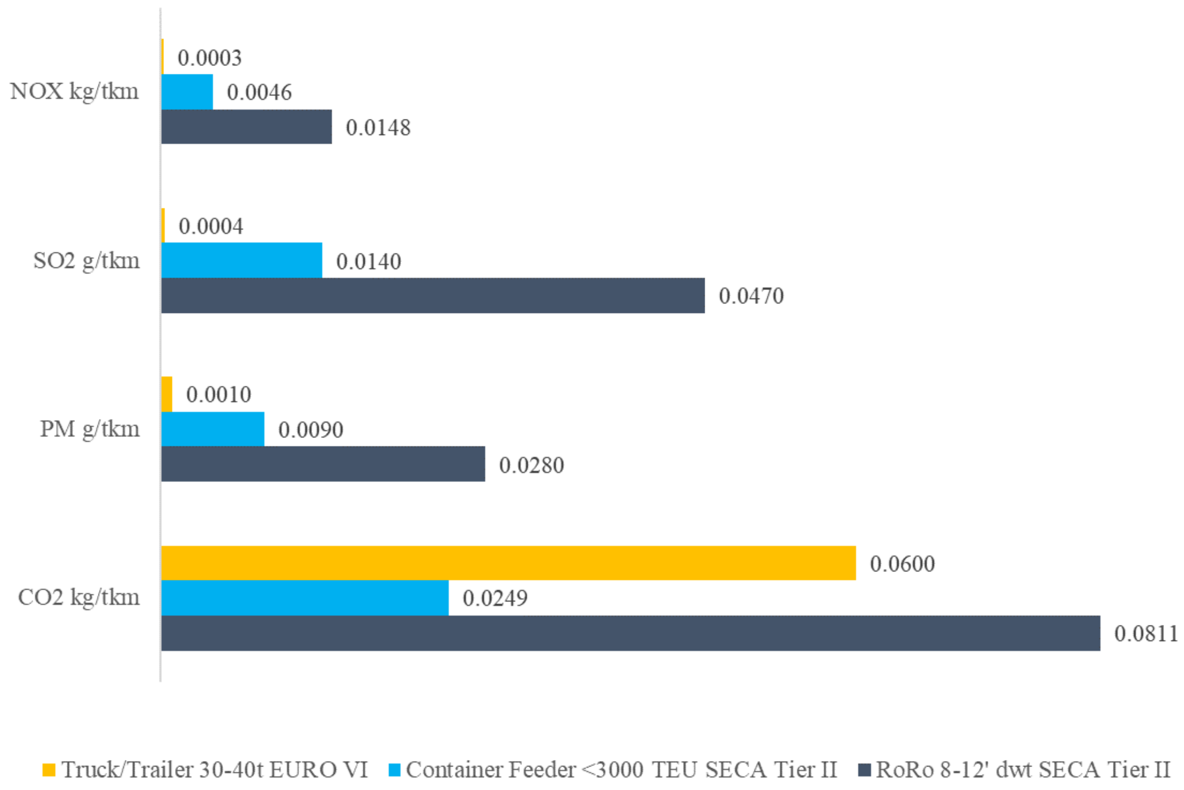

Figure 6. Emission factors for 2020

6 Analysis and results

Based on the methodology and data presented above, we end up with the emission factors presented in Figure 6 for 2020, and in Figure 7 for our 2030 scenario. Road freight transport has the lowest NO_X, SO_2 and PM-emissions. Container vessels have the lowest CO_2-emissions with an emission factor that is less than half that of road freight transport. RoRo-vessels, however, have a significantly higher CO_2-footprint per the transport work unit than road transport.

Our 2030 scenario shows that we expect all three modes of transport to have significantly lower emissions of both local pollutants and CO_2. The comparative picture, however, does not change much.

