# Development of Performance Indicators and Methods for a Comparison of Various Transport Modes (Road, Rail, Sea)


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# ABSTRACT

Transportation of cargo and passengers is part of the everyday life for almost every human being. This is a big industry which requires continuously large amount of resources. In order to get maximum benefit from the transport sector, there is need for an economically effective and environmentally friendly transport system. This is a complex task to solve which requires high level knowledge from various fields of education.

This Master Thesis is a part of analysis which takes into account the cost and environmental impact and time of container transportation. The latter is taken into consideration because the cargo unit is clearly fixed and is a very widespread way of transporting cargo. Large amount of transported cargo could mean significant impact on cost and environmental impact aspects and therefore it is believed that the potential to improve the overall transport chain is to be substantial. Basing on this, the objective of this Master Thesis is set to develop such comprehensive and universal methodology as well as providing theoretical background, which allows performing comparative analysis on various modes of transport in the frame of cost and environmental impact. Transport modes taken into consideration are road, rail and sea. Air transport is excluded because it is very much distinguished from other modes. Developed methodology is finally tested and analyzed with two separate transport scenarios.

To reach the objective, results and methods available from existing and up to date works are utilized. Available methods will be adapted according to the needs of the analysis.

The main interest about this methodology is the outcome of the analysis in order to find the fastest, cheapest or most environmentally friendly way of cargo transport. Moreover, the obtained method allows to determine the influencing factors, their importance of the impact and bottlenecks of various transport scenarios. Consequently, the outcome of the methodology could be a significant contributor on deciding about the improvement measures of the transport chain.

## ABSTRAKT (Translation into German language)

Der Transport von Fracht und Passagieren ist ein Bestandteil des alltäglichen Lebens für fast jeden Menschen. Der dahinterstehende Wirtschaftszweig ist auf eine kontinuierlich große Menge an Ressourcen angewiesen. Um den maximalen Nutzen aus dem Transportwesen zu ziehen, ist es notwendig ein Transportmittel zu wählen, dass wirtschaftlich effizient und umweltfreundlich ist. Um die daraus entstehende komplexe Aufgabe zu lösen, erfordert es weitreichende Kenntnisse aus verschiedenen Bereichen der Wissenschaft.

Die vorliegende Masterarbeit beschäftigt sich mit den Auswirkungen von Umwelt- und Kostenaspekten auf den Containertransport. Diese Art von Ladungstransport bietet sich an, weil das Transportvolumen pro Einheit klar definiert ist und Weltweit zum Einsatz kommt. Die Größe des gesamten Transportvolumens übt erheblichen Einfluss auf die Kosten und den daraus resultierenden Umweltauswirkungen aus. Jedoch ist sie auch entscheidend für das Potential der Transportkette und kann diese in den Grundzügen verändern.

Ziel dieser Arbeit ist es, neben der Bereitstellung von theoretischem Hintergrundwissen, eine Methodik zu entwickeln, die den Vergleich verschiedener Transportmittel im Hinblick auf Kosten und Umweltauswirkungen ermöglicht. Berücksichtigung findet der Transport per Straße, Schiene und Seeweg. Der Transport über den Luftweg wird ausgeschlossen, weil die Unterschiede für den Vergleich zu groß wären. Anschließend soll die Methodik anhand von zwei separaten Einsatzszenarien getestet und analysiert werden.

Um ein optimales Ergebnis zu erzielen, werden aktuelle Arbeiten in die Untersuchung mit einbezogen. Es erfolgt eine Übernahme von vorhandenen Methoden mit Anpassungen auf die Bedürfnisse der vorliegenden Analyse.

Die Hauptinteressen, die mit dieser Methode verfolgt werden, sind im Ergebnis die schnellste, billigste oder die umweltfreundlichste Art des Gütertransports zu finden. Darüber hinaus soll es ermöglicht werden Einflussfaktoren zu bestimmen. Diese sind im Hinblick auf die Bedeutung und für die Grenzen der einzelnen Szenarien zu bewerten. Folglich könnten die Methode und ihre Ergebnisse einen bedeutenden Beitrag für Maßnahmen für Verbesserung der Transportkette liefern.

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## DECLARATION OF AUTHORSHIP

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*Where I have consulted the published work of others, this is always clearly attributed.*

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*Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.*

*This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.*

*I cede copyright of the thesis in favor of the University of Rostock.*

*Date: 18.01.2012*

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# 1. INTRODUCTION

Transport that mankind is using every day has very different purposes and forms. Every industry, as well as transport sector, needs resources and energy, which have to be consumed sustainably. Because transport industry is so widespread and frequently used, it has to have significant impact on the people and environment. But then there arises a question: What are these impacts and how much of energy or resources are consumed?

This question is not very easy to answer, because there exist of large number of influencing factors for energy consumption, cost or environmental impact. Therefore a comprehensive methodology has to be used, which helps to determine different impacts by various transport modes.

There are many parties (consigner, ship or lorry operator, politicians, etc.) involved either directly or indirectly who are interested to know different impacts and influencing factors of transportation. These main influencing factors which are considered in this Master Thesis are environmental impact, cost and time of transport. The further refinement is the consideration of cargo transport by containers, because of its relatively simple nature and this is offering good opportunity to evaluate described impacts. Considered modes are sea, road and rail transport, because all those ways are widely used for container transport.

There exist plenty of different studies focusing on environmental impact assessment or cost estimation of cargo transport, but these studies, which focus on container transport, do not meet fully the needs. Therefore a methodology is developed in order to evaluate its different impacts and allow combining them. The advantage of this approach is for instance the possibility to see the impact on the cost by the carbon tax, which can be applied to the transport vehicles and vessels in the future. On one hand, it comprises the evaluation of environmental impact, but on the other hand it consists of assessment of cost and analysis of the impact of the tax on this.

The development of such a methodology needs also thorough theoretical background on the environmental and cost analysis, which is given in the first part. There are references to the existing works and those are combined according to the needs. In addition to environmental impact and cost issues, other factors are also described which have influence on transport. The application which is done and analyzed in the end shows the results of developed methodology and is demonstrating its applicability and possibilities.

# 2. MAIN DEFINITIONS, BOUNDARIES, CALCULATION RULES

This chapter gives an overview of basic definitions and assumptions concerning principles of transport. The focus will be on common rules for all transport modes and the basic differences between them.

## 2.1. Principles of transport

There are different concepts used within cargo transport sector and it is necessary to define these distinctions. This report is focusing on the following principles which are defined by the European Conference of Ministers (ECMT) and the European Committee for standardization (CEN):

- Intermodal transport – the movements of goods in one and the same loading unit or vehicle which uses successively several modes of transport without handling of goods themselves in changing modes.
- Multimodal transport – The carriage of goods of at least two different modes of transport.

Other general assumption is the transport loading unit, which refers to containers, swap bodies and trailers. Each transportation mode can be used as a prevailing in the specific scenario (Weinreich et al. 2000).

Transportation of freight is performed by different transport modes. In this Master Thesis, focus is on container transport and short sea shipping, which is interregional trade within a continent where all types of shipping and all sizes of ships fall under this segmentation. However, containerships operating a short sea service are mostly up to capacity of 5000 TEU (Wijnolst and Wergeland 2009), but this is not the restriction of applying the calculation methodology. Container transport is studied because it is very widespread way to transport freight and the cargo amounts are very easily determined due to its standardized unit. Short sea shipping is studied in detailed, because this transportation mode has various competitors in the frame of other modes (e.g. road and rail) and it is believed that there is still a lot of potential to improve short sea shipping as a part in the transport chain. In addition to that, to perform a comparison between various modes of transport, ocean going vessel are generally not suitable for such comparison, while they are basically only mode of transport operating between continents. Under these circumstances three different modes of transportation will be compared. They are sea, road and rail transportation. Air transport and inland waterway transport are excluded because of following reasons.

Air transport is not taken into account because this mode is drastically different from the others. It is faster (up to 900 km/h). The main reason why air transport is excluded from this report, is that the main cargo unit in the study is container as mentioned before and airplanes are not generally carrying containers because of weight and volume limitations. For example Boeing 747-230F has a weight limit of 104 tons and the volume limit of 600 $m^3$ (Brandenburg 2008). Moreover, the air transport has drastically higher environmental impact, such as air pollution, noise etc. compared to the other modes. There is an example of comparison of various transport modes in the frame of $CO_2$ emissions per km·TEU and it is given on the figure 2.1.

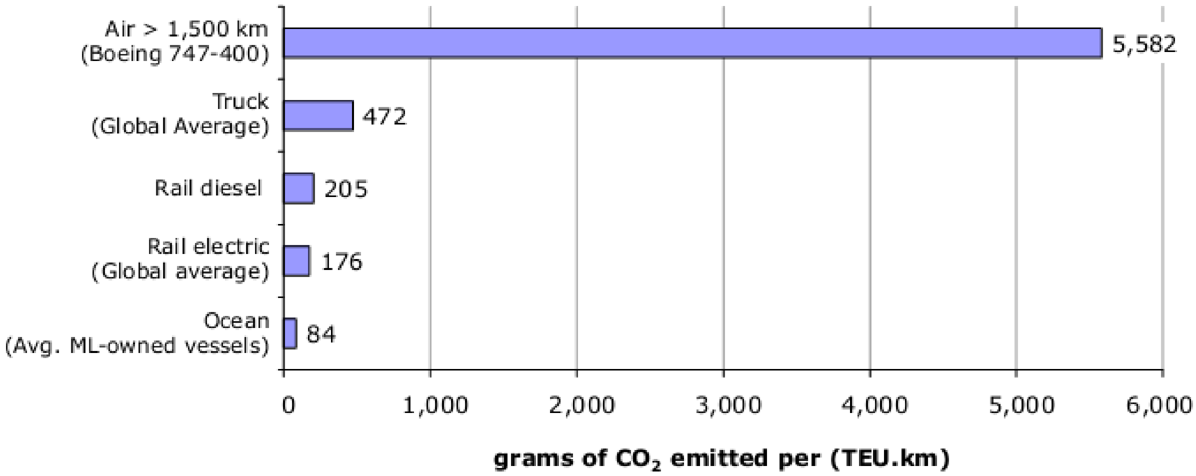


Figure 2.1. $CO_2$ emissions by the mode of transport. Available from: http://www.gsb.stanford.edu/ser/documents/SER08-Maersk.pdf

In addition, transportation cost for air cargo is much higher compared to the other modes of transport.

Inland waterways are excluded because of restrictions on choosing suitable routes and this mode of transport is not so widespread in most of the countries.

In this Master Thesis, there is no differentiation between countries (e.g. topography) and local regulations (e.g. operating time restrictions of Lorries during the weekends) applied to the methodology. However, global and more general regulations and restrictions are applied.

## 2.2. Logistic parameters

The main factors affecting the environmental impact and cost of freight transport are vehicle size, payload capacity and capacity utilisation. Payload capacity refers to the total weight of cargo allowed. Capacity utilisation takes into account the ratio between mass of freight transported and payload capacity and capacity utilisation takes into account also empty trip factor, which refers to the ratio of distances traveled empty and loaded (Knörr et al. 2010)

Each transport vessel has a maximum payload capacity and the maximum volume available. Volume limited freight normally has a specific weight of around 200 kg/$m^3$ (Knörr et al. 2010; Van de Reyd and Wouters 2005).

It is evident that volume restricted goods need more transport vessels and as a result more wagons for rail transport, more trucks for road transport or more container space for all modes. Therefore more vehicle weight per tonne of cargo has to be transported and more energy will be consumed. At the same time, higher cargo weights on trucks and rail lead to an increased fuel consumption (Knörr et al. 2010).

Marine container vessels behave slightly different with regard to cargo weight and fuel consumed. The vessels' final energy consumption and emissions depend significantly less by the weight of the cargo in containers. It is due to other more relevant factors such as physical resistance factors and the uptake of ballast water for safe travelling. (Knörr et al. 2010).

## 2.3. Payload capacity

Payload capacity could have handled roughly in two different ways:

- Mass related parameter: Payload capacity [tonnes] = maximum mass of freight allowed.
- Volume related parameter (marine container): TEU capacity [TEU] = maximum number of containers allowed in TEU (Knörr et al. 2010).

Conditions for determining of payload capacity are different for each transport mode, as explained in the following sections:

*Lorry*

The payload capacity of a lorry is limited by the maximum vehicle weight allowed. Thus the payload capacity is the difference between maximum vehicle weight allowed and empty weight of vehicle (including equipment, fuel, driver and other stuff).

*Train*

The limiting factor for payload capacity of a freight train is the axle load limit of a railroad line. International railroad lines normally are dimensioned for more than 20 tonnes per axle.

List of possible vehicles for container and trailer transport are given in the table 2.1.

Table 2.1. Transport vessels and payload capacities

| Vehicle/ vessel | Vehicle/ vessel type | Empty weight | Payload capacity | TEU capacity | Max. total weight |
|---|---|---|---|---|---|
| | | [tonnes] | [tonnes] | [TEU] | [tonnes] |
| Truck | 24-40 gross tonnes | 14 | 26 | 2 | 40 (44) |
| | 12-24 gross tonnes | 10 | 12 | 1 | 24 |
| Train | Standard wagon | 23 | 61 | 4 | 84 |

(Carstens et al. 2000 and Knörr et al. 2010)

*Ship*

Considering container/trailer transport, there are several ship types to carry this cargo unit by sea, mostly various size of container vessels. In addition, in case of short sea shipping, it is very common to carry trailers and swap bodies with Ro-Ro and Ro-Pax ships.

The cargo capacity of a ship is measured by the TEU capacity. In contrary, the payload capacity for bulk and general cargo vessels is expressed in dead weight tonnage (DWT).

*Freight in Container*

Freight containers are in different lengths, which most common are 20' (= 1 TEU) and 40' containers (= 2 TEU), but 45', 48' and even 53' containers are used for transport purposes. The table 2.2. provides the basic dimensions for the 20' and 40' ISO containers.

Table 2.2. ISO 20 and 40 feet containers' data

| | L*W*H | Volume | Empty weight | Payload capacity | Total weight |
|---|---|---|---|---|---|
| | mm | $m^3$ | kg | kg | kg |
| 20' = 1 TEU | 6058 x 2438 x 2591 | 32,1 | 2 250 | 21 750 | 24 000 |
| 40' = 2 TEU | 12 192 x 2438 x 2591 | 65,7 | 3 780 | 26 700 | 30 480 |

(GDV 2011)

The maximum payload lies between 13,35 t/TEU for 40 feet container and 21.75 t/TEU 20 feet container. Special containers, for example for carrying liquids or open containers may differ from those standard weights.

For the calculation model average values for the container weight per TEU are used and the values are given in table 2.3 (Knörr et al. 2010, assumptions Öko-Institut).

Table 2.3. Average weights per TEU.

| | Container | Net weight | Total weight |
|---|---|---|---|
| | [tonnes /TEU] | [tonnes/TEU] | [tonnes/TEU] |
| Bulk | 2,0 | 14,5 | 16,5 |
| Average | 1,95 | 10,5 | 12,45 |
| Volume | 1,9 | 6,0 | 7,9 |

It is pointed out that this table consists of average values which base on port statistics of the Ports of Amsterdam, Rotterdam, Hamburg, Bremerhaven, Seattle, Singapore, Hong-Kong and Sydney (Knörr et al. 2010).

## 2.4. Environmental impact

There are some ways to assess the environmental impact by the transportation. Mainly it depends on the type and the scope of the assessment. The most comprehensive study on this field is life cycle assessment (LCA). It is a “cradle-to-grave” approach for assessing industrial systems. “Cradle-to-grave” begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. Therefore LCA draws the most comprehensive picture about the product’s or service’s cumulative environmental impacts resulting from all stages in its life cycle (Curran 2006).

Figure 2.2 illustrates the possible life cycle stages that can be considered in an LCA and the typical inputs/outputs measured.

