External costs in short sea shipping based intermodal transport chains

Mónica Marques Ramalho

Naval Architecture and Ocean Engineering, Instituto Superior Técnico, Universidade Técnica de Lisboa – PORTUGAL, November 2019

ABSTRACT: The European Union (EU) transport policy has included for many years now the promotion of intermodality and the use of transport modes which have less negative consequences for the environment, health and well-being of European citizens. The external costs of transport reflect, monetarily, those consequences and shall be considered for more efficient transport decisions. This paper is focused on the study and implementation of the methodologies presented in the existent literature for calculation of the external costs implied by intermodal transport chains, with particular focus on the specific features of its application to short sea shipping (SSS) using roll-on/roll-off and container ships. This work builds upon an existent methodology for the economic assessment of SSS routes. A transport network model is improved and used to assess the full costs of transport and therefore the true competitiveness of different SSS Ro-Ro routes in comparison with road and rail alternatives. The methodologies have been tested in different case studies which include different routes using all modes of freight transportation: road, rail, inland waterways and maritime, in different countries, regions, road types and travelling conditions. While SSS shows to be in some cases a suitable alternative, the detrimental effects of speed and of the use of current marine fuels (significant emissions and external costs) are clear and enhance the need for a quick transition into green shipping.

Key Words: External costs, Short Sea Shipping, Intermodality, Transport Networks, Freight transportation, Shipping emissions

1. INTRODUCTION

The focus of the European Union (EU) transport policy regarding its negative externalities has been the shifting of freight transport from the roads to other modes of transport. Freight transport (heavy good vehicles), which is responsible for more than three quarters of total externalities in the EU, contributes significantly to road degradation and air pollution, leading to increased maintenance costs and health related costs, including a significant number of fatalities arising from accidents. The rail and waterborne modes of transport, which include short sea shipping (SSS) and inland waterways (IWW), may well assist the EU in attaining its policy objectives. However, rail and IWW networks of most peripheral countries in the EU are not as developed as in Central Europe and, in most cases, are not effectively interconnected with other regions of the EU. Simultaneously, many issues remain in terms of technical compatibility of railway lines and inland waterways in different countries. Therefore, for peripheral countries, SSS remains the most feasible alternative.

Increasing the utilization of SSS will depend on the relative performance of this mode of transportation in comparison with other modes. While it is known for being cost competitive, its transit time is generally much larger than for road transport. Also, SSS based routes often rely on integration of different transport modes, becoming less reliable when compared to the door to door road service. Furthermore, while shipping is recognisably green regarding CO₂ emissions, its performance is lagging in terms of reducing air pollution, for example due to the much higher sulphur content of maritime fuels in comparison with road diesel. The environmental performance of shipping can be taken into account when making transport decisions based on the social (and not only private) costs. Hence, the internalisation of transport externalities is being discussed as a way of promoting sustainable multimodal transport in the EU[1].

1.1. External costs of transport

When the full costs of an activity are not included in its private costs but are partly imposed in society, a party who did not chose to incur in that activity, there is a deadweight loss of social welfare. This difference between social and
private (internal) costs is called external cost and its existence leads to market inefficiency.

In the freight transport market this means that the real price of transport is not fully imputed to transport users. The external costs of transport reflect the environmental impacts (air pollution, climate change, noise and up and downstream processes), accidents, congestion and infrastructure wear and tear. Internalizing these costs means making the external effects of transport part of the decision-making process of the transport users (Korzhenevych et al. 2014). This can be implemented by means of taxes and charges which will make the users look for different, and more environmentally and socially friendly, possibilities in terms of vehicle type, vehicle utilization, transport mode or transport volume.