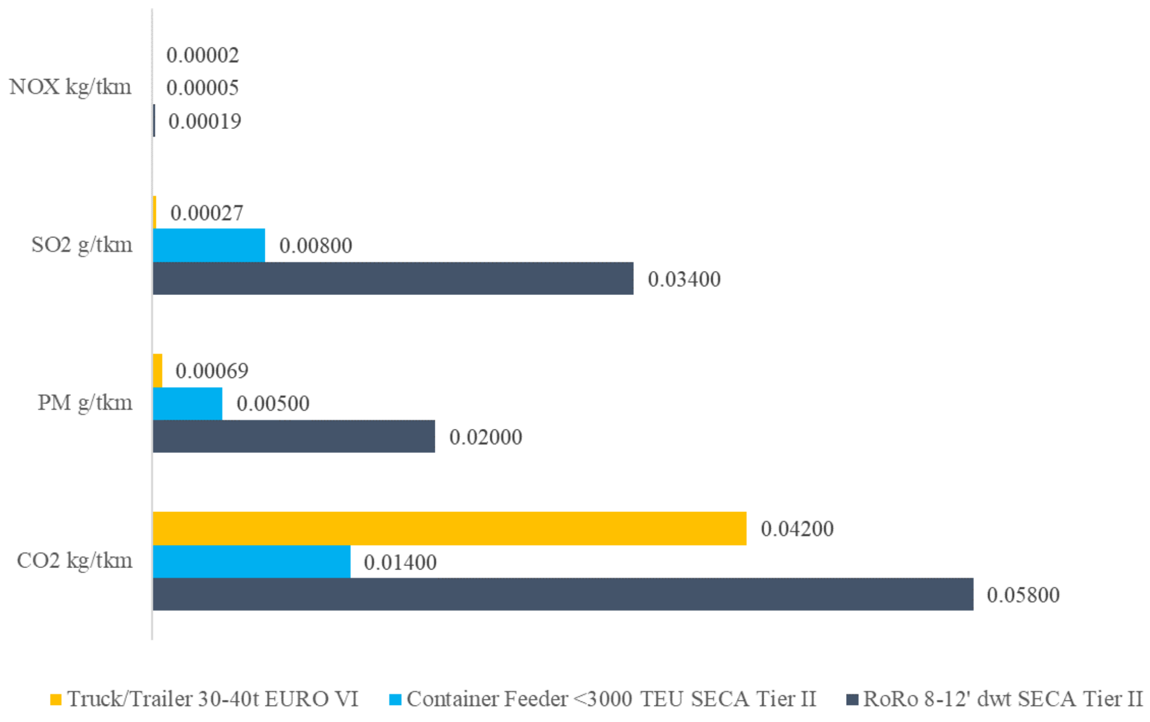

Figure 7. Emission factors for 2030.

Table 4 2030 emission factors as percentage of 2020 factors

	CO_2	NO_X	PM	SO_2
RoRo	72 %	13 %	72 %	72 %
Container	56 %	10 %	56 %	56 %
Truck	70 %	70 %	70 %	70 %

All emission factors are significantly reduced from 2020 to 2030 (

Table 4). The most significant reductions could be expected with respect to NO_X-emissions for the vessels.