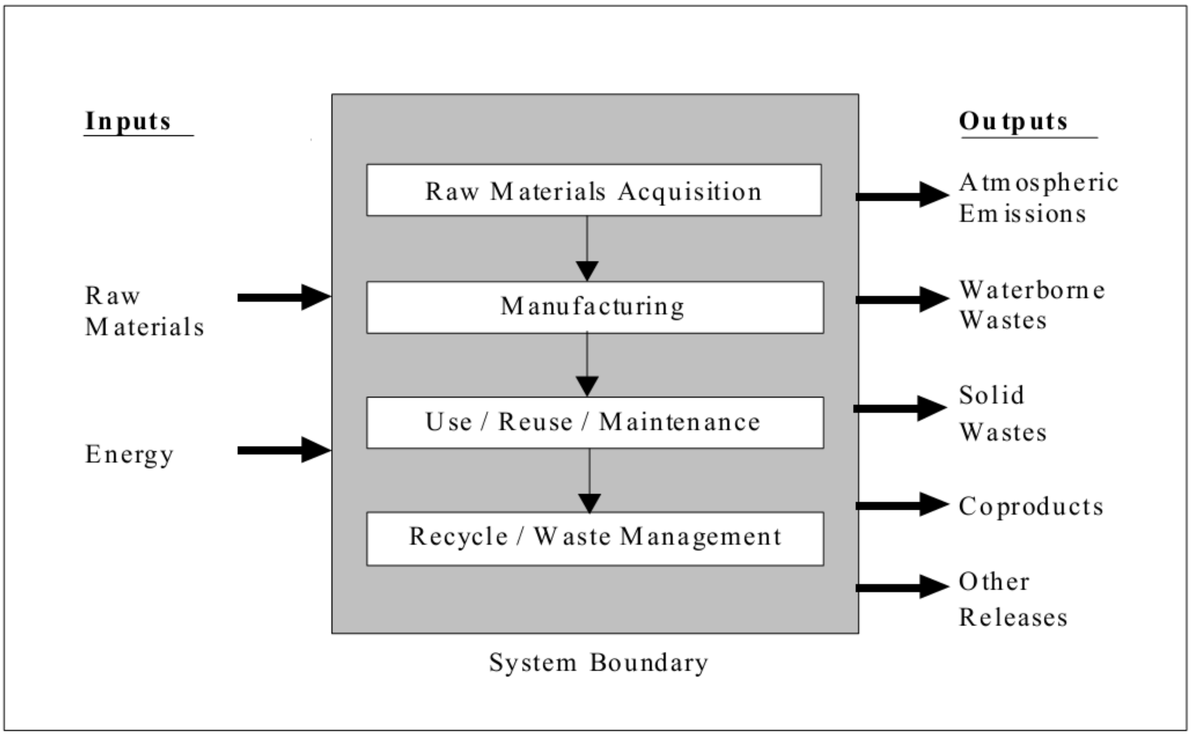


Figure 2.2. Life cycle stages (EPA 1993)

The term “life cycle” refers to the major activities in the course of the product’s life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product.

Curran (2006) points out that performing an LCA can be resource and time intensive. Depending upon how thorough an LCA the user wishes to conduct, gathering the data can be problematic, and the availability of data can greatly impact the accuracy of the final results. Therefore, it is important to weigh the availability of data, the time necessary to conduct the study, and the financial resources required against the projected benefits of the LCA.

Basing on this information, considering the time and the scope of the Master Thesis, it remains out of the scope of this work to carry out life cycle assessment. Therefore the focus is put on the phase of the use of transport service which only part of the actual environmental impact, but this concerns most of the people directly and is one of the stage giving the biggest impact.

Borken (1999) carried out an extensive investigation and outlined of all kinds of environmental impacts by transportation. The following categories were determined:

- Resource consumption
- Land use
- Greenhouse effect
- Depletion of the ozone layer
- Acidification
- Eutrophication (increasing plant biomass in aquatic systems)
- Eco-toxicity (toxic effects on ecosystems)
- Human toxicity (toxic effects on humans)
- Summer smog
- Noise

The transportation of freight has impacts within all these categories. However, it is possible only for some of these categories to make a comparison of individual transports on a quantitative basis.

Within the frame of this Master Thesis it is unable to perform a comparison for all previously mentioned categories which rises the necessity to limit the work further and to rather relevant environmental impact categories. The selection of different impacts is basing on the similar assumptions in the study by Knörr et al. (2010) and following criteria are considered:

- Particular relevance of the impact
- Data availability
- Methodological suitability for a quantitative comparison of individual transport mode.

One of the most important emissions to the air, as a result of fuel-oil combustion, are carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$). Nearly all the fuel carbon (99%) in fuel oil is converted to $CO_2$ during the combustion process. Although the formation of CO acts to reduce $CO_2$ emissions, the amount of CO produced is insignificant compared to the amount of

$CO_2$ produced. The majority of the fuel carbon not converted to $CO_2$ is due to incomplete combustion in the fuel stream (Davis 2000). In addition to $CO_2$ and NOx, also $SO_2$ and PM emissions are studied.

Chosen indicators to assess the environmental impact are given on the table 2.4.

Table 2.4. Environmental impacts

| Abbr. | Description | Reason for choice |
|---|---|---|
| $CO_2$ | Carbon dioxide emissions | Main indicator for greenhouse effect |
| $NO_X$ | Nitrogen oxide emissions | Acidification, eutrophication, eco-toxicity, human toxicity, summer smog |
| $SO_2$ | Sulphur dioxide emissions | Acidification, eco-toxicity, human toxicity |
| PM - Particle matter | Exhaust particulate matter from vehicles and from energy production and provision (power plants, refineries, sea transport of primary energy carriers) | Human toxicity, summer smog |

(Knörr et al. 2010)

The categories of resource consumption, land use, noise and depletion of the ozone layer were not taken into consideration.

## 2.5. Defining the indicator for emissions

Many studies use the performance indicator related to the ton-kilometers and that seems to be the best way to describe transportation of goods, but to define this term in case of waterborne traffic is not unambiguous. Instead of mass-based approach, other possibilities include area- or volume-based options can be considered (VTT, 2011). Krapp (2011) gives some examples of emission indicators (e.g. $CO_2$-indicators) for sea transport which based on different cargo units depending on ship type: [$gCO_2$/t*nm], [$gCO_2$/TEU*nm], [$gCO_2/m^3$*nm], [$gCO_2$/lane m*nm], [$gCO_2$/Pax*nm]. Because this work studies road and rail transport as well where distances are calculated in kilometers (km), it is decided to convert the nautical miles into kilometers. In addition, because container transport is analyzed, the best emission indicator would consider TEU-s. As a result, the unit will obtain the form [$gCO_2$/TEU*km]. For other type of emissions, $CO_2$ is replaced by the corresponding substance, e.g. $SO_2$, $NO_X$, and PM.

## 2.6. Emission factors

Exhaust gas emissions depend on the type of fuel used, on its chemical composition, as well as fuel consumption and engine efficiency, taking into account burning process.

In the table 2.5, different fuels are described with emission factor ($C_F$) for $CO_2$.

Table 2.5. Emission factors of $CO_2$ for marine fuels

| **Type of fuel** | **Reference** | **Carbon content** | **$C_F$ (kg$CO_2$/t-Fuel)** |
|---|---|---|---|
| Diesel/Gas Oil | ISO 8217 Grades DMX through DMC | 0,875 | 3206 |
| Light Fuel Oil (LFO) | ISO 8217 Grades RMA through RMD | 0,860 | 3151 |
| Heavy Fuel Oil (HFO) | ISO 8217 Grades RME through RMK | 0,850 | 3114 |
| Liquified Petroleum Gas (LPG) | Propane | 0,819 | 3000 |
| | Butane | 0,827 | 3030 |
| Liquified Natural Gas (LNG) | | 0,750 | 2750 |

(IMO, 2009c)

Natural gas has about 20% lower $CO_2$-emissions per MJ fuel compared to gasoline (LPG) due to its higher content of hydrogen (Uherek et al. 2010). Other emission factors are given in the table 2.6.

Table 2.6. Emission factors

| | **Type of emission** | | | |
|---|---|---|---|---|
| | $CO_2$ | NOx | $SO_2$ | PM |
| Emission factor, [kg/t-fuel] | 3170 | 79 | 47 | 6 |

(Corbett and Köhler, 2003 and Endresen et al. 2003)

Eyring et al. (2010) provides in his research a summary of studies about different values of emission factors.

# 3. ENVIRONMENTAL IMPACT

This chapter gives an overview about environmental impact assessment and giving specifics for various transport modes.

## 3.1. General

The rapid growth of the population and growing energy demand results the use of fossil fuels with tremendous amounts, which are causing the increase of pollution (Devanney 2010).
Environmental impact by the transport is one field of industry contributing growing level of $CO_2$ and other emissions, which cause damages to the nature and human health. Therefore it is of great importance to put a lot of effort to the reduction of greenhouse gas emissions.

## 3.2. Sea transportation

This subchapter gives overview of the environmental impact by ships. Description of necessary parameters will be given in order to perform the environmental impact assessment in the end. It is noted hereby that the focus is put on the evaluation of atmospheric emissions.
As mentioned before the focus in sea transport is put on the short sea shipping (SSS). One reason is the fact that EU has clearly demonstrated its interest in a modal shift from road to sea, but despite major efforts provided by the EU with its modal shift policy, objectives of freight transfers from road to the sea remain disappointing. The hypothesis is that an unclear definition of SSS used by the EU leads to the implementation of unfit, contradictory public policies and that the potential for modal shift has been overestimated by the EU (Douet and Cappuccilli 2011). Kowalczyk (2010) states another issue, why the short sea shipping is not performing as well as expected. The problem is that EU customs legislation makes no difference in the border procedures for vessels calling the ports in the EU countries coming from other EU ports or from non-EU ports. The only clear difference exists between "regular shipping line" and "non-regular shipping line". A regular shipping line between EU ports can be authorized by customs to get the status of "authorized regular shipping service", and there is no requirement for formalities.
In other segments than liner shipping the border formalities always have to be executed, even if the vessel arrives from another EU port, and no authorization can be issued in order to exempt the shipping from the formalities.
A solution to this problem is to eliminate the border formalities in maritime transport in intra EU trade. Procedures in maritime transport between EU member states should be reduced to

the same level as in other transport modes. This places maritime transport on similar condition and chance as land transport in intra-EU trade. It will facilitate the development of intermodal transport chain to be more efficient and fluent (Kowalczyk 2010).

Basing on these aspects, there is necessity to compare various transportation modes finding the most sustainable solution for various scenarios.

#### ***3.2.1. Emissions by ships***

The vast amount of emissions to the atmosphere is exhaust gas which is a product of burning the fuel by main and auxiliary engines. This exhaust gas is very hot mix of carbon dioxide, nitrogen oxides, unburnt oxygen, sulphur dioxide, and carbon. The sulphur oxides are harmful. With water they form acids, which are corrosive to steel exhaust pipes, and not environmentally friendly. This of course also counts for carbon dioxide and the nitrogen oxides (Dokkum 2006).

For 2007, shipping was estimated to have emitted 3.3% of global $CO_2$ emissions, to which international shipping contributed 2.7%, or 870 million tonnes. Although international shipping is the most carbon efficient mode of commercial transport, total emissions are largely influencing environment, necessitating emission reduction (Rightship 2011). Moreover, according to the IMO's 2nd GHG Study (2009c), if unabated, shipping's contribution to GHG emissions could reach 18% by 2050.

A significant potential for reduction of GHG through technical and operational measures has been identified. Together, if implemented, these measures could increase efficiency and reduce the emissions rate by 25% to 75% below the current levels. Many of these measures appear to be cost-effective, although non-financial barriers may discourage their implementation (IMO 2009c).

*Baltic Sea*

In 2008 the trade volume in Baltic Sea shipping was 822 million tonnes. This constitutes about 11% of the global shipping trade volume and makes the Baltic Sea one of the areas in the world with the highest density of ships; about 2,000 ships are present in the Baltic Sea at any point in time (DNV 2010).

According to Johansson et al. (2011) Baltic Sea shipping in 2010 emitted about 99 500 tonnes $SO_2$, 382,000 tonnes NOx and 19,5 million tonnes $CO_2$. The study by Jalkanen and Stipa (2009) indicates that $SO_2$ and NOx emissions are showing decreasing tendency in the Baltic Sea region, however, the number of ships, fuel consumption and emissions of $CO_2$ are increasing. DNV (2010) study pointing out that passenger and Ro-Pax vessels only account for approximately 5% of the ships operating in the Baltic Sea region but they are accountable for approximately 27% of the emissions which makes them one of the biggest contributors to the air pollution.

In addition to that, Larsson (1985) stated that eutrophication is a single major problem in the Baltic Sea and air emissions from shipping significantly contribute to this through nitrogen emissions. Since the beginning of the 20th century, the Baltic Sea has changed from a clear-water sea into a highly eutrophic marine environment.

Baltic Sea is a semi-enclosed sea and one of the largest brackish-water basins in the world. Due to its special geographical, climatological, and oceanographic characteristics, there is only little exchange of water through the Danish Straits with the neighboring North Sea, which makes it highly sensitive to the environmental impacts of human activities both in the sea and the surrounding lands, which are home to some 85 million people (HELCOM 2010). This is therefore important to put attention on reducing the emissions by shipping. In 2005 Baltic Sea was classified as a “particularly sensitive sea area” by IMO in order to protect the marine eco systems.

*Cargo handling emissions*

A wide range of cargo handling equipment exists at ports due to the diversity of cargo. Container terminals use cargo handling equipment most extensively, truck to rail equipment and dry bulk terminals also have high use of cargo handling equipment. Liquid bulk and auto terminals use cargo handling equipment the least (EPA 2009). Because of the specifics of different harbors and its equipment, the environmental impact needs to be assessed case-by-case basis.

According to the press release by APM Terminals (2009), the $CO_2$ emission per TEU handled, in the APM container terminal, Rotterdam harbor, was 17,5 kg·$CO_2$/TEU.

### *3.2.2. IMO conventions and other regional regulations*

In the following, the rules of International Maritime Organization (IMO) for ship emissions are described. These rules are defined as limits in the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78. This is one of the most important international conventions covering prevention of pollution of the marine environment by ships. Its stated object is: to preserve the marine environment through the complete elimination of pollution by oil and other harmful substances and the minimization of accidental discharge of such substances. The document itself is initially composed of two different treaties from year 1973 and 1978 which is from time to time updated with different technical annexes. Currently there exist 6 different annexes which are named and shortly described as follows:

- **Annex I –** Regulations for the Prevention of Pollution by Oil *(entered into force 2 October 1983)*
- **Annex II –** Regulations for the Control of Pollution by Noxious Liquid Substances carried in Bulk *(entered into force 2 October 1983)*
- **Annex III –** Prevention of pollution by Harmful Substances carried in Packaged Form *(entered into force 1 July 1992)*
- **Annex IV** – Prevention of Pollution by Sewage from Ships *(entered into force 27 September 2003)*
- **Annex V** – Prevention of Pollution by Garbage from Ships *(entered into force 31 December 1988)*
- **Annex VI –** Prevention of Air Pollution from Ships *(entered into force 19 May 2005)* (IMO 2011a)

States that are joined MARPOL convention must accept Annexes I and II, but the other annexes are voluntary. 99 % of the world tonnage is involved in Annex I and II, in the Annexes III, IV and V somewhat less. The latest Annex IV is accepted by the least counties and comprising therefore 80% of world tonnage.

**MARPOL 73/78 Annex VI: Air Pollution**

Considering pollution, this master Thesis is focusing on air pollution and therefore this part is reliable in this case and described in details. The main changes to MARPOL Annex VI are a progressive reduction globally in emissions of $SO_2$, NOx and particulate matter and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas. Under the revised MARPOL Annex VI, the global sulphur content is reduced initially to 3.50% (from the 4.50%), effective from 1 January 2012; then progressively to 0.50 %, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. In the sulphur emission control areas (SECAs), shown on figure 3.1, the limits applicable on sulphur and particulate matter were reduced to 1.00%, beginning on 1 July 2010 (from the original 1.50%); being further reduced to 0.10 %, effective from 1 January 2015 (IMO 2011b). The use of sulphur scrubbers are still be allowed, so that the fuel grades currently in use on vessels fitted with them can also be used (Kalli et al 2009).

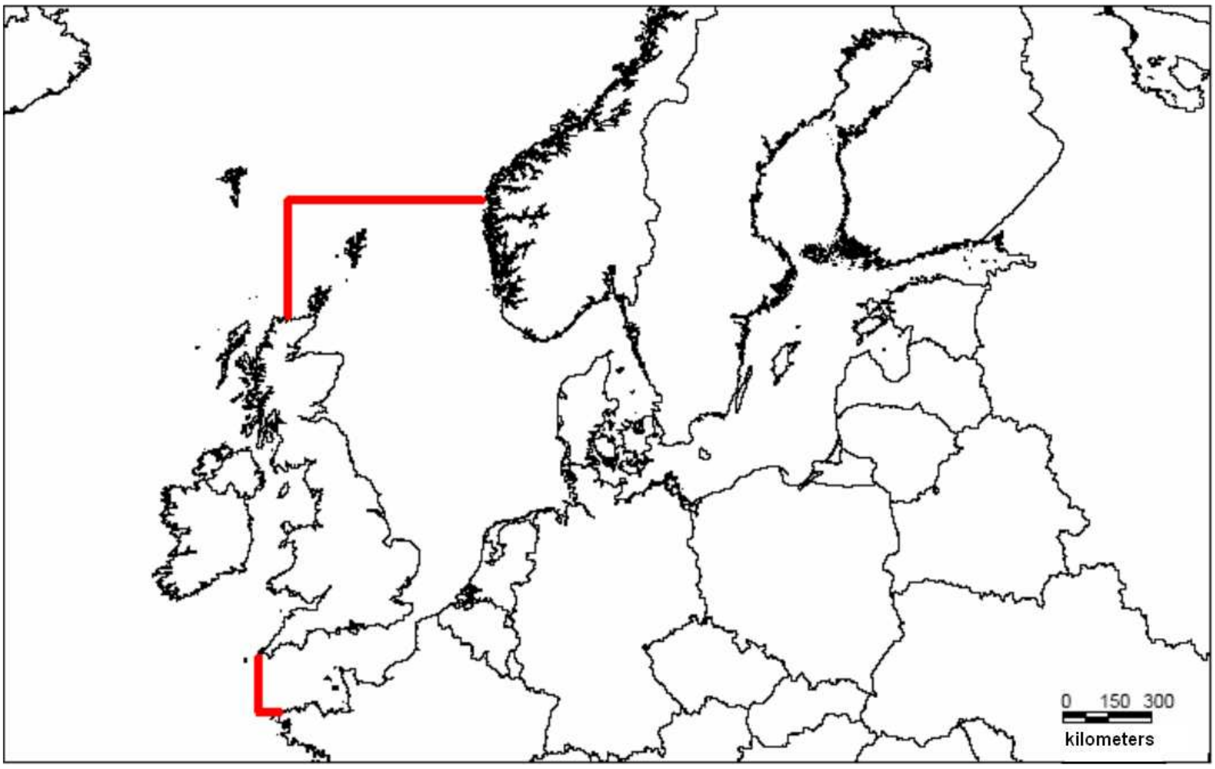


Figure 3.1. The SECA (Sulphur Emission Control Area) special area (Baltic Sea, North Sea [latitude 62° north and longitude 4° west] and the English Channel [longitude 5° west]) (Kalli et al 2009).