A set of studies on the economics of external costs in the transport sector emerged from the quest for an optimal pricing policy. In the light of the Eurovignette Directive on road infrastructure charging, the EU commissioned the study IMPACT (Internalisation Measures and Policies for All External Cost of Transport) on the internalisation of external costs of transport. The resultant handbook presented at the time the state of the art and best practice on external cost estimation. It recommended methods for calculating external cost figures using the best available input values and presented estimated unit values for different traffic situations in a vehicle kilometre basis for the base year of 2000. In 2011, part of the committee responsible by the IMPACT study published an update of the report using 2008 as base year in CE Delft, Infras and Fraunhofer ISI (2011). The original handbook (Maibach et al. 2008) has been revised and updated (Korzhenevych et al. 2014; van Hessen et al. 2019) and presents now the state of the art and best practice on the estimation of external costs of transport.

Meanwhile the Marco Polo programme, dating from 2003, was active in the European Union and aimed at assisting companies shifting freight transport off the roads to other more environmentally friendly transport options. The merits of this project were measured by the difference in external costs between the transport service before the project and the transport service after the project implementation. The most recent external cost methodology implemented under the Marco Polo Calculator (Brons & Christidis 2013), and used in the latest call for projects, covers cost calculations for road, rail, inland waterways and short sea shipping providing cost coefficients for both environmental (air pollution, noise and climate change) and socio-economic impacts (accidents and congestion). This methodology follows the previous IMPACT study approach with an update to 2011 and allows for the estimation of external cost coefficients for different subcategories of the transport modes based on fuel technology, cruising speed, vehicle size and cargo type. However, the differences in the emission factors and specially in the load factors used in this study, produce very disparate unit cost figures particularly for the case of waterborne transport. The most recent versions of the handbook recognize this and therefore the Marco Polo estimates are not exploited further in this paper.

### 1.2. Ship emissions and its external costs

To access the real potential and competitiveness of SSS based routes, its external costs need to be carefully monitored and compared with those of other transport modes. The major external impacts of shipping are related with air pollution and climate change not only during navigation but from up and downstream activities (construction, maintenance and disposal of ships and vessels and port terminals). An analysis of the latest methodologies, available technologies and policy options for regulating air emissions from ships concludes that the limited availability of data has resulted in differing calculation methodologies of ship emissions that are often not easy to compare (Miola et al., 2010). In the Marco Polo calculation method, the calculation of external costs of waterborne transport is based on different emissions factors and damage costs from the ones in the handbook of 2014. However, it provides useful references on the emission reduction factors of alternative fuel technologies other than low sulphur fuel for IWW, see Table 1, and conventional high sulphur fuel for SSS, Table 2.

#### Table 1: Emission reduction factors of IWW fuel technologies for various air pollutants and CO₂

<table>
<thead>
<tr>
<th>Fuel technology</th>
<th>NO₂</th>
<th>PM</th>
<th>SO₂</th>
<th>CO₂</th>
<th>Fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Particulate Filter (DPF)</td>
<td>-</td>
<td>-68 %</td>
<td>-</td>
<td>-</td>
<td>+2 %</td>
</tr>
<tr>
<td>Selective Catalytic Reduction (SCR)</td>
<td>-85 %</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DPF+SCR</td>
<td>-85 %</td>
<td>-68 %</td>
<td>-</td>
<td>-</td>
<td>+2 %</td>
</tr>
<tr>
<td>LNG</td>
<td>-75 %</td>
<td>-97 %</td>
<td>-</td>
<td>-10 %</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Table 2: External cost correction factors per alternative fuel technology in SSS

<table>
<thead>
<tr>
<th>Fuel technology</th>
<th>Air pollution</th>
<th>Climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td>High sulphur fuel</td>
<td>Base option</td>
<td></td>
</tr>
<tr>
<td>Low sulphur oil (0.1%)</td>
<td>0.642</td>
<td>0.980</td>
</tr>
<tr>
<td>Seawater scrubbing</td>
<td>0.580</td>
<td>-</td>
</tr>
<tr>
<td>Freshwater scrubbing</td>
<td>0.573</td>
<td>-</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.054</td>
<td>0.800</td>
</tr>
<tr>
<td>LNG</td>
<td>0.054</td>
<td>0.800</td>
</tr>
</tbody>
</table>