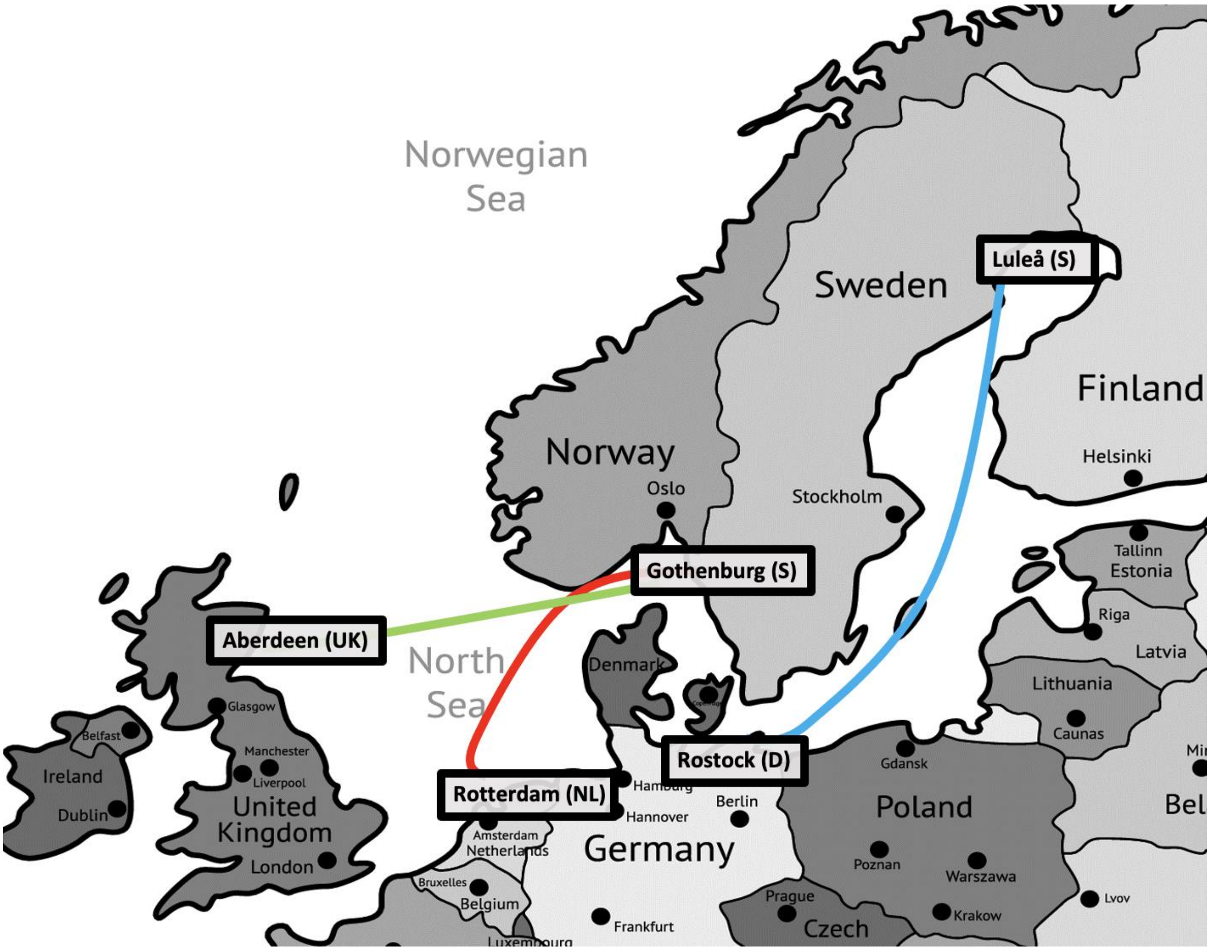

Figure 8. North Sea and Baltic Sea short sea connections selected for the comparative environmental analysis. Based on vector graphics by Colourbox.com/Ildogesto

To illustrate how the comparative environmental performance plays out in realistic North-European cases, we have calculated emission figures for four different origin-destination pairs:

- **Gothenburg-Rotterdam.** This is an important feeder link between the biggest intercontinental hub port of Europe and the biggest Scandinavian port. In this case the distances of sea and land transport are quite similar.
- **Gothenburg-Aberdeen**. A link between Sweden/Scandinavia and Scotland is a case where the sea transport alternatives have a significant distance advantage.
- **Luleå-Rostock** represents a Baltic Sea link connecting the northern part of Scandinavia and Germany, and again a case where the distances of road and sea transport are quite similar.

For each of these cases we have calculated the emissions related to the transport of 1000 tons cargo, as we did in our original paper (Hjelle and Fridell, 2012). Routing and distances are based on the EcoTransIT-model.

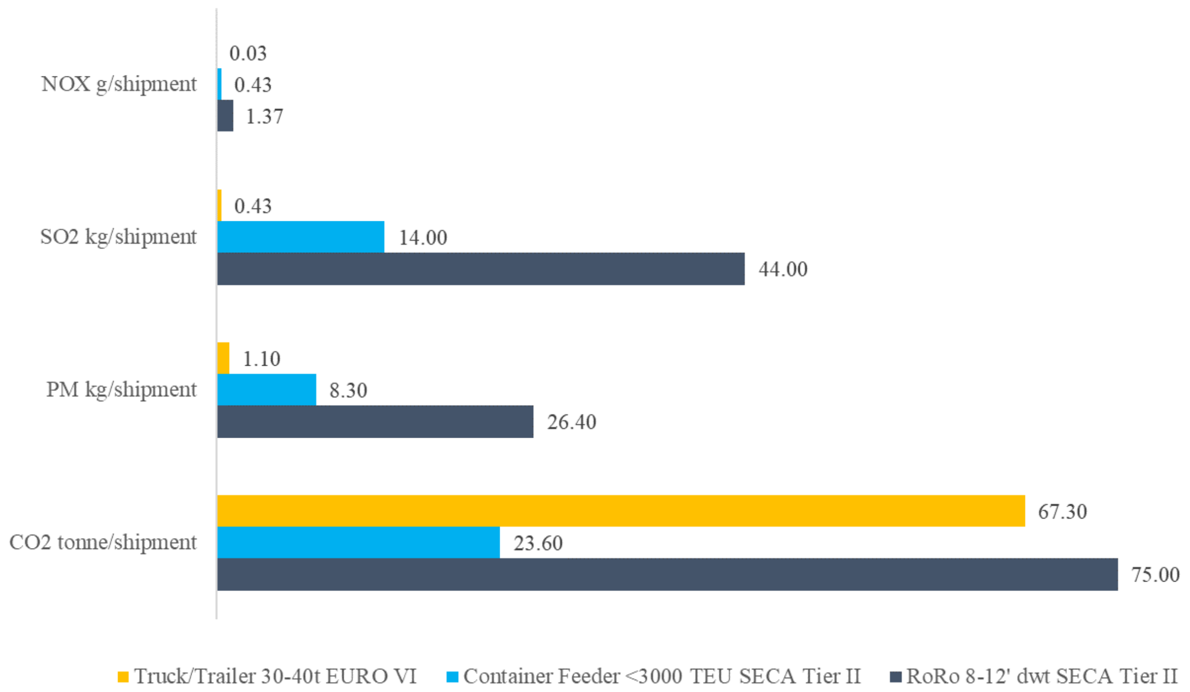

Figure 8. Emissions for the route Gothenburg – Rotterdam 2020

Since transport distances over land and sea are quite similar in the Gothenburg-Rotterdam case (Figure 8), the comparative picture resembles that of the emission factors presented above. The major difference is that RoRo shipping only has marginally higher CO_2-emissions compared to truck transport. From a CO_2-perspective the best alternative is maritime container transport, but this would also mean higher SO_2, NO_X and PM emissions than the road transport alternative.

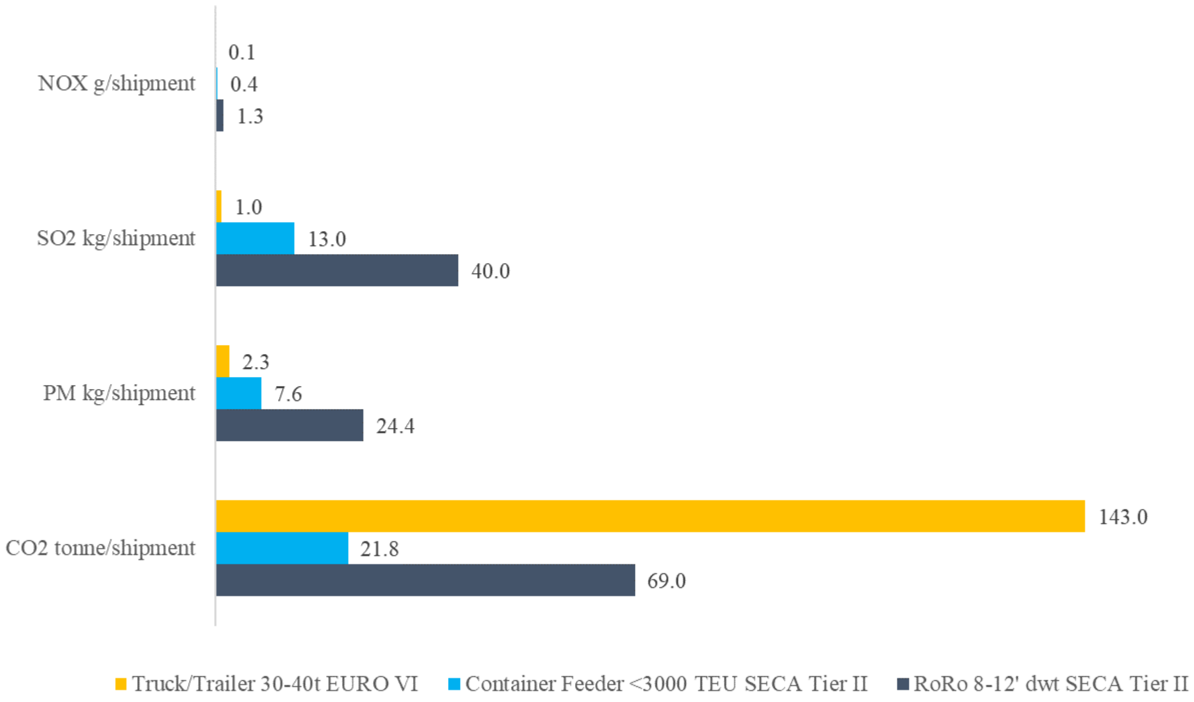

Figure 9. Emissions for the route Gothenburg-Aberdeen 2020

When shipping cargo from Sweden to Scotland, represented by the Gothenburg to Aberdeen case in Figure 9, however, the sea alternatives are much shorter due to the long road connection via Dover-Calais. This means that the lowest CO_2-emissions pertain to the maritime transport alternatives. Even with such a distance disadvantage for the road transport alternative, the emissions of local pollutants are lowest using the truck/trailer combination. However, it is likely that the impacts of these emissions may be lower for the ship alternatives, because a significant part of the emissions take part far from residential areas (in the North Sea).

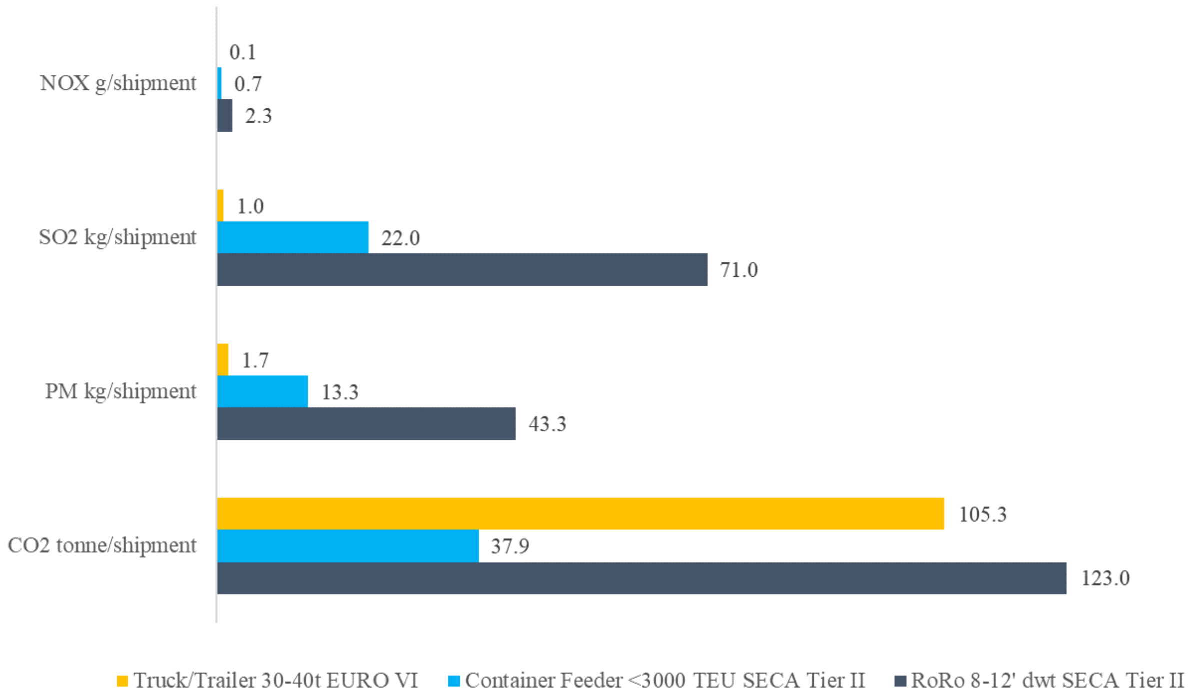

Figure 10. Emissions for the route Luleå-Rostock 2020

Our final case represents a Baltic Sea case (Figure 10), but still one where the distance advantage of the sea transport alternatives is not very prominent, which leads to a situation where road transport is preferable to a RoRo vessel, but where the container vessel is preferable to the truck from a CO_2-perspective.

7 Discussion

In Figure 11 we have illustrated how the CO_2-efficiency figures presented in this paper for 2020 and 2030 compares to the ones we published ten years ago (Hjelle and Fridell, 2012). It should be noted that both the definitions of the representative vehicles and vessels and the applied methodology were different in that study, so to use these figures as an accurate exposition of the development over these two decades would not be fair. A major methodological difference is that the figures presented for 2010 were entirely based on modelling approaches for the vessels, whereas the figures for 2020 are based on the reported figures from the EU MRV regime. The figures for 2030 are partly based on the empirical data from 2020, and partly based on our best judgement of a likely development over the 2020s.

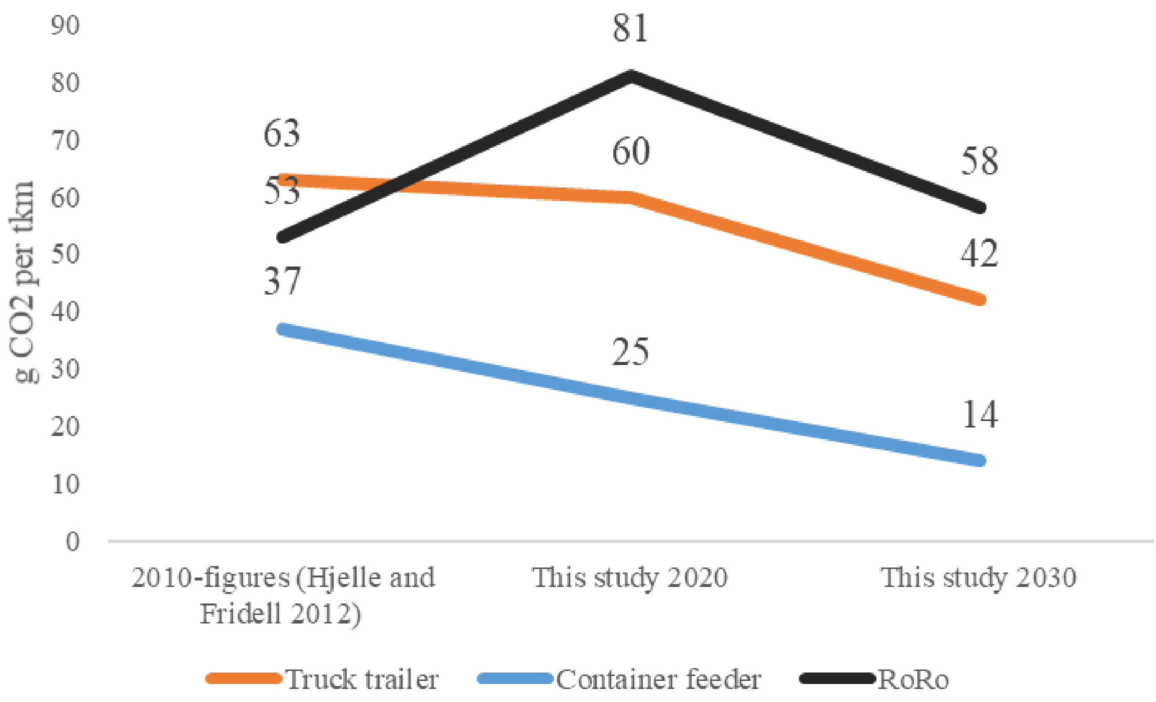

Figure 11 Our CO2-efficiency estimates at three stages

If we are to interpret these figures as representative of the development for European freight transport, it seems that both the road transport alternative and the container vessels follows a relative steady development towards a better CO_2-efficiency. The figures representing the RoRo shipping alternative, however, seems to follow a less consistent development. We suspect that this is due to the fact that the modelling approach applied in our first study relied upon information sources that did not consider realistic estimates of average net cargo volumes on RoRo-vessels. The implication of the availability of new data from the EU MRV-system seems to be that RoRo-transport is not the most climate-friendly mode when compared to road transport in most cases. This is a recognition that we have suspected for some time (Hjelle, 2011, Hjelle, 2010), which seems to be corroborated by new real-world data.

Although the higher estimated CO_2-emission factor for RoRo ships in 2020 compared to 2010 probably is to a large extent driven by methodological issues, rather than a real-world development, RoRo transport may have had a similar increase in CO_2-efficiency as for the container vessels, but this we cannot verify. The indication of a significant drop in CO_2-emissons per tkm for container vessels may be driven by several factors. We will explore a few of the likely candidates in the following section.

7.1 Potential candidates explaining the increased CO_2-efficiency of the SSS fleet

7.1.1 Impact of the EEDI for new ships

The EEDI was adopted by the IMO in 2011 and came into force from 2013. This factor is calculated as the ratio of the total CO_2-emissions produced by the vessel over the product of the ship's capacity and reference speed. This ratio, expressed in grams CO_2 per tonne-mile is then compared to a reference line based on the average performance of ships built between 2000 and 2010 within the relevant category. In the first step the required reduction was set to 10%, for ships built from 2016 to 2020, 20% for ships built from 2020 to 2025, and 30% for ships built between 2025 and 2030 (Psaraftis, 2019). Although the actual impact of the EEDI in real operating environments has been questioned (Zis et al., 2020, Lindstad et al., 2019), it is likely that the introduction of this measure has had some impact on the average CO_2-

efficiency of the short sea fleet over the last decade. However, with an assumed average age of short sea vessels around 20 years, the impact of the EEDI regime is likely to be relatively marginal in our setting, because it only applies to new tonnage. Even if the EEDI-regime itself may have had a limited impact, the incentives for achieving better fuel-economy through improvements in hull design and propulsion technology are still very much present, especially when bunker prices are high. It is therefore likely that a significant part of the increased CO_2-efficiency gains stems from improvements in ship design, but the drop from 37 g/tkm for the container vessels in our 2010 figures, to the 25 g/tkm in 2020 may also be partly explained by differences in the methodological approach and the data availability.

7.1.2 Slow-steaming in short-sea shipping

Although it is likely that part of the increased fuel-efficiency comes from better ship design, operational patterns may also have changed over this 10-year period. It may therefore be natural to ask if the reduction in CO_2-emissions to some extent could be explained by increased slow-steaming practices in European short sea shipping. A traditional stance has been that slow-steaming practices seem to pay off mainly in long range (deep-sea) shipping, but this has been challenged by some authors investigating this issue (Ferrari et al., 2015, Zis and Psaraftis, 2019, Zis et al., 2020). Other studies maintain that service quality requirements and the fierce competition against land-based modes may restrict the potential for slow steaming practices (Raza et al., 2019). Slow-steaming may not appear to have been applied widely within short sea shipping – not even in periods of high bunker prices (Raza et al., 2019, European Commission, 2020a). The last data from the EU MRV-system does not indicate that slow-steaming practices have increased over the last years either (European Commission, 2022). A further investigation of this possible explanatory factor lies beyond the scope of this study.

7.2 Future policy scenarios

In our 2030 scenario above, we have included policies that have already been implemented (e.g. the CII / EEXI instruments) and instruments or political aims that are very likely to be implemented within this timeframe (e.g. the inclusion of shipping into the ETS regime).

Looking further ahead, it seems clear that the implemented instruments are far from powerful enough to achieve the political targets of emission reductions. Introducing some form of carbon pricing for maritime transport, or other forms of market-based incentives may seem inevitable (Cullinane and Yang, 2022). The zero-emission technologies related to land-based modes would also have to be stimulated through policy actions beyond the currently existing ones. A key element is also the political support for the necessary investments in green energy supplies and energy distribution infrastructure. Potential industrial first movers in the transition to green technologies would need firm and stable policies in order to limit the financial risk of adopting new technologies (Christodoulou and Cullinane, 2020), and environmental regulations should support sustainable business operations (Raza, 2020).

7.3 Future technological scenarios

In the EU roadmap towards a sustainable mobility (European Commission, 2020c), the target is 30 million zero-emission vehicles on European roads and the first zero-emission vessels by 2030. This policy paper is not specific about how much of this zero-emission vehicle fleet should be freight vehicles, nor is it specific with respect to the kind of zero-emission technology that should contribute to these aims, but it indicates that the road transport sector in general would move faster towards a zero-emission future than maritime transport. This is also supported by the Net Zero Emissions scenario presented by the International Energy Agency

(Bouckaert et al., 2021), where the technology maturity even for HGVs is expected to be a bit better than that of international shipping. This scenario does not, however, present a specific perspective for short sea shipping, which may be more mature in a net zero emissions perspective than international shipping in general.

DNV (Eriksen et al., 2021) has been publishing it´s Energy Transition Outlook (ETO) for several years, where they outline what they think is the most likely pathway for the world´s energy future. In a recent report (DNV, 2021b) the same model is applied to outline a pathway to net zero emissions, i.e. a pathway that could support the aim of curbing global warming to the 1.5 °C target within the "bounds of techno-economic and political feasibility". This pathway is based on a perspective where the net-zero aim is reached in 2050 by applying carbon capture and carbon removal for 20% of the emission cuts. For the perspectives of this paper, the roadmaps for road transport and maritime transport contained in this analysis are of particular interest. While the scenario assumes that battery-electric vehicles will dominate in the passenger road transport market, the assumption is that also fuel-cell electric vehicles will prevail in long-haul trucking.

A few years ago, most analyses concluded that battery-electric HGVs were not suitable for the long-haul market in the foreseeable future, however, more recent studies seem to think that this is not unthinkable with the rapid development in both battery- and charging technology (Nykvist and Olsson, 2021, Björk et al., 2022, Giuliano et al., 2021). The first series production of heavy (above 16 ton) electrified trucks has started. However, there are still many challenges before these vehicles are commercially competitive at a larger scale. Two key challenges are related to high manufacturing costs and a lack of charging infrastructures. New European semi-trailer standard modifications may have a significant impact on fuel economy in a relatively short perspective (Madhusudhanan et al., 2021).

It is not given that battery-electric propulsion of HGVs will be dominant zero-emission technology for long haul transports. The use of biofuels is one alternative, but where the access to larger volumes of fuel may be the main concern. Maybe, the capacity to produce these fuels should be reserved for more hard-to-abate sectors like aviation and deep-sea shipping.

Within maritime freight, a change towards low carbon fuels is necessary according to the net zero scenario. This change has already started, where alternative fuels increased from 6% in 2019 to nearly 12% in mid 2021 (DNV, 2021b). The scenario foresees a gradual phasing out of fossil fuels, where the early years still will see diverse fossil fuels like LNG, Liquefied Petroleum Gas (LPG) and Marine Gas Oil (MGO), but where electro-based hydrogen, ammonia and LPG, and bio/electro-based methanol, LNG and MGO will gradually play a greater role. The technologies for the use of hydrogen and ammonia are expected to be developed within a 4-8-year perspective, but optimal choice of fuels would depend on the GHG reduction ambition levels (Lagemann et al., 2022, Gore et al., 2022) and fuel price scenarios (Bui et al., 2022). This transition seems easier for short-sea than for deep-sea vessels. For the short-sea fleet hybrid-electric propulsion systems are likely to play a greater role (Bach et al., 2020). On top of the change of fuels, a general development of ship and engine designs and operational efficiency gains are expected to contribute to the net-zero scenario. This transition would mean high investments (both in vessels, and green fuel production) and significantly higher fuel costs. It is quite clear that multiple fuels will play an important role in the pathway to net-zero emissions for maritime transport (Franz et al., 2021). The availability of biomass and green power, along with future regulatory regimes, will be among the most critical factors deciding which path this development takes. Many e-fuels are, however, likely to be costly and energy-consuming to make (Lindstad et al., 2021), which poses some questions around the optimal future decarbonizations strategies (Lindstad et al., 2022).

8 Conclusions

We have re-visited the issue of the comparative environmental performance of transport modes in the perspective of the intra-European transport market. Ten years ago our analysis had to rely heavily on models which to some extent were based on assumed energy use and assumed performance in terms of transport work made. Now, the availability of data from real sea-transport operations has become available, and our analysis utilises data from the EU MRV-system. Our study indicates that both road transport and sea transport have made significant progress in their environmental-friendliness over the last decade, although it is difficult to make firm conclusions about the magnitude of these gains, - because it could partly be due to differences in methodology and data availability.

We have also made predictions on how we expect this picture to develop in the current decade, based on plausible policy- and technology scenarios. It seems that both road and sea transport will achieve significantly lower emissions by the end of the decade, but this development does not seem likely to alter the comparative picture between the modes to a large extent.

The biggest change from our original analysis with 2010 figures, however, are the estimated emission levels for RoRo transport, where emission levels are much higher than those have presented before. Our figures indicate that in general, road transport would be preferable to RoRo-transport when emissions to air is considered.

It seems likely that the actors within European short sea shipping may face a tougher competition in the years to come, partly because of the announced policies related to the inclusion in the ETS-regime and partly due to other reforms aimed at reducing emissions. The impact of these policies may hit the maritime transport business harder than the road transport actors because the transition to new low- or zero-emission technologies may prove to be slower for ships than for trucks. Our analysis finds that in particular the RoRo-business could struggle to compete with respect to CO_2-emissions per unit of transport work. There is also a growing concern among ferry operators that the new ETS-regime, as well as the CII / EEXI regime, will hit this part of the market particularly hard (Christodoulou et al., 2021).

In the longer run the maritime transport business may also face a period where it could be hard to argue that they represent the “green mode of transport”, when zero- or low-emission technologies may have penetrated the road transport market, but where the maritime transport sector is still struggling to keep up with the pace of the green shift. This may happen even if the technology readiness level of maritime green technologies may be on par with that of the land-based transport modes, merely because of the comparative longevity of the means of transport. Actors in the maritime business will then have to hope that political support is still coming their way because maritime transport may still be desirable due to other externalities, e.g. related to congested transport infrastructure or accidents, being lower (Mellin et al., 2013, Vierth and Johansson, 2003, Ramalho et al., 2021).

In this paper we have build our conclusions on new data sources that bring about real world data regarding fuel use and transport work from maritime transport. There is, however, a need for improving the precision level of these databases in order to make more accurate estimates of emissions per unit of transport work. The accuracy of our emission figures is somewhat limited by the assumptions made about assumed net vs. gross weights of the cargo transported. It should be possible to include more accurate information about the ways the transport work is estimated in both the EU MRV system and the IMO DCS system, by including the method of estimation in the databases. In our setting, where we have focused on the intra-continental perspective, more information about the trading area of the vessels would also be useful. While waiting for such a development, there should be a scope for further research refining the data by combining databases containing AIS positioning data with the EU MRV system.

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