Fast measures for fast vessels

What measures should policy makers take to slow down passenger ferry vessels in order to reduce Greenhouse gas emissions?

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EXAMENSARBETE

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Abstrakt

Det kan sägas att Finland är en ö. Finland är till största delen omringat av vatten. 92% av landets export och 79% av landets import fraktas med fartyg. Allmän last exporteras till 60% och importeras till 50% på passager färjor, vars livslängd kan vara ända upp till 30 år. Finland har slutit avtal med både IMO och Europeiska unionen om nedskärningar gällande utsläpp och där till har regeringen ställt fokus på att Finland år 2035 skulle vara ett koldioxidneutralt land. Med en hastig tidtabell som denna, räcker inte endast bättre teknologi till. För att stöda nationalekonomin är det viktigt att ställa fokus på de redan existerande passagerarfärjorna och på att radikalt förminska deras utsläpp.

Detta examensarbete undersöker olika sätt under korta och medellånga tidsperioder få växthusgasutsläppen att minska på de redan existerande passagerarfärjor. De åtgärder som görs måste göras genom att ta i beaktande alla fartyg samt rutten de använder på fartygsspecifikt plan, då det inte finns en lösning som skulle lämpa sig för alla. Att minska utsläppen med 10-tals % på fartygens årliga co_2-utsläpp är möjligt.

Språk: engelska Nyckelord: sjöfart, växthusgasutsläpp

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Tiivistelmä

Suomi on saari. Monesti kuultu sanonta perustuu siihen, että 92% maan viennistä ja 79% tuonnista kulkee laivoilla. Kappaletavarasta 60% viennistä ja 50% tuonnista liikkuu matkustaja-autolautoilla, joiden elinkaari on erittäin pitkä, jopa yli 30 vuotta. Suomi on sitoutunut sekä Kansainvälisen merenkulkujärjestö IMOn että Euroopan unionin päästöleikkaustavoitteisiin, ja lisäksi hallitus on asettanut tavoitteeksi Suomen hiilineutraliuden vuoteen 2035 mennessä. Näin nopealla aikataululla pelkkä teknologia ei auta: kansantalouden ja huoltovarmuuden kannalta elintärkeiden matkustaja-autolauttojen päästöjä on pystyttävä vähentämään radikaalisti olemassa olevalla kalustolla.

Tämä pro gradu tutkii eri lyhyen ja keskipitkän aikajanan keinoja liikenteessä olevien matkustaja-autolauttojen kasvihuonekaasupäästöjen vähentämiseksi. Mitään yhtä ratkaisua ei ole olemassa, vaan toimenpiteet on sovittava kunkin laivareitin erityispiirteiden mukaiseksi. Kymmenien prosenttien säästöt laivojen vuotuisissa CO_2-päästöissä ovat mahdollisia.

Kieli: englanti Avainsanat: merenkulku, kasvihuonekaasupäästöt

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Abstract

Finland is an island. This often-heard saying is based on the fact that 92% of the country's export and 79% of import is transported on ships. Of packaged goods, 60% of exports and 50% of imports are transported on passenger ferry vessels, which have exceptionally long lifespans, often surpassing 30 years. Finland is committed to the International Maritime Organization's (IMO) and the European Union's emission reduction targets, and the Finnish government has set a target goal for the country to be carbon neutral by 2035. Current technological solutions are not enough to achieve this within the timeframe. In accordance to this, the emissions of the existing vessels must be radically reduced.

This Master thesis investigates different short and medium term timeline measures to cut down Greenhouse gas emissions from passenger ferry vessels in operation. There is no single solution that would solve the problem. Measures need to be implemented fitting the special needs for each shipping route, and reduction of several tens of percent in annual CO_2 emissions are achievable.

Language: English Key words: seafaring, Greenhouse gas emissions

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Table of contents

Glossary of abbreviations

BIMCO:	Baltic and International Maritime Council
CATCH:	Cost of Averting a Tonne of CO_2-equivalent Heating
CATS:	Cost of Averting a Tonne of oil Spill
CEN:	European Committee of Standardization
CIMAC:	International Council of Combustion Engines
CO_2:	Carbon dioxide
CSI:	Clean Shipping Index
DWT:	Deadweight
ECA:	Emission Control Area
ECDIS:	Electronic Chart Display and Information System
EEDI:	Energy Efficiency Design Index
EEOI:	Energy Efficiency Operational Index
EEXI:	Energy Efficiency Existing Ship Index
EIV:	Estimated Index Value
EMSA:	European Maritime Safety Agency
EPL:	Engine Power Limitation
ESI:	Environmental Shipping Index
EVDI:	Existing Vessel Design Index
FAEC:	Fleet Annual Emission Cap
FSA:	Formal Safety Assessment
GDP:	Gross Domestic Product
GHG:	Greenhouse Gas
GWP:	Global Warming Potential
HFO:	Heavy Fuel Oil
IEE:	International Energy Efficiency Certificate
IMO:	International Maritime Organization
JIT:	Just In Time

LNG:	Liquefied Natural Gas
LSHFO:	Low-Sulphur Heavy Fuel Oil
MBM:	Market Based Measure
MDO:	Marine Diesel Oil
MEPC:	Marine Environment Protection Committee
MGO:	Marine Gas Oil
MRV:	Monitoring, Reporting, Verification
MSC:	Maritime Safety Committee
NCAF:	Net Cost of Averting a Fatality
NGO:	Non-Governmental Organization
SECA:	Sulphur Emission Control Area
SEEMP:	Ship Energy Efficiency Management Plan
TEU:	Twenty-foot Equivalent Unit
UNFCCC:	United Nations Framework Convention on Climate Change
VLCC:	Very Large Crude oil Carrier
VSR:	Vessel Speed Reduction
VTS:	Vessel Traffic System
VTT:	Technical Research Centre of Finland
WPSP:	World Ports Sustainability Program

1 Introduction

The world is in the process of decarbonation and the process is getting faster. We have realized that technology will save humanity, instead humans need to take care of technology to sustain life on planet Earth. Transportation plays a big part in the process as the world has become more global than ever: ships make it possible for companies to be based wherever they want, produce whatever they want and locate their consumers wherever they want. Decarbonation may change the global economy, but before it does, measures need to be taken to reduce emissions in all areas including shipping.

Shipping is estimated to contribute to about 2.7% of the world's annual CO_2 emissions with 796 million tons (IMO, 2014). This is based on a study conducted by the International Maritime Organization (IMO) in 2014. The same study concluded that if nothing changes the emissions will rise between 50% to 250% by 2050 depending on economic growth among other factors. IMO has realized the urgency to reduce shipping emissions as the organization is committed to fulfil the Paris climate agreement and the UN Agenda for sustainable development.

Shipping is facing the same challenge as other transportation industries. Compared to land transportation, vessel-based shipping is mostly conducted in international waters and therefore international conventions are needed for regulation spanning the entire industry. Local decisions can be made to take force within each country's territorial waters, which will have an impact on the ship's route.

In its 72nd meeting held in April 2018 IMO's Marine Environment Protection Committee (MEPC) came up with the Initial IMO Strategy to reduce Greenhouse gases (GHG) from ships (IMO, 2018). The resolution is known as the MEPC.304(72). The main goals are to peak all GHG emissions from shipping as soon as possible and to reduce them by at least 50% by 2050. In addition, more specific carbon intensity reduction goals were set and they are to reduce the emissions divided by transport work (cargo carried multiplied by distance sailed) by at least 40% by 2030 and by 70% before 2050 compared to the level measured in 2008.

The IMO strategy to fight climate change is divided in three timelines: short term, mid-term and long-term measures. Short-term measures are defined as actions that will take place between 2018 and 2023, mid-term between 2023 and 2030 and long-term beyond 2030. MEPC.304(72) listed the candidate measures for each timeline. Among the short-term measures is: *to consider and analyse the use of speed optimization and speed reduction as a measure*.

This thesis focuses on this specific measure to aid in reducing shipping emissions. Ships produce other harmful air emissions as well. Such are for example Nitrogen Oxides (NOx), Sulphurous Oxides (SOx), Black Carbon and small particles, but the goal for this thesis is to focus on GHGs and more specifically on CO_2 emissions. When limiting CO_2, most other emissions are also reduced. The equation does not necessarily work the other way. For example, Sulphur Emission Control Areas (SECA) have led to ships to optimize speeds according to the total fuel cost, which can mean speeding up when using cheaper fuel with more sulphur outside SECA and slowing down to reduce the consumption of more expensive low sulphur fuel (Fagerholt and Psaraftis, 2015). In the end more emissions may be produced even if the emissions inside a regulated area can be reduced. Every measure has benefits and drawbacks: one will gain and another will lose. When designing measures to reduce emissions, the ones that will lose most also have more to say. In an industry the size of global shipping, shipowners also find ways to get their message through. Clear priorities are therefore needed for best results.

If ships slow down, they take longer to transport the same amount of cargo or to carry as many passengers while consuming less fuel. To actually achieve a reduction in emissions is a matter of optimization and this needs to be prioritised. The hypothesis is that shipping companies are already optimizing their vessel speed, but the optimization is towards best profit per day and not towards least consumption of fuel. If freight rates are high and/or fuel price is low, ships speed up (Psaraftis and Kontovas, 2014). Also, some emission control measures can be counteractive. For example, to minimize increased costs of more expensive fuel inside ECAs, ships are rerouting around them and sailing a longer distance (Xiaoli and Rutherford, 2018).

This thesis first shows that speed is the single most important factor to control ship GHG emissions in the short-term timeline. It then investigates measures, regulation and incentives, that individual ports, governments, flag states, class societies and IMO could adapt to force shipping companies to optimize vessel speed to achieve minimum CO_2 emissions.

2 Research problem

Three categories have been identified when listing possible measures to reduce shipping emissions. The first category includes technological inventions such as optimization software, hull and propulsion improving efficiency, alternative fuels such as biofuels and hybrid systems, heat and energy recovering systems and shore power connections. The second category includes market-based measures (MBM) such as port fee incentives, emission trading schemes and bunker taxes. The third category includes logistics-based measures such as port schedule optimization, weather routing, speed optimization and speed restrictions (IMO MEPC.304(72), 2018).

Technological innovations would allow ships to continue more or less in the same manner but in a less polluting way. MBMs twist the market to force ship owners to reduce emissions as it becomes more profitable, and logistical measures optimize the operation by cutting slack away where it is found. The ultimate question is then, which one is best? Or are there multiple solutions and if we choose only one, will it solve the actual problem?

Speed reduction and speed optimization in shipping have been discussed actively in recent years. It is an undisputable fact that reducing vessel speed leads to a reduction of fuel consumption and therefore to a reduction of emissions. Slow steaming was successfully adopted by shipping companies, specifically by the container ship market, to fight the declining transport rates during the financial downturn followed by the sub-prime crisis in 2009 (Bouwman et al, 2017; Psaraftis, 2019).

Many Non-Governmental Organizations (NGOs) have lobbied IMO to use clear speed limits to cut down emissions, but the organization has not reached a consensus on the matter. Also, scientific evidence is not clear if this would be the best course of action (Psaraftis, 2019). Reducing speed leads to increased need for transport work. It is a matter of careful optimizing to make sure the result is actually reduced emissions. Shipping is suffering from overcapacity so an increased need would provide work for additional ships that are laid up. More ships equals more emissions, but also idle ships produce emissions. Careful analysis is therefore needed before introducing any restrictions on speed to minimize the possibility to end up with greater overall emissions than before. It is also important to understand that speed limits might affect some economies more than others.

It has been debated that simple speed reduction will not be a good tool as it will lead to twisted markets and possibly allowing older more polluting ships to operate longer instead of newer and more efficient vessels (Psaraftis, 2019). Many countries have stated that speed optimizing should be used instead of reduction (Psaraftis, 2019). Another suggested measure is a bunker fuel levy, which would lead to speed reductions and therefore have similar effects on emission as speed limits. In addition, power production limits have been suggested such as those found in Japan's submission for MEPC 74 (IMO, 2019).

The actual research problem is **which is the best possible measure to cut GHG emissions from shipping in the short- and medium-term, when it comes to vessel speed**? It is likely that there is no single solution that would please all stakeholders and all ship types, so the solution may need to be a compromise. What also should be considered is that different solutions may suit different markets. In this study, an in-depth analysis is conducted on the passenger ferry vessels that operate from Finland as they are crucial to the country's supply chain.

A ship produces the least amount of emissions when it is operated at its' most energy efficient state. The way to measure this is by using energy efficiency indexes. Every new ship has to meet the existing energy efficiency criteria as per the Energy Efficiency Design Index (EEDI) in the Marpol Annex VI that was entered in force in 2013. The EEDI is expressed as grams of CO_2 emitted by transport work, which is expressed usually as tons of cargo transported multiplied by distance travelled in nautical miles. When building new ships, the aim is to achieve the minimum possible EEDI and there are maximum allowable EEDI limits for each ship type. The actual EEDI for a vessel is calculated for full cargo and for a speed achieved in the sea trials, in calm weather, while using 75% engine power. It is worth noting that when any of these parameters are changed the ship will emit a different amount of CO_2 and it is usually a greater amount (Lindstad et al, 2019). A conclusion can be made that an energy efficient ship is only efficient if it is operated correctly.

As the average life cycle of ships is 28 years (Bullock et al, 2020), there are still many ships in operation built before the EEDI requirements. It is likely these vessels will continue to sail until 2033 and possibly longer. One of the problems identified by setting straightforward speed limits is that they favour ships that were built before the introduction of the EEDI formula. Therefore, in the IMO MEPC 74 held in February 2019, Japan proposed a goal-based approach to limit ship emissions by an introduction of an Energy Efficiency Existing

Ship Index (EEXI) that would cover all ships (IMO, 2020). Specific goals could then be set for every individual ship regardless of their age. The proposal did not have an example formula for the index rating but suggested a formula should be designed. A formula already exists and currently is in use. It is called Existing Vessel Design Index (EVDI) and it is provided by a private shipping consultancy company, Rightship, in collaboration with a NGO, Carbon War Room (Kedzierski et al, 2012) that later merged in to Rocky Mountain Institute.

Reducing emissions is not a first priority for shipping companies as they are trying to optimize the operation for best return on investment. Even though reducing speed means reducing fuel costs, it also means sailing less distance annually and therefore carrying less cargo on an annual basis and generating less revenue. Vessel speed is optimized to match cargo fares, fuel prices, port schedules and weather. Rising cargo fares normally cause ships to sail faster and rising fuel prices have the opposite effect. A measure such as cargo tax or a bunker levy would change vessel speed towards desired.

What then is the optimum speed vessels should sail to produce minimum GHG emissions? A quick conclusion would be to use the EEDI as a baseline for new ships that were built after its creation and implementation. However, the EEDI has flaws as it is calculated based on calm weather speed at 75% engine power. Ships that operate on routes with less optimal conditions would be emitting a greater amount. Therefore, a better baseline should be considered. In addition, what baseline can be used for existing ships that have no EEDI? The privately introduced EVDI or similar can be a solution. Japan suggested an EEXI that would cover all ships regardless of their building time.

3 Methods

To reduce GHG emissions, shipping needs to reduce fuel consumption or change to non-fossil fuel. Fuel consumption can be reduced by either making ships sail less or by making ships consume less fuel. A literary review is made to identify possible methods to calculate vessel fuel consumption and a comparison is made between methods to find the most suitable one for passenger ferry analysis.

One way to minimize fuel consumption is making transport more energy efficient. That is also the only measure in force in the IMO’s work of cutting GHG emissions (Olmer et al, 2017). Energy efficiency in shipping can be defined as minimizing fuel consumption towards cargo carrying capacity. The actual energy efficiency of a vessel is defined in IMO circular letters and in Marpol Annex VI (Marpol, 2017). All formulas are analysed together with the optimum index for new ships (EEDI) and existing ships (EIV, EEXI and EVDI) and the operational index (EEOI). New parameters for defining the optimum energy efficiency of a ship and a rating in how efficiently the ship is operated are introduced. The methods used include mathematical analysis and market professional interviews.

Different measures to limit vessel emissions are analysed: speed reduction by regulation, speed reduction by incentives, energy efficiency by regulation and incentives, bunker levy and cargo tax.

60% of Finland’s packaged goods export and 50% of import goods are transported with passenger ferries. Three different specific passenger ferry shipping routes Helsinki–Tallinn, Helsinki–Stockholm and Turku–Stockholm are analysed, and the different measures to affect vessel speeds are compared by a method of calculation. Based on the mentioned research methods, conclusions are made and suggestions provided to law makers, ports, flag states, class societies and other operators.

4 Literature review

When conducting a review about research papers concerning shipping, care needs to be taken when evaluating the results. In many cases, papers are published just before major decisions are made in IMO meetings, especially by NGOs lobbying their cause. These papers are rarely peer reviewed before publishing and proper reviews are sometimes made after decisions are made. Speed reduction as a measure is one good example: as there was a big debate about its efficiency in cutting emissions, research papers showing very different results were introduced (i.e., Faber et al, 2017 and Psaraftis, 2019), shortly before the MEPC meeting decided which short-term measures should be implemented. Another point when reviewing environmental related shipping papers is that every country’s main priority is to protect their economy and rarely prioritise the global effect on the environment. Therefore, the flag state suggestions and research done to them should be carefully analysed.