The calculations for the handbook of 2014 for air pollution and climate change costs for inland water transport are based in the emission factors from the STREAM (Study on Transport Emissions for All Modes) database (den Boer, Otten, & van Essen 2011) and emission reduction factors from the Marco Polo methodology. The marginal air pollution and climate change costs for maritime transport are reported differentiated per sea area according to the
damage costs in sea areas from the NEEDS\textsuperscript{2} project (Preiss & Klotz 2007). Other interesting types of vessels, namely container ships and Ro-Ro, are not included due to lack of data according with this version of the handbook. An update of the original STREAM study was more recently published (Otten, Hoen, & den Boer 2017). This study reviews the emission factors of freight transport for the year 2014 providing solutions for direct intermodal comparison. The emissions are calculated based on the new sulphur limit of 0.1 % (ships sailing on MGO) using the most recent emission factors available from the third IMO GHG study (IMO 2015). The NO\textsubscript{x} emissions depend on engine type, rpm and Tier category to which the engine belongs. This report explains clearly how the load capacity and the utilisation factor determine the emissions per tonne-km and presents particular emissions from container transport assuming an average load per TEU. Using these emissions factors along with the damage costs reported in the handbook, in € per tonne, allows for a new and updated estimation of air pollution, climate change and of part of the up and downstream costs. Based on the same emission factors for maritime shipping from IMO (2015) the EcoTransIT World (Ecological Transport Information Tool – Worldwide) was developed and available online for calculation of the environmental impact of freight transport for any route and any transport mode (EcoTransIT World Initiative (EWI) 2018).

In the most recent version of the handbook, marginal air pollution and climate change costs are now presented for selected cases of different types of freight vessels based on those emission factors. Container IWT barges, pushed convoys and containerships of different deadweights are included and the cost factors are presented in € per vessel-km.

1.3. Emissions abatement technologies

The recent application of the 0.1 % MARPOL limit in Sulphur Emissions Control Areas (SECAs) and the upcoming implementation in 2020 of the 0.5 % global limit of sulphur emissions sponsored the development of technologies capable of significantly cutting air pollution from ships.

In general, ships are allowed today to used fuels with sulphur content up to 3.5%. The new standards will apply to the entire fleet up to 2020. Regarding NO\textsubscript{x} limits, those apply only to new ships. The current global standard from IMO Tier II limits the emissions to 7.7-14.4 g of NO\textsubscript{x}/kWh. The stricter Tier III NO\textsubscript{x} standard of maximum 2-3.4 g of NO\textsubscript{x}/kWh will apply to new ships built after 2021 only when sailing in NO\textsubscript{x} Emission Control Areas (NECAs) (NO\textsubscript{x} emissions reduced in 80% in relation to the Tier 1 limits of 9.8-17.0 g/kWh). The North and Baltic Sea and the English Channel are ECAs where the stricter emissions control standards, both for SO\textsubscript{2} and NO\textsubscript{x}, apply.

Air pollution is, in shipping, the greatest contributor to external costs having a great impact on human health. Understanding the options to cut pollution from ships is important to help define which fuel technologies can and must be used depending on the geographical location of the network links. The environmental impact of the SSS services will be analysed per link (a ship route is composed of several links, inside or outside ECAs) depending on the emissions limits in force. These alternatives to the use of conventional high sulphur oil, for which impact on emissions is quantified, include:

- Using low sulphur fuels.
- Exhaust gas treatment systems (Diesel Particulate Filters (DPF) and Scrubbers).
- Selective catalyst reduction (SCR).
- Combined DPF+SCR.
- Gas or duel-fuel engines (LNG, methanol).

SO\textsubscript{2} compliance options include the use of low sulphur fuels, reducing the emissions at source, and the use of exhaust gas treatment systems (scrubbers) on the exhaust system of higher sulphur fuels. Low sulphur distillate oils (LSDO) are usually marine diesel oil (MDO) or marine gas oil (MGO) (Lloyd's Register Marine 2015). A popular alternative is the use of LNG which is a sulphur free fuel.