Today, about 95 % of ships worldwide run on heavy fuel oil or intermediate fuel oil (HFO/IFO) and 5 % of them are running on marine diesel oil (MDO) or marine gas oil (MGO). In auxiliary engines, MDO or MGO is used, normally with a maximum sulphur content of 0.1%) (Kalli et al. 2009).

With this kind of above mentioned requirements, when the next phase of the MARPOL annex VI enter into force, industries are facing massive challenges to provide low sulphur content fuel to ships, because demand for this type of fuels increase significantly. However, it has proven difficult to estimate the availability of low sulphur fuels. It is estimated that the problems will not be owing to the demands on SECA areas, at least not yet, but to the fact that when light fuels start to be used worldwide, the oil industry will have to increase its refining capacity considerably to meet the rise in demand for light fuel grades.

Nevertheless, there are alternative ways, which help a little to satisfy the demand for the low sulphur fuel demand. Before the requirement for very low sulphur limit in fuel, there are two ways to achieve that:

1) heavy fuel oil can be made from crude oil, which naturally contains less sulphur or

2) high sulphur and low sulphur fuel are mixed together

Before the 2010, the fuel that was used in the SECA contained less than 1.5% sulphur. This was normally high sulphur fuel, which had been mixed with a slightly lower sulphur content fuel, to keep the sulphur content under the 1.5% mark. After the 2010 the sulphur content limit dropped to 1.0%, which will in practice meant that mixing proportions were changed, resulting in a greater need for low sulphur fuel. Mixing different fuel grades could however, lead to increasing engine problems due to poorer quality fuel (Kalli et al. 2009). By 2015 the maximum sulphur content limit will fall to 0.1% in the SECA areas. Then it will be technically impossible to mix fuel grades, and ships will have to switch to gas oil (MGO), which would be the only option among the fuel grades presently available. Because of the way it is manufactured, MGO is far more expensive than heavy fuel oils. Furthermore, as the demand for it increases, it will also presumably go up in price.

The study by Kalli et al. (2009) reveals that when using low sulphur content fuels (0,1%), the cost of the shipping operation day will rise significantly. For example the operational costs of container ship could rise by 49-57%, while the fuel price increase is expected to be between 73-84%. Hereby it will be pointed out that container ship is one of the most sensitive ship type related to the fuel cost increase. With the same conditions, ro-ro vessel could face the operational costs' increase by 37-42% and Passenger vessel 32-36%.

The purpose of these regulations of lowering the sulphur content of fuel is to reduce emissions of particulate matter from shipping and through it to reduce its harmful effects on human health and the marine environment.

The sulphur content linearly affects the mass volume of particles, as does lowering its ash content. While the new regulations will reduce the particulate emissions in total, they will not as yet actually limit fine particulate emissions. To be able to set emission limits for fine particles from diesel engines, and if there is wish to install the same type of particulate traps as there are in cars now, the fuel should be light fuel oil with a sulphur content of less than 0.05%. The sulphur and ash content of fuel needs to be low if the particulate trap's oxidation catalyst is to work properly. The IMO has not yet been prepared to go to such low sulphur content levels, but things may well change in the future. (Kalli et al. 2009)

In addition to the sulphur content limit in the marine fuel, there are three Tier rules for NOx emission limits (Tiers I-III) as well, shown on figure 3.2. Global limit Tier I entered into force at 2000, Tier II standard for new engines entered into force from 2011; around 20% lower than Tier I. The Baltic Sea States proposed on 2009 to IMO to designate the Baltic Sea as an Emission Control Area for the control of nitrogen oxide (NOx) emissions and the regulation will enter into force from 2016 as Tier III emission limits (around 80% less than Tier I). The

Tier III standard is to be applied as a special Nitrogen Emission Control Areas (NECA) (Kalli et al. 2009 and IMO 2010).

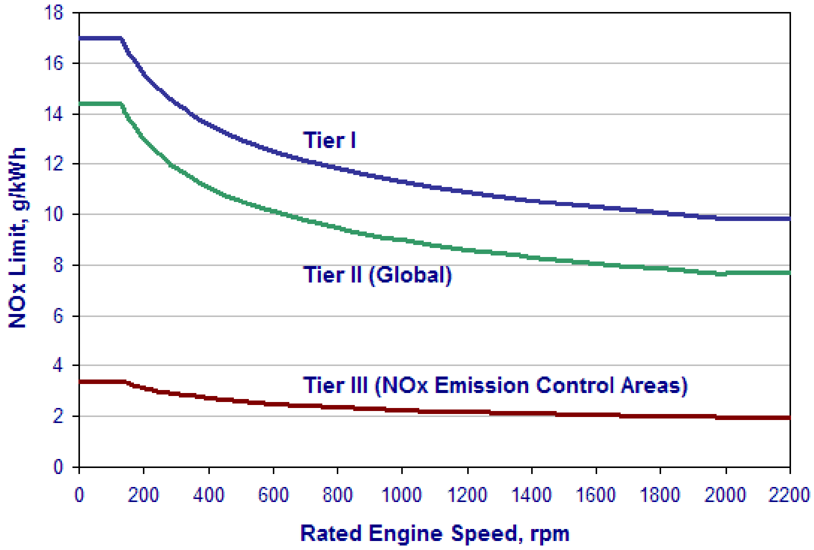


Figure 3.2. NOx emission limits.
Available from: http://www.dieselnet.com/standards/inter/imo.php [Accessed 06 December 2011]

The Tier II standard can be attained through improved engine technology and the regulations of Tier III would mean to use for instance catalyst system, when current technology is considered. (Kalli et al. 2009).

### *3.2.3. Energy efficiency design index (EEDI)*

In 2009 IMO published the calculation method to assess the energy efficiency of new ship. This method is called Energy Efficiency Design Index (EEDI). Its objective is to improve environmental effectiveness by generating, through enhanced energy efficiency measures, significant reductions in GHG emissions from ships. (IMO 2011c).

In general it is explicitly recognized that EEDI formula is not suitable for ship types that are not carrying cargo or ships with diesel-electric, turbine or hybrid propulsion systems. Those ships will need additional correction factors. The formula is intended to be applicable directly on ship types, such as oil and gas tankers, bulk carriers, general cargo ships, refrigerated cargo carriers and container ships.

In order to obtain energy efficiency and environmentally friendly output, the EEDI formula require reducing the power onboard the ship. Because the engine power and fuel consumption and thus the emissions are directly related. The easiest way to improve a vessel's fuel efficiency, ship speed has to be restricted. However, there are other ways to improve fuel efficiency, such as waste heat generators, which do not impact on speed (they impact on auxiliary engines). Indeed, the installed propulsion power shall not be less than the propulsion power needed to maintain safe navigation in adverse weather conditions to ensure both the safety and efficiency (IMO 2011c).

As described previously the EEDI is not applicable to all type of ships, for instance Ro-ro and Ro-Pax vessels. Krüger (2009) conducted a research on this topic. In the frame of this research several Ro-Ro ships which were known to be very fuel efficient were analyzed according to the proposed EEDI- concept. It was found that this EEDI actually results in a severe speed limit for those ships. It was further found that this type of ship can fulfill the EEDI only at physically impossible negative wave resistances for their desired design speed. Therefore the EEDI is not currently the issue for Ro-Ro and Ro-Pax ships.

The simplified EEDI formula 3.1 is given as follows:

$$\text{EEDI}=\frac{CO_2\text{emission}}{\text{transport work}} \tag{3.1}$$

The $CO_2$ emission represents total $CO_2$ emission from combustion of fuel, including propulsion and auxiliary engines and boilers, taking into account the carbon content of the fuels in question. If energy-efficient mechanical or electrical technologies are incorporated on board a ship, their effects are deducted from the total $CO_2$ emission. The energy saved by the use of wind or solar energy is also deducted from the total $CO_2$ emissions, based on actual efficiency of the systems (IMO 2011c). This formula purports to be “a measure of a ship’s performance which reflects the emissions related to value to society (Devanney 2010). The full EEDI formula is available on the IMO publication (2009a).

The transport work is calculated by multiplying the ship’s capacity (dwt), as designed, with the ship’s design speed measured at the maximum design load condition and at 75 per cent of the rated installed shaft power (IMO 2011c).

According to the Lloyd’s Register (2010) Energy Efficiency Design Index (EEDI) will enter into force as an amendment to MARPOL Annex VI. The date has not been decided yet, but it is most likely to be around January 1, 2013. The introduction of the EEDI for all new ships will mean that between 45 and 50 million tonnes of $CO_2$ will be removed from the atmosphere annually by 2020, compared with “business as usual” and depending on the growth in world trade. For 2030, the reduction will be between 180 and 240 million tonnes annually from the introduction of the EEDI (IMO 2011c).

However, there is still time to correct the EEDI formula and make improvements but Devanney (2010) performed a thorough study about the applicability of the EEDI calculation on various types of ships. He describes also some possible results and scenarios what could happen, once the EEDI will enter into force. The detailed analysis is available on the study itself, but hereby some important errors and biases of the EEDI concept will be pointed out. According to Devanney (2010) the core idea of EEDI is to lower the installed capacity onboard the ships in order to reduce the $CO_2$ emissions. The problem is that $CO_2$ emissions and installed power are not related linearly. The fuel consumption and therefore the emissions depend on the engine load. It is well known that the most efficient fuel consumption of an engine is at 70-80% of maximum continuous rating. To limit the engine power on board the ship, the engine load has to be higher in order to preserve the required speed, which means higher specific fuel oil consumption. To say it in another way, for a given speed, fuel consumption is reduced by increasing installed power. As a result, the fuel consumption and therefore also $CO_2$ emissions could even increase.

### *3.2.4. Power prediction of ship*

The speed of a ship depends on the used power on board and emissions depend on the power, because power and fuel consumption is related and in the same way, fuel consumption and emissions are related. In order to assess the ship power according to the speed, empirical Admiralty coefficient method may be used. This method is probably the oldest and best known empirical formula for such prediction and it is described with formula 3.2 and given as follows:

$$P=\frac{\left(\Delta^{2/3}V^3\right)}{A_C} \tag{3.2}$$

where

P – Ship power, [kW]

Δ – Displacement of ship, [t]

V – Ship speed, [kn]

$A_C$ – Admiralty Coefficient, [-] (Carlton 2007)

The value of Admiralty Coefficient ($A_C$) varies between 350 and 750 dependent on the type of ship. According to Moody (1996) Munroe-Smith (1975) provided the following formula (3.3) for estimating the value of $A_C$:

$$A_C=26\left(\sqrt{L}+\frac{150}{V}\right) \tag{3.3}$$

where

L – Length of waterline, [m]

V – Ship speed, [kn]

Empirical equations are generally dedicated to a specific ship type, mainly due to the fact that the accuracy of the formula is being directly influenced by hull form and operating conditions (Moody 1996).

Schneekluth and Bertram (1998) give in table 3.1 some typical range of values for Admiralty coefficient for different type of ships.

Table 3.1. Admiralty coefficients for various types of ships

| **Type of ship** | **Value of Admiralty coefficient** |
|---|---|
| general cargo ships | 400–600 |
| bulker and tanker | 600–750 |
| reefer | 550–700 |
| feeder | 350–500 |
| warship | 150 |

### *3.2.5. Environmental impact assessment*

Environmental impact to air is mainly depending on the fuel consumption of a ship. In addition to that, the chemical composition of fuel is also influencing factor.

*Fuel consumption*

Fuel consumption is calculated per hour with formula 3.4 as follows:

$$FC_{t\text{-}h} = \frac{n \cdot P \cdot LF \cdot sfoc}{10^6} \qquad (3.4)$$

where

$FC_{t\text{-}h}$ – Fuel consumption per hour, [t/h]

n – Number of generating sets, [-]

P – Power of each diesel engine, [kW]

LF – Load Factor (percent of vessel's total power), [%]

sfoc – Specific fuel oil consumption, [g/kWh]

(EPA 2009, Knörr et al. 2010)

Specific fuel oil consumption depends on the engine load, where the specific fuel oil consumption is optimized on the engine load of 85% of maximum continuous rating (EPA 2009). The actual value has to be determined by the engine manufacturer. According to ISO regulation 3046-1, +5% is added to the fuel consumption as a tolerance. Fuel consumption can be additionally increased by 2% because of low quality fuel when necessary.

*Determining emissions*

Exhaust gas emissions depend on the fuel consumption, operating profile of vessel and fuel related vehicle emission factors. The bulk of the work involves determining representative engine power ratings for vessel and the development of operating. Emission factors are given in the subchapter 2.7. Exhaust gas emissions by ship are calculated with formula 3.5 as follows:

$$E=FC_{t\text{-}h,i}\cdot A_i\cdot EF\cdot 10^3 \qquad (3.5)$$

Where

E – Emissions, [g]

$FC_{t\text{-}h,i}$ – Fuel consumption per hour according to the activity, [t/h]

$A_i$ – Duration of corresponding activity (e.g. voyage, maneuvering), [h]

EF – Corresponding Emission Factor, [g/kg-fuel] (EPA 2009).

The formula is used for all emission components which are directly correlated to fuel consumption and for combustion related emissions.

After determining the total amount of emissions, those have to be spread over the amount of cargo transported, in order to obtain the indicator, which allows comparing various ships and ships with other transportation modes. For some ships, this deviation is relatively easy, e.g. container ships, but it can be also quite complex process allocate emission for Ro-Pax ships, which carries also passengers and passenger cars in addition to trailers or swap bodies. Both these allocation principles are described further.

*Container vessels and Ro-Ro ships*

To obtain the environmental performance indicator for container vessel the emissions are calculated on a g/(TEU·km) basis. Energy consumption of the ship only marginally depends on the load of the container (Knörr et al. 2010), therefore the total emissions of container vessel can be divided by the number of TEU-s on board.

*Ro-Pax ships*

Different problem is to assess the environmental impact by the Ro-Pax ferries. It could be difficult to find a suitable common transport unit as they often transport a mix of cargo, such as passengers, passenger cars, lorries, busses and other rolling transport units (Hagemeister and Kristensen 2011). Basing on this, it is complicated to find the comprehensive unit to evaluate the emissions. For vessels like Ro-Pax ships, which carry a combination of passengers (either travelling with their cars or as ‘foot passengers’) and freight, operators may wish to consider some form of weighted average based on the relative distribution of passengers and freight. On a Ro-Pax ship, some of the internal volume is meant for the carriage of rolling cargo, while other volume is solely dedicated to the carriage of passengers (restaurants/cafeterias, corridors, toilets and cabins). The structural part and associated equipment of these volumes contribute to the light weight of the ship, which together with the deadweight have an influence on the propulsion power and therefore on the exhaust gas emissions. For a reasonable allocation of emissions to the different types of cargo on a Ro-Pax ship, the emissions have to be distributed relative to the volume that each cargo type occupies (Hagemeister and Kristensen 2011).

There exists some studies about the emission allocation of Ro-Pax ship, but the best seems to be the method formulated by Hagemeister and Kristensen (2011). This method suggests the common transport unit for Ro-Pax ships. In this approach, they calculated the average weight (ship structural weight + cargo) for the different volume types, to show that the weight is roughly independent of the volume type. This means that a volumetric allocation principle can also be considered as a weight-based allocation method. As the power demand is proportional to the ship's total weight (displacement), the method is therefore rationally seen from a ship design and hydrodynamic point of view, which is of paramount importance for the validity and understanding of the method.

To obtain the plausible results for the volumetric allocation principle, general arrangement plans were analyzed for the 60 typical West European and Scandinavian Ro-Pax ships, to determine the following spaces:

- Cargo space for rolling cargo
- Accommodation for restaurants, cafeterias, corridors, toilets, etc.
- Accommodation for pantries, galleys, air condition rooms and storerooms
- Accommodation for passenger cabins and associated corridors and storerooms.

Having established the volume for each separate cargo type, it is possible to establish the allocation principles. For an actual sailing condition, the occupied volume ($V_{tot}$) is calculated with formula 3.6 as follows:

$$V_{tot} = 24 \cdot lm + 67{,}5 \cdot ca + 10 \cdot pa + 13 \cdot be \quad (3.6)$$

where

lm – number of utilised lane meters

ca – number of cars on board

pa – number of passengers

be – number of occupied berths.

The comfort class of the actual ship must be judged individually, so that the volume per passenger can correctly be evaluated to be 7, 10 or 13m$^3$ per passenger.

The actual occupied volume is used instead of the maximum volume with 100% utilisation. (Hagemeister and Kristensen (2011).

Described method will be proposed on 2012 on the Marine Environment Protection Committee meeting in London by the Danish Maritime Authorities in order to introduce the method as international standard (Kristensen – personal communication 2011.12).

### *3.2.6. Uncertainties of environmental impact assessment*

Concerning the ship transport there are number of uncertainties to assess the environmental impact.

Power prediction of the ship can lead to uncertainties when assuming the fuel consumption, which can cause emission values with errors or uncertainties.

Considering shipping operations, it is important to note that the “maneuvering” and “in port” emission factors will have an increased uncertainty compared to emission factors “at sea”, firstly, because in some cases ship is started with a cold engine, which will give significantly different emissions (especially PM), compared to starts with relatively warm engines. Secondly since engine loads can change rapidly during maneuvering operations, the variability in emissions is increased (European Commission and Entec UK Limited 2002)

Uncertainties can arise also while determining the volume allowances for different type of cargoes in case of evaluating the environmental impact of Ro-Pax ships (Hagemeister and Kristensen 2011).

## 3.3. Road transportation

Nowadays the lorry transport sector is very well developed with high technological and economical standards. There is no doubt that automotive and truck industry has put a lot of effort to make lorries more energy efficient and environmentally friendly. High flexibility and speed makes road transport the most used mode for intermodal cargo transport (Planco Consulting GmbH 2007).

### *3.3.1. General requirements*

The European Union regulates land transport-related air emissions by automobile emissions standards (Euro) and by automotive fuel quality standards. Emissions from road vehicles are regulated individually for light-duty vehicles (LDV) and for heavy-duty vehicles (HDV).

European regulations determine 6 different vehicle classes (Euro I ... VI) according to emissions (ECOpoint Inc, 2011).

### *3.3.2. Vehicle specification*

There is wide variety of lorries transporting containers or trailers. In order to obtain reliable results for environmental impact, it is of great importance to determine as accurately as possible the specification of vehicle. In following, some important parameters of vehicles are given together with data which is gathered from various studies.

*Fuel consumption*

Fuel consumption is the main characteristic influencing emissions by lorries. Table 3.2, the fuel/energy consumption of a truck is given considering various cargo loading factors such as empty, average or fully loaded. Corresponding data is given in the study of Knörr et al. (2010). This data is valid for type Euro V trucks and on average motorway (including gradient).

Table 3.2. Energy consumption of trucks with different load factors

| Truck type | Unit | Full | Average | Empty |
|---|---|---|---|---|
| | | 100% | 50% | 0% |
| Truck >24-40t | l/100km | 37,1 | 30,2 | 22,7 |
| | MJ/km | 13,3 | 10,8 | 8,1 |
| | g/km | 309 | 251 | 189 |

Source: Handbook Emission Factors for Road Transport 3.1 (INFRAS 2010)
(Knörr et al 2010)

*Road gradient*

Another parameter influencing fuel consumption and therefore emissions is the gradient, which takes into account country-specific factors which represent the average topology of the country. In some cases the energy consumption and emissions for heavy duty vehicles could be 5-10 % higher if the country specific (hilly landscape) gradients are taken into account (Knörr et al. 2010).

*Driving cycles*

Energy consumption and therefore also exhaust gas emissions, however, does not depend only on the truck type and loading conditions, but also on the driving pattern which could be described for instance as highway traffic and traffic on other roads (Knörr et al. 2010). Table A.3. in annexes shows the selection of driving cycles and also gives the average speeds according driving cycles for trucks. This dataset gives a good coverage of the whole range of vehicle speeds from highway to stop & go conditions (Hausberger et al 2009).

### 3.3.3. *Environmental impact assessment*

This subchapter gives guidelines how to determine the airborne exhaust gas emissions by road transport. Road transport is also significant contributor to non-exhaust emissions to air (e.g. particle (PM) emissions due to tyre, break and road wear), however, this is not taken into account in the frame of this Master Thesis.

The first phase in assessing environmental impact by lorries is to determine the truck specifications and loading conditions, because the fuel consumption is depending largely on this data.

*Fuel consumption*

Fuel consumption of a lorry is determined on distance based and has to be determined by the manufacturer of a truck or given as input data.

In order to determine the exhaust gas emissions, fuel consumption has to be preferably presented as specific fuel consumption (g/km). This is due to the fact that environmental impact depends on the mass of combusted fuel. The common practice representing fuel consumption is the unit of $L/_{100}km$. If only this kind of input data is available, the transformation to the g/km should be made with formula 3.8:

$$FC_{g/km}=0,1\cdot FC_{L100}\cdot FD \qquad (3.8)$$

where

$FC_{g/km}$ – Specific fuel consumption per vehicle km, [g/km]

$FC_{L100}$ – Fuel consumption in liters per 100 km, [$l/_{100}km$]

FD – Fuel density, [$g/cm^3$]

*Determining emissions*

Calculation rules for airborne exhaust gas emissions are derived from study Knörr et al. (2010). Such emissions as $CO_2$, NOx, $SO_2$ and Particulate Matter (PM) are determined with formula 3.9 as follows:

$$VE=\frac{EF\cdot 10^3\cdot FC_{g/km}}{n_{TEU}} \qquad (3.9)$$

where

*VE* – Vehicle emissions per km·TEU, [g/(km·TEU)]

*EF* – Fuel related vehicle emission factor, [g/kg-fuel]

$FC_{g/km}$ – Fuel consumption, [g/km]

$n_{TEU}$ – Number of TEU-s transported, [-]

### *3.3.4. Uncertainties of environmental impact assessment*

The data used in this chapter have been developed on the basis of information collected by literature review, which makes it difficult to check if the data correspondse with the conditions simulated in the various transport scenarios.

Hausberger et al. (2009) points out some influencing factors, which could add additional uncertainty in the environmental assessment by the lorry transport.

- Driving cycles including gear shift behaviour
- Cold start conditions
- Effects of malfunctions, deterioration and maintenance conditions
- Tampering (e.g. chip tuning)
- Loading conditions
- Operation of air condition and other auxiliaries
- Fuel influence (e.g. use of alternative fuels or low fuel quality)
- Vehicle specifications ().

There is no data available concerning the cargo handling emissions, which can cause unfair estimation of emissions for road transport compared to the other transport modes.

Additional uncertainties can be caused by the varying weight of TEU, because the payload capacity is directly influencing fuel consumption and therefore also emissions.

## 3.4. Rail transportation

Assessing the environmental impact by rail transport begins with determining energy consumption of the train, which depends on the total gross tonne weight (Knörr et al. 2010). For a technical and ecological consideration of rail transport services, a distinction between the traction type, electric or diesel-electric have to be made (Spielmann et al. 2009). When electric train uses electricity directly from the power lines, the diesel electric trains produce electricity with diesel engines onboard the locomotive. The architecture of diesel-electric train traction system is showed on figure 3.3.

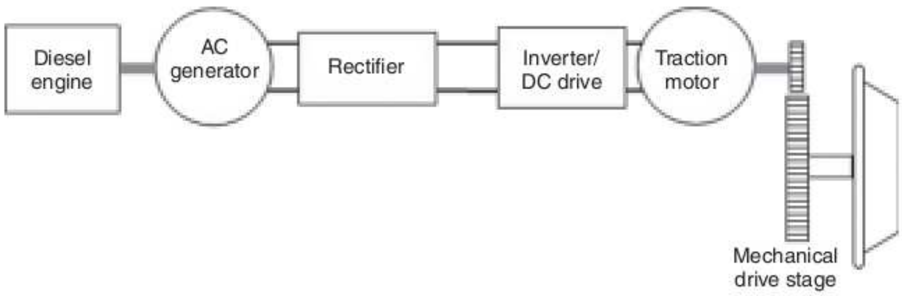


Figure 3.3. Diesel–electric propulsion system architecture. (Source: Wen et al. 2007)

### 3.4.1. *Energy consumption of trains*

In the following, energy consumption of different traction systems is described.

<u>*Energy consumption of electric trains*</u>

According to the study by Knörr et al. (2010) the methodology to determine the energy consumption is valid for train weight between 600 and 1800 gross tonnes. This methodology is checked with data from various train companies and good correlation is identified. Energy consumption of electric trains is calculated with formula 3.10 as follows:

$$ECS_{GT}=1200 \cdot GTW^{-0,62} \qquad (3.10)$$

$ECS_{GT}$ – is specific energy consumption per gross tonne, [Wh/Gtkm]

GTW – is Gross Tonne Weight of freight train, [tonne]

Below 600 gross tonnes the diffusion of the values is higher, which lead to increased uncertainty. Above 1500 gross tonnes the values show no significant reduction of specific energy consumption with growing train weight. This general trend is confirmed by values of heavy trains (4000 gross tonnes and more) for Canada, China, and USA. Therefore it is propose to use the function until 2200 gross tonnes (specific energy value: 10 Wh/Gtkm) and then keep it constant for larger trains. However, European railway companies have 1000 t as a typical average gross weight for international trains and the maximum gross weight for international traffic is up to 2000 tonnes. The function is valid for "hilly" countries. For flat countries, the values of the function are multiplied by 0,9, for mountainous countries the factor is 1,1. (Knörr et al. 2010). The relation between gross tonnage of train and specific energy consumption is depicted on the figure 3.4.

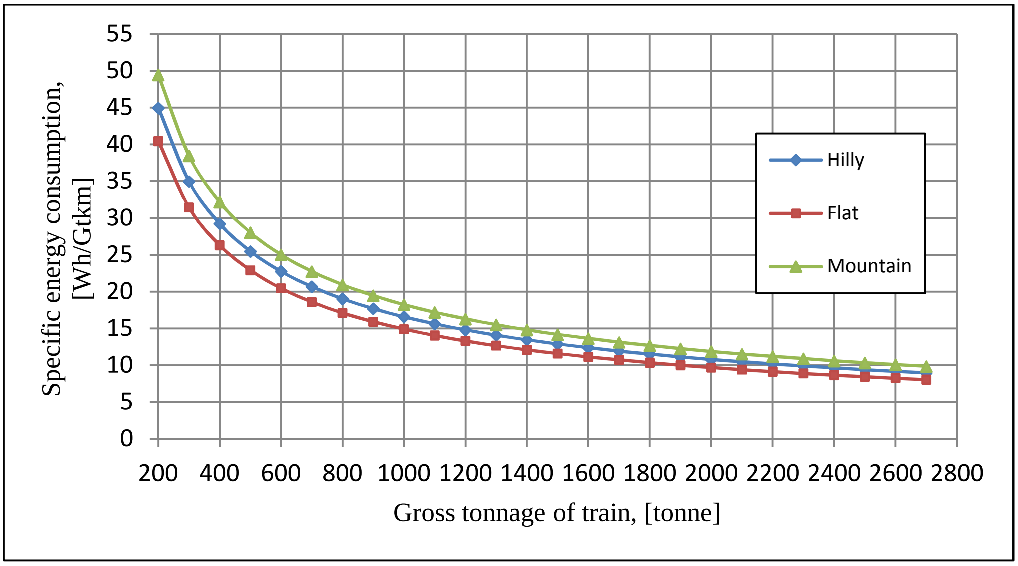


Figure 3.4. Specific energy consumption of electric trains.

With the previous formula, energy consumption for whole train was performed, but in order to determine the fuel consumption and finally emissions per transported unit (TEU), specific energy consumption per net tonne km has to be calculated. This can be determined with formula 3.11 as follows:

$$ECS_{NT}=\frac{ECS_{GT}}{CU_{NG}} \tag{3.11}$$

where

$ECS_{NT}$ – Specific energy consumption per net tonne kilometer, [Wh/Ntkm]

$ECS_{GT}$ – Specific energy consumption of train, [Wh/Gtkm]

$CU_{NG}$ – Net tonne – gross tonne relation, [net tonnes/gross tonne]

The ratio between net tonne kilometer and gross tonne kilometer is principally the capacity utilisation of trains, because normally railway companies report net tonne kilometer and gross tonne kilometer when describing the amount of cargo transported. It takes into account also empty trip factor.

Typical values for net tonne –gross tonne relation are:

- 0,40 for volume freight
- 0,52 for average freight
- 0,60 for bulk freight (Knörr et al. 2010)

*Energy consumption of diesel-electric trains*

According to Knörr et al. (2010) the primary energy consumption of trains with diesel-electric traction is estimated on the basis of the primary energy consumption of electro traction. This procedure can be used, because the total efficiency of diesel-electric traction (including the production of fuel) is similar to that of total efficiency of electro traction (including electricity generation).

So the same functional dependence as that of electric traction is taken and has to be divided by the conversion efficiency of diesel power to final energy consumption. According to Knörr et al. (2010) this efficiency is 37 %. The calculation rule of final energy consumption for diesel-electric trains is given with the formula 3.12 as follows:

$$ECS_{NT}=\frac{ECS_{GT}}{0{,}37 \cdot CU_{NG}} \tag{3.12}$$

where

$ECS_{NT}$ – Specific energy consumption per net tonne kilometer, [Wh/Ntkm]

$ECS_{GT}$ – Specific energy consumption of train, [Wh/Gtkm]

$CU_{NG}$ – Net tonne – gross tonne relation, [net tonne/gross tonne]

Figure 3.5 gives an overview about the energy profiles with various phases in its chain and describes the difference between the electric and diesel-electric trains.

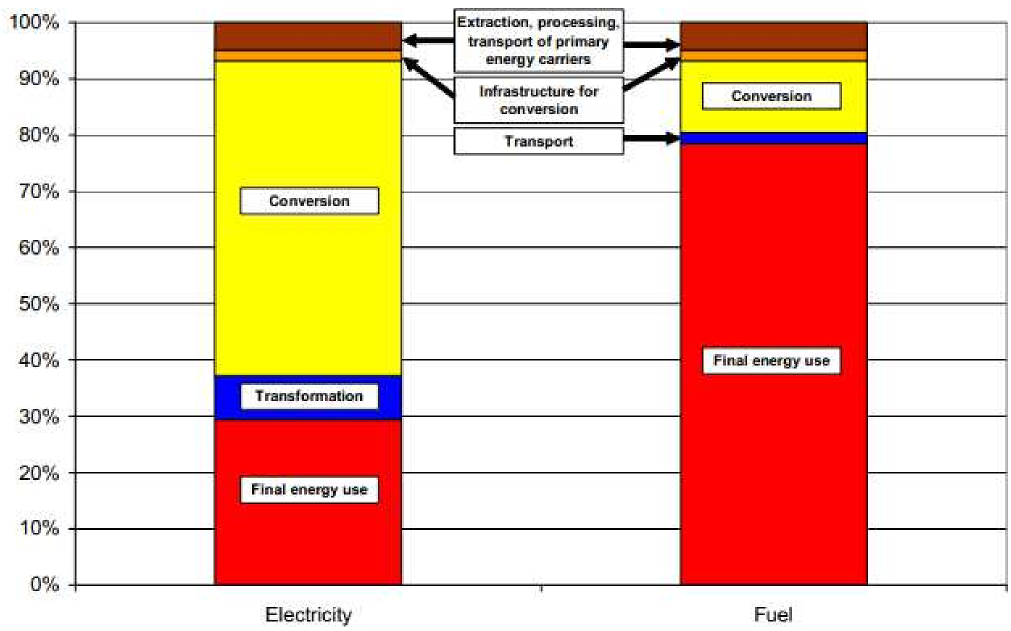


Figure 3.5. Energy chain for diesel fuel and electric powered trains (Knörr et al. 2010)

### *3.4.2. Environmental impact assessment*

<u>*Environmental impact assessment of trains*</u>

Trains with electric or diesel-electric propulsive systems are generally similar, they use electric engines for traction, but the power source for those electric engines are different, which makes the nature of environmental impact assessment for considered two types of trains also different. Diesel-electric trains create pollution due to the combustion of fossil fuels on board the locomotive, but electric trains create basically no emissions by the locomotive, but emissions are mainly released in the phase of electricity production before it is transferred to the train. In this case, pollution depends on the electricity production, its technology, used fuel and efficiency.

To assess the environmental impact, the first step in the calculation procedure is the estimation of the energy consumption of a given type of train. Secondly, pollutant emissions are calculated from the energy specific emission factors. The procedure can be applied both diesel-electric and electric trains, but in the latter case, the emission factors are related to the production of the electricity in power plants (Ceuster et al. 2007), which makes more difficult to determine the actual emissions due to the operation of the train. In general, this assumes the analysis of electricity mix of the country or countries where the train is operated, as well as efficiency of electricity production. This, however, is out of the scope of this Master Thesis.

For additional details, it is suggested to review the study of Knörr et al. (2010). As a consequence, it is assumed that applying developed methodology, only diesel-electric trains are used for cargo transport.

To use fuel related emission factors the conversion from energy use to fuel consumption can be made. This can be obtained when using specific fuel oil consumption (g/Wh).

Exhaust gas emissions g/(km·TEU) by diesel-electric trains are calculated with formula 3.13 as follows:

$$E=\frac{ECS_{NT}\cdot sfoc\cdot M_{TEU}\cdot EF}{10^3} \quad (3.13)$$

where

E – Emissions, [g/(km·TEU)]

$ECS_{NT}$ – Specific energy consumption per net tonne kilometer, [Wh/Ntkm]

sfoc – Specific fuel oil consumption, [g/kWh]

$M_{TEU}$ – Weight of TEU, [t]

EF – Emission factor, [g/kg]

*Cargo handling emissions*

Cargo handling is performed whenever is necessary to load, unload or change the transporting mode for cargo. According to Knörr et al. (2010), the energy used by a handling container in a rail cargo transport centre was estimated with 4,4 kWh per transfer process. Cargo handling emissions depend hereby again on the electricity mix of a country, because it is assumed that most of the cargo handling equipment is running on electricity. Assessment of environmental impact by cargo handling in rail cargo transport center is out of scope of this Master Thesis.

### *3.4.3. Uncertainties of environmental impact assessment*

To estimate the environmental impact of diesel-electric trains, the efficiency of diesel-electric conversion for final energy consumption is assumed of 37 % in case of formula 3.8. This value can vary for different machinery and set up of the locomotive, which could cause some uncertainties to arise in environmental impact assessment.

For electric trains, as described above, the analysis of environmental impact is somewhat more difficult than that of diesel-electric trains. However, the environmental impact assessment by electric trains is excluded from this work, short explanation about the difficulties and uncertainties is given, which explains even more, why that part is not taken into account.

The main problem of quantifying ecological impacts of electricity is that electrons cannot, in actuality, be traced to a particular power plant and therefore, special properties of electricity have to be considered, which may cause also higher uncertainties in the environmental assessment:

- Each country has its own electricity production mix.
- The split of production differs between night and day and also between winter and summer.
- The liberalization of the energy market leads to an international trade of electricity making the determination of a specific electricity mix even more difficult.
- For combined production of heat and power the total efficiency of the energy production is higher (Knörr et al. 2010).

# 4. COST

This chapter gives overview about cost of the containers transportation by various transport modes. The cost can be divided roughly into 2 main categories: direct (or internal) and indirect (or external) costs. Direct costs are expenses which are paid by the transportation company in order to keep the business running. Transportation like any other industry causes also external costs which are generally not paid by the company but are caused by the operation of transport vehicles or vessels and those cost items are for instance cost of accident, pollution, wear and tear, climate change, congestion and noise nuisance (Weinreich et al. 2000 and Beuthe et al. 2002). The focus in this Master Thesis is put on determining the direct costs of various transport modes.

## 4.1. General

Various transport modes are closely interrelated and have to be separated from each other very strictly, so that there is no double counting (Weinreich, 2000). The cost as a transport performance evaluator has to have the common measurement unit, which describes the cost in Euros per loading unit (€/LU). In current case the cost is calculated in TEU basis. As a result, all the cost items having different units, such as €/year, €/tonne, €/kWh, €/good unit, €/vkm etc, have to be converted into the common unit.

In the following table (4.1), the guidelines are given to convert various cost units into the common cost unit:

Table 4.1. Conversion of cost items into common measurement unit

| Cost item | Measurement unit | Conversion to €/TEU |
|---|---|---|
| Salary of worker, Social security, Overhead, Administration, Profit, Advertising, Advocating, Insurance, Taxes and Charges, Investment | Euro/year | $\frac{€}{\text{year}} \Big/ \frac{\text{TEU}}{\text{year}} = \frac{€}{\text{TEU}}$ |
| Insurance of cargo, Duty, Sales tax | Euro/value of one unit of good | $\frac{€}{\text{good}} \Big/ \frac{\text{good}}{\text{TEU}} = \frac{€}{\text{TEU}}$ |
| Insurance of assets | Euro/year | $\frac{€}{\text{year}} \Big/ \frac{\text{km}}{\text{year}} \cdot \frac{km}{TEU} = \frac{€}{\text{TEU}}$ |
| Fuel, diesel, Oil, Fat, Additional variable cost | Euro/vkm | $\frac{€}{\text{vkm}} \Big/ \text{TEU}\cdot\text{km} = \frac{€}{\text{TEU}}$ |
| Electricity, Energy consumption | Euro/kWh | $\frac{€}{\text{kWh}} \Big/ \frac{\text{TEU}}{\text{year}} \cdot \frac{\text{kWh}}{\text{year}} = \frac{€}{\text{TEU}}$ |
| Loading/Unloading of cargo | Euro/h | $\frac{€}{\text{h}} \Big/ \frac{\text{h}}{\text{TEU}} = \frac{€}{\text{TEU}}$ |

## 4.2. Sea transportation

The cost of sea transport is basing mainly on the book Maritime Economics by Stopford (2009).

The cost of running a shipping company depends on a combination of three factors. First, the cost of shipping depends largely how it is operated and the cost is influenced therefore through ship's fuel consumption, the number of crew required to operate it, and its physical condition, which dictates the requirement for repairs and maintenance. Second, the costs of bought-in items, particularly bunkers, consumables, crew wages, ship repair costs and interest rates, are subject to economic trends outside the ship owner's control. Third, costs depend on how efficiently the owner manages the company, including the administrative overheads and operational efficiency.

### *4.2.1. Cost breakdown list*

The breakdown list classifies costs into five main categories:

- Operating costs, which constitute the expenses involved in the day-to-day running of the ship (cost of crew, stores, maintenance and administrative)
- Periodic maintenance costs, which incur when the ship is dry-docked for major repairs,
- Voyage costs, which are variable costs associated with a specific voyage, e.g. cost of fuel, port charges and canal dues.
- Capital costs, which depend on the way the ship has been financed.
- Cargo-handling costs represent the expense of loading, stowing and discharging cargo.

These categories are subdivided further and described on the figure 4.1. In addition to that, there are two central cost-related principles which have to be taken into account in general, first the relationship between cost and age, and second the relationship between cost and size (Stopford 2009).

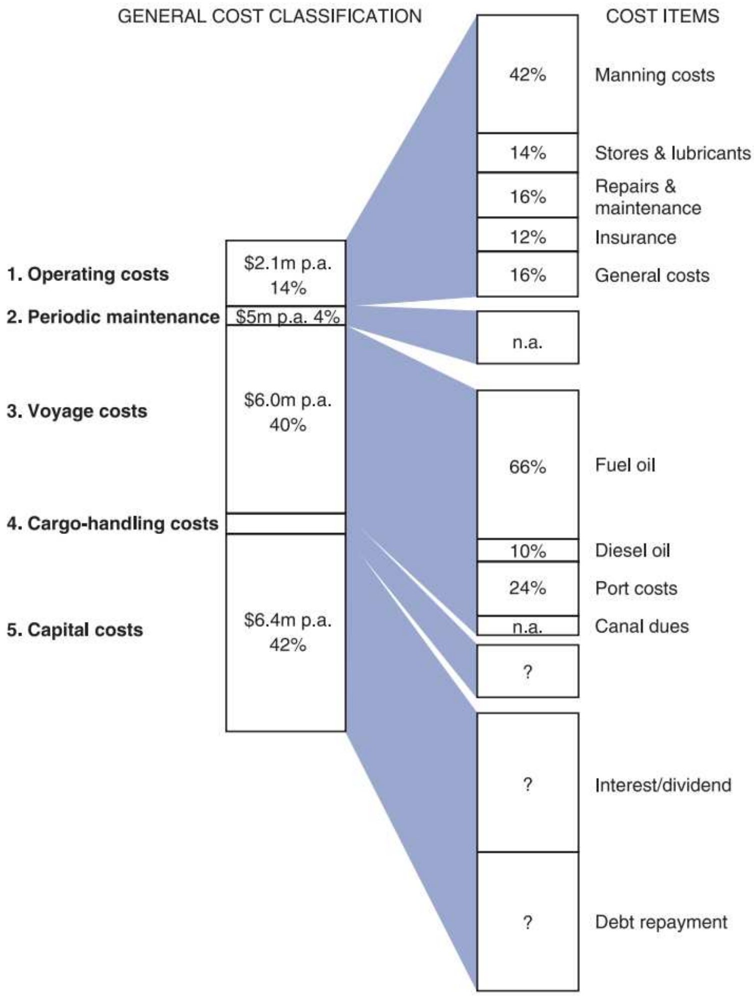


Figure 4.1. Cost structure of running a bulk carrier.

This figure is created by Stopford (2009) from various sources. The analysis is composed for 10 years old Capesize bulk carrier under Liberian flag at 2005 prices. Relative costs depend on many factors that change over time, so this is just a rough guide. However, this figure is not directly related to the container ship or some similar ship carrying containers, but could be used as an orientation for creating the cost structure for another specific ship.

It is also noted hereby that the cost structure changes over the life time of the ship. This is due to the fact that when ship gets older, its capital cost decreases, but voyage and operating cost increases relatively to the newer ships, which are more efficient due to a combination of technical improvement since the ship was built (e.g. more efficient engines) and the effect of ageing (Stopford 2009).

### 4.2.2. *Operation costs*

Operating costs are the ongoing expenses connected with the day-to-day running of the vessel (excluding fuel, which is included in voyage costs), together with an allowance for day-to-day repairs and maintenance (but not major dry dockings, which are dealt separately in the periodic maintenance section). Operation costs are calculated with formula 4.1 as follows:

$$OC = M + ST + MN + I + AD \quad (4.1.)$$

where

M – Manning cost, [€]

ST – Cost of stores, [€]

MN – Routine repair and maintenance, [€]

I – Insurance costs, [€]

AD – Administration costs, [€]. (Stopford, 2009)

*Crew costs*

Crew costs include all direct and indirect charges incurred by the crewing of the vessel, including basic salaries and wages, social insurance, pensions, victuals and repatriation expenses. The level of manning costs for a particular ship is determined by two factors, the size of the crew and the employment policies adopted by the owner and the ship's flag state. Manning costs may account for up to half of operating costs, depending on the size of the ship.

The minimum number of crew on a merchant ship is usually set by the regulations of the flag state. However, it also depends on commercial factors such as the degree of automation of mechanical operations, particularly the engine room, catering and cargo handling; the skill of the crew; and the amount of on-board maintenance undertaken (Stopford, 2009).

The annual cost of crew could be evaluated multiplying the average number of crew members onboard with the average cost of a crew member per annum. It is important to note that the number of crew members on board could vary from season to season. Although, this is valid only for some specific ships such as passenger ships.

*Stores and consumables*

Another significant cost of operating a vessel, accounting for about 15% of operating costs, is expenditure on consumable supplies. These are divided into two categories: General stores including cabin stores and the various domestic items used on board ship; and lubricating oil which is a major cost (most modern vessels have diesel engines and may consume several hundred liters of lube oil a day while at sea).

*Repairs and maintenance*

Routine maintenance, which accounts for 14% of operating costs, covers the routine repairs needed to maintain the vessel to the standard required by company policy, its classification society and the charterers of the vessel who choose to inspect it (it does not include periodic dry docking which is dealt under ‘periodic maintenance’ below).

Broadly speaking, maintenance covers the cost of routine maintenance, including breakdowns and spares:

- *Routine maintenance*. Includes maintaining the main engine and auxiliary equipment, painting the superstructure and carrying out steel renewal in those holds and cargo tanks which can be safely accessed while the ship is at sea. As with any capital equipment, the maintenance costs of merchant ships tend to increase with age.
- *Breakdowns*. Mechanical failure may result in additional costs outside those covered by routine maintenance. Work of this type is often taken by ship repair yards on ‘open order’ and is therefore likely to be expensive. Additional costs are incurred owing to loss of trading time.
- *Spares*. Replacement parts for the engine, auxiliaries and other on-board machinery. Expenditure on spare parts and replacement equipment is also likely to increase with age (Stopford, 2009).

*Insurance*

Typically insurance accounts for about 14% of operating costs, though this is a cost item which is likely to vary from ship to ship. Two-thirds of the cost is to insure the hull and machinery, which protects the owner of the vessel against physical loss or damage, and the other third is third party insurance, which provides cover against third party liabilities such as injury or death of crew members, passengers or third parties, pilferage or damage to cargo, collision damage, pollution and other matters that cannot be covered in the open insurance market. Additional voluntary insurance may be taken out to cover against war risks, strikes and loss of earnings. Hull and machinery insurance is obtained from a marine insurance company or through a broker who will use a policy backed by underwriters in one of the insurance markets. Two important contributory factors in determining the level of hull and machinery insurance are the owner’s claims record and the claimed value of the vessel (Stopford, 2009).

*General costs*

A registration fee is paid to the flag state, the size of which depends on the flag. Included within the annual operating budget for the ship is a charge to recover shore-based administrative and management charges, communications, owners’ port charges, and miscellaneous costs. The overheads cover liaison with port agents and general supervision. The level of these charges depends on the type of operation (Stopford, 2009).

### *4.2.3. Periodic maintenance costs*

Periodic maintenance, involves a cash payment to cover the cost of dry docking and special surveys. It accounts for about 4% of costs, though this depends on the age and condition of the ship. To maintain a ship in class for insurance purposes, it must undergo regular surveys with a dry docking every 2 years and a special survey every 4 years to determine its seaworthiness. At the special survey the vessel is dry-docked, all machinery is inspected and the thickness of the steel in certain areas of the hull is measured and compared with the requirements by classification societies. In addition, dry docking allows marine growth, which reduces the operating efficiency of the hull, to be removed (Stopford, 2009).

### *4.2.4. Voyage costs*

Voyage costs are the variable costs incurred in undertaking a particular voyage and can determined with formula 4.2. The main items are fuel costs, port dues, tugs, pilotage and canal charges:

$$VC=FC+PD+TP+CD \qquad (4.2.)$$

where

VC – Voyage costs, [€]

FC – Fuel costs for main and auxiliary engines, [€]

PD – Port dues, [€]

TP – Tugs and pilotage, [€]

CD – Canal dues, [€]. (Stopford, 2009)

*Fuel costs*

Fuel oil is the single most important item in voyage costs, accounting for nearly half of the total voyage costs. Nowadays the fuel oil prices are very much fluctuating and the increase of future prices is mainly unpredictable. Although shipping companies cannot control fuel prices, they have some influence on the level of fuel consumption. Like any other piece of complex machinery, the fuel a ship burns depends on its design and the care with which it is operated.

In operation, the ship's fuel consumption depends on its hull condition and the speed at which it is operated. When a ship is designed, naval architects optimize the hull and power plant to a prescribed design speed. Operation of the vessel at lower speeds results in fuel savings because of the reduced water resistance and lower power demand (Stopford, 2009). The power dependence according to speed of a ship is related roughly with "cube rule", but the empirical method for power prediction of ship is described in the section 3.2.4.

*Port charges*

Port-related charges represent a major component in voyage costs and include various fees levied against the vessel and/or cargo for the use of the facilities and services provided by the port. Charging practices vary considerably from one area to another and generally they are divided into two components – port dues and service charges.

Port dues are levied on the vessel for the general use of port facilities, including docking and wharfage, and the provision of the basic port infrastructure. The actual charges may be calculated in four different ways, based on: the volume of cargo; the weight of cargo; the gross registered tonnage of the vessel; or the net registered tonnage of the vessel. The service charge covers the various services that the vessel uses in port, including pilotage, towage and cargo handling.

*Canal dues*

The main canal dues payable are for transiting the Suez and Panama canals. The charges depend on the various factors such as cargo capacity of a ship.

#### *4.2.5. Cargo handling*

The fourth major cost item is the cost of loading and discharging cargo, which represents a significant component in the total cost equation and one to which considerable attention has been paid by ship owners, particularly in the liner business. Cargo-handling costs are given with formula 4.3 as the sum of loading costs, discharging costs and an allowance for the cost of any claims that may arise:

$$CHC = L + DIS + CL \qquad (4.3.)$$

where

CHC – Cargo-handling costs, [€]

L – Cargo loading charges, [€]

DIS – Cargo discharge costs, [€]

CL – Cargo claims, [€]

The level of these costs may be reduced by investment in improved ship design – to facilitate rapid cargo handling, along with advanced shipboard cargo-handling gear (Stopford, 2009).

#### *4.2.6. Capital costs*

The fifth component in the cost equation is capital cost. This accounts for large part of total costs, but in economic terms it has a very different character from the other costs. Operating and fuel costs are necessities without which the ship cannot trade. Once a ship is built, its capital costs are obligations which have no direct effect on its physical operation. In practice these obligations take three forms as far as the shipping company's cash flow is concerned. First, there is the initial purchase and the obligation to pay the shipyard; second, there are the periodic cash payments to banks or equity investors who put up the capital to purchase the vessel; and third, cash received from the sale of the vessel. How these obligations appear in the cash flow is not determined by the ship's trading activities (Stopford, 2009).

There are two common arrangements, if a loan is repaid by regular installments:

- Principal paid in equal installments, and interest paid on the declining balance, where interest predominating in early years, repayments of principal in later years. This is the usual method with shipbuilding loans and it is depicted on figure 4.2.
- Uniform payments: which is the usual method for house purchase loans (Buxton, 1987 and Iqbal, 2011)

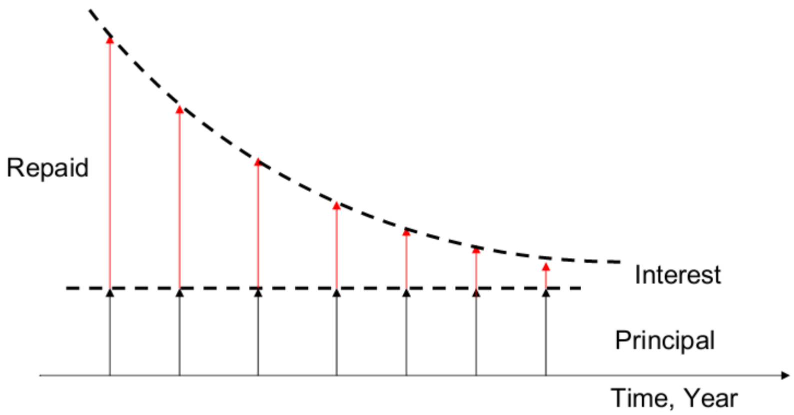


Figure 4.2. Loan repayment in shipping industry. (Source: Iqbal, 2011)

## 4.3. Road transportation

Cost breakdown list of direct costs for road transport is given in the following section.

### *4.3.1. Cost breakdown list*

Composing the cost breakdown list of direct costs, the study by Weinreich et al. (2000) is used as a basis for that. Cost items are divided into 3 main categories, where each consists of several items. Hereby the cost categories of road transport are presented:

- Operation costs have similar buildup like in shipping industry, where this category reflects the expenses of day-to-day running of road transport company (salary of driver, overhead, maintenance, insurance etc)
- Capital costs, which constitute the depreciation and financial costs.

- Voyage costs are variable costs which depend on the transport activity and specific routes (cost of fuel, lubricants, tyres, etc)

First two categories are fixed costs and those are not dependent on transportation routes or distance travelled by the lorries, but voyage costs are variable costs and depend on these factors. Each category is described further in the following sections.

#### *4.3.2. Operation costs*

Operating costs incurred with ongoing running of the road transport enterprise and the category consists of various cost items. Operating costs of road transport in yearly basis is calculated with formula 4.10 as follows:

$$OC=SD+ITC+AD \tag{4.10}$$

where

OC – Operating costs per annum, [€]

SD – Salary of driver, [€]

ITC – Insurance, taxes, charges, [€]

AD – Administrative costs, [€]

*Salary of driver*

Salary of driver includes the wage of the lorry driver or drivers per year. This includes also social insurance, pension and transportation cost of the driver.

*Insurance, taxes and charges*

This cost item constitute of insurance for vehicle and loading units (container/swap body/trailer). This includes also third party motor vehicle insurance and vehicle tax if applicable.

*Administrative costs*

This cost category includes administration cost, social security, overhead, advertising, advocating and consulting of the enterprise.

#### *4.3.3. Capital costs*

Financial costs per annum for financing various assets are calculated with formula 4.23.
Depreciation cost per annum of an asset over its lifetime is calculated with formula 4.24.

#### 4.3.4. Voyage costs

Voyage costs are variable costs incurred with transport work and are determined with the formula 4.13 as follows:

$$VC=DC+FC+TC+RM+RC+OC \quad (4.13)$$

where

VC – Voyage costs, [€]

DC – Costs incurred by the driver, [€]

FC – Fuel costs, [€]

TC – Cost of a tyres, [€]

RM – Repair and maintenance, [€]

RC – Road charges (tolls, road-pricing, fixed road charges), [€]

OC – Other costs (rest time for driver, parking, port liner terms charge), [€] (Weinreich et al. 2000)

<u>*Driver expenses*</u>

These costs include driver allowance per year and depend much of the region where the lorry is operating. These expenses constitute cost items such as traveling tickets of the driver if necessary, accommodation, visa, telephone, telecommunication, radio.

<u>*Fuel costs*</u>

Fuel costs constitute significant part of voyage cost and depend on the current fuel prices. Truck producing factories are putting a lot of effort to develop more fuel efficient engines and lighter constructions in order to reduce fuel consumption. If heated or refrigerated containers are transported, necessary power to them are provided by auxiliary engines and the fuel consumption of that has to be taken into account as well. In the frame of this Master Thesis, it is not taken into account and it is assumed that containers without extra power supply are transported. Annual fuel cost is calculated with formula 4.14 as follows:

$$FC=\frac{fv \cdot cv \cdot ad}{100} \quad (4.14)$$

where

FC – annual fuel cost of lorry, [€]

fv – Fuel cost per liter for lorry, [€/l]

cv – Average fuel consumption of lorry, [l/100km]

ad – Annual distance travelled with lorry, [km] *Cost of tyres*

Cost of tyres is also one of the significant cost item in the voyage cost category. The annual cost of tyres are calculated with the formula 4.15 as follows:

$$TC = \frac{ct \cdot n \cdot ad}{lt} \quad (4.15)$$

where

TC – Annual cost of tyres, [€]

ct – Cost of one tyre, [€]

n – Number of tyres in the vehicle set, [-]

ad – Annual distance travelled by lorry, [km]

lt – lifetime of a tyre, [km]

The cost of one tyre should include also the cost of changing the tyre. Annual performance of a lorry is assumed to be 135 000 km (Planco Consulting GmbH, 2007). Total performance of a lorry is expected to be 540 000 km (Spielmann et al. 2007), in the same study, the lifetime of a tyre is assumed 75 000 km.

*Repair and maintenance of lorry*

This cost item includes the repair and maintenance of lorry. The maintenance is done on the basis of distance travelled. After certain amount of distance that lorry is travelled the periodic maintenance needed to be performed, therefore the repair and maintenance costs are calculated also on kilometer basis. Calculation is done with formula 4.17 as follows:

$$RML=(rcl+mcl) \cdot ad \quad (4.17)$$

where

RML – Repair and maintenance cost per annum for lorry, [€]

rcl – Repair costs per kilometer, [€/km]

mcl – Maintenance costs per kilometer, [€/km]

ad – Annual distance travelled, [km]

*Road charges*

This cost item consists of various charges for the roads, toll and bridge taxes. These items are specific for the region where the lorry is operating.

*Other costs*

This cost item constitutes for instance parking fees, port liner terms charge and some additional costs if applicable.

#### *4.3.5. Time*

The regulation (EC) No 561/2006 by the European Commission describes the daily and weekly driving cycles for lorries. The article 6 in this document says:

1. The daily driving time shall not exceed nine hours. However, the daily driving time may be extended to at most 10 hours not more than twice during the week.
2. The weekly driving time shall not exceed 56 hours and shall not result in the maximum weekly working time laid down in Directive 2002/15/EC being exceeded.
3. The total accumulated driving time during any two consecutive week s shall not exceed 90 hours (European Commission 2006).

Article 7 says:

After a driving period of four and a half hours a driver shall take an uninterrupted break of not less than 45 minutes, unless he takes a rest period. This break may be replaced by a break of at least 15 minutes followed by a break of at least 30 minutes each distributed over the period in such a way as to comply with the provisions of the first paragraph (European Commission 2006).

## 4.4. Rail transportation

Cost breakdown list of direct costs for rail transport is given in the following section. The cost structure follows the study composed by Weinreich et al. 2000.

#### *4.4.1. Cost breakdown list*

Cost items of rail transportation, similarly to road transport, are divided into 3 main categories, where each consists of several items. The cost categories are as follows:

- Operation costs, which consists of expenses of day-to-day running the railway transport company (salary of driver, overhead, maintenance, insurance etc)
- Capital costs, which constitute the depreciation and financial costs.
- Voyage costs are variable costs which depend on the performed specific transport work (cost of fuel, lubricants, etc)

First two categories are fixed costs and those are not dependent on transportation routes or distances, but voyage costs are variable costs and depend on these factors. Each category is described further in the following sections.

### *4.4.2. Operation costs*

Operating costs incurred with ongoing running of the railway transport company and the category consists of various cost items. Annual operating cost of rail transport is calculated with formula 4.18 as follows:

$$OC=SC+ITC+NC+AD \quad (4.18)$$

where

OC – Operating cost per annum, [€]

SC – Salary of crew, [€]

ITC – Insurance, taxes, charges, [€]

NC – Operational costs for the railway (signaling, station and network management), [€]

AD – Administrative costs, [€]

*Crew cost*

This cost item describes annual salary of crew members who are working in one train. This includes also social insurance and pension. The total crew cost is calculated with formula 4.19 as follows:

$$SC=n\cdot SD \quad (4.19)$$

where

SC – Annual total crew cost of train, [€]

n – Number of crew members onboard the train, [-]

SD – Average salary of one crew member per year, [€]

*Insurance, taxes and charges*

This cost item constitute of insurance for vehicle and loading units (container/swap body/trailer). This includes also third party motor vehicle insurance and vehicle tax if applicable.

*Administrative costs*

This cost category includes administration cost, social security, overhead, advertising, advocating and consulting of the enterprise.

### *4.4.3. Capital costs*

Financial costs per annum for financing various assets are calculated with formula 4.23.

Depreciation cost per annum of an asset over its lifetime is calculated with formula 4.24.

#### 4.4.4. Voyage costs

Voyage costs are variable costs incurred with transport work and are determined with the formula 4.20 as follows:

$$VC=DC+FC+LC+RC+OC \qquad (4.20)$$

where

VC – Voyage costs per annum, [€]

DC – Costs incurred by the crew, [€]

FC – Cost of fuel, [€]

LC – Costs of lubricating oil, fat and other variable costs, [€]

RC – Rail track user charges, [€]

OC – Other costs, [€] (Weinreich et al. 2000)

*Crew expenses*

These costs include crew allowances per year. These expenses constitute cost items such as traveling tickets of the driver if necessary, accommodation, visa, telephone, telecommunication, radio.

*Fuel costs*

Fuel costs constitute significant part of voyage cost and depend on the current fuel prices. There can be also auxiliary engines, which are providing energy to the heated or refrigerated cargo. When this is the case, that fuel consumption needs to be taken into account as well. Annual fuel cost of diesel-electric is calculated with formula 4.21 as follows:

$$FC=fv \cdot cv \qquad (4.21)$$

where

FC – annual fuel cost of diesel-electric train, [€]

fv – Fuel cost per tonne, [€/t]

cv – Fuel consumption per annum, [t]

*Cost of Lubrication oil*

This cost item describes the annual cost of lubrication oil, fat and other variable consumables for the train.

*Repair and maintenance of locomotive*

This cost item includes the repair and maintenance of locomotive. The maintenance is done on the basis of distance travelled. Repair and maintenance costs are calculated on distance basis. Calculation is done with formula 4.22 as follows:

$$RML=(rcl+mcl)\cdot ad \tag{4.22}$$

where

RML – Repair and maintenance cost per annum for locomotive, [€]

rcl – Repair costs per kilometer for locomotive, [€/km]

mcl – Maintenance costs per kilometer for locomotive, [€/km]

ad – Annual distance travelled, [km]

*Rail track charges*

This cost item consists of charges for tolls and using the rail tracks.

*Other costs*

This cost item consists of all the other costs if applicable.

## 4.5. Calculation of capital costs

Capital costs are calculated for each transportation mode. Although the transport vessels or vehicles and corresponding equipment are different, the calculation rules are universal for each asset.

*Financial costs*

Financial costs are the annual expenses of financing various assets. Basing on the annuity method, the financial cost per year over the lifetime of an asset is calculated with the formula 4.23 as follows:

$$F=\frac{\left(N\frac{P\cdot i\cdot(1+i)^N}{(1+i)^N-1}\right)-P}{\nu} \tag{4.23}$$

where

F – Financial cost per year, [€]

P – Loan for buying an asset, [€]

i – interest (expressed as a fraction e.g. 5 percent is 0,05), [%]

N – financing period, [years]

ν – useful life of an asset, [years] (Iqbal, 2011)

This formula does not take into account the repayment of the principal, while it is subtracted in the formula.

*Depreciation costs*

Depreciation is a systematic and rational process of distributing the cost of assets over its lifetime. Because it is of interest to find all the cost for a year the depreciation cost per annum is calculated with formula 4.23 as follows:

$$DP=\frac{AC-RV}{\nu} \tag{4.24}$$

where

DP – Depreciation cost per year, [€/year]

AC – Acquisition cost, [€]

RV – Residual value of an asset, [€]

ν – Useful lifetime of asset, [years] (Blauwens et al. 2008)

## 4.6. External costs

External costs are defined as non-compensated impacts by transport agents on not involved third parties. 'External' means: the negatively affected third party receives no (or no full) compensation (Planco Consulting GmbH, 2007). There are many works, which have been studying the external cost of cargo transport. Weinreich et al. (2000) describes such external cost elements:

- Accident
- Air Pollution
- Climate change
- Noise nuisance

Maibach et al. (2008) is describing also other external costs which are very often neglected from main external cost items. These factors are:

- Costs for nature and landscape
- Costs for soil and water pollution
- External costs in sensitive areas
- Costs of up- and downstream processes
- Additional costs in urban areas
- Costs of energy dependency

According to Weinreich et al. (2000) some factors have internal and also external parts. For road transport, these are congestion and specific road bottlenecks. For rail and sea transport, such cost item is scarcity. In this study, those cost items are considered as external costs and their effect on the direct cost is not taken into account. Therefore, the congestion cost is in the frame of this Master Thesis considered as external cost and this only arise when congestion is generated. When dealing with external cost, distinction between congested travel time and non-congested travel time must be introduced. Usually, higher monetary values are associated to congested travel time, considering that stress, schedule disruption and other factors.

## 4.7. Other factors influencing transport

In addition to cost, there are other factors that influence the nature of a transport service: speed, frequency, reliability and quality. Speed is important to the shipper who desires to market his goods against an accurate arrival date and to eliminate banking charges for opening credits. This can be achieved by selecting the fastest service available and thereby obtaining the minimum interval between the time the goods are ordered/dispatched and the date of delivery at their destination. Speed is particularly important to manufacturers of consumer goods as it avoids expense and the risk of obsolescence to the retailer carrying large stocks. In the case of certain commodities, and especially fresh fruit and semi-frozen products and fashionable goods, a regular and fast delivery is vital to successful trading. The need for speed is perhaps most felt in the long-distance trades, which are done mainly by ships and where voyage times may be appreciably reduced and the shipper given the benefit of an early delivery and frequent stock replenishment. These various needs are fully recognized by the liner operator, to whom speed is expensive, both in terms of initial expenditure on the marine engines and the actual fuel cost. His aim is to obtain the optimum and provide a vessel with the maximum speed at the minimum cost which will fulfill the requirements of the shipper. These aspects have been the major driving force in the logistic container service embracing global supply chain management (Branch 2007).

Branch (2007) is also pointing out that speed is not so important in the world tramp trades, where generally lower-value cargoes are being carried and where many trades are moving under programmed stockpile arrangements. In this category are included coal, mineral ores, timber, bulk grain and other cargoes which normally move in shiploads and have a relatively low value: these demand a low transport cost.

### *4.7.1. Time cost for intermodal transport*

Weinreich et al. (2000) is pointing out two main components of time cost associated to freight transport:

- inventory costs
- costs which measure the loss of value of the goods as a result of the transport time

The inventory costs correspond to the traditional notion of immobilization of an asset. During the transport, the goods do not generate an added value, and therefore generate a financial cost to its owner.

The other cost component concerns the loss of value for the goods, which are transported for the benefit of a user who needs the consignment as input for a further value-added-generating process. It is assumed that when agreeing to the delivery of the expected goods at a given schedule time, the user accepts the fact that the value of the goods will receive is not affected by the duration of the transport process. On the other hand, if the agreed delivery time is not met, damage may be suffered by the user, which is the direct consequence of the amount of the delay suffered.

Inventory costs are calculated with formula 4.25 as follows (Weinreich et al. 2000):

$$IC = V \cdot P \cdot \frac{D}{H} \tag{4.25}$$

where

IC – the hourly inventory cost, [€]

V – Economic value of the unit of goods being transported, [€]

P – Amount (number of units) of goods transported, [-]

D – Discount rate as a fraction of unit (e.g. 5% is 0,05), [-]

H – Number of yearly hours for which inventory costs must be calculated, [h]

The loss of value to the user, on the other hand, depends on many other factors which depend on the individual transaction.

The contractual transactions describing the terms and conditions of delivery of a consignment will increasingly include explicit penalty clauses, whereby the amount of delay-related penalties to be imposed on transport operators is specified. Therefore, one can assume that the value of loss to the user can be directly derived from the amount of penalties agreed by the parties in the said transaction (Weinreich et al. 2000).

### *4.7.2. Cargo handling time*

Cargo handling time is one great influencing factor in transport time. It is more important in case of shorter transport routes such as short sea shipping, where cargo handling time has relatively greater part in total transport time. In case of Ro-Ro ships the cargo handling time is significantly shorter than that of container ship which makes this ship type for short sea shipping very competitive with other modes. Reduced cargo handling time for Ro-Ro and Ro-Pax ships explains also why these ships are widespread in short sea shipping. Although the cargo handling time is in many phases already very well optimized, but there are still many aspects to improve and implement for instance innovative cargo handling solutions. One such innovative solution is the double deck ramp for Ro-Ro and Ro-Pax ships which is currently under construction in port of Rostock, Germany, where developers are able to reduce the cargo handling time to 15 min per ship. (Günzl, 2011)

#### *4.7.3. Frequency*

Frequency of service is most important when goods can only be sold in small quantities at frequent intervals. The transport operator will phase his sailings to meet shippers' requirements, whilst the transport vessels/vehicles must be suitable in size, speed and equipment for the cargoes offered.

Frequency is important for: perishable, fashionable goods and replacement spare stock.

To the tramp charterer, frequency is not of paramount importance, it is of course, not allowed the stocks to run down too far (Branch 2007).

#### *4.7.4. Reliability*

Reliability is intended as that specific characteristic of the transport service which guarantees that the consignment will actually reach its planned destination and that the goods will reach their destination without have been deteriorated in the process (Weinreich et al. 2000). Reliability is an essential requirement to the shipper engaged in the liner service which is usually multi-modal, whose goods are sold against expiry dates on letters of credit and import licenses. Furthermore, the liner shipper relies upon the operator to deliver his traffic in good condition. To the shipper, therefore, reliability infers that the vessel will sail and arrive at the advertised time. (Branch 2007).

#### *4.7.5. Quality*

Quality of service is especially important in the competitive world of shipping and international trade today. The service provided must be customer-oriented with emphasis being placed on providing a reliable service and handling the goods and documentation in an efficient way (Branch 2007).

# 5. METHODOLOGY

This chapter summarizes the calculation methodology for determining the environmental impact and cost of sea, road and rail transport. The use of the comparison tool is relatively simple, the user need to provide the input data for the tool and the calculations will be performed according to the calculation rules which are described in the previous chapters. Before the methodology is described, assumptions, limitations and possibilities of using it will be given.

## 5.1. Usage, assumptions and limitations of methodology

Corresponding methodology is used to determine the environmental impact, cost and time of transport. Calculations can be done for following modes of transport:

- Sea
- Road
- Rail

Methodology can be used for single mode or multiple modes and in both cases, provided output data gives results for every single phase and also in total for whole transport scenario.

Environmental impact is evaluated in the frame of exhaust gas emissions by the transport vessel or vehicle and related emissions are:

- $CO_2$
- NOx
- $SO_2$
- PM

Cost of cargo transport takes into account the operation costs, voyage costs and financial cost. In case of ships, also cargo handling and period maintenance are added as separate cost items. Because of the different nature of various transport modes, the cost structure varies, which can cause some uncertainties to occur in the cost.

It is important to note that during the application of the methodology the user have to be careful calculating various parameters not to do double counting or overlapping (e.g. cargo handling time)

In the following, specifics for each mode are described:

*Sea transport*

Environmental impact by ships is assessed on the basis of fuel combustion on board the ship by main and auxiliary engines. Additional installations, such as boilers, production facilities etc., and their emissions are not taken into account in this methodology.

It is assumed that when the container weight is average, ship can be fully loaded. Only in case of heavy containers there can be restrictions on loading. By default, it is assumed that ship can be fully loaded.

Transporting container with Ro-Ro or Ro-Pax ship, the standard length for 2 TEU lorry (truck with trailer) is 16,5 m (Source: Tallink and Finnlink). Standard length for 2 TEU trailer is considered 13,6 m (Source: Tallink) and 14,0 m according to Finnlink and Finnlines. Those lengths are necessary to calculate occupied lane meters, in order to assess environmental impact of Ro-Pax ship and also calculate the TEU capacity of Ro-Ro and Ro-Pax ships.

Capital costs are calculated basing on annuity method, but this is normally not the case, when calculating the interest of ship building loans. The idea is to simplify the methodology and divide capital costs equally over the lifetime of a ship. Like mentioned also before, cost structure of ship is changing when it is ageing, but hereby it is out of the scope to consider this aspect.

*Road transport*

Heavy duty truck with 2 TEU container is taken as reference composition for truck transport. Truck speed is calculated as average speed over the whole trip, simulation of average speed is given in the annex A.3.

There is no difference made on fuel consumption according to driving conditions (e.g. free flow, stop & go etc.). Fuel consumption is calculated only basing on the distance travelled, however, the fuel consumption per km is higher in stop & go condition compared to the free flow condition and therefore this assumption can be in favor to the road transport.

Used roads for lorry transport are assumed to be flat and there is no road gradient applied to the methodology which can increase the fuel consumption. In most cases this is not true and therefore this assumption is also in favor to road transport.

*Rail transport*

In case of rail transport, when calculating the environmental impact, only trains with diesel electric traction are taken into account, but trains with electric traction system are left out in this assessment due to its complexity.

It is assumed that only containers are transported with the train, it means that there is no other type of wagons added to the train configuration.

## 5.2. Input parameters

Input parameters are used in the calculations in order to provide desired output performance indicators. Those parameters should be provided by the user and all the parameters are described in the following section for each mode separately and where input parameters are further subdivided into environmental impact, time and cost parameters.

### *5.2.1. Sea transport*

Table 5.1 consists of input parameters which are necessary to assess the environmental impact of sea transport. In the end of the table, some parameters for Ro-Pax ships are given. Those parameters are specific for this type of ship and do not concern other ships.

Table 5.1. Input parameters for environmental impact of sea transport.

| **Parameter name** | **Unit** | **Description** |
|---|---|---|
| $N_{TEU}$ 1) | - | Number of TEU-s transported with specific ship |
| $FC_{t-h,i}$ | t/h | Fuel consumption per hour of specific activity |
| D | km | Distance for voyage |
| $V_i$ | kn | Speed during the specific activity |
| L | m | Length of waterline |
| Δ | t | Displacement of ship |
| $P_m$ | kW | Power of each main diesel engine |
| $n_{m,i}$ | - | Number of main generating sets running during specific activity |
| $LF_{m,i}$ | % | Loading factor of main engine(s) according to the specific activity |
| $A_{m,i}$ | h | Running time of main engine during the specific activity (voyage, maneuvering) |
| $sfoc_m$ | g/kWh | Specific fuel oil consumption of main engine |
| $sfoc_l$ | g/kWh | Specific lube oil consumption |
| $P_a$ | kW | Power of each auxiliary diesel engine |
| $n_a$ | - | Number of auxiliary generating sets running during specific activity |
| $LF_{a,i}$ | % | Loading factor of auxiliary engine(s) according to the specific activity |
| $A_{a,i}$ | h | Running time of auxiliary engine during the specific activity (voyage, maneuvering) |
| $sfoc_a$ | g/kWh | Specific fuel oil consumption of auxiliary engine |
| $CHE_i$ | g/TEU | Cargo handling emissions per TEU for the corresponding emission |
| $EF_{CO2}$ | g/kg | Mass related emission factor for $CO_2$ |
| $EF_{NOx}$ | g/kg | Mass related emission factor for NOx |
| $EF_{SO2}$ | g/kg | Mass related emission factor for $SO_2$ |
| $EF_{PM}$ | g/kg | Mass related emission factor for particulate matter (PM) |
| *Ro-Pax ship* | | |
| lm | - | Number of utilised lane meters |
| ca | - | Numbers of cars on board |
| pa | - | Number of passengers onboard |
| be | - | Number of occupied berths |

1) Number of TEU-s cannot be bigger than maximum number of TEU-s allowed.

Table 5.2 consists of input parameters which are necessary to calculate the time for transport. It is subdivided into operations like voyage, maneuvering, leaving and entering the port, which are determined for each specific voyage separately.

Table 5.2. Input parameters for duration of sea transport.

| **Parameter name** | **Unit** | **Description** |
|---|---|---|
| VT | h | Time at sea |
| CH | h | Cargo handling time for loading/unloading or at berth |
| MT | h | Duration of maintenance |
| DT | h | Duration of dry docking |

Table 5.3 consists of input parameters for calculation the cost of road transport.

Table 5.3. Input parameters for cost of sea transport.

| **Parameter name** | **Unit** | **Description** |
|---|---|---|
| P | € | Loan for buying an asset |
| i | % | Interest (expressed as a fraction e.g. 5 % is 0,05) |
| N | years | Financing period |
| ν | years | Useful lifetime of an asset |
| AC | € | Acquisition cost of an asset |
| RV | € | Residual value of an asset |
| SD | € | Average salary of one crew member per annum |
| n | - | Number of crew members onboard the ship |
| STG | € | Cost of general stores per annum |
| STL | € | Cost of lube oil per annum |
| $sfoc_l$ | g/kWh | Specific fuel oil consumption |
| CL | €/t | Cost of lube oil per tonne |
| MN | € | Routine repair and maintenance cost per annum |
| I | € | Insurance cost per annum |
| AD | € | Administration cost per annum |
| FC | € | Fuel cost for main and auxiliary engines per annum |
| PD | € | Port dues per annum |
| TP | € | Tug and pilotage cost per annum |
| CD | € | Canal dues per annum |
| L | € | Cost of loading the cargo |
| DIS | € | Cost of discharging the cargo |
| CL | € | Cargo claims |
| DA | km | Annual distance traveled |
| $A_{TEU}$ | TEU | Annual amount of TEU-s transported |

### *5.2.2. Road transport*

Table 5.4 consists of input parameters which are necessary to assess the environmental impact of road transport.

Table 5.4. Input parameters for environmental impact of road transport.

| Parameter name | Unit | Description |
|---|---|---|
| D | km | Distance for voyage |
| U | km/h | Average speed of lorry |
| $FC_{km}$ | g/km | Specific fuel consumption per kilometer |
| FD | $g/cm^3$ | Density of the fuel |
| $CHE_i$ | g/TEU | Cargo handling emissions per TEU for the corresponding emission |
| $EF_{CO2}$ | - | Mass related emission factor for $CO_2$ |
| $EF_{NOx}$ | - | Mass related emission factor for NOx |
| $EF_{SO2}$ | - | Mass related emission factor for $SO_2$ |
| $EF_{PM}$ | - | Mass related emission factor for particulate matter (PM) |

It is assumed in this methodology, that lorry is hauling 2 TEU container/swap body.

Table 5.5 consists of input parameters for calculating the duration of transportation. It is important to note that for longer distances and driving times driver's resting time has to be taken into account. Allowance principles of driving time are given in chapter 4.3.5. It is also important to note that durations in table 6.5. are annual durations, because in order to calculate the cost of transport, the yearly times for various activities are necessary to know. In order to assess the duration of simple voyage, simple approach can be used considering speed and distance and taking into account the resting time of the lorry driver.

Table 5.5. Input parameters for duration of road transport.

| Parameter name | Unit | Description |
|---|---|---|
| VT | h | Annual duration of driving |
| CH | h | Cargo handling time for loading and unloading (connecting/disconnecting the trailer or swap body (annual) |
| RT | h | Resting time of truck driver (annual) |
| MT | h | Duration of maintenance and repair (annual) |

Table 5.6 consists of input parameters which are necessary to calculate the cost of road transport.

Table 5.6 Input parameters for cost of road transport.

| Parameter name | Unit | Description |
|---|---|---|
| P | € | Loan for buying an asset |
| i | % | Interest (expressed as a fraction e.g. 5 % is 0,05) |
| N | years | Financing period |
| ν | years | Useful lifetime of an asset |
| AC | € | Acquisition cost of an asset |
| RV | € | Residual value of an asset |
| SD | € | Salary of driver per annum |
| ITC | € | Insurance, taxes, charges of road transport (operational cost) per annum |
| AD | € | Administrative cost per annum |
| DC | € | Cost incurred by the driver |
| fv | €/l | Fuel cost per liter |

Continuing.

Continuation of table 5.6.

| Parameter name | Unit | Description |
|---|---|---|
| cv | $l/_{100}km$ | Fuel consumption in liters per 100 km |
| ad | km | Annual distance travelled with lorry |
| ct | € | Cost of a tyre |
| n | - | Number of tyres per vehicle set |
| lt | km | Lifetime of a tyre |
| rml | €/km | Repair and maintenance cost per km |
| LF | - | Loading factor (% of distance is loaded) |
| RC | € | Road charges per annum |
| OC | € | Other costs per annum |

Although the annual performance of a lorry is expected to be 135 000 km, this is believed to be not very realistic, because when taking into account the resting time for driver (section 4.3.5), the annual performance can be about 140 000 km at the maximum in case of estimated average speed of lorry (see Annex A.3). Therefore, the annual performance is estimated in a way, where the total performance is divided over 5 years, which is assumed to be the lifetime of the lorry. As a result, the annual performance of a lorry is 108 000 km.

### *5.2.3. Rail transport*

Table 5.7 consists of input parameters for assessing environmental impact of rail transport. According to Pier (2010) typical specific fuel oil consumption for diesel engine on board the diesel-electric train is 210 g/kWh.

Table 5.7. Input parameters for environmental impact of rail transport.

| Parameter name | Unit | Description |
|---|---|---|
| CP | tonne | Payload capacity |
| M | tonne | Mass of freight |
| $M_{TEU}$ | tonne | Mass of freight per TEU |
| $N_{TEU}$ | - | Number of TEU-s transported per train configuration |
| EW | tonne | Empty weight of wagon |
| ET | % | Empty trip factor (distance empty/distance loaded) |
| D | km | Distance for voyage |
| U | km/h | Average speed of the train |
| $ECS_{GT}$ | Wh/Gtkm | Specific energy consumption of train |
| sfoc | g/kWh | Specific fuel oil consumption |
| $CHE_i$ | g/TEU | Cargo handling emissions per TEU for the corresponding emission |
| $EF_{CO2}$ | - | Mass related emission factor for $CO_2$ |
| $EF_{NOx}$ | - | Mass related emission factor for NOx |
| $EF_{SO2}$ | - | Mass related emission factor for $SO_2$ |
| $EF_{PM}$ | - | Mass related emission factor for particulate matter (PM) |

Table 5.8 consists of input parameters for calculating the time duration during the transportation. It is determined on yearly basis, in order to be able to calculate the total cost of transport.

Table 5.8. Input parameters for duration of rail transport.

| Parameter name | Unit | Description |
|---|---|---|
| VT | h | Annual duration of cargo transport |
| CH | h | Cargo handling time for loading and unloading (annual) |
| MT | h | Duration of maintenance and repair (annual) |

Table 5.9 consists of input parameters for calculating the cost of rail transport.

Table 5.9 Input parameters for cost of rail transport.

| Parameter name | Unit | Description |
|---|---|---|
| P | € | Loan for buying an asset |
| i | % | Interest (expressed as a fraction e.g. 5 % is 0,05) |
| N | years | Financing period |
| v | years | Useful lifetime of an asset |
| AC | € | Acquisition cost of an asset |
| RV | € | Residual value of an asset |
| SD | € | Average salary of one crew member per annum |
| n | - | members of crew members onboard the train |
| ITC | € | Insurance, taxes, charges of road transport (operational cost) per annum |
| AD | € | Administrative cost per annum |
| DC | € | Cost incurred by the crew |
| **Parameter name** | **Unit** | **Description** |
| fv | €/t | Fuel cost per tonne |
| cv | t | Fuel consumption per annum |
| ad | km | Annual distance travelled with train |
| LC | € | Cost of lubricating oil, fat and other variable costs per annum |
| RMC | € | Annual cost of repair and maintenance of wagon, container, trailer |
| rc | €/km | Repair cost per km of locomotive |
| mc | €/km | Maintenance cost per km of locomotive |
| RC | € | Rail track user charges per annum |
| OC | € | Other costs per annum |

## 5.3. Applying methodology

This subchapter describes step-by-step approach to derive the performance indicators of this methodology for environmental impact, time duration and cost.

### *5.3.1. Sea transport*

<u>*Environmental impact*</u>

Environmental impact by the sea transport can be determined basing on the single voyage from one port to another.

Following steps have to be going through in order to perform the environmental impact assessment of a ship:

<u>*Creating of operating profile*</u>:

To determine the environmental impact, the operating profile for the ship has to be composed. This means that all the different activities are listed and corresponding time, distance, needed engine power etc. are determined. For operating profile, table 5.10 is given as an example for main engine. The same has to be done for auxiliary engine. Ship is using different power configuration (number of engines running, different loading factors) for each activity, which is important to determine as accurately as possible. If the power profile of a ship according to speed is not known, Admiralty method can be used (see chapter 3.2.4). To determine the fuel consumption per hour, formula 3.4 can be used. As a result of this operating profile, the total consumption of fuel will be obtained.

Table 5.10. Operating profile for ship

| | | | | Main/auxiliary engine | | | |
|---|---|---|---|---|---|---|---|
| Ship operation/activity | Speed | Distance | Time | Used power | Required power | Fuel consumption | Total fuel consumption |
| | kn | nm | h | % | kW | t/h | t |
| Loading/unloading | 0 | 0 | | | | | |
| Maneuvering in Port | | | | | | | |
| Leaving and Entering Port | | | | | | | |
| Voyage | | | | | | | |
| **Total** | | | | | | | |

Exhaust gas emissions will be obtained when applying the emission factors on the amount of fuel burnt. For each fuel, emission factors are different due to the varying chemical composition.

Once the emissions are calculated, those will be divided with number of TEU-s transported (taking into account empty trip factor) and with distance travelled. Therefore the performance indicator g/(km·TEU) will be obtained.

*Time*

Time can be determined by summarizing the durations of all activities. Total duration allows comparison between other transport modes when there exists alternative way for transportation. Annual durations are determined according to the defined voyage and maintenance schedule is known.

*Cost*

Cost can be determined on yearly basis because many cost items are calculated annually (e.g. insurance, administrative costs). This assumes of determining the yearly operation schedule of ship, which depend on many aspects (duration of voyage, time for cargo handling, dry docking, maintenance etc). This yearly operation schedule allows calculating the amount of cargo (number of TEU-s) transported per year. This allows to obtain the cost indicator parameter, when the annual cost is divided by the amount of cargo transported and by distance travelled.

As described in chapter 4.2, cost of sea transport is divided into 5 main cost categories. The calculation rules are also given in that chapter.

### *5.3.2. Road transport*

<u>*Environmental impact*</u>

Determining the environmental impact by the road transport is somewhat easier compared to sea transport. This is on one hand due to the simple engine configuration (ship has multiple main engines and auxiliary engines) and on the other hand due to the assumptions made for the road transport (e.g. no road gradient, no different fuel consumption for various traffic conditions). In addition, loading conditions has to be taken into account, because the fuel consumption is largely affected by this, but only fixed contained weight is used in the frame of this methodology and therefore fuel consumption does not have alternative values during the voyage. Determining the environmental impact is described in the chapter 3.3.3.

<u>*Time*</u>

Duration of the cargo transport can be determined according to the average speed and distance travelled. There has to be taken into account the resting time of driver as well. Guidelines to determine the resting time for driver are given in the subchapter 4.3.5.

<u>*Cost*</u>

Cost has to be determined also yearly basis like in sea transport, because many cost items are determined on annual basis. The calculation rules for cost are given in the chapter 4.3.

### *5.3.3. Rail transport*

<u>*Environmental impact*</u>

Determining the environmental impact by the rail transport assumes determining the gross tonnage of train and according to that the power demand per kilometer. The power demand for gross tonnage-kilometer is derived further to the power demand for net tonnage-kilometer (see chapter 3.4.2.)

Once the power demand per net tonne-kilometer is determined, it is then related with specific fuel oil consumption of diesel engine.

When the fuel consumption per net tonne kilometer is determined, it is easy to derive the fuel consumption per TEU, once the weight of TEU is known. Currently the average weight (12,45 t) of a TEU is used.

Applying emission factor to the fuel consumption, the emission performance indicator g/(km·TEU) will be obtained (see chapter 3.4.2).

*Time*

Duration of the cargo transport can be determined according to the average speed and distance travelled. Also cargo handling has to be taken into account. unfortunately there is lack of data about the speed of a railways and therefore such information is not provided.

*Cost*

Cost has to be determined also yearly basis, because many cost items are determined on annual basis. The calculation rules for cost are given in the chapter 4.4.

## 5.4. Output data

Output data gives opportunity to compare various transport modes on the basis of environmental impact (airborne emissions of $CO_2$, NOx, $SO_2$ and PM), cost and time. Environmental impact and cost is derived to the km-TEU basis which allows easily make rough estimations of total values for different cargo amounts transported and distances traveled. Although, it has to be taken into account that these indicators are not linearly depending on the distance and cargo amounts for every transport mode.

# 6. SCENARIOS

For testing the developed methodology, two transport scenarios were composed, various indicators determined and finally analyzed. As described earlier the focus is put somewhat more on the short sea shipping and therefore both scenarios are consisting sea transport as one part of transport chain. In both cases, transportation begins in Berlin, Germany and ends in Tampere, Finland. This kind of transportation route allows choosing various modes to deliver the cargo. It is therefore possible to simulate the transportation route in such a way, when one mode of transport is prevailing along the transport chain in order to see its influence on cost and emissions. Another reason to choose this route is its existence in reality. In addition, cargo capacity which moves from north to south and vice versa along the Baltic Sea is remarkable. An example of existing cargo routes describing also cargo capacities in the Baltic Sea region is shown on the figure 6.1. Key locations of these 2 scenarios are also drawn on the map.

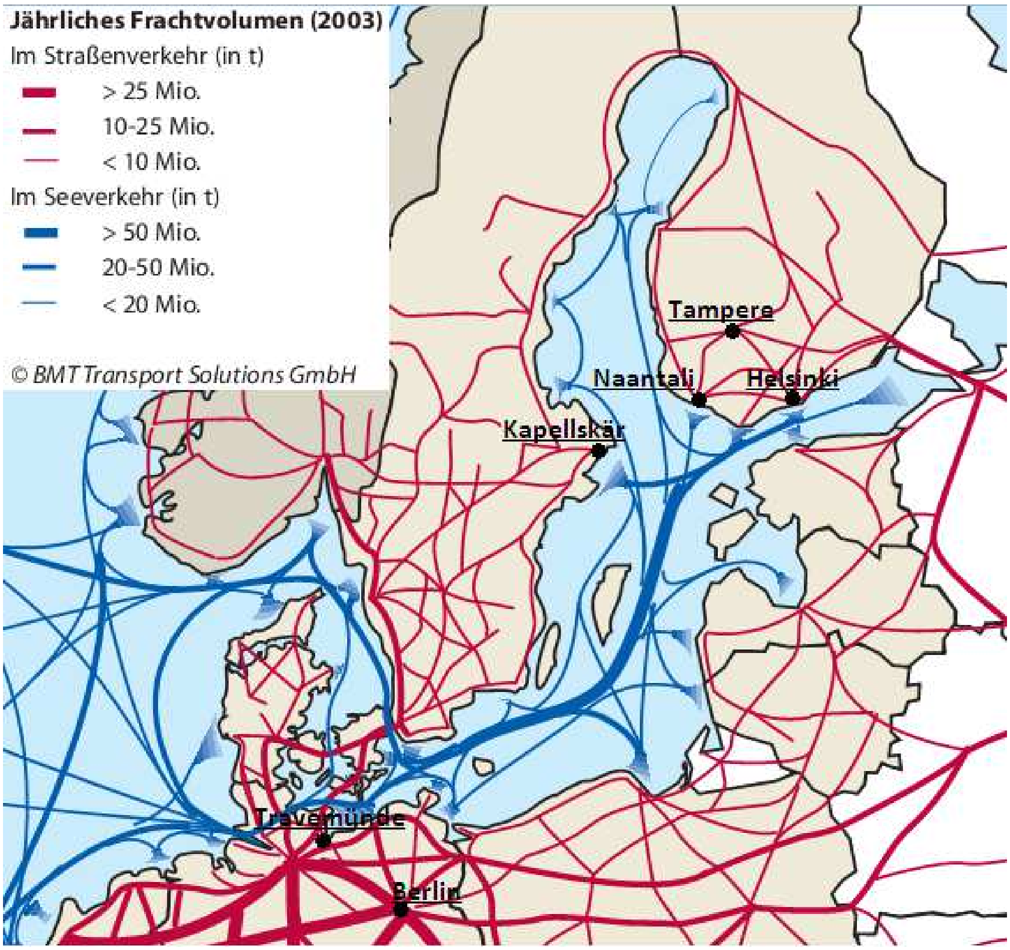


Figure 6.1. Cargo transport in northern Europe. Available from: ec.europa.eu/transport/intermodality/motorways_sea/doc/2006_motorways_sea_brochure_de.pdf [Accessed 15 August 2011]

Defined scenarios are:

1) Berlin (GER) – Travemünde (GER) – Helsinki (FIN) – Tampere (FIN)

2) Berlin (GER) – Kapellskär (SWE) – Naantali (FIN) – Tampere (FIN)

For those transportation routes, the link in the middle is performed by sea and other links are done by road transport. In the current scenarios, rail transport is not included, because of the lack of the input data available. Existing Ro-Pax or Ro-Ro ferry connections are chosen in order to use the data from reality as much as possible. Both connections are operating on a liner trade and the schedule is followed in calculations.

Distances of corresponding transport scenarios are shown on the figure 6.2.

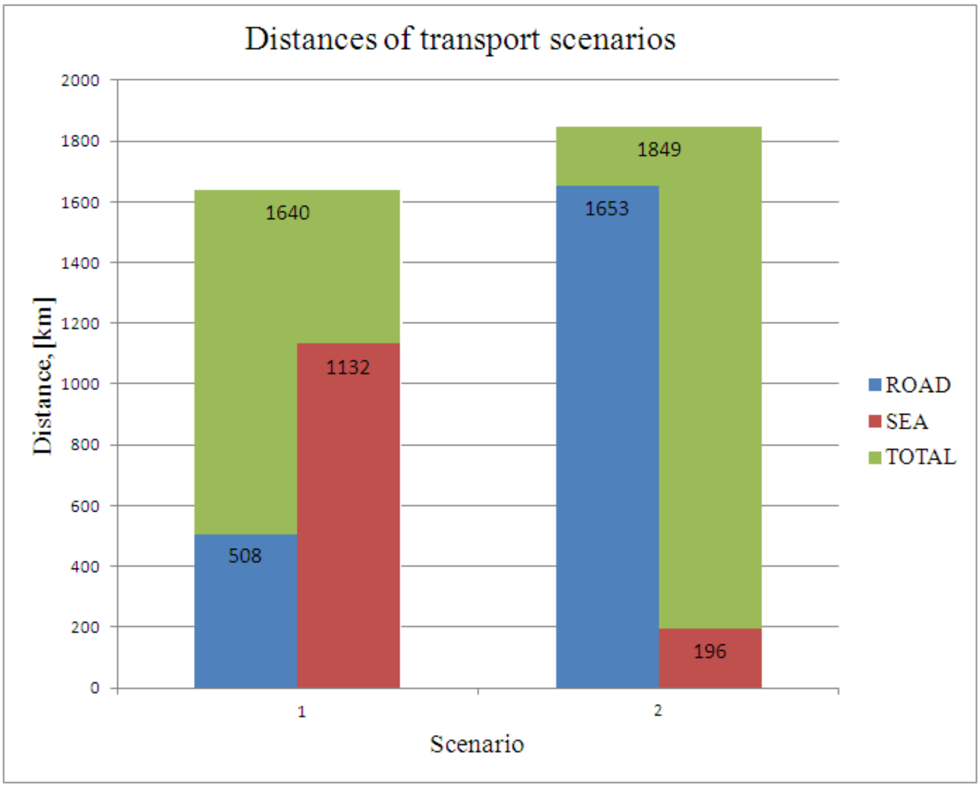


Figure 6.2. Transport scenarios with distances

## 6.1. Scenario 1

Scenario 1 is composed as follows:

| Phase | Transportation mode | Departure | Arrival | Distance, [km] |
|---|---|---|---|---|
| Phase 1 | Road | Berlin | Travemünde | 325 |
| Phase 2 | Sea | Travemünde | Helsinki | 1132* |
| Phase 3 | Road | Helsinki | Tampere | 183 |
| | | | **Total** | **1640** |

* - 1132 km = 611 nm (1 nm = 1,852 km)

# 7. CONCLUSIONS

In the frame of this Master Thesis a methodology was developed which allows to evaluate the environmental impact, cost and calculate the time of transport. Good theoretical background, which was provided in the first part of the Thesis, was composed from various sources and up to date works. This gives solid base for performing the analysis using the developed methodology.

This methodology was build up in a very simple way, where before the each part (environmental impact, cost) of assessment, user has to enter necessary input parameters for each transport mode. When all the input data is available, calculations can be performed according to rules and various performance indicators are the result.

Obtained performance indicators allow simple and transparent comparison between various transport modes, because those are universal and reflecting the data per km·TEU and therefore not depending directly on the voyage distance and amount of cargo. In addition, it is very easy to calculate the amount of pollutions or total cost whatever the amount of cargo is transported and what is the distance. Simplicity is also the main advantage of this methodology. However, there are also restrictions of using performance indicators in such a way, because the dependence of distance and amount of cargo could not be linear in every case.

Although many other studies in this field describe similar methodologies, but these are done it in more detailed way and often connected with the software (e.g. EcoTransIT, Ecoinvent), which is usually not available for free. This work, however, gives possibility to find the impacts by various modes of transport fast and easy. In addition to that, all the calculation rules are described in theoretical part, which allows the user to review their plausibility and do some adjustments when it should be necessary. Because its simplicity, obtained results do not have high accuracy, but in the purpose of rough estimation of environmental impact, cost or some other aspects, this methodology is suitable.

Another advantage of this methodology is the description of allocation principle of environmental impact by cargo, carried by Ro-Pax ship, therefore this methodology is especially suitable for short sea shipping, where this type of ships are widespread. This is actually individual method developed in the frame of another study.

As a drawback of the methodology, it does not allow calculations on the basis of tonne, because it is build up on the TEU basis and each time the weight of TEU has to be fixed.

Due to its simple approach, the methodology could cause some additional inaccuracy to results. Therefore, there are some further improvements to be made:

- Widen the database with various input data with suitability for different conditions.
- Take into account the ageing of the ship and adjust the calculations according to that.
- Implement the algorithm for considering the fuel consumption dependence on the container weight in case of road and rail transport.
- To take into account the influence of road gradient on fuel consumption in case of road transport.
- Include the influence (cost, time) of the congestion in case of road transport.
- Add additional emissions if necessary (currently can calculate $CO_2$, $NO_X$, $SO_2$ and PM emissions)
- Add section for external cost calculation.

To sum up, it can be said that development of this kind of methodology is very time consuming and needs a lot of effort, but as a result the obtained tool is very useful for many people, who are directly or indirectly related with the transport business. In addition to that, this tool helps to find out the environmental impact and cost in the operating phase of the ship/vehicle and to see advantages and drawbacks compared to the other transport modes.

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# A. ANNEXES

## A.1 Abbreviations

$CO_2$ – carbon dioxide
EEDI – energy efficiency design index
EU – European Union
GHG – greenhouse gases
HDV – heavy duty vehicle
HFO – heavy fuel oil
IMO – International Maritime Organization
kWh – kilo Watt hour
MCR – maximum continuous rating
MDO – marine diesel oil
MGO – marine gas oil
$NO_x$ – nitrogen oxides (NO and $NO_2$)
PM – particulate matter
Sfoc – specific fuel oil consumption
$SO_2$ – sulphur dioxide
TEU – twenty feet equivalent unit of container with length of 20 feet (ca 6,1 m).

## A.2 Glossary

**Consignee** – is the receiver; the company receiving the freight; the place where the load or goods are delivered.
**Driving cycle –** Course of vehicle speed and road gradient over time.
**Heavy duty vehicle** – Vehicle for transportation of goods or persons with a gross vehicle weight > 3.5 tons.
**Liner trade –** Ships operating on a schedule basis.
**Lorry** (Articulated vehicle) **–** is a truck coupled to a semi-trailer (or a swap body) which has a permanent or semi-permanent pivoting joint in its construction, allowing the vehicle to turn more sharply.
**PM –** defined as Particulate Matter. According to the emission regulation Particulate Matter ("PM") is defined as "any material collected on a specified filter medium after diluting the exhaust with clean filtered air so that the temperature does not exceed 325 K (52 ºC).
**Ro-ro –** is the shortening of the term, "Roll on/Roll off." It is a method of water cargo service using a vessel with ramps which allows wheeled vehicles to be loaded and discharged without cranes.
**Semi-trailer –** Goods road vehicle with no front axle designed in such way that part of the vehicle and a substantial part of its loaded weight rests on the road tractor.
**Swap body –** carrying unit 2½ meters wide, strong enough for repeated use, but not enough to be top-lifted or stackable more than two deep when loaded, and designed for intermodal transport by road or rail of which at least one leg is by road or rail.
**Tramp trade** – Ships operating with no fixed schedule
**Road tractor** – Road motor vehicle designed, exclusively or primarily, to haul other road vehicles which are not power-driven (mainly semi-trailers).
**Trailer –** Goods road vehicle designed to be hauled by a road motor vehicle.

## A.3 Average speed for road transport

Average speed is calculated according to statistical data provided by Hausberger et al. (2009) and Maibach et al. (2008)

Table A.3. Average speed of road transport

| Area type | Fraction | Road type | Fraction | Level of service | fraction from total trip | Average speed (km/h) | Final average speed (km/h) |
|---|---|---|---|---|---|---|---|
| Rural | 0,82 | Motorway national (>130 km/h) | 0,31 | freeflow | 0,18 | 86,3 | 15,53 |
| | | | | heavy | 0,07 | 81 | 5,67 |
| | | | | saturated | 0,04 | 66,3 | 2,65 |
| | | | | stop&go | 0,02 | 16,6 | 0,332 |
| | | Distributor/ Secondary road (100 km/h) | 0,51 | freeflow | 0,30 | 66 | 19,8 |
| | | | | heavy | 0,09 | 52,7 | 4,74 |
| | | | | saturated | 0,07 | 41,6 | 2,91 |
| | | | | stop&go | 0,05 | 13,5 | 0,675 |
| Urban | 0,18 | Trunk road / Primary city road (70 km/h) | 0,09 | freeflow | 0,05 | 59,1 | 2,95 |
| | | | | heavy | 0,02 | 48,6 | 0,972 |
| | | | | saturated | 0,01 | 38,6 | 0,386 |
| | | | | stop&go | 0,01 | 13,5 | 0,135 |
| | | Distributor / Secondary road (50 km/h) | 0,09 | freeflow | 0,05 | 39,8 | 1,99 |
| | | | | heavy | 0,02 | 30,1 | 0,602 |
| | | | | saturated | 0,01 | 28,7 | 0,287 |
| | | | | stop&go | 0,01 | 11,8 | 0,118 |
| **Total** | **1** | | **1** | | **1** | | **59,8** |