4.1 Calculating fuel consumption based on speed

CO_2 emission from a ship correlates directly to its fuel consumption, and the fastest way to reduce ship emissions in the existing fleet is to reduce the main engine power demand and therefore its speed (Olmer et al, 2017).

Fuel cost is one of the largest costs in shipping and with some vessel types it is the largest cost (Chrzanowski, 1989). Thus, vessel fuel consumption has been studied carefully from many different aspects. For example, on a 10-year old Capesize bulk carrier, fuel costs contribute to 76% of the voyage costs and 30% of all costs, whereas manning contributes to 42% of the operating costs and 6% of total costs (Stopford, 2009).

When other attributes, such as fuel price, change, vessel speed changes. One can therefore say that when fuel consumption needs to be changed, the most effective way to do it is to change the speed of the vessel. Vessel fuel consumption can be estimated by function of speed as shown in the formulas below. Fuel price and freight rates have always had an impact on ship speeds. For example, the optimum speed of a VLCC trading from the Persian Gulf to Japan will be 8.5 knots if the heavy fuel oil (HFO) costs 1000 USD per ton and 14.0 knots when HFO is 400 USD per ton with a same spot freight rate of WS60 (Psaraftis, 2019).

Ships' daily fuel consumption can be estimated by function of speed. There are other factors as well, such as weather, displacement and trim but the **approximate fuel consumption per day is proportional to the cube of the speed** (Hughes, 1996) also known as the cube-rule.

If a ship doubles its speed, the fuel consumption increases by 8 times. A 10% increase in speed would result in 33% increase in fuel consumption and a 10% reduction of speed would lead to a 27% reduction of fuel consumption. A vessel consumes fuel also for power production. This can be done using auxiliary engines or, if the ship has electric propulsion, the main engines might power other consumers. The latter vessels are called diesel-electric. Obviously, if a ship travels faster, it reaches the destination quicker, which also means that the fuel needed for power production will be reduced. This impact needs to be taken into account especially when making precise calculations for vessels on long routes.

The cube-rule is a generalized formula that does not take in account if the ship is in ballast or fully laden nor does it make a difference between different kind of vessels. A more defined version that separates different ships has been defined as (Wang and Meng, 2012):

$$F(v) = \lambda \times v^{\Omega} \quad \lambda > 0;\ \Omega > 1 (1)$$

Where v is the vessel speed, λ is a constant coefficient related to the ship's main engine. Wang and Meng (2012) stated that Ω varies between 2.7 and 3.3 with container ships.

When the ship's status wants to be taken in account the following formula (Barras, 2004) can be used:

$$F(v) = \lambda v^3 \nabla^{\frac{2}{3}} \qquad (2)$$

where ∇ is the displacement of the vessel. As shown in the formula, vessel speed has a much bigger impact on fuel consumption than the total mass of the ship. Therefore, fuel consumption does not change dramatically when a ship is sailing fully laden or in ballast. Also, large draught changes are only seen on cargo ships whereas passenger and ropax ships are sailing with more or less constant displacement.

Another way to estimate vessel fuel consumption is to compare its speed to the vessel's design speed and the fuel consumption at the design speed (Stopford, 2009).

$$F(v) = F'\ x\ (\frac{v}{v'})^3 \qquad (3)$$

where *v'* is the ship's design speed and *F'* is the fuel consumption at the design speed. Design speed is the velocity that the vessel is designed to operate and which to the fuel consumption is optimized.

A conclusion can be made that optimizing the vessel bunker capacity and bunkering schedules have an effect on vessel fuel consumption. Bunkering less at a time and more often reduces fuel consumption by reducing total displacement or by freeing vessel deadweight to cargo capacity making the ship more energy efficient. When calculating vessel fuel consumption based on speed, the cube-rule can be used for rough estimates. If more precise figures are needed or when other variables change, a better formula should be used.

4.2 Speed reduction as measure to cut emissions

Ever since IMOs Marine Environmental Committee (MEPC) 72nd meeting, that took place between 9–13 April 2018, there has been debate and scientific dialogue on what would be the most appropriate short-term measure to reduce ship emissions based on speed. Ships, especially container vessels, started slow steaming in the aftermath of the financial crisis 2009, and even the design speeds of new container vessels have dropped significantly. The Maersk Triple-E class vessels have a design speed of 17.8 knots compared to 22–25 knots from the previous generation of vessels (Psaraftis et al, 2014).

The delegation of France (IMO, 2019) suggested straightforward speed reductions to be implemented as soon as possible. The second step in the proposal was annual GHG emission limits allotted to each ship owner described as Fleet Annual Emission Cap (FAEC). The French proposal pointed out that for the short-term measures to actually have an effect they need to have an effect on the existing fleet and be based on existing instruments and data. It also acknowledges the drawbacks of speed restrictions and points out that they should only be a transitory measure.

The strongest opponents at IMO are South American countries such as Chile and Peru, who claim that speed reduction would have a severe impact on their economies as their export routes are much longer than most other countries. Chile and Peru insisted to use the term speed optimization instead of speed reduction in the resolution (Psaraftis, 2019).

The NGO Clean Shipping Coalition lobbied hard during MEPC 72 for straight-forward speed reduction and they introduced a research paper titled, *Regulating speed: a short-term measure to reduce maritime GHG emissions* (Faber et al, 2017). The research analysed several shipping routes with actual cargos such as oilcake and beef transport between South America and The Netherlands (Faber et al, 2017). It incorporated different shipping types such as tanker, container and bulk carriers. Analysis was done not only for the impact on emissions but also the economic effect on the exporting countries. 10, 20 and 30% speed reductions were used for the analysis and the hypothesis was made that increased travel time would be covered by bringing laid up ships back into service (Faber et al, 2017). The paper concluded that CO_2 emissions could be reduced by 13, 24 and 33% with the speed reductions of 10, 20 and 30% without significant impact on South American countries gross domestic product (GDP).

However, mistakes have been pointed out in the paper by Faber et al, (2017). One error is that the ships using the trading routes are already slow steaming due to overcapacity (Psaraftis, 2019). Also, if the vessel speeds would be forced to decline, the freight rates would increase and that effect was left out in the calculations on the impact of economy (Psaraftis, 2019).

To conclude, straight-forward speed reduction is much more complicated as a measure than most of its supporters are trying to claim. The longer the shipping route, the more effect it will have on local and global economy. Speed restriction should also not be excluded completely at least as a short-term measure as it has a positive effect in reducing emissions.

4.3 Speed optimization as a measure to cut emissions

Ships currently sail at optimum speeds most of the time. The vessel speed is optimized for best productivity and multiple parameters have an effect on it. These parameters include freight rate, fuel price, schedule and weather. When all other parameters are taken into account, tactical decisions are made on board the vessel to minimize fuel consumption. As lesser fuel consumption leads to reduced emissions, one could argue that shipping companies are already optimizing speeds toward less pollution. However, this is not completely accurate because shipping companies are businesses that thrive to maximise profits and their vessel speed optimization is aimed to make the ship accrue the best possible daily profits (Psaraftis, 2019).

Voyage charters often lead to unoptimized sailing. As it is the ship owner's responsibility in voyage charter agreements to meet the agreed schedule, ships often end up on anchorages when a berth is not available. There are several on-going projects around the world to find solutions and algorithms to more optimised port scheduling. One is Wärtsilä's Just-In-Time (JIT) sailing system, which connects Vessel Traffic System (VTS) data to the ship systems.

4.4 Power reduction as a measure to cut emissions

Diesel piston engines produce most efficient output when operated at high engine loads. Preferred loads on board ships are typically around 80% of maximum. Gas turbines, which can be found on some vessels, are most efficient at maximum output load. On top of the efficiency ratio, on modern day ships many auxiliary systems are connected to the main engines to maximise efficiency. These can be shaft generators, exhaust heat recovery systems, or potable water production. These auxiliary systems also demand a high load on the main engine to work properly and provide the added efficiency.

Understanding these factors, restricting vessel speed will lead to inefficient operation, when the main engine load is reduced to meet the lower speed. Therefore, a suggestion has been made to restrict engine output power instead of speed. The measure is known as engine power limitation (EPL). The EPL measure generally could be applied in a cost-efficient way by simply adding a physical restriction to fuel supply or reprogramming the software on more modern engines for the existing fleet.

The first initiative arose in 2018 from Germany, and the subject was brought up in the May 2019 conference of the International Council of Combustion Engines (CIMAC) shortly before the IMO MEPC 74 meeting. CIMAC concluded with a press statement supporting power limitations. The largest international shipping association representing shipowners, the Baltic and International Maritime Council (BIMCO), also concluded that power reductions would be better than speed restrictions. Japan made an official suggestion at MEPC 74 to reduce emissions from the existing fleet of ships by introducing an energy efficiency index for existing ships (EEXI), which is explained in more detail in section 4.6.3.2. The EEXI would allow the shipowner to find a way to reduce the ship's potential for emission and a likely way to do this is by limiting engine power.

Current scientific evidence is not clear if power reduction is really the best choice for short-term CO_2 emission reductions. As the majority of the commercial fleet is still slow steaming post the financial downturn of 2008, the engine power limitation would need to be very aggressive to have the desired effect (Rutherford et al, 2020). Information gathered from AIS data showed that containerships in 2018 were sailing at 32–50% of their maximum engine load and bulk carriers and tankers at 45–55%. A simulation was made on the existing fleet and only more than 50% EPL would meaningfully reduce emissions (8–19 %) from the three chosen categories of ships, which represent more than 50% of all emissions from sea transport. A 30% EPL would reduce emissions by 1% at 2030 and 60% EPL by 6% if only applied to ships that were in service 2018. If the EPL would be applied also to later produced ships the emission reductions would be tripled. Surprisingly, EPL would have least CO_2 emission reducing effect on containerships that have a higher average speed than tankers and bulk carriers. This is because containerships are already running at a more reduced engine load than other ships. One thing EPL would do is limit a possible speed increase of ships if the market parameters would change.

Also, it is worth noting that EPL only complies to ships with one or maximum two main engines. Most of the roro, ropax, passenger ferry and cruise vessels have multiple main engines and can adjust the power output to the required speed and still operate the engines at high load. There are also multiple computer-based software solutions for speed optimization in the market, for example the Finnish product Eniram by Wärtsilä and Napa.

4.5 Bunker levy as a measure to cut emissions

IMO MEPC 72 resulted in a list of candidate measures for short-, mid- and long-term timelines to achieve the set goals for reduction of GHG emissions from ships. Among these, there were a few measures that would reduce vessel speed; but different measures would end up with the same outcome. For example, a speed limit, an incentive to reduce speed and a bunker levy would all lead to the same: ships would slow down and emissions would be reduced.

One of the mid-term measures listed in the MEPC 72 resolution is new/innovative emission reduction mechanisms, possibly including Market-based Measures (MBMs), to offer incentives for GHG emissions reduction. One that was identified was a bunker levy that would drive shipping companies to reduce speed and therefore cut emissions. A bunker levy of $150 USD/ton would reduce CO_2 emissions by 20–30% in the container fleet. A speed restriction that would achieve 20% CO_2 emission reduction would cost $30–200 USD/ton depending on how the container shipping companies and shipper would react to the regulation (Corbett et al, 2009).

Speed reduction and bunker levy for container vessels on a 20000 nautical mile voyage were compared in a paper published by the Technical University of Denmark in April 2019 (Psaraftis, 2019). A speed limit of 22 knots would reduce CO_2 emissions by 9%, 20 knots by 25% and 18 knots by 39%. A bunker levy of $100 USD/ton would reduce CO_2 emissions by 17%, $300 USD/ton by 37% and $500 USD/ton by 50%. The paper also noted that freight rates already have an effect on the optimum speed of the vessel: as extreme examples with a rate of 500 $/TEU, the ship's optimum speed would be 16 knots and with 2000 $/TEU optimum speed would be 26 knots. (Psaraftis, 2019).

The shipping industry first introduced a suggestion for a bunker levy of $10 USD/ton to match the 2.2% emission impact to the $100 billion USD that United Nations Framework

Conference on Climate Change (UNFCCC) wants to raise to fight climate change (Psaraftis, 2019). In late 2019, international shipping associations proposed a levy of $2 USD/ton to raise a fund worth $5 billion USD in 10 years to finance carbon free shipping innovations (IMRB proposal, 2019). As shown above: as a MBM, a bunker levy of $2–10 USD/ton would have minimum effect on emissions. Also, the bunker levy proposal can be compared to the emission trading system (ETS) of the European Union, which concerns all heavy industry and aviation but excludes shipping. The cost of emitting a ton of CO_2 is worth 25–30 € in ETS, and a bunker levy of $2 USD/ton of burned HFO that has a carbon factor of 3.114 would transfer to 0.6 € per ton of CO_2. The president of the European commission, Ursula von der Leyden, announced that she will extend the ETS system to also cover shipping as part of her Green Deal program (EU, 2019).

4.6 Alternative fuels

Modern ships use either 2 or 4-stroke piston engines that run using Heavy Fuel Oil (HFO), Low Sulphur Fuel Oil (LSHFO), Marine Diesel Oil (MDO), Marine Gas Oil (MGO) or Liquified Natural Gas (LNG). Some vessels have gas turbines that are normally operated with MGO or steam turbines using boiler steam. Engines can be directly connected to the propeller shaft, via gearbox or they can power a network that can be used for electric propulsion. Choosing the right fuel is a major decision for a ship owner when building a new ship or considering a conversion of an old vessel. From a CO_2 emissions standpoint, each fuel has its benefits and drawbacks.

As per MARPOL HFO has a carbon factor of 3.114, which means for each kg of burned HFO, 3.114 kg of CO_2 is emitted. Therefore it is a slightly less GHG emitting fuel option compared to LSHFO (3.151) or MGO (3.206). However, an underlying issue is that HFO creates other substantial non-CO_2 emissions. HFO has a sulphur content of > 0.5%, and is typically between 2.0–3.5%. The IMO 2020 global sulphur cap of 0.5% means that any ship using HFO must possess an exhaust gas cleaning system, also known as a scrubber. Scrubbers can be open or closed loop systems, where the wash water is either directly run overboard or retained on board for further cleaning. Open loop systems are cheapest both to install and run, but an increasing amount of countries and ports are banning their use because of potential harm to the marine environment. Singapore was the first port to ban the use of open loop scrubbers in November 2018. China and Fujairah followed suit in early 2019.

(Khasawneh, 2019) In Finland, the Neste operated oil terminals at Naantali and Kilpilahti are the only ports not allowing the use of open loop scrubber systems.

Operating a ship with high-sulphur HFO has traditionally been significantly cheaper per ton than the low-sulphur fuel options and therefore ship owners have opted to install scrubbers even on their existing fleet. This can be seen in the 6 month average bunker fuel prices shown in Table 1 below.

Table 1: 6 month average (August 2019–February 2020) prices of different ship fuels at Rotterdam, their carbon factors and calorific values. LNG price is calculated as equivalent of MGO (MGOe). (Ship and bunker, 2020 and Bluegoldresearch, 2020)

Fuel	Carbon factor (g CO2 per g of fuel)	Price (USD/t)	Energy content (MJ/kg)
HFO (3.5% sulphur)	3.114	293.00	39–42
LSHFO (0.5% sulphur)	3.151	517.00	41–43
MGO (0.1% sulphur)	3.206	557.00	42–44
LNG	2.750	347.35*	52–55

Lately, namely after the oil production battle between Saudi Arabia and Russia and the effect of the coronavirus crisis, the bunker fuel prices have dropped. These factors have contributed toward closing the price gap between HFO and LSHFO as seen on Figure 1 below. This has led to an extended payback time of scrubber installations (Liang, 2020). As more and more ports and sea areas have introduced bans for scrubber sludge discharges and the ban from carrying HFO is likely to expand from Antarctic waters to other areas low sulphur fuel might become a more attractive option than installing scrubbers.

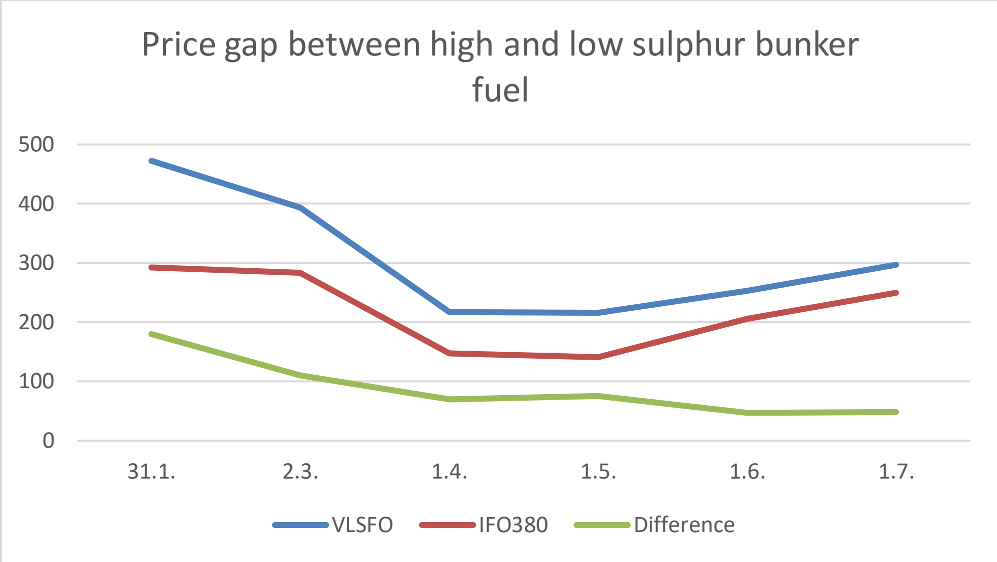


Figure 1: bunker fuel prices at Rotterdam of VLSFO (Very Light Sulphur Fuel Oil with less than 0.5% sulphur), IFO380 (Intermediate Fuel Oil with a viscosity of 380 mm^2/s and sulphur content of less than 3.5%) and the price gap between them the first 6 months of 2020. (Ship and bunker, 2020).

LNG has become increasingly popular as a fuel choice for ship owners to reduce their environmental impact. When operating inside sulphur control (SECA) areas, LNG is a viable solution as it produces sulphur free, very low NOx and little small particle emissions. However, a problem with using LNG is on board storage as pressurized gas tanks require more space than liquid fuel tanks. An LNG-powered passenger ferry typically has a range of 3–7 days instead of weeks, when using for example Marine Gas Oil (MGO). With a proper bunkering logistics plan, LNG can still be used on short and medium range sea transport. The carbon factor of LNG is 2.750 so it has a significant advantage over the liquid fuels in CO_2 reduction. In general, a ship using LNG produces approximately 25% less CO_2 emissions than her counterpart burning oil-based liquid fuel (Stenersen et al, 2017).

For ships operating in areas with possible ice more propulsion power is needed. The Phase 3 Energy Efficiency Design Index (EEDI) requirements for new vessels are so tight that LNG is almost the only possible fuel option for a proper ice going vessel. The EEDI is better described in Chapter 3.6.1.

LNG also has environmental drawbacks. First, it is still a fossil fuel containing carbon that will emit CO_2 when burned. It is therefore not the ultimate solution for carbon free shipping, and major investments in LNG logistics have been questioned. LNG engines may leak methane when running (termed 'methane slip'), and methane is a worse GHG gas for climate change compared to CO_2 (IPCC, 2013). Methane dissipates from the atmosphere faster than

CO_2, so the GHG effect will depend on the timeframe it is evaluated. Methane traps heat 120 times more efficiently than CO_2 in the atmosphere within a one year period, 86 times more in a 20-year time period and 34 times more in a 100 year period (Pavlenko et al, 2020). Methane slips occur when unburned gas is released into the atmosphere from the combustion chamber especially when running with a low engine load. A recent research paper by The International Council on Clean Transportation suggests that even though methane slips from engines have been reduced, they happen more often on medium rotations per minute (RPM) than slow rotating engines, and that the full 20-year lifecycle GHG effect of a medium RPM ship is actually much worse (70–82%) than a vessel running MGO (Pavlenko et al, 2020). The methane slips are not taken in consideration in EEDI, but after recognizing their significance, the EU has announced that ships need to report methane slips in the future as part of the EU MRV program, which is explained in Chapter 4.8.

The key factor for judging LNG engines by their GHG footprint is the amount of methane that the engine slips. LNG does not ignite by itself in a piston engine and additional systems have been implemented to force ignition. These additional systems use a spark plug or pilot fuel injection. The latter normally uses MGO as pilot fuel and the engines therefore are called dual fuel (DF) systems. The amount of MGO burnt in relation to LNG is increased when the engine load decreases (Anderson et el, 2015). Dual fuel engines can be further divided into low- and high-pressure injection engines and also to 4-stroke medium-speed and 2-stroke slow-speed engines. A high-pressure 2-stroke slow-speed engine has a minimum methane slip, but on the other hand it loses the benefit of burning LNG as it produces more NOx emissions. Low-pressure LNG engines produce very little NOx emissions but can have methane slips. The most significant methane slips are produced with low-pressure 4-stroke medium-speed engines (Pavlenko et al, 2020), which are the most common engines installed on passenger ferry vessels.

The amount of methane slip increases when the engine load decreases (Repka et al, 2019, Anderson et al, 2015). Repka et al, (2019) values were taken from two spark ignited gas engines in an industrial heating plant. The methane slip varied between 3.5–9.5 g/kWh on one engine and 10–19.5 g/kWh on the second engine when engine load varied between 10–100%. Another study measured the methane slip from a passenger ferry vessel in operation with various engine loads (29–90% MCR). At higher engine loads the slip was 0.8% of the total fuel consumption and 2.7–4.1% at low loads (Anderson et al, 2015). If the consumption is estimated to be 200 g/kWh, the methane slip at high engine load was estimated to be 1.6

g/kWh and at low engine loads the methane slip was estimated to be 5.4–8.2 g/kWh. Pavlenko et al, (2020) examined multiple papers and concluded 5.5 g/kWh should be used as a calculation base for ships with 4-stroke medium rpm DF engines. The Global Warming Effect of two LNG-powered passenger ferry vessels are analysed using the methane slip values in Chapter 4.7.1.4.

Fuel cell technology and hybrid solutions have been raised as alternatives to efficiently power ships. The technology in 2020 is not ready to provide full propulsion and power for ship operations but parts of the voyage are already completed free of CO_2 emissions.

4.7 Energy Efficiency

Another point of view to speed optimization is to use energy efficiency as the unit for comparison. Two identical ships can be operated in very different ways: operating with less cargo and at higher speeds is less efficient than operating while carrying close to the deadweight maximum and with optimum velocity. Also, all other means to reduce fuel consumption, such as hull cleanliness, weather routing or reduced hotel load, are variables in the equation. Normally, energy efficiency is calculated by comparing fuel consumed divided by the transport work, but it can also be calculated by comparing emitted CO_2 to the amount of cargo carried and distance travelled. As different fuels produce different amounts of CO_2 emissions and ships even blend fuels on board, using emissions for energy efficiency seems to be a fair comparison for all ships. There is a lot of potential to optimize ship energy efficiency and it has been estimated that 75% of GHG emissions per freight transport unit can be reduced by 2050 (Bouman et al, 2017).

One of the first actual IMO measures to counteract greenhouse gas (GHG) emissions of shipping was the introduction of the EEDI and the Ship Energy Efficiency Management Plan (SEEMP). Both came in to force in July 2011 as amendments to the Marpol Annex VI. EEDI applies to new ships built after the resolution and SEEMP applies to all ships more than 400 gross tons.

EEDI is an index figure that can be calculated for any ship being built using a specific formula. IMO has established limits to EEDI that ships need to pass, which basically means ships need to be at or more energy efficient than the current limits in force. The limits are defined from baselines that have been calculated using data from existing ships.

SEEMP is a plan that every ship must have. The idea of SEEMP is to ensure ships and shipping companies have a systematic plan how to be more energy efficient. As many factors have an effect on a ship's fuel consumption, multiple solutions can be found to make progress. These can be hull and propeller cleaning, auxiliary power reduction and voyage planning optimization. To control the previous, ships need to have an issued International Energy Efficiency Certificate (IEEC), which is issued by the vessel flag administration and is obtained with an appropriate survey, in practice often done by an authorised classification society. The IEEC states that a ship has an approved SEEMP and EEDI, or if the ship is exempted from EEDI based on age.

4.7.1 EEDI

The Energy Efficiency Design Index (EEDI) is calculated for each new vessel and it defines the theoretical maximum allowable limit for CO_2 emitted per ton-mile of the vessel. EEDI requirements are tightened every 5 years to make sure new ships will produce less emissions. The Initial Phase 0 lasted from 1st July 2011 until 1st January 2013, Phase 1 with a 10% restriction was in force until 2018 and currently EEDI is in Phase 2 with a 20% reduction to the reference baseline representing the average efficiency of ships constructed during 2000–2010. IMO estimates that since the introduction and through 2020, CO_2 emissions will be reduced by 9–16% and from 2020–2030 will be reduced by 17–25% because of EEDI.

Table 2: Reduction factors in percentage for the EEDI to the reference line for each phase (IMO, 2017)

Ship type	**Size (DWT)**	**Phase 0** 1.1.2013– 31. 12.2014	**Phase 1** 1.1.2015 – 31.12.2019	**Phase 2** 1.1.2020– 31.12.2024	**Phase 3** 1.1.2025 ->
Bulk carrier	≥ 20000	0	10	20	30
	10000–20000	n/a	0–10	0–20	0–30
Gas carrier	≥ 20000	0	10	20	30
	2000– 10000	n/a	0–10	0–20	0–30
Tanker	≥ 20000	0	10	20	30
	4000– 20000	n/a	0–10	0–20	0–30

Container ship	≥ 15000	0	10	20	30
	10000– 15000	n/a	0–10	0–20	0–30
General cargo	≥ 15000	0	10	15	30
	3000– 15000	n/a	0–10	0–15	0–30
Refrigerated cargo carrier	≥ 5000	0	10	15	30
	3000– 5000	n/a	0–10	0–15	0–30
Combination carrier	≥ 20000	0	10	20	30
	4000–20000	n/a	0–10	0–20	0–30

The reference value is calculated with the following formula:

$$a \times b^{-c} \qquad (4)$$

And the parameters for the formula are given in the following table.

Table 3: Parameters for determination of reference values for each ship type (IMO, 2017)

Ship type	**a**	**b**	**c**
Bulk carrier	961.79	DWT	0.477
Gas carrier	1120.00	DWT	0.456
Tanker	1218.80	DWT	0.488
Container ship	174.22	DWT	0.201
General cargo	107.48	DWT	0.216
Refrigerated cargo carrier	227.01	DWT	0.244
Combination carrier	1219.00	DWT	0.488

The actual formula to calculate the EEDI represented in Resolution MEPC.245(66) for a vessel is quite complex with multiple parameters to guarantee each different vessel and engine combination a relevant index number.

Simplifying the EEDI is calculated with the following formula:

$$EEDI = \frac{Power\ installed\ x\ Specific\ fuel\ consumption\ x\ Carbon\ conversion}{Available\ capacity\ x\ Speed} \quad (5)$$

Each fuel type has its own carbon content (% of mass) and carbon index value (C_F) representing the amount of CO_2 emitted by fuel consumed as represented in Table 4. An observation can be made that HFO, which is considered to be a worse pollutant, actually has a better carbon factor than Marine Gas Oil. As of 1st January 2020, the global sulphur cap for shipping fuels is 0.5%. This can be fulfilled by either using low sulphur fuel or by using exhaust gas cleaning systems also known as scrubbers. From the CO_2 emissions perspective scrubbers seem to be a better choice. As most of the scrubbers installed are open loop and discharging all the pollutants from the fuel to the sea, the total pollution effect can be more complex (Winnes et al, 2018).

Table 4: Carbon content and carbon index for each ship fuel type (IMO, 2017)

Type of fuel	**Reference**	**Carbon content**	**C_F (t-CO_2/t-Fuel)**
Diesel/Gas oil	ISO 8217 grades DMX trough DMB	0.8744	3.206
Light Fuel Oil (LFO)	ISO 8217 grades RMA through RMD	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 grades RME through RMK	0.8493	3.114
Liquefied Petroleum Gas (LPG)	Propane	0.8182	3.000
LPG	Butane	0.8264	3.030
Liquefied Natural Gas (LNG)		0.7500	2.750
Methanol		0.3750	1.375
Ethanol		0.5217	1.913

When the parameters for the vessel are known, EEDI can be calculated using Equation 5. An example calculation for a single main engine cargo vessel with auxiliary engines and without shaft generators is made on the next page showing the vessel parameters in Table 5 below.

Table 5: An example EEDI calculation for a standard one main engine and auxiliary engines that runs on HFO without shaft generators (IMO, 2014)

Example calculation for EEDI	
MCR_{ME} (kW)	15000
Cargo capacity (DWT)	25000
Carbon factor main engine $C_{F\,ME}$ (g CO_2 per g fuel consumed)	3.114
Carbon factor auxiliaries $C_{F\,AE}$ (g CO_2 per g fuel consumed)	3.114
Fuel consumption main engine SFC_{ME} (g/kWh)	190
Fuel consumption auxiliaries SFC_{AE} (g/kWh)	215
Reference speed v_{REF} (knots)	18

$$P_{ME} = 0.75\ x\ MCR_{ME} = 0.75\ x\ 1500kW = 11250kW \qquad (6)$$

Main engine power is assumed to be 75% of MCR.

$$P_{AE} = 0.025\ x\ MCR_{ME}\ + 250\ kW = 625kW \qquad (7)$$

Auxiliary engine power is assumed 2.5% of MCR + 250kW.

$$EEDI = \frac{(P_{ME}\ x\ C_{F\,ME}\ x\ SFC_{ME}) + (P_{AE}\ x\ C_{F\,AE}\ x\ SCF_{AE})}{v_{REF} x\ Capacity} \qquad (8)$$

$$EEDI = \frac{11250\ x\ 3.114\ x\ 190) + (625\ x\ 3.114\ x\ 215)}{18\ x\ 25000} \qquad (9)$$

$$EEDI = 15.721\ \frac{g\ CO_2}{t-nm} \qquad (10)$$

The EEDI is not completely bullet proof: the calculations are based on sea trials conducted in calm weather. Ships that perform well in good weather but not in rough seas benefit in the EEDI formula. When ships are sailing in heavy seas, they are consuming more fuel than their counterparts that are better designed to operate in poor weather conditions (Lindstad et al 2019).

The same principle applies to ships that navigate in sea ice. To be efficient in sea ice conditions, a ship needs more engine power than its counterpart that only sails in open water. To compensate for the worse EEDI, there are correction factors for each Finnish-Swedish ice class (IMO, 2012).

4.7.2 EEOI

While EEDI is the theoretical optimum emission rate for the vessel, the actual rate is calculated with the Energy Efficiency Operational Indicator (EEOI). EEOI can be used as a tool when analysing the efficiency to meet goals set in the SEEMP of the vessel.

EEOI is calculated with the following formula:

$$EEOI = \frac{Fuel\ consumed\ x\ Carbon\ conversion}{Distance\ sailed\ x\ Cargo\ transported} \qquad (11)$$

The same vessel in the previous example of EEDI calculation that transports a full cargo over 1000 nautical miles and travelling at a speed of 18 knots (kn) would have EEOI:

$$Fuel\ consumed = \frac{distance\ travelled}{speed}\ x\ fuel\ consumption \ (12)$$

$$Fuel\ consumed_{ME} = \frac{1000\ nm}{18\frac{nm}{h}}\ x\ 190\ \frac{g}{kWh}\ x\ 11250\ kW = 118.75t \qquad (13)$$

$$Fuel\ consumed_{AE} = \frac{1000\ nm}{18\frac{nm}{h}}\ x\ 215\ \frac{g}{kWh}\ x\ 625\ kW = 7.47t \qquad (14)$$

$$EEOI = \frac{Fuel\ consumed\ x\ Carbon\ conversion}{Distance\ sailed\ x\ Cargo\ transported} \qquad (15)$$

$$EEOI = \frac{126.22t\ x\ 3.114}{1000\ nm\ x\ 25000t} = 1572\ x\ 10^{-6}\ \frac{t\ CO_2}{t\ x\ nm} \qquad (16)$$

EEOI = 15.72 g CO_2 /t-nm, which is equal to the EEDI. If the parameters are changed, the EEOI will change. For example, if the ship sails with only 80% of its cargo carrying capacity, the EEOI will be 19.65 g CO_2 /t-nm. If the vessel sails with an engine load of 80% instead of 75% and reaches a speed of 19 kn instead of 18 kn, the EEOI will be 15.83 g CO_2 /t-nm.

One way to measure the energy efficiency of the vessel is to compare the ratio between the EEOI and EEDI. Larger ratio corresponds to a decrease in the efficiency. If these figures are made public, the drawback of the EEOI is that it requires actual cargo amounts, which is sensitive information for the ship owners and other stakeholders. Another way to measure the energy efficiency without exact cargo data is to use the Annual Efficiency Ratio (AER), which divides the vessel annual CO_2 emissions with the distance sailed and the vessel DWT.

$$AER = \frac{Annual\ CO_2 emitted}{DWT\ x\ Distance\ sailed} \quad (17)$$

4.7.3 Indexes for existing ships

As explained above, EEDI is the design index on which the ship is built. It is a theoretical value, which is practically impossible to achieve in normal conditions as ships sail with different cargo capacity, schedules and weather conditions. To have an understanding of the state of the ship's energy efficiency, its operational index (EEOI) can still be compared to the EEDI. As EEDI was only introduced in 2011, there are still many ships in use that have no baseline to compare their operational energy efficiency with EEOI.

4.7.3.1 EIV

The European Union started to collect data from ships in 2018 as part of the Monitoring, Reporting and Verification (MRV) plan (further explained in Chapter 4.8). As part of the MRV data collecting program ships must report their EEDI values and if such values have been established, the ship operators need to supply an index called the Estimated Index Value (EIV), which is the baseline on which the EEDI limits have been created.

The calculation method for the EIV was introduced in the IMO Resolution MEPC.231(65), adopted in May 2013. The following assumptions are made:

1. The carbon emission factor used for all engines is 3.1144 g CO_2/g fuel
2. Specific fuel consumption for all ship types for all main engines is SCF_{ME} = 190 g/kWh
3. $P_{ME(i)}$ is 75% of the total installed main power ($MCR_{ME(i)}$)
4. Specific fuel consumption for all ship types for all auxiliary engines is SCF_{AE} = 215 g/kWh
5. Auxiliary engine power P_{AE} is calculated according to MEPC.212 (63)

6. P_{AE} for roro passenger ships is calculated as: $P_{AE} = 0.866 \times GT^{0.732}$
7. No correction factors are used except for roll on, roll off loaded ships (roro) and combined roro and passenger ship (ropax)
8. All innovative energy efficiency technology installed on board such as shaft generators are excluded.

The formula for the EIV for all other ships except container ships, car carriers, roro cargo ships, roro passenger ships and LNG carriers:

$$EIV = 3.1144\ x\ \frac{190\ x\ \sum_{i=1}^{NME} P_{MEi} + 215\ x\ P_{AE}}{Capacity\ x\ v_{REF}} \qquad (18)$$

Capacity in the formula is the ship's DWT, except for containerships that use 70% of their DWT for the capacity. In addition, car carriers have correction factors, roro passenger vessels use GT instead of DWT and LNG carriers have their own specific formula (IMO, 2013). The speed used in EIV calculation is the vessel reference speed. Reference speed is the velocity of the vessel measured in sea trials. When a ship is ordered from a shipyard, a contract speed is defined and the vessel needs to achieve it in calm weather conditions. To cope with adverse weather, a sea margin is added.

$$Reference\ speed = Design\ speed + Sea\ margin \qquad (19)$$

There are many flaws in the EIV because it generalizes parameters. A main engine fuel consumption rate of 190 g/kWh is typically average but it can vary between 165–260 g/kWh (Jalkanen et al, 2009). The EIV is strictly a baseline for ships of the same type based on data from existing ships rather than the specific ship in question. With some ship types, such as tankers and gas carriers, EIVs correlate with EEDIs, but for example bulk carriers, EIVs are less accurate (Jasper et al, 2015).

4.7.3.2 EEXI

Japan made an official proposal at the IMO MEPC 74 meeting to create an Energy Efficiency Existing Ship Index (EEXI), which would be compatible with the EEDI of new ships and would make all ships comparable. The proposal pointed out that the EEDI leads to increasingly restricted engine power output which will put new ships in an unfavourable position against the existing fleet. Reducing new ships' operational efficiency would provide a better option. Japan's proposal did not include a specific formula for the EEXI.

4.7.3.3 EVDI

An index similar to the EEDI for existing ships exists. The NGO Carbon War Room, founded by billionaire Richard Branson, teamed up with a private maritime consultancy company Rightship to develop the Existing Vessel Design Index (EVDI). Similar to EEDI, the EVDI is the theoretical optimum that the vessel can operate given its engine configuration and cargo capacity. Unlike EEDI, which is based on design factors and sea trial data, the EVDI is calculated based on existing vessel data. Shipping companies that are using the EVDI also can have their vessels surveyed and EVDI updated to better match the current condition of the vessel. EVDI calculations have been created for over 60000 vessels and they are available online (Kedzierski et al, 2012).

Table 6: Examples of EVDI and EIV ratings calculated for some of the passenger ferry and ropax vessels operating between Helsinki and Tallinn. Note (*) that the EIV for Megastar is actually its EEDI

Name	**Star**	**Viking XPRS**	**Finlandia**	**Sea Wind**	**Finbo Cargo**	**Silja Europa**	**Megastar**
Built	2007	2008	2001	1972	2000	1993	2017
GT	36249	34000	36365	15879	22152	59914	49000
DWT	4700	5184	5506	4000	7477	4650	6080
Engine kW	48002	40002	50403	7355	23761	31802	45600
Reference speed	27.0	25.0	29.0	18.0	22.5	21.5	27.0
EVDI g CO_2 / t-nm	22.862	20.798	22.270	14.871	23.547	12.148	n/a
EIV g CO_2 / t-nm	3.26	12.00	18.50	9.29	n/a	2.32	2.38*

Table 7: Examples of EVDI & EIV ratings calculated for passenger ferries operating between Helsinki and Stockholm

Name	**Silja Serenade**	**Silja Symphony**	**Gabriella**	**Mariella**
Built	1990	1991	1992	1985
GT	58376	58376	35492	37860

DWT	5100	5340	2962	3000
Engine kW	32580	32580	23761	23008
Reference speed	21.0	21.0	21.5	22.0
EVDI g CO_2 / t-nm	13.074	13.074	15.380	13.651
EIV g CO_2 / t-nm	2.27	2.30	17.00	15.00

Table 8: Examples of EVDI & EIV ratings calculated for passenger ferries operating between Turku and Stockholm. Note (*) that the EIV for Viking Grace is actually its EEDI

Name	Amorella	Viking Grace	Baltic Princess	Galaxy
Built	1988	2013	2008	2006
GT	34384	57565	48915	48915
DWT	3690	6107	6287	4850
Engine kW	23761	30400	32002	26241
Reference speed	21.5	21.8	22.0	22.0
EVDI g CO_2 / t-nm	15.876	n/a	13.917	11.441
EIV g CO_2 / t-nm	16.00	5.00*	2.86	2.79

Several observations can be made from Tables 6–8. The EVDI indexes are derived from the Rightship database and the EIV indexes are derived from the EU MRV database. Therefore, the EVDI is calculated by Rightship but the EIV is calculated by the shipowner and verified. The vessel details are from the Rightship database as these parameters where used for the EVDI calculation. Some of them are not correct: for example the DWT of Galaxy is actually 5800 instead of 4850. The EIV have therefore been calculated on different parameters as the shipowners have not verified the figures with Rightship. All of the TallinkSilja owned vessels have very low EIV ratings compared to the other vessels. The EIV can be verified by calculation using Equation 18 from Chapter 4.7.3.1 with the appropriate correction factors for roro passenger ships (MEPC.245(66), 2014). An example is provided for the vessel *Silja Serenade*:

$P_{ME} = 32580\ kW$; $P_{AE} = 11200\ kW$

$SFC_{ME} = 190\ \frac{g}{kWh}$; $SFC_{AE} = 215\ \frac{g}{kWh}$

$V_{REF} = 21\ kts$; $GT = 58376$; $DWT = 5100$

$P_{ME} = 0.75\ x\ 32580 = 24435\ kW$; $P_{AE} = 0.866\ x\ GT^{0.732} = 2670\ kW$

$$f_{jRoRo} = \frac{1}{F_{nL}^{\alpha}\ x\ (\frac{L_{pp}}{B_s})^{\beta}\ x\ (\frac{B_s}{d_s})^{\gamma}\ x\ (\frac{L_{pp}}{\nabla^{\frac{1}{3}}})^{\delta}}$$

where $F_{nL} = \frac{0.5144\ x\ V_{ref}}{\sqrt{L_{pp} x\ g}}$

and α = 2.50, β = 0.75, γ = 0.75 and δ = 1.00 for a roro passenger ship. If $f_{jRoRo} > 1$ then f_j=1.

For Silja Serenade:

$$f_{jRoRo} = \frac{1}{0.26^{2.50} x\ (\frac{180.7}{31.5})^{0.75} x\ (\frac{31.5}{7.1})^{0.75} x\ (\frac{180.7}{31828^{\frac{1}{3}}})^{1.00}} = 0.46$$

$$f_{cRoPax} = (\frac{\frac{DWT}{GT}}{0.25})^{-0.8} = (\frac{\frac{5100}{58376}}{0.25})^{-0.8} = 2.32$$

$$EIV = 3.1144\ x\ \frac{(0.37\ x\ 190\ x\ 24435) + (215\ x\ 2670)}{2.32\ x\ 58376\ x\ 21} = 2.99\ \frac{g}{t - nm}$$

When the same calculation is made without the correction factors for roro passenger ship, the EIV is 13.25. With a reference speed of 23.0 knots, which is in many sources correct for Silja Serenade the EIV is calculated to 2.29 and without correction factors 12.10. It is safe to assume that TallinkSilja has calculated the EIV using the correction factors and all other shipowners in above tables have calculated the indexes without correcting. Should the correction factors be used is a matter of interpretation of if they are only meant for ropax vessels or also for passenger ferry vessels.

None of the vessels have had their EVDI recalculated meaning that no mistakes have been rectified. One can see that there likely is a mistake in the Rightship calculation as *Silja*

Serenade and *Symphony* have the same rating even though *Symphony* has 240 tons more DWT cargo capacity (Table 7). Using the roro passenger vessel correction factors there is a difference in the EIV ratings (2.27 and 2.30) but it is the wrong way around (Table 7). As both vessels have the same engine power, *Symphony* should emit less CO_2 per ton-nautical mile than *Serenade*.

The newest ships, LNG powered *Megastar* and *Viking Grace*, have EEDIs instead of EIVs in the tables and their EVDIs are missing because electric propulsion ships do not have an EVDI index. According to Rightship, electric propulsion equipped vessels will be added to the database with proper EVDI calculated in late 2020.

Another observation can be made: passenger ferries and ropax vessels that are designed for higher speed are less energy efficient than their slower counterparts even if they are relatively new.

4.8 EU MRV data

EEDI, EEXI, EIV and EVDI are design indexes that give an estimate of the ship’s energy efficiency when operated in ideal conditions with full cargo and using the optimum speed. This is not the case most of the time; for example, ships on scheduled shipping routes cannot wait to be fully laden every time and weather conditions cannot be controlled. Even a very efficiently designed ship can be operated in an inefficient way: either run with higher speed than optimal or with less than optimal cargo load. To have a better understanding of the ship’s actual energy efficiency, the energy efficiency operational index (EEOI) should be monitored.

One way to look at the rate of efficiency that ships are actually run with is to compare the actual data from vessels. IMO MEPC 70 resolution made it mandatory for all ships larger than 5000 gt to report their actual fuel consumption data to their flag states and then further to IMO starting 1st January 2019. The European Union started one year before and has been collecting data from ships in EU ports together with the European Maritime Safety Agency (EMSA) since January 1st 2018, as part of the Monitoring, Reporting, Verification (MRV) plan. The data has been supplied by the vessels themselves, but it has been verified by third parties such as classification societies. All vessels above 5000 gt that call in to European

Union ports are required to participate in the monitoring plan. The first annual data from 2018 was released in June 2019 and can be used for comparison.

The data that ships need to collect are departure and arrival times, cargo (and/or passengers) carried, fuel consumption and type of fuel used. From annual cumulative data, energy efficiency can be determined as grams of CO_2 emitted per cargo carried multiplied by the nautical miles sailed. The EU has released all of this data and it is available online.[1]

4.8.1 CO_2 emissions at berth

Many observations can be made from the EU MRV data. Apart from the fuel consumption-based data, another interesting way to look at a ship's energy efficiency is to compare the emissions at berth. The more time the ship spends at berth burning fuel, the less efficient it is. CO_2 emissions in port also can be obtained from the EU MRV data as the ships need to report their sailing times and total fuel consumptions. A solution to minimise emissions in port is implementing "cold ironing", which is to connect the vessel to shore power while alongside in port. Shore power connections are being installed by ports, but the current technical difficulty is that there are no standardized connections and vessels use different voltages and frequencies. Cold ironing is also only available on the pier and not at anchor.

4.8.2 Allocation of emissions between passengers and cargo

Vessels carrying both cargo and passengers face a dilemma when reporting energy efficiency: how to allocate the emitted CO_2 between the cargo and passengers. In estimates, such as the ones completed by the VTT Research Centre in Finland, an 80–20 share has been used so that passenger ferry ships allocate 80% of emissions to passengers and 20% to cargo, and vice versa for ropax. As different allocations produce completely different results, the passenger ferry and the ropax industry should agree on one standard for allocation so that shipping emissions become comparable (Bäckström, 1999).

France has forced by law all transport operators to publish the emissions per passenger, but the allocation dilemma has made comparisons between different means of transport difficult even when using the same units. To tackle this issue, France submitted a request in 2008 to

[1] EU MRV data is available online at: https://mrv.emsa.europa.eu

the European Committee of Standardization (CEN), who then developed the EN 16258 standard in 2012.

The EN 16258 did not succeed completely to make allocation comparable between ships, land transport and air travel. The reason being that ships carrying both passengers and cargo can still use two different methods: they can allocate the emissions by either mass or surface area. If the mass method is used, the mass of passengers, passenger cars, caravans, buses and all trailers connected to passenger cars needs to be considered as passenger transport and the mass of the actual cargo such as trucks, semi-trailers and packages to the cargo mass. Actual masses can be used, if known, or standard masses can be used such as those described in Table 9. The mass method would be somewhat comparable with other means of transport.

If the area method is used, all public areas besides technical and crew areas are considered to be for passenger transport. The car deck needs to be split between areas needed for passenger car transport and actual cargo transport. To complicate things further, this split can be made by either using actual surface area or mass of the cars. As such, there are still three different ways to allocate the CO_2 emissions on ships carrying both passengers and cargo even with a specified EN standard.

To report the efficiency, the total annual transport work is calculated for each voyage separately for passengers (amount of carried passengers multiplied by nautical miles sailed) and cargo (tonnes carried multiplied by nautical miles sailed) and then summed together. Allocated CO_2 emissions are then divided by the corresponding transport work.

Table 9: Default values for mass, length and width of cargo units for ropax and passenger ferry vessel emission allocations. Source: Standard EN 16258:2012 Table B.1

Default values	**Mass (kg)**	**Length (m)**	**Width (m)**
Passenger with luggage	80		
Passenger car	1200	6	3.1
Bus	12000	12	3.1
Caravan S	800	3	3.1
Caravan M	1600	6	3.1

Caravan L	2000	10	3.1
Mobile home	2800	8	3.1
Motorcycle	160	1.5	3.1
Unaccompanied trailer	6400	14	3.1
Accompanied trailer	12800	17	3.1
Road train Continent	14800	19	3.1
Road train Scandinavia	16000	24.5	3.1

4.8.3 EU MRV data for passenger ferries operating from Finland

In June 2019, the first data collected by the EU MRV program was released. Tables 10–12 contain the 2018 annual data from passenger ferry vessels operating regular routes from ports between Finland–Sweden and Finland–Estonia. The carbon factor, total annual miles sailed, average speed and average fuel consumption (t/h) are calculated using the obtained EU MRV data.

One observation which can be made from these data is that Tallink-Silja owned vessels (*Star*, *Silja Europa*, *Sea Wind*, *Megastar*, *Silja Serenade*, *Silja Symphony*, *Baltic Princess* and *Galaxy*) allocate CO_2 emissions between cargo and passengers carried using the area method whereas all other companies use the mass method making the efficiency indexes incomparable.

Another observation is that the vessels which used liquid fuel all report a carbon factor of 3.15–3.17 to obtain the emitted CO_2 from the fuel consumed. This is not correct, as all ships operating in the Baltic Sea are mandated to use 0.1% sulphur content Marine Gas Oil (MGO), which has a carbon factor of 3.206. Use of the correct carbon factor would increase the submitted emissions by 1.8%. The LNG powered vessels *Megastar* and *Viking Grace* reported a carbon factor of 2.77 whereas the carbon factor of pure LNG is 2.750 (MARPOL, 2017). This might be due to the fact that these vessels have dual fuel engines that use MGO as pilot fuel and at very low loads, only MGO is used (Anderson et al, 2015).

Vessel name	**Star**	**Viking XPRS**	**Finlandia**	**Sea Wind**	**Silja Europa**	**Megastar**
Total fuel consumption (t)	22709.1	12480.0	21188.2	4079.7	12566.1	17267.5
Total CO_2 emission (t)	71556.3	39324.5	66929.3	12912.4	39595.9	47909.1
CO_2 emission allocated to passenger transport (t)	52105.2	11249.9	13385.9	3085.4	23206.5	33899.8
% of CO_2 allocated to passenger transport	78.6	32.8	22.0	25.2	96.2	75.3
Carbon factor (g CO2 / g fuel)	3.15	3.15	3.16	3.17	3.15	2.77
CO_2 emission in port (t)	5274.7	5050.0	6175.0	669.0	15462.0	2871.5
Total time at sea (h)	4883.4	3849.0	4882.2	3787.0	2678.0	4645.4
Fuel consumption (kg/nm)	238.7	179.3	227.9	83.7	354.8	181.1
Total nautical miles sailed	88138.4	60707.3	84390.0	46199.9	21589.6	89628.0
Average speed (knots)	18.05	15.8	17.3	12.2	8.1	19.3
Fuel consumption (t/h)	4.3	2.8	3.9	1.0	2.9	3.5
CO_2 emissions kg/nm	752.0	565.0	719.9	265.0	1117.8	502.5
g CO_2/pax-nm	675.5	136.9	163.0	1873.4	372.5	363.6
g CO_2/t-nm	101.3	393.1	452.0	172.8	44.5	83.3

Table 10: EU MRV 2018 annual energy efficiency data of vessels operating on Helsinki–Tallinn route. (EU MRV, 2019)

The LNG-powered *Megastar* is run with highest average speed (19.3 knots), which makes it to consume more fuel (181.1 kg/nm) than for example the much older diesel powered *Viking XPRS* (179.3 kg/nm) that is run with a lower annual average speed (15.8 knots). The carbon factor of LNG (2.77) is better than Marine Gas Oil (3.15) and therefore *Megastar* is emitting less CO_2 per nautical mile (502.5 kg/nm) than *Viking XPRS* (565.0 kg/nm).

Connecting all the above vessels to shore power while alongside would reduce CO_2 emissions annually by 35502 tons.

Vessel name	**Silja Serenade**	**Silja Symphony**	**Gabriella**	**Mariella**
Total fuel consumption (t)	18703.8	19067.6	15809.0	15410.0
Total CO_2 emission (t)	58936.7	60082.6	49814.2	48556.9
CO_2 emission allocated to passenger transport (t)	46423.4	46716.9	10902.5	10335.3
% of CO_2 allocated to passenger transport	86.2	85.7	23.1	22.8
Carbon factor (g CO2 / g fuel)	3.15	3.15	3.15	3.15
CO_2 emission in port (t)	4807.1	5548.7	2680.0	3240.0
Total time at sea (h)	6052.5	6220.2	6175.0	6331.0
Fuel consumption (kg/nm)	201.7	197.5	162.1	155.3
Total nautical miles sailed	84800.7	87628.7	92385.4	92547.9
Average speed (knots)	14.0	14.1	15.0	14.6
Fuel consumption (t/h)	2.83	2.78	2.43	2.27
CO_2 emissions kg/nm	635.4	622.3	510.9	489.5
CO_2/pax-nm	267.3	261.6	88.6	73.3
CO_2/t-nm	61.6	261.6	422.8	360.6

Table 11: EU MRV 2018 annual energy efficiency data of vessels operating on Helsinki–Stockholm route. (EU MRV, 2019)

Surprisingly on the Helsinki–Stockholm route, the oldest vessel on the route, *Mariella*, is significantly more energy efficient than the others. She consumes 46.3 kg less fuel per nautical mile than *Silja Serenade* even though her average speed (14.6 knots) is higher (14.0) due to the summer schedule, where the Viking Line vessels also make a daily sail to Tallinn while in Helsinki, which on the other hand also reduces their CO_2 emissions in port.

Silja Serenade and *Symphony* are almost identical with the same route and schedule. Yet, *Silja Symphony* consumes (197.5 kg/nm) less fuel than *Serenade* (201.7 kg/nm) with a higher average speed (14.1 knots). This can be due to more recent dry docking of *Silja Symphony*, engine maintenance or simply a different way of managing engine configurations as these vessels have multiple main engines. To conclude, notable reductions in fuel consumption and emissions can be achieved with a more efficient ship operation.

Connecting all the above vessels to shore power would reduce annual CO_2 emissions by 16275.8 tons and combining the passenger ferry ships operating from Helsinki annual reduction would be 51777.8 tons.

Table 12: EU MRV 2018 annual energy efficiency data of vessels operating on Turku–Stockholm route. (EU MRV, 2019)

Vessel name	**Baltic Princess**	**Galaxy**	**Amorella**	**Viking Grace**
Total fuel consumption (t)	19102.3	21477.2	17224.0	15629.0
Total CO_2 emission (t)	60205.9	67674.7	54272.8	43334.6
CO_2 emission allocated to passenger transport (t)	49738.2	55428.2	12320.4	7594.3
% of CO_2 allocated to passenger transport	89.5	88.9	23.7	18.3
Carbon factor (g CO2 / g fuel)	3.15	3.15	3.15	2.77
CO_2 emission in port (t)	3676.0	5305.0	2250.0	1850.0
Total time at sea (h)	6537.5	7876.0	7368.0	7282.0
Fuel consumption (kg/nm)	194.4	183.1	149.8	135.9
Total nautical miles sailed	90729.2	108132.0	109975.1	110400.2

Average speed (knots)	13.9	13.7	14.9	15.2
Fuel consumption (t/h)	2.70	2.51	2.24	2.06
CO_2 emissions kg/nm	612.6	576.8	471.9	376.8
CO_2/pax-nm	406.8	500.9	133.5	47.8
CO_2/t-nm	48.5	64.6	406.8	201.7

From the Turku–Stockholm route, it can be noted that the Viking Line vessels are more fuel efficient consuming less than the Tallink-Silja counterparts even though running at higher average speeds (Table 12). *Amorella* is scheduled to be replaced on the route in 2021 with the new-build *Viking Glory*, which is similar to *Viking Grace*. Assuming the fuel consumption will be the same than with Grace, annual CO_2 emissions will be reduced by 10938.2 tons, but adding cargo capacity by 44% (1500 lane meters compared to 900 meters for *Amorella*) therefore increasing the energy efficiency.

The vessels on this route make four port calls each day (Turku, Långnäs, Stockholm and Mariehamn). The calls at Turku and Stockholm are about one hour and the calls at Långnäs and Mariehamn much shorter. Connecting the vessels to shore power would reduce CO_2 emissions annually by 13081 tons (Table 12).

4.8.4 Global warming potential of LNG-powered ships

The two most recently built passenger ferries operating from Finland, *Megastar* and *Viking Grace*, are run with LNG as primary fuel. Both have Wärtsilä 50 Low Pressure Dual Fuel medium RPM engines that use MGO as pilot fuel. Also, three additional LNG powered passenger ferry vessels are being built: *Mystar*, *Viking Glory* and *Aurora Botnia*. LNG has been praised as being the best solution for ships in transition to full carbon neutral propulsion, but methane slips from the engines have not been considered enough in the discussion. Based on Pavlenko et al (2020), Anderson et al (2015), Stenersen et al (2017) and the EU MRV data, the Global Warming Potential (GWP) of the LNG vessels can be calculated using an average methane slip value. In Table 13, the GWP has been calculated for *Megastar* and *Viking Grace* for 1, 20 and 100 year perspectives as added CO_2 emissions.

The GWP values for methane are 120 for 1 year, 86 for 20 years and 34 for 100 years (IPCC, 2013).

Anderson et al (2015) measured the methane slip on board *Viking Grace* during normal operation. At higher engine loads (72–90 % of MCR) the slip was 0.8%. At lower loads (29–40% of MCR) such as low speed cruising and manoeuvring, the slip was 2.7–4.1%. At berth the engine load was 16% of MCR and the engine used purely MGO. (Anderson et al, 2015). According to the Wärtsilä product guide, the total fuel consumption of the 8L50DF engine is 8560–7360 kJ/kWh with engine loads 50–100 % of MCR (Wärtsilä, 2019), which is 171–147 g of LNG per kWh using a relative energy content of 50 MJ/kg. The methane slip measured by Anderson et al (2015) was 1.2 g/kWh on high engine loads and 4.6–7.0 g/kWh on lower engine loads. Pavlenko et al (2020) concluded that the methane slip to be used for analysis for this engine type should be 5.5 g/kWh and fuel consumption 147 g/kWh.

Vessel name	**Grace 1.2**	**Grace 5.5**	**Megastar 1.2**	**Megastar 5.5**
Annual fuel consumed (t)	15629	15629	17267	17267
Annual kWh	78145000	78145000	86337350	86337350
Annual CH_4 slip (t)	128	585	141	646
1 year CH_4 GWP (as t CO_2)	15310	70171	16915	77527
20 years CH_4 GWP (as t CO_2)	10972	50289	12122	55561
100 years CH_4 GWP (as t CO_2)	4338	19882	4793	21966
Annual CO_2 (t)	43335	43335	47909	47909
1 year CH_4+CO_2 (t)	58645	113506	64824	125437
20 years CH_4+CO_2 (t)	54307	93624	60032	103470
100 years CH_4+CO_2 (t)	47672	63216	52702	69875

Table 13 Total Global Warming Potential calculated as t of CO_2 emitted for two LNG powered passenger ferry vessels Viking Grace and Megastar using a methane slip of 1.2 and 5.5 kW/h and fuel consumption of 147 g/kWh

The actual methane slip from these vessels falls somewhere in between of the values in Table 13 as the engines are run with variable loads. *Viking Grace* has 4 engines and sails through the Stockholm archipelago that has strict speed limits so it likely is run with sub-maximum engine loads whereas *Megastar* has 5 engines and sails at high speeds most of the route.

For comparison *Amorella* that has the same route than *Viking Grace* but is run with MGO and emitted 54273t of CO_2 in 2018 (EU MRV, 2019). It is safe to say based on the values in Table 13 that *Viking Grace* produces more GHG emissions than *Amorella*. *Star* operates with MGO on the same route as *Megastar* and emitted 71556t of CO_2 in 2018 (EU MRV, 2019). In a 100 year perspective (GWP 100) *Megastar* produces less GHG emissions but with GWP 20 a lot more. GWP 100 is chosen to be the standard for calculation but as ship lifecycle is less than 30 years (Bullock et al, 2020) and LNG is considered to be only a bridging fuel, it is worth asking should we rather look at it with GWP 20. When analysing the GWP of LNG vessels, not only methane slips from engines should be considered but also the entire well to wake supply chain. Since it is also known that there are large methane slips in LNG production (Alvarez et al, 2018), a conclusion can be made that replacing MGO run passenger ferry vessels with LNG powered ships will most likely lead to increased GHG emissions.

4.9 Localised emission control measures

Global restrictions for shipping emissions are decided in IMO. EEDI and SEEMP are examples of progressive measures in force to reduce GHG emissions from ships and the global sulphur cap of 0.5% that came into force on January 1st 2020 is an example of a single measure to reduce sulphur air emissions. Not all restrictions are global and some localised emission control measures are in force. Some of them, such as a local speed restriction, have a larger impact than what they were originally designed for.

4.9.1 Restrictions

Some geographical areas, countries and individual ports have reacted to ship air pollution with measures exceeding current IMO rules and regulations. These can be divided into speed restrictions or speed suggestions and emission restrictions. As of 2011, there were four established Emission Control Areas (ECA) listed in the Marpol Annex VI: North America, US Caribbean, North Sea and the Baltic Sea. The ECA restrictions are set for Sulphur

(SECA) and Nitrogen Oxide (NECA). SECAs were established to reduce the detrimental health effects of sulphur air emissions. Their impact on CO_2 emissions have been counteractive as ships have found ways to minimize the added cost of the SECAs. Running a cheaper more polluting fuel outside and more expensive fuel inside SECA areas has been reported, leading to rerouting vessels around SECA areas, with increased speed outside and reduced speed inside these areas. This has led to increased emissions rather than reducing them (Xiaoli, 2018).

Strict speed limits have been established in many coastal areas such as the Stockholm archipelago. To compensate for this, the regular ferry traffic needs to travel at high speeds in other areas to maintain their schedules. Again, this leads to emission increases rather than reductions. Another approach implemented in some areas such as along the coast of Taiwan are suggested speed limits; ships are encouraged to limit their speeds to 12 knots when operating within 20 nautical miles of any Taiwanese ports.

The existing programs are mostly incentive-based, offering ships and shipping owners compensation or deduction of regulatory fees if they participate. Many of these programs work with voluntary environmental certificate or scoring systems.

4.9.2 Incentives

Another way to encourage ships and shipping companies to reduce their environmental footprint is through incentives. On the contrary to restrictions, incentives offer carriers compensation for voluntary actions. Some incentives come in the form of aid to finance new ship construction and new environmental innovations. Others aim for more environmentally friendly operation of vessels. According to a recent study, shipowners have a positive or neutral attitude towards environmental incentives, but a more long-term perspective is sought (Johnsen et al, 2020).

An incentive that has shown success is a voluntary Vessel Speed Reduction (VSR) program in California, where shipping companies are returned awards ranging $1000–$35000 when following a 10-knot speed limit in established areas in the Santa Barbara Channel and San Francisco Bay Area. The ports of Long Beach and Los Angeles offer a reduction in port fees when vessels follow a 12-knot voluntary speed limit within 40 and 20 nautical miles to the entrance of the harbour. 95% of ships are reported to follow the 20 nautical mile speed limit and 80% follow the 40 nautical mile (cleanairactioplan.org, 2020).

The port of Mariehamn, Finland, offers 4–16% discounts to calling vessels that produce less than 10 g per kWh of Nitric Oxide (NOx) emissions at 75% engine load (Mariehamn harbour charges, 2019). More complex incentive programs have been established in many European ports and the Canadian ports of Vancouver and Prince Rupert. These programs are connected to one or multiple voluntary environmental index ratings presented in sections 4.9.3–4.9.5.

4.9.3 Environmental Shipping Index ESI

The Environmental Shipping Index (ESI) is a scoring system for ships based solely on their air emissions. ESI is designed by an organization called World Ports Sustainability Program (WPSP) and many ports offer reduction to port fees for ships with ESI based on their score. Many ports run the system cost neutral meaning that non-compliant ships pay more, and ESI-rewarded ships pay less.

Participation in ESI is free for ship owners. In November 2019, there were over 50 ports that were participating in the ESI incentive program. Most of these ports are in Europe, including the port of Helsinki, but also are found in ports in Canada, Australia and Japan.

Ships receive the ESI certificate based on self-declaration. If a received score is questionable, additional data to prove the score can be requested by the ESI office. Also, audits are performed by a few ports that offer incentives based on ESI such as Rotterdam and Amsterdam (The Netherlands), Antwerp (Belgium) and Hamburg (Germany). From the 48 audits performed between 2015–2016, 12.5% of ships were found to be non-compliant (Becqué et al, 2018), indicating that there are flaws in this self-declarative system.

The formula for ESI is simple: the maximum score is 100 and the total is a sum of individual scores for NOx, SOx and CO_2 efficiency. Additional points are given if the ship is equipped with an On-shore Power Supply system (OPS) that connects the vessel to the shore power grid while alongside in port. The formula is as follows:

$$ESI = \frac{2\ x\ ESI\ NOx + ESI\ SOx + ESI\ CO2 + OPS}{3.1} \tag{20}$$

Where ESI NOx and ESI SOx are variables with a range of 0 to 100 points. ESI NOx is calculated by comparing the NOx rating of each engine on board with the NOx limits at the time the engine was built. ESI SOx takes in account the actual sulphur level used on board and compares it to the set limit value. For example, if the ship is running outside Emission

Control Area (ECA), before Jan 1st 2020 the limit value for sulphur was 3.5%. If the ship is using bunker fuel with a sulphur content of 2%, it will benefit in the ESI SOx score. Scrubbers will also enhance the ship's ESI SOx score as they limit SOx air emissions.

ESI CO_2 is a bonus point factor with 5 points added if the vessel can report the total fuel consumption and distance travelled over 3 years. An additional 0 to 10 points is added if the vessel has succeeded in improving its energy efficiency over that time period. A ship with installed OPS receives 35 bonus points.

The discounts received when participating in ESI vary from port to port by amount and by parameter. For example, Rotterdam offers a 10% discount in the gross tonnage fees for ships with an ESI score of 31 or higher whereas the port of Helsinki gives a 4% discount to berthing fees for ships with an ESI 80 or higher.

4.9.4 Clean Shipping Index CSI

The Clean Shipping Index (CSI) is a Swedish-based rating system for ships that not only considers their air emissions but also other environmental aspects such as waste handling and chemical usage. CSI rates ships into 5 categories based on their score, which has a maximum of 150 points. Ships with a CSI certificate are entitled for port fee reductions in certain Swedish ports, and Vancouver and Prince Rupert in Canada, but also reduction to the fairway dues that are collected by the Swedish government. The CSI score is also aimed toward shippers to select ships that are better for the environment. In 2017 a total of 30 cargo owners and 74 shipping companies participated in the CSI and 2250 ships had a CSI rating (Becqué et al, 2018).

Clean Shipping Index members pay an initial fee of 500€ and an annual membership fee of 2800€. The verification of the data supplied for the CSI certificate has to be done by an approved party, which is normally a classification society such as DNV-GL or Lloyds.

The CO_2 emissions portion of the CSI rating is calculated based on actual data using the EEOI formula. Ships need to report cargo carried, distance travelled and fuel consumed for a 12-month period. Reported data are compared to the EEDI reference data for the same type and size of ship. For ropax vessels, a combination of passenger capacity with lane meter data is used:

$$RoPax\ EEDI_{REF} = 619.14L^{-0.381} \quad (21)$$

where L = 2 x (number of lane meters) + 0.7 x passenger capacity and L = 0.6 x DWT.

For pure passenger and cruise vessels a reference function has been developed by using empirical data:

$$Cruise\ EEDI_{REF} = 2279.7PC^{-0.209} \quad (22)$$

where PC is the passenger capacity.

4.9.5 GHG Emission Rating

Rightship is a private ship consultancy company that has designed multiple indexes that rate vessels for different parameters such as safety or energy efficiency. In collaboration with a US-based NGO Carbon War Room, it launched the Greenhouse Gas Emission Rating for ships in 2010. The rating was developed in Australia by major cargo owners with the purpose to help find the most fuel-efficient ships. The rating is given with a simple A to G scale, which resembles the ordinary household energy efficiency rating scale for electrical equipment. As of 2019, 123 organizations, of which 63 were charterers representing over 20% of global shipped tonnage, were using the GHG Rating when selecting ships for their operation. Normally F and G rated ships are excluded in the process. Apart from the shipping companies, several insurance companies and the ports of Vancouver and Prince Rupert in Canada are offering discount for fees based on the GHG Emission Rating index.

Table 14: Ships operating on the Helsinki–Tallinn route and their corresponding GHG Emission rating. (Rightship, 2020)

Ship	**Star**	**Viking XPRS**	**Finlandia**	**Sea Wind**	**Finbo Cargo**	**Silja Europa**
GHG rating	E	E	E	B	E	D

Table 15: Ships operating on the Helsinki–Stockholm route and their corresponding GHG Emission rating and their Clean Shipping Index. (Rightship, 2020 and Clean Shipping Index, 2020)

Ship	**Silja Serenade**	**Silja Symphony**	**Mariella**	**Gabriella**
GHG Rating (A–F)	D	D	B	C

CSI rating (1–5)	3	3	4	3

Table 16: Ships operating on the Turku–Stockholm route and their corresponding GHG Emission rating and their Clean Shipping Index. (Rightship, 2020 and Clean Shipping Index, 2020)

Ship	Amorella	Baltic Princess	Galaxy	Viking Grace
GHG Rating (A–F)	D	D	C	n/a
CSI rating (1–5)	n/a	4	3	5

Only ships operating to Sweden have a CSI rating as it comes with a cost to the ship owner and only gives benefits in Sweden. For an unknown reason *Amorella* does not have a CSI rating as per the CSI database and provided in Table 16.

One can observe that based on the GHG and CSI ratings, old vessels such as *Mariella* (built 1985) can be very energy efficient (*Mariella* has a GHG rating B out of A to F, where A is most efficient). The GHG rating indicates that the ship has optimum amount of engine power to the cargo capacity. CSI rating is based on actual and verified data provided by the vessel, meaning that a higher rated ship is also run in a very efficient way (*Mariella* has a CSI rating of 4 out of 5).

4.9.6 Green Award

The Green Award is a Dutch-based environmental certification system. It is a voluntary program that covers around 900 vessels that are both ocean-going and inland ships. The Green Award covers over 140 ports and other stakeholders offering discounts and other incentives for ships that have been audited. Finnish managed tankers, *Mastera* and *Stena Arctica*, participate in the Green Award program. (Green Award, 2020).

4.9.7 Blue Angel

The Blue Angel Ecolabel is a German certificate that is about to be phased out as it is only valid until the end of 2020. It is similar to the Swedish CSI such that the certificate is awarded to vessels based on several different operational, safety and environmental criteria. Some of the criteria are mandatory and others are optional for vessel compliance. The Blue Angel has a point system for ships and to qualify, ships are required to score at least 40 points and passenger vessels 43 points. The maximum score is 113 points and 124 for passenger vessels. If the vessel is equipped with exhaust cleaning systems, only closed loop scrubbers are accepted to qualify. Extra points are awarded for shore power usage in port. For GHG emissions, the mandatory requirement is that the ship needs to be more energy efficient every year. Additional points are awarded to ships that are more than 5% and 10% energy efficient than the previous year. Vessels with the Blue Angel certificate receive a 2% discount for port fees in Hamburg. (Blue Angel, 2020).

4.10 Cost-effectiveness of decarbonation measures (CATCH)

International shipping needs to meet its targets for GHG reduction. The European Union has expressed the intention to make even stricter goals as part of its Green Deal program. One identified problem is that not all measures suit different ship types evenly.

One way to look at the effect of CO_2 reduction measures is to compare their cost effectiveness in the same way safety assessments are made based on risk analysis. The Maritime Safety Committee (MSC) uses a standardised tool called Formal Safety Assessment (FSA) to analyse the effect of risk to potential loss of human life. The unit used is Net Cost of Averting a Fatality (NCAF), and according to FSA guidelines, all risk reducing measures with a NCAF less than $3 million USD should be made mandatory by IMO. One good example of this was the transition to the Electronic Chart Display and Information System (ECDIS) from paper charts.

For pollution risk, similar formulas have been developed such as Cost of Averting a Tonne of oil Spill (CATS) and Cost of Averting a Tonne of CO_2-equivalent Heating (CATCH) in USD/t. The formula calculating CATCH is:

$$CATCH = \frac{\Delta C - \Delta B}{\Delta E} \qquad (23)$$

where ΔC is the cost of implementation of the measure on the vessel, ΔB is the expected commercial benefit from the implemented measure other than the emission reduction (such as fuel saving) and ΔE is the expected reduction of CO_2-equivalent emissions during the expected lifetime of the vessel.

Eide et al (2009) concluded that a CATCH value of $50 USD/t should be used for shipping to achieve its 2030 targets set by IMO. Furthermore, the Eide and colleagues show that speed reductions from nominal service speed of 14.5 knots to 13.5 and 12.0 knots on a 74000 DWT bulk carrier would have slightly positive CATCH values but well below $50 USD/t. On an 8000 TEU container ship, the same calculation was made with speed reductions from 25 knots to 22 and 19 knots. The CATCH values were negative, meaning the reduction would actually be beneficial for the shipowner. (Eide et al, 2009).

Chang et al (2016) came to similar conclusions when assessing a 12 knot speed limit 20 nautical miles from the port of Kaohsiung in Taiwan. Chang et al. (2016) found that while CO_2 emissions were reduced by 41% on container ships and 14% on bulk carriers, the container ships would have negative CATCH values whereas on the bulk carriers they would be positive. (Chang et al, 2016). With a set CATCH value different CO_2 emission reducing measures can be used for different ship types while keeping the cost effect stable.

5 Shipping route analysis

In conclusion to the literary review in Chapter 4, there is no clear one size fits all type of solution to reduce ship speeds in aim to reduce CO_2 emissions. A speed restriction could work on one shipping line, an incentive would be better for another and a bunker levy could work on a third type.

On longer routes, an identified issue is optimizing port schedules as many ships arrive too early when a berth is not available, and the vessels end up anchoring. Many studies have been conducted to attempt to identify an algorithm that would solve this problem. The greatest issue still lies with the contracts between the shipper and the ship owner. If the contract is for a voyage charter, it is in the ship owner's interest to follow the contract schedule because delays at the arrival port will cause the shipper to pay compensation to the ship owner.

Passenger ferry vessels that sail in and out from Finland were selected for this thesis for more specific analysis. One reason for choosing these vessels was their importance to the supply chain of Finland. Another reason is that they are sailed at fast speeds, and some are not operated 24 hour per day, thus it is possible that there is room for optimization.

5.1 Key figures

Finland is a unique country when it comes to transporting goods. With 2690 kilometres of land border and 1250 kilometres of coast, Finland is often defined to be similar to an island and highly dependent on sea transport. 91.9% of Finland's exports (44 million tons) and 78.6% of imports (47 million tons) were through ships in 2018 (Tulli, 2020). 84.5% of combined imports and exports were conducted through ships, while only 13.4% occurred from land transport and 0.2% from air freight.

Of packaged (non-bulk) goods, 60% of exported and 50% of imported goods are transported on passenger-ferry ships (Finnish Shipowners' Association, 2020). The most common routes are Helsinki–Tallinn, Helsinki–Stockholm and Turku–Stockholm. These routes are analysed further with an aim to find measures to reduce speeds and emissions.

5.2 Helsinki–Tallinn

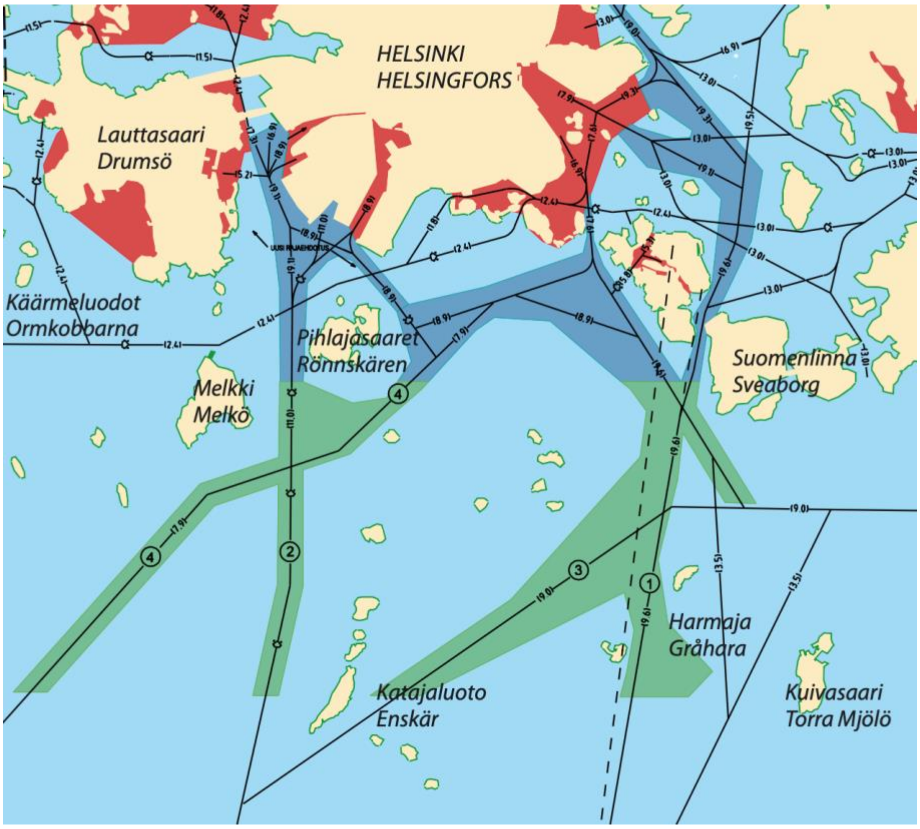
One of the busiest passenger ferry routes from Finland is the Helsinki–Tallinn route. It has been operated constantly since 1965, and over time it has grown significantly, with additional growth predicted. In 2019, the route had 8.9 million passengers and 4.5 million tons of cargo (Port of Helsinki, 2020). Currently, the route is operated daily and year round by three companies; Viking Line, Tallink and Eckerö Line with five passenger ferry vessels (*XPRS, Star, Megastar, Europa* and *Finlandia*) and two ropax vessels (*Sea Wind* and *Finbo Cargo*). In addition, during the busy summer season Viking Line redirects the passenger ferry vessels *Mariella* and *Gabriella* to do one round trip to Tallinn from Helsinki as soon as the vessels arrive from their normal route from Stockholm.

Very high speeds are used on the Helsinki–Tallinn route; up to 28 knots. This is due to two reasons: to include as many departures as possible per day and also to restrict the competition of smaller vessels such as Nordic Jet Line, Linda Line and SuperSeaCat that were forced out of the market by raising fuel prices and the introduction of new fast ferry vessels (Lisko, 2008). The vessels operating on the route have a significant daily break (4–12 hours) from sailing, which is used for cleaning, bunkering, refilling stores and maintenance. A hypothesis can be made that by either regulating or optimizing speeds on this route, significant reductions can be achieved in CO_2 emissions. Shortening the daily break would free more time for sailing, which would lead to a reduction in emissions.

5.2.1 Speed limit as measure

As described in Chapter 4, the shipping companies optimize the speed of their vessels but not for the sake of lesser fuel consumption and reduced emissions, but for the highest profit achievable and the Helsinki–Tallinn route is no exception. When fuel is cheap and there are no added cost for emissions, the incentive to operate ships with fast speeds increases. If ships slow down, they consume less fuel but at some point it drives more competition to the market or leads to reduced sailings and therefore loss of revenue. To force reduction of emissions on the route, one of these parameters needs to be changed. Finland has officially announced not to favour speed restrictions in the Baltic Sea, and the emission reduction targets are claimed to be met with digitalization and new technologies such as rotor sails and bio fuels (Helsingin Sanomat, 2019). Not much scientific evidence has been offered to back up the these claims, and it is worth noting that there are speed restrictions already in place on part of the Helsinki–Tallinn route which in fact increase the average speed of the whole route and increase the emissions.

The distance from Helsinki West Harbour to Tallinn is 46.1 nautical miles using the deep water fairway, which is the usual route for the passenger ferry vessels. *Finlandia*, *Star*, *Megastar* and *Silja Europa* operate from the West Harbour of Helsinki, and there is a speed restriction of 5.4 knots for the first 0.3 nautical miles and another restriction of 16.2 knots for the next 2.9 nautical miles. The speed restricted part takes 14 minutes to sail and the remaining 42.9 nautical miles is then unrestricted. The distance from Katajanokka terminal, where *Viking XPRS* and the other Viking Line vessels operate, is 47.4 nautical miles. The first 0.2 nautical miles has a speed restriction of 5.4 knots and the next 4.0 nautical miles has a restriction of 16.2 knots. The speed restricted part takes 17 minutes to sail and the remaining 43.2 nautical miles is unrestricted.



Picture 1 Map of Helsinki showing the speed limits of 16.2 knots (green and blue) and 5.4 knots (red). (City of Helsinki, 2020)

There are no speed restrictions in the Tallinn Bay. Inside the Tallinn harbour basin ships are instructed to move at a minimum speed to maintain steerage, but in a way that does not cause wake (Port of Tallinn Port Rules, 2020). AIS data shows that vessels slow down at the breakwater to less than 10 knots and keep reducing until manoeuvring to the berth. For the sake of calculation in the following models, manoeuvring time is not included in the sea passage and the route is considered only to have speed restrictions on the Finnish side. In Table 17, the required speeds for the unrestricted parts of the voyage are calculated from both the West Harbour and Katajanokka with extended total sailing times. Table 18 has the passenger ferry vessels that operate regularly and during the summer on the Helsinki–Tallinn route with their total sailing times one way according to regular schedules (Ferry operator websites, 2020).

Table 17 Required speed for the unrestricted parts of the voyage from Helsinki To Tallinn with different total sailing times

Sailing time	Required speed from West Harbour (kn)	Required speed from Katajanokka (kn)
2h 00min	24.3	25.2
2h 10min	22.2	22.9
2h 15min	21.3	22.0
2h 20min	20.4	21.1
2h 30min	18.9	19.5
2h 45min	17.0	17.5

Table 18 Passenger ferry vessels on the Helsinki–Tallinn route with their total sailing times one way, amount of sailings per day and the longest time in port. a) Finlandia is alongside 12 hours once per week, all other days the break is 6.17h. b) XPRS is alongside for 3.75h once per week, all other days the break is 8–8.5h. (Tallinksilja, Viking Line, Eckerö Line, 2020)

Ship	Travel time	Sailings per day	Time in port
Star	2h 00min	6	6.5–7h
Megastar	2h 00min	6	6.5–7h
Finlandia	2h 15min	5–6	6.17–12h **a)**
XPRS summer	2h 15min	4–6	3.75–8.5h **b)**
XPRS winter	2h 30min	4–6	3.75–8h **b)**
Mariella/Gabriella summer	2h 45min – 2h 50min	2	n/a
Silja Europa	3h 30min	2	14.5h

A speed limit on the Helsinki–Tallinn route would reduce CO_2 emissions. This conclusion can be made based: 1) reducing speed reduces fuel consumption as proven in previous chapters, and 2) speed reduction will not lead to added trips caused by running out of time as the ships on the route are spending extended time in port. The ships that run the route regularly overnight in port, so the schedules can be altered without the need to increase the capacity on the route. The passenger ferry vessels operating on the route have 4–5 main engines. Thus, the ferry can be run with a slower speed using less engines online with optimum (high) engine load.

Possible negative effects of speed restrictions on the route are 1) reduction of passengers transported as travel time increases and as some sailing schedules become less popular. In extreme circumstances this might lead to cancelation of scheduled sailings 2) a reduction of cargo carried as the travel time increases 3) reduction of freight fares as the travel time increases.

A strict speed limit could be established on part of the route by either the Finnish or Estonian authorities or both. Usually when there is a speed restriction on part of a route, ships will catch up on the lost time by speeding up when sailing through the non-restricted part. A good example of this are the routes leading to Stockholm as there are strict speed limits of 8–12 knots throughout the archipelago route. To maintain schedules, ships operate with high speeds just before entering the speed restricted part of the voyage. Therefore, a joint agreement between Finland and Estonia should be established if speed restriction should be chosen as an emission reduction method.

A fuel calculation estimate was made on the Helsinki–Tallinn route using the NAPA Fleet Efficiency Tool for different total sailing times. The ship model used was a generic passenger ferry vessel with only one propeller shaft. Thus, the fuel consumptions are not extremely accurate but the reduction of the fuel consumption based on the speed can be assumed to be accurate. The NAPA Fleet Efficiency Tool also takes into account the weather conditions for the fuel consumption calculation. The calculation was made on May 12th 2020 and the weather conditions were: 6.5 °C, SW wind 10 m/s, wave height 0.6 m from WSW.

Table 17: Difference in vessel fuel consumption on Helsinki–Tallinn route with increased sailing time. Required speeds calculated for departures from Western Harbour (WH) and Katajanokka (KN). Fuel consumptions calculated using the NAPA Fleet Efficiency Tool with a generic passenger ferry ship model burning MGO as fuel. CO_2 emissions calculated using the carbon factor of MGO (3.206)

Sailing time	Required speed WH (knots)	Required speed KN (knots)	Fuel consumed (t)	CO_2 emitted (t)	CO_2 reduction (t)	CO_2 reduction (%)
2h 00min	24.3	25.2	9.7	31.1	0	0

2h 10min	22.2	22.9	8.2	26.3	4.8	15.5
2h 15min	21.3	22.0	7.6	24.4	6.7	21.6
2h 20min	20.4	21.1	7.2	23.1	8.0	25.8
2h 30min	18.9	19.5	6.3	20.2	10.9	35.1
2h 45min	17.0	17.5	5.4	17.3	13.8	44.3

Vessel fuel calculations based on increased sailing time were also calculated using the cube rule formula (1) described in Chapter 4.1.

$$F(voyage) = \lambda \times v^3$$

For the calculation, 9.7 tons of fuel were consumed sailing the route and 2 hours was used as the travel time baseline. The speeds required sailing from West Harbour as presented in Table 17. The constant λ was calculated to be 0.00067601.

Table 18 Effect of increased sailing time to vessel fuel consumption and CO_2 emissions calculated using the cube-rule formula

Sailing time	**Fuel consumed (t)**	**CO_2 emitted (t)**	**CO_2 reduction (t)**	**CO_2 reduction (%)**
2h 00min	9.7	31.1	0	0
2h 10min	7.4	23.7	7.4	23.7
2h 15min	6.5	20.9	10.2	32.7
2h 20min	5.7	18.4	12.7	40.8
2h 30min	4.6	14.6	16.5	52.9
2h 45min	3.3	10.6	20.5	65.8

The NAPA Fleet Efficiency Tool predicts more fuel being consumed than by calculating consumption based on the cube-rule. As the cube-rule is designed for one main engine, the additional time running auxiliary engines are not calculated and the passenger ferry vessels have multiple main engines it is likely than the NAPA Fleet Efficiency Tool calculations are more accurate.

In Table 19, CO_2 emissions were re-calculated for each vessel with a 22, 21, 20, 19 and 18 knot speed limit for the voyage and annual totals were summed. The baseline used was the annual CO_2 emitted at sea in 2018 reported in the EU MRV database. Reduction of emissions were calculated using the CO_2 reduction (%) from Table 17 interpolated accordingly for each vessel. Only the vessels operating the route regularly were selected. *Silja Europa* does not need to slow down for these limits and therefore would produce the same emissions in any scenario. *Mariella* and *Gabriella*, which sail the Helsinki–Tallinn route only during the summer with one round trip daily, would not need to slow down either, but their emissions allocated for this route cannot be defined based on the EU MRV data and they are therefore excluded. The reductions in t would not change with the *Mariella*/*Gabriella* data but the % would change.

Table 19: Effect of different speed limits on CO_2 emissions on Helsinki–Tallinn route with the EU MRV data as baseline and reductions calculated with the reduction % from Table 17

Vessel	Annual CO_2 (t)	CO_2 (t) limit 22 kts	CO_2 (t) limit 21 kts	CO_2 (t) limit 20 kts	CO_2 (t) limit 19 kts	CO_2 (t) limit 18 kts
Star	66282	51368	47723	41956	39769	35328
Megastar	45038	34904	32427	28509	27023	24005
Finlandia	60754	60754	56441	53038	49636	45687
Viking XPRS	34300	34300	33082	31162	30613	29498
Silja Europa	24134	24134	24134	24134	24134	24134
Total CO_2	230507	205461	193807	178799	171174	158652
Reduction (t)	0	25047	36701	51708	59333	71855
Reduction (%)	0	10.9	15.9	22.4	25.7	31.2

5.2.2 Incentive as measure

Reduction of CO_2 emissions can be achieved by various market based measures (MBM) such as bunker levy as described in Chapter 4.5. One MBM to reduce vessel speed between Helsinki and Tallinn would be to offer incentives. The incentives could be offered for reduced speed, reduced emissions, increased energy efficiency or a combination of the above. Better energy efficiency could be achieved with other means, such as hull and propeller cleaning, reduced hotel load and increased cargo and passenger averages.

There are a few examples from the world: one would be from one or both ports to offer discounts to port fees based on speed limits in the similar way than ports in California. Finland and Estonia both have also fairway dues that can be used for incentives. The drawback to this incentive is that the ships are catching up with lost time on the approach to the port by keeping a higher speed before entering the restriction zone, which most probably leads to more emissions on the whole voyage than keeping the most efficient speed all the way. This could be the case between Helsinki and Tallinn if the speed incentive would be from one side only.

Another example is the Swedish Clean Shipping Index (CSI) that is renewed every year and more points are earned if the vessel is run more efficiently than the previous year. With the CSI, vessels earn both a reduction in port fees in Sweden but also a discount to the fairway dues that are collected by the government of Sweden. Finland and the ports of Helsinki and Tallinn could adopt the CSI and start implementing the incentive. Currently, the Port of Helsinki has an incentive for vessels with a CSI certificate but only vessels sailing to Sweden possess it.

Another energy efficiency index could also be designed specifically on the Helsinki–Tallinn route. This could be based on comparing the EEOI to the baseline, which could be EEDI if available, EIV, EVDI or similar provided it would be calculated correctly and fairly. It is worth noting that passenger ferry vessels have very high EEOI to EEDI ratios as presented in Chapters 4.7.3 and 4.8.3 compared to cargo ships. It is therefore important not to rate the vessels by their theoretical emissions but rather based on their actual data, which is accessible for example through the EU MRV database.

Also, the ship's operational energy efficiency could be compared to the previous year as per the EU MRV data. Incentives could be offered simply on approved figures. The problem is that different owners have chosen to allocate the emissions between cargo and passengers differently making the comparison impossible.

The benefit on offering incentives on energy efficiency instead of speed reduction is that all efforts towards less emissions would be accounted for. This could be amending the ship's schedule for less speed, but also better efficiency in cargo operations, shore power connection while alongside, hotel power reduction by better energy efficiency, hull cleaning, technological investments and any other similar measures.

5.2.3 Passenger action as a measure

One way to reduce emissions on the Helsinki–Tallinn route is to direct passengers to favour less emitting vessels when booking their tickets. This has been implemented in several other areas such as directing people to choose a carbon free power source for household electric and heating arrangements and promoting people to eat less meat to reduce phosphorus emissions to the Baltic Sea. The GHG Emission Rating created by the NGO Carbon War Room and shipping consultancy company Rightship is directing companies to choose more energy efficient ships to transport their products with the GHG Emission Rating that is given to every ship in the world. The GHG Emission Rating is explained in Chapter 4.9.5.

For passenger action to work, the shipping companies should be forced to adapt standardized indexes for energy efficiency and then to communicate them to the public. The problem with declaring emissions per passenger for ships is the allocation of emissions to cargo and passengers, which is explained in Chapter 4.8.2. Also, the total GHG footprint of the means of transport should be declared and not only the CO_2 emissions. For example, the methane slips of LNG powered ships should also be taken in account when ranking a ship by its GHG footprint. The Global Warming Potential of LNG-powered ships is explained in Chapter 4.8.4.

The problem of emission allocation was subject to a debate in the Finnish press about the carbon footprint of different means to travel in 2019. There were several articles in the Finnish media comparing air and sea travel based on CO_2 emissions per passenger. The reason for a relatively easy comparison was internet-based data provided by various sources that would transform the emissions to the same unit: grams of CO_2 emitted per passenger-kilometre.

For ship emissions the most referred source is the Technical Research Centre of Finland (VTT) calculation[2], which concluded that using a medium speed (18 knots) passenger ferry, the CO_2 emissions are 143 g/passenger-kilometre, and with a high speed (24–27 knots) ferry the CO_2 emissions are 280 g/passenger-kilometre. VTT uses an emission allocation of 80% towards passengers on car ferries that operate between Finland–Sweden and Finland–Estonia and 20% on ropax vessels such as the ones on Finland–Germany route. This allocation is more or less the area option of the EN 16258 standard, which is explained in Chapter 4.8.2.

For air travel, there are multiple available online calculators. Some are more conservative than others using different parameters for the calculation. Using the Finnair CO_2 emissions calculator[3], a flight from Helsinki to Tallinn would produce 177 g/passenger-kilometre with an ATR-72 propeller plane and 299 g/passenger-kilometre using an Embraer E190 jet plane. Quick conclusions can be made with the above data that flying might actually be a more environmental-friendly way to travel than by sea (Arola, 2019).

The Ship Owners' Association of Finland made a press statement defending sea travel with a sample calculation indicating an average CO_2 emission of 149,15 g/passenger-km on the Helsinki–Tallinn route. The question is: which calculation is correct: the VTT's or the Ship Owners' Association, and why are they such different values?

The VTT calculation used two different ships models. The first is a 60000 gross ton passenger ferry with a capacity of 3000 passengers and 30000 kW engines transiting with a speed of 18 knots. The closest to this on the route is the *Silja Europa*, which matches the size but sails the voyage with its current schedule at an average speed of 13 knots (3.5 hours).

The second ship model is a 34000 gross tons ferry with a capacity of 2000 passengers and 44000 kW engines making the voyage with 24 knots. This does not match any of route's vessels, but is close to the *Star*, *Viking XPRS*, *Finlandia* and *Megastar* that operate the route on a regular bases using around the same speed.

Both imaginary vessels have a total cargo capacity of 5000 DWT and both are assumed to operate with an average 50% capacity taking 1000 t of cargo on average each voyage. Fuel consumption on both vessels is estimated to be 205 g/kWh for main engines and 210 g/kWh

[2] The VTT Lipasto database can be found at: http://lipasto.vtt.fi
[3] The Finnair emissions calculator can be found at: https://www.finnair.com/fi/fi/emissions-calculator

for auxiliary engines. The distance used is 88 kilometres, which is 47.5 nautical miles. The ship travelling 18 knots completes the distance in 2 hours 39 minutes and the vessel travelling 24 knots in 1 hour 59 minutes. The slower ship is estimated to consume 7.47 tons of fuel during the passage and the faster ship 9.74 tons. The consumptions are then turned into grams, divided by the distance travelled and multiplied by the carbon factor of 3.15 (CO_2 emitted per fuel consumed). The slower ship consumes 84984 grams of fuel and emits 267783 grams of CO_2 per kilometre, whereas the faster ship consumes 110635 grams of fuel and emits 348611 grams of CO_2 per kilometre. The CO_2 emissions are then weighted by 80% on the passengers and 20% on the cargo carried. When these are then divided by the passengers carried (50% of maximum capacity) the values are 143 g/passenger-kilometre for the slower vessel and 279 g/passenger-kilometre for the faster ship. The formula is as follows:

$$\frac{\frac{fuel\ consumed\ (g)}{distance\ traveled\ (km)}\ x\ carbon\ factor\ x\ 0.8}{passengers\ carried} = \frac{g\ CO_2}{passenger\ x\ kilometer} \quad (24)$$

The Shipowners' Association calculation uses a fixed fuel consumption of 10 tons, which is claimed to be based on observed values. Passenger count is 857 and cargo 1191 tons – both values are claimed to be averages for one year. To obtain the CO_2 emissions per passenger-distance the following formula is used:

$$\frac{fuel\ consumed\ in\ g}{(distance\ x\ cargo) + (distance\ x\ passengers)}\ x\ carbon\ factor\ x\ 0.8$$

$$= \frac{g\ CO_2}{passenger\ x\ kilometer} (25)$$

The fuel consumed is divided by the transport work, the obtained figure (59.19) is then multiplied with the carbon factor of 3.15 and the result (186.43) is allocated by 80% to the passengers (149.15 g/pax-km) and 20% to the cargo (37.29 g/ton-km).

So, which one is correct? The parameters for the calculations are analysed first. It is notable that the given figures of the Shipowners' Association are actually worse than what the VTT estimates. Average passenger count of 857 is much less than 1000 and 1500. Also, the average fuel consumed (10 t) is more than the estimates of 7.5 and 9.7 t. This would mean that if the same calculation method is used, the Shipowners' Association calculation should then have worse results. However the results are not worse, so the difference must be in the formula. It is also worth noting that the NAPA Fleet Intelligence estimated a passenger ferry fuel consumption to be 9.7 tons for a 2 h 00 min sail from Helsinki to Tallinn.

The carbon factor used on both calculations is 3.15 g CO_2 emitted per g of fuel, which is for Light Fuel Oil (Marpol, 2017). This is not correct as all the vessels on the route are restricted to use Marine Gas Oil with sulphur cap of 0.1%, which has a carbon factor of 3.206 and will result in producing more emissions or LNG, which has a carbon factor of 2.750 and would result in less emissions.

As explained in Chapter 5.2.1, passenger vessels that operate between Helsinki and Tallinn use either the West Harbour or Katajanokka terminals in Helsinki. The distance berth to berth from West Harbour to Tallinn is 46.1 nautical miles, which is 85.4 km. The first 3.2 miles from West Harbour are speed restricted to 5.4 (10 km/h) and 16.2 knots (30 km/h), and the restricted portion takes 14 minutes. The distance from Katajanokka to Tallinn is 47.4 nautical miles, which is 87.8 km. The speed restriction is for 4.2 miles, which takes 17 minutes.

To make the voyage in 2 hours from West Harbour, the average speed for the remaining 43.5 miles is 24.3 knots. To make the voyage from Katajanokka in 2 hours, the average speed for the remaining part is 25.2 knots. Adding 0.5 hours to the sailing time reduces the average speed to 18.9 knots from West Harbour and to 19.5 knots from Katajanokka. A passenger ferry travelling at a maximum speed of 18 knots would take 2h 37min to complete the route from West Harbour and 2h 41min from Katajanokka.

Fuel consumption in both calculations is limited to the actual sailing time. This not completely accurate as the ship emits CO_2 even when alongside in port as it is using auxiliary engines. More accurate numbers would use the daily fuel consumption, daily distance travelled, with passengers and cargo carried and even including the loading time to the calculation.

Overall, both calculations are likely too optimistic. The biggest flaw is in the formula used by the Shipowners' Association. As the EEOI formula (11) is as presented in Chapter 4.7.2:

$$EEOI = \frac{Fuel\ consumed\ x\ Carbon\ conversion}{Distance\ sailed\ x\ Cargo\ transported}$$

Transport work is defined by distance sailed x cargo transported and the units need to be same. Therefore, transport work for passengers and cargo cannot be added, but they need to be pre-allocated.

Using the parameters given by the Shipowners' Association (fuel consumption average 10 t, 857 average passengers and 1191 tons of average cargo) the following CO_2 emissions can be calculated as below.

Table 20: CO_2 emissions per passenger-kilometer on Helsinki–Tallinn route using EEOI formula, allocated by 80% to passenger transport and 20% to cargo using the data provided by Finnish Shipowners' Association

Fuel consumed	10	t
Distance sailed	85,2	km
Passengers carried	857	Pax
Cargo transported	1191	T
Fuel carbon factor	3.206	g CO_2/g fuel
Total fuel consumed / distance sailed	117371	g/km
Total CO_2 emitted / distance sailed	376291	g CO_2/km
80% allocation to passengers	301033	g CO_2 / km
20% allocation to cargo	23474	g CO_2 / km
Per passenger	**351.3**	g CO_2 / pax-km
Per cargo t	**19.7**	g CO_2 / t-km

When the figures are re-calculated for nautical miles instead of kilometres (650.5 g CO_2 / pax-nm and 36.5 g CO_2 / t-nm) compared to the EU MRV data (Table 8), similar figures can be observed with Star (675.5 and 101.27). The Shipowners' Association has later removed the press statement from their website, but the calculation can be found online.[4]

[4] The Shipowners' calculation can be found online at https://shipowners.fi/wp-content/uploads/2019/02/Formel-nr-2-Cf-003.pdf

In August 2019, The Shipowners' Association issued another press statement[5]. It stated that the newly published EU MRV data proves ship travel to be less pollutant than flying. According to the statement the issue attributed to allocating emissions on a ship that carries both passengers and cargo is weather to use weight or area as the method. As the International Civil Aviation Organization (ICAO) uses weight in their calculations, weight also should be used for ships.

The Shipowners' Association press statement provided two examples: Helsinki–Stockholm would produce 20–24 kg CO_2 per passenger on a ship and 41–64 kg on an airplane. Helsinki–Travemünde would produce 69–79 kg on a ship and 142 kg on an airplane. The sources for ships was derived from the EU MRV and the ICAO calculator for air travel.

The ICAO CO_2 emission calculator uses the international Revenue Tonne-kilometres (RTK) data for the passenger/freight factor, which changes. Computed on February 3rd 2020, a one-way flight between Helsinki and Stockholm in economy class would produce 65.5 kg of CO_2 per passenger. The distance travelled is 398 km. There are four ships on a scheduled route between Helsinki and Stockholm and their recorded emissions as per EU MRV data are shown in Table 9. Tallink-Silja owned ships cannot be used in this comparison as the allocation of emissions between passengers and cargo are done with the area method. The ship producing the least CO_2 emissions per passenger (*Mariella*) emitted one way is 15.8 kg.

For the comparison between air and sea travel from Helsinki to Travemünde, the press statement does not tell which airport was used for the calculation as Travemünde does not have an airport. A flight from Helsinki to Hamburg would produce 148.6 kg of CO_2 per passenger as per the ICAO calculator and the distance travelled would be 1168 km. Using the EU MRV data of the ropax vessel *Finnlady*, that is on a scheduled Helsinki–Travemünde route, the CO_2 emitted on the same distance would be 81.5 kg per passenger.

The statement no longer uses Helsinki–Tallinn as an example. According to the ICAO calculator a flight would produce 16.3 kg of CO_2 per passenger on a distance of 101 km. Using the least emitting ship on the route (*Viking XPRS*) the CO_2 emissions are 6.3 kg and with the *Finlandia* the CO_2 emissions are 7.5 kg.

[5] The press statement can be found online at: https://shipowners.fi/mainettaan-parempi-merimatka/

When allocating emissions between cargo and passengers for EU MRV, the ship owner can choose between two methods as explained in Chapter 4.8.2. One method uses mass and the other method uses area. According to the Shipowners' Association's press statement, mass should be used to be comparable with air travel. That is true to have a fair comparison but then the cargo carrying efficiency would be poor. The *Viking XPRS* has an EVDI of 22.8 g CO_2 / t-nm based on its cargo carrying capacity and engine power but in reality it produces 393.1 g CO_2 / t-nm, which is 17 times more.

In conclusion, a true comparison between different means to travel is still difficult. A lot of emissions also happen on the way to the port or airport and during the time in port, which should be included. Marine transportation is very energy efficient, when cargo is transported with appropriate cargo ships: tankers, bulkers and containerships. Roro and ropax vessels on the other hand are not as efficient; travelling on a ship that also carries cargo can be seen less polluting than flying but then these same ships are not an efficient way to transport cargo. The faster the ship and the more it pollutes and also the less efficient it is.

5.3 Helsinki–Stockholm

The passenger ferry route Helsinki–Stockholm is operated by two companies, Viking Line and Tallink-Silja, with a total of four vessels, which are all relatively old (built between 1985 and 1992). The companies have not showed any interest to build new vessels for the route as the passenger traffic between Finland and Sweden has been declining slowly for the past 15 years (Väylä, 2017). The Tallink-Silja vessels, *Silja Serenade* and *Silja Symphony,* lie alongside in port every day in either Helsinki or Stockholm between arrival and departure for 7–7.5 hours. The Viking Line vessels *Mariella* and *Gabriella* make a daily round trip to Tallinn from Helsinki during the summer season. The distance on the route between Helsinki and Stockholm is 265.8 nautical miles of which 185.5 is from Helsinki to Mariehamn and 80.3 is the remaining Mariehamn to Stockholm. The vessels have to stop in Mariehamn each time to avoid paying value added tax on sold goods on board as Åland has been given special right within the European Union. Without the stop, the route would be 20.4 nautical miles shorter (7.7%). The Tallink-Silja vessels sail 84801–87629 nautical miles annually and Viking Line vessels sail 92385–92548 nautical miles annually based on EU MRV data. Without the call to Mariehamn these vessels would sail 6530–6747 nautical miles less in a year, and as they consume with the current operational speeds 155–202 kg of fuel per nautical mile (EU MRV, 2019), the reduction in annual fuel consumption would be 1012–

1363 t even without reducing speed. The shorter route would mean more time available on the voyage and lower speed and therefore even less fuel consumed. Unless the tax-free regulation can be changed so that the vessels would not need to go alongside each voyage, cutting the Mariehamn stop would have a significant economic impact to the tax-free sales on board and also reduce the regular traffic from mainland Finland to Åland.

Energy efficiency per transported unit cannot be compared between the companies due to the different method of allocating emissions between passengers and cargo. The Tallink Silja vessels emit 622–635 kg of CO_2 per nautical mile with average speed of 14–14.1 knots whereas the Viking Line vessels emit 489–511 kg of CO_2 per nautical mile with an average speed of 14.6–15.0.

Table 21 contains the different schedules of the four aforementioned vessels with the corresponding required speeds. The A schedule is Tallink-Silja's standard winter and B summer schedule for *Silja Serenade* and *Symphony*. C and D are the same schedules without a call to Mariehamn. E and F are Viking Line's winter and summer schedules. G and H are the same schedules without a call to Mariehamn. Schedules E and F have the highest required speeds, 16.6 and 17.8 knots, between Helsinki and Mariehamn, which means that a stricter speed limit would make the Viking Line summer schedule impossible to maintain. The average speed of the Mariehamn–Stockholm part of the voyage does not seem to be high (12.4–14.6 knots), but in reality the vessels need to sail full speed (20+ knots) from Mariehamn for the first 32 nautical miles until Kapellskär as the remaining part of the leg (48 nautical miles) is speed restricted to 8–12 knots.

In conclusion, the stop in Mariehamn dictates the schedule for all vessels that call there. The port is extremely busy as all passenger ferry and ropax vessels carrying passengers between Estonia–Sweden and Finland–Sweden call there. Every vessel has their dedicated slot with a scheduled five minutes alongside. Any delays cause changes for all vessels as there is no room to wait. A hypothesis is made that without the stop in Åland, a significant reduction in CO_2 emissions can be made.

Schedule	**Departure Helsinki**	**Arrival Mariehamn**	**Required speed (kts)**	**Departure Mariehamn**	**Arrival Stockholm**	**Required speed (kts)**	**Fuel consumed (t)**

A	1700	0415	16.5	0420	1045	12.5	37.1
B	1700	0415	16.5	0420	1030	13.0	37.6
C	1700	-	-	-	1045	13.8	28.7
D	1700	-	-	-	1030	14.0	29.1
E	1715	0425	16.6	0430	1100	12.4	37.2
F	1800	0425	17.8	0430	1050	12.7	40.5
G	1715	-	-	-	1100	13.8	28.7
H	1800	-	-	-	1050	14.6	31.0

Table 21: Schedules, required speeds and fuel consumptions on Helsinki–Stockholm route with and without a call in Mariehamn. All times in Finnish local time. (Tallinksilja & Viking Line, 2020)

In Table 22 the fuel consumptions were calculated for the different versions of the Helsinki–Stockholm route one way with and without a call to Mariehamn using the NAPA Fleet Efficiency tool. CO_2 emissions were calculating using the carbon factor of MGO (3.206). Without the stop in Mariehamn the vessel would produce 22.6–29.1 % less CO_2.

Schedule	Fuel consumed (t)	CO_2 emitted (t)	Reduction of CO_2 (t)	Reduction (%)
Silja summer	37.6	120.5	0	0
Silja winter	37.1	118.9	1.6	1.3
Silja summer w/o Mariehamn	29.1	93.3	27.3	22.6
Silja winter w/o Mariehamn	28.7	92.0	28.5	23.7
Viking summer	40.5	129.8	0	0
Viking winter	37.2	119.3	10.6	8.1

Viking summer w/o Mariehamn	31.0	99.4	30.5	23.5
Viking winter w/o Mariehamn	28.7	92.0	37.8	29.1

Table 22: The effect on CO_2 emissions of the stop in Mariehamn on Helsinki–Stockholm route

5.4 Turku–Stockholm

The passenger ferry route from Turku to Stockholm is also operated by two ship owners with two vessels each. All four ships have two calls in Åland in every 24 hours; one in Mariehamn and the other at Långnäs. The schedule is very tight: the ships only have about one hour for discharging and loading cargo and passengers in Turku and Stockholm, 10–15 minutes in Mariehamn and 5 minutes in Långnäs. More than 60 nautical miles of the route occurs in the Stockholm archipelago with speed limits of 8–12 knots throughout, with some exemptions for ships on this particular route, and the only way to achieve this time schedule is by making very high speeds on the other parts of the route. Any other speed limit on this route would make it more or less impossible to run. Any delays especially with the Åland port calls have a snowball effect on all vessels and normally it can take days for vessels to be back on schedule.

The only way to slow ships down on this route is to stop or reduce the port calls in Åland. Some of the passengers on board these vessels take the morning ferry from either Turku or Stockholm and then exchange ships in Mariehamn and arrive back in the same evening exercising the right for tax-free purchases on board. Banning this would have a significant economic effect. The distance from Turku to Stockholm via Långnäs is 160.8 nautical miles, via Mariehamn it is 170.2 nautical miles and without the stop 159.7 nautical miles. Without the need to stop in Långnäs, the vessels would sail 1.1 less nautical mile per day (0.3%) and without both stops, 11.6 fewer miles per day (3.5%). The vessels sail 90730–110400 nautical miles per year, so eliminating Långnäs would cut annual miles by 272–331 and eliminating both stops would reduce travel by 3176–3864 miles. The vessels consume 136–194 kg of fuel per nautical mile (EU MRV, 2019) so they consume 370–749 t of fuel to make the stops in Åland. Without the stops, the schedule would allow lower speeds and even less fuel would be consumed.

In Tables 23–26, two scenarios for two vessels operating the route, *Baltic Princess* and *Viking Grace*, are calculated with the corresponding CO_2 emissions: one scenario with no calls at all in Åland, which would mean removing the day-cruiser passengers and the second scenario with only the call at Mariehamn but no call at Långnäs, which would reduce the amount of tax-free sales on board with the current regulations but not stop it completely. The vessel average fuel consumption (t/d) was calculated from the EU MRV data using the average speed, and the change of fuel consumption was calculated using the cube-rule.

Table 23: Baltic Princess normal schedule and simulated alternate schedules with the corresponding required speeds. (Tallinksilja, 2020)

Departure	Arrival	Sailing time (h)	Distance (nm)	Required speed (kts)
Turku 20:15	Långnäs 00:40	4.42	67.9	15.4
Långnäs 00:45	Stockholm 07:10	6.42	92.9	14.4
Stockholm 08:10	Mariehamn 13:35	5.42	80.3	14.8
Mariehamn 13:45	Turku 19:15	5.50	89.9	16.3
Turku 20:15	Stockholm 07:10	10.92	159.7	14.6
Stockholm 08:10	Turku 19:15	11.08	159.7	14.4

Table 24: Effect on fuel consumption and CO_2 emissions for the Baltic Princess with two simulated schedules

Route	Annual miles	Average speed	Fuel cons. t/d	Fuel cons. kg/nm	Annual fuel (t)	Annual CO_2 (t)	Reduction of CO_2 (%)
EU MRV 2018	90729	15.3	64.7	194.4	17636	56541	0
Only Mariehamn	90428	15.1	63.4	190.3	17204	55157	2.5
No calls in Åland	87550	14.5	56.2	168.8	14775	47370	16.2

Table 25: Viking Grace normal schedule and simulated alternate schedules with the corresponding required speeds. (Viking Line, 2020)

Departure	Arrival	Sailing time (h)	Distance (nm)	Required speed (kts)
Turku 20:55	Långnäs 01:05	4.17	67.9	16.3

Långnäs 01:10	Stockholm 07:30	6.33	93.1	14.7
Stockholm 08:45	Mariehamn 14:10	5.42	80.3	14.8
Mariehamn 14:25	Turku 19:50	5.42	89.9	16.6
Turku 20:55	Stockholm 07:30	10.58	159.7	15.1
Stockholm 08:45	Turku 19:50	11.08	159.7	14.4

Table 26: Effect on fuel consumption and CO_2 emissions for the Viking Grace with two simulated schedules

Route	**Annual miles**	**Averag e speed**	**Fuel cons. t/d**	**Fuel cons. kg/nm**	**Annual fuel (t)**	**Annual CO_2 (t)**	**Reduction of CO_2 (%)**
EU MRV 2018	110400	15.5	49.5	135.9	15003	41559	
Only Mariehamn	110033	15.4	48.4	133.0	14633	40533	2.5
No calls in Åland	106531	14.7	42.4	116.6	12417	34395	17.2

Removing the very short call at Långnäs would reduce fuel consumption and CO_2 emissions on the *Viking Grace* and on the *Baltic Princess* by 2.5%. Removing both calls in Åland would lead to a 17.2% reduction on *Viking Grace* and 16.2% on the *Baltic Princess*. The above calculations are based purely on average speeds and not actual speeds and methane slips from *Viking Grace* were not taken in account for.

6 Conclusions

Global shipping will see increasing pressure towards decarbonation as all other means of transport have set much stricter goals and are aiming towards zero emissions or at least being carbon neutral by mid-century. The IMO targets are to peak shipping's GHG emissions as soon as possible and reduce them by 50 % by 2050 compared to 2008. Before the Corona virus crisis, total emissions of shipping were still increasing, which means maritime transport's share of total emissions is likely to increase from 2.7 % as other industries are reaching their targets much sooner. IMO has been collecting fuel consumption data from all vessels starting 1st January 2019. The analysis of the IMO data together with the EU MRV data was used for the 4th IMO GHG Study that was published in August 2020 before the

MEPC 76 meeting and the revised IMO Strategy should be ready to be implemented by spring 2023 as per the roadmap laid out in 2018 (MEPC 70, 2018).

The only effort that shipping has put emphasis on so far is carbon intensity: reducing CO_2 emissions per transport work. IMO's target is to reduce carbon intensity by 40 % by 2030 and 70 % by 2050 compared to 2008. Many shipping companies claim that they have already achieved this target but in reality their total emissions have increased or not reduced. In the Baltic Sea shipping's carbon intensity has improved in 2006–2018 by 20 % but in the same time total CO_2 emissions only decreased by 6 % (Helcom, 2019).

Good results have been obtained with the new vessels either by being able to carry more cargo than the previous generation or by being built under the EEDI design rule, which is becoming increasingly strict. On the other hand, loopholes have been found in EEDI and as it does not cover the Global Warming Potential of the vessel, some emissions are neglected. It is becoming obvious that technology will not solve the emission reduction problem completely.

There is no clear single solution for how to most effectively reduce vessel speeds as each type of shipping has its unique features. While a straight forward speed limit could work for one type of shipping, it might be counterproductive for another. A dynamic model with multiple measures would probably be most effective. A logistic-based measure could work on one type of shipping and a market-based one on the other. All policy makers, governments, flag states and other shipping administration, should consider and adapt all measures to achieve the targets. Even single ports and cities could have a significant impact if applying the correct measures.

Technology will not solve the whole puzzle. The biggest problem is the long lifespan of ships (Bullock et al, 2020). Therefore, measures need to be implemented on existing ships and not wait until the new builds will reduce emissions. An estimate made by Norway assumes that in 2030 7–12% of global shipping emissions will be produced by ships constructed between 2000–2010, and in 2050 15–16% of emissions will be produced by ships constructed 2020–2030 (Norway's proposal for MEPC 74, 2019).

Finland is very dependent on shipping and also on the passenger ferry vessels. The passenger ferry vessels are not energy efficient when comparing their emissions per transport work to cargo ships. When transporting both passengers and cargo, the transportation costs become less and therefore the passenger ferry vessels can beat the roro cargo ships out of the market. As the passenger ferry vessels transport almost 50% of all packaged goods in and out of Finland, the emissions that they create play a significant role. There are multiple measures to be taken to reduce the GHG emissions from passenger ferry vessels.

6.1 Recommendations

Passenger ferry vessels continue being an important part of Finland's supply chain. As Finland is committed to comply with the international, European Union and national goals to decarbonise transportation, all options should be considered when aiming to reduce the GHG emissions from ships. Currently there are three new passenger ferry vessels under construction for three different routes: *Aurora Botnia* for the Vaasa–Umeå route, *Mystar* for the Helsinki–Tallinn route and *Viking Glory* for the Turku–Stockholm route. All three vessels will run with LNG and they will produce less CO_2 than the ships that they will replace. Also, the *Viking Glory* will reduce CO_2 emission per transport unit as it can carry significantly more cargo than *Amorella*, which she will replace. When methane slips are taken in account, LNG-powered vessels may produce more GHG emissions than their MGO counterparts. It would be important to define and report the actual methane slips of LNG-powered passenger ferry vessels with sensor data to have a better understanding of their impact to global warming. A useful data comparison would be to compare the methane slips of a LNG-powered passenger ferry on Helsinki–Tallinn route that is using very high engine load most of the time and to another on Turku–Stockholm route, that has to slow down due to the speed restrictions of the Stockholm archipelago. EEDI should be recalculated to take all the vessels GHG emissions in account especially the methane slips from LNG powered vessels.

A speed restriction should be considered on the Helsinki–Tallinn route as a short-term measure. A 22-knot speed limit would reduce emissions from the passenger ferry vessels by 11% and an 18-knot speed limit by 31%. The speed reduction can be reached by regulation or incentive, which would offer discount on port fees, fairway dues or taxes.

Shore-power connection should be first provided and then forced to at least the ships on regular routes. Connecting only the passenger ferry ships operating from Helsinki annual direct CO_2 emissions would be reduced by 51778 tons. Even if the shore power is produced with means that produce emissions, connecting ships to shore power eliminates other emissions such as sulphur, NOx and small particles.

The special status of Åland as a VAT free zone should be reconsidered or the rules for ships needing to go alongside to comply with tax free sales should be altered from the environmental impact aspect. CO_2 emissions from vessels that now stop in the Åland Islands every day would be reduced by 2.5–29.1% if not needed to do the stop. Even if the 5-minute stop in Långnäs would be taken off from the passenger ferry vessels operating between Turku and Stockholm 2.5% reduction to CO_2 emissions would be achieved.

Passenger ferry and ropax operators should agree on a common way to allocate the emissions between passengers and cargo to make comparison possible. Ship owners should be forced to communicate their energy efficiency to the public. CO_2 emissions per passenger should be available in the same way than airlines provide. This would encourage people to personally compensate for their emissions and choose the less polluting option if multiple are choices available. Passenger ships should also have a third party provided rating based on their energy efficiency and it should be visible for the passengers.

Now that actual fuel consumption and energy efficiency data is available via the EU MRV system, the VTT should update the Lipasto database accordingly. Also, the methane slip should be taken in account for the LNG-powered vessels.

6.2 Summary

The research problem for this thesis was to identify the best possible measure to reduce GHG emissions from passenger ferry vessels in the short and medium term when it comes to vessel speed. The passenger ferry vessels were chosen as they were proven to be very important for the supply chain of Finland during the acute phase of the Corona virus crisis.

Not one single solution was found that would solve the entire emissions equation, but two were identified: speed reduction by regulation or incentive on the Helsinki–Tallinn route and the reconsideration of the Åland tax-free regulation to reduce the port calls of the vessels trafficking between Finland and Sweden. Both measures should be analysed more in depth especially considering the economic impact of them to the shipping companies and possibly to Åland.

Implementation of short-term timeline measures should take place as soon as they are found effective. As per their definition they can be followed by proper mid-term and long-term measures.

It is imperative to point out that based on all available research data shipping is slipping away from the emission reduction targets it set itself and outside regulation is needed to put the industry back in line towards decarbonation.

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