NO\textsubscript{x} emissions are created during the combustion process and depend on the fuel being used as well as on the engine design. Selective catalytic reduction (SCR) is a developed technology for NO\textsubscript{x} control which can be fitted in medium-speed four stroke and low-speed two stroke diesel engines. (Lloyd's Register Marine 2015).

1.4. Application studies to different transport modes

Several studies have emerged on the comparison between short sea shipping and other transport modes services based on the calculation of external costs in Europe. The works of Sambracos and Maniati (2012), Tzannatos, Papadimitriou and Katsouli (2014), Vierth, Sowa and Cullinane (2018) and Jiang, Kronbak and Christensen (2010), just to mention a few, lead to the conclusion that the competitiveness of the sea alternative in comparison with the road alternative (and other modes) depends not only on the methodology used but upon several factors such as the world region and the distance travelled and so the need for a case-by-case analysis of the external costs.

Furthermore, the green label of shipping has been questioned by Hjelle (2010). While there is no doubt about the superior comparative efficiency of ships when fuel consumption is calculated per deadweight tonne (conclusions often based on bulk carriers), that might not be the case for SSS services based on container or Ro-Ro technologies when dividing fuel consumption per cargo tonne as these ships have a lower payload capacity, cargo utilization factors and operated at higher speeds. Also, while in terms of CO\textsubscript{2} emissions shipping is accepted as an environmentally friendly transport mode that is not the case

\textsuperscript{2} NEEDS - New Energy Externalities Developments for Sustainability.
for other pollutant emissions when no emissions abatement technologies are applied (Hjelle & Fridell 2012).

2. METHODOLOGY

Based on the unit values from the references, a methodology was developed and applied to an existing transportation network for calculation of the external costs and emissions in routes of interest. As a result of this, two computer programs – Subroutine External Costs 2014 and Subroutine External Costs 2019 - were developed that implement the methodology and use the pre-existing transport network, being only different by the input files with the costs coefficients data they work upon. Those are based on the handbook versions of 2014 and 2019, respectively. Below, in general, the calculation is explained using the 2014 version of the handbook, but the code implementing the 2019 version is similar. The chart in Annex A summarizes all the input files, main calculation alternatives and tasks performed by the programs.

2.1. Transport network model

The network consists, currently, on 3018 nodes connected by 3828 links spread over the geographical region comprised between Portugal and Northern Europe, but including also Italy, Greece and Sweden. It is an intermodal transportation network accounting for four different modes of transportation: road, rail, inland waterways and short sea/maritime shipping. The nodes and links form an extensive database along with its relevant node-specific and link-specific characteristics for the calculation of both internal and external costs of transportation.

The specification of transport services is done by the user through paths. The user may specify as many paths as are necessary to describe alternative transportation services between a pair origin-destination. A path is a set of links used in succession and is specified using an ordered list of nodes. A computer code will identify the succession of links connecting the different nodes included in this list and will also identify the type (road, rail, IWW, SSS) of each link.

For each path, there is also a number of definitions specific of each transport mode involved in the carriage of goods between the origin and the destination. First, a variable takes the information on whether the trip takes place during the day or during the night. For the truck, the truck type, cargo capacity, gross weight, type of propulsion, EURO class, utilization factor, engine power and specific consumption and the number of axles is included. For ships (SSS) the ship type, deadweight, freight capacity (trailers), capacity utilization, type of fuel for main and auxiliary machinery, IMO emission standard, main and auxiliary engines speed rating and propulsion power and ship’s design speed, are included. Similar definitions are included for trains and inland waterways vessels.

2.2. Method for costs calculation

As mentioned before, the external costs fall in the following categories: congestion, accidents, noise, air pollution, climate change, costs of up and downstream processes and marginal infrastructure costs. External costs are expressed as function of marginal cost coefficients which, depending on type of cost (and on the version of the handbook) are expressed in euros per ton, ton-km or vehicle-km. In this chapter, the vehicle will be considered as roughly equivalent to a road semi-trailer or a FEU container. Depending on the ship type (Ro-Ro or container ship), the cargo unit will then be of one or the other type. The external costs are given by:

$$C_{Ext-ij} = C_{Cong-ij} + C_{Acc-ij} + C_{Noi-ij} + C_{Air-ij} + C_{CC-ij} + C_{ud-ij} + C_{Inf-ij}$$

(1)

where the different terms are self-explanatory, but is must be taken in consideration that over a path between i and j, there will be, for example, air pollution costs arising from road, rail, IWW and maritime transportation. It may happen that the path involves only some of these transport modes, implying that some air pollution cost components will be inexistent. Also, Korzhenevych et al. (2014) indicates that for maritime transportation (IWW and SSS) there are no accident, congestion and noise external costs.

The general formulation for the external costs’ calculation will be exemplified below for selected cases which serve to illustrate the general principles. Let us take again a path between an origin i and a destination j. Within this path there will be a number of links in succession, each one being denoted as k. These links may correspond to different modes of transportation. For example, the congestion cost borne in a given link k of road type, in € per vehicle, may be calculated by:

$$C_{cong-ijroad-k} = c_{m cong road} \times \frac{d_{ijk}}{100}$$

(2)

where $d_{ijk}$ is the travelled distance within the link in km and the marginal coefficient $c_{m cong road}$, given in €ct/vkm, is taken from the tables provided in Korzhenevych et al. (2014). This coefficient is dependent on the type of vehicle, the link’s region, road type and its congestion band:

$$c_{m cong road} = f(\text{vehicle, region, road type, congestion band})$$

(3)

The metropolitan regions in Korzhenevych et al. (2014) are considered to be referring to the suburban regions in the method’s implementation. Also, the links labelled as motorways in urban areas are treated as urban main roads when choosing the most suitable cost coefficient. The congestion band of a road is defined by its volume (actual traffic flow v) to capacity (theoretical maximum traffic flow c) ratio, which may range from less than 0.25 to over 1.0, as categorized in the FORGE model (Department for Transport (2015)). As it was not possible to find information enabling a characterization of the different types of road at a European level, only the free flow band and the higher bands are chosen as the most representative. In the implementation, congestion bands 1
to 3 are considered free flow (up to v/c equal to 0.75). The links in urban and suburban areas have been assigned category 4 (near congestion) while the others are categorized as free flow. A few notoriously congested motorways in urban areas where categorized as category 5 (over capacity).

While road transportation is carried out on an individual basis (on a truck), rail, IWW and maritime transportation is carried out collectively and the external costs need to be split by the individual cargo units. The procedure adopted for this split is now exemplified, for the case of a link of rail type. The congestion cost, in € per cargo unit, is calculated by:

$$C_{cong;i\_rail-k} = \frac{c_{m\_cong\_rail} \times d_{ijk} \times LF_{MR}}{1000 \times TraCap_{ij} \times TraUt_{ij}}$$  \hspace{1cm} (4)

where the cost coefficient $c_{m\_cong\_rail}$, given in €/1000tkm, is a coefficient from Korzhenevych et al. (2014) and depends on the country of transit:

$$c_{m\_cong\_rail} = f(\text{country})$$  \hspace{1cm} (5)

When country specific values are not available, the EU average values are used. The unit costs per tonne kilometre are transformed into costs per train kilometre using the rail-specific load factors ($LF_{MR}$) in tonnes referred in Brons et al. (2013), actually based on the TREMOVE model (De Ceuster et al. 2004). The cost is divided by the train capacity in trailers $TraCap_{ij}$ multiplied by the train capacity utilization factor $TraUt_{ij}$ in order to obtain the values per carried trailer. These variables are included in the path definition.

The climate change cost borne in a given link $k$ of maritime transport type, in € per cargo unit, is calculated by:

$$C_{cc;i\_mar-k} = \frac{c_{cc\_mar} \times d_{ijk}}{SssCap_{ij} \times SssUt_{ij}}$$  \hspace{1cm} (6)

The cost coefficient $c_{cc\_mar}$ given in € per ship-km and depends on the type of ship, DWT and sea region:

$$c_{cc\_mar} = f(\text{type of ship, DWT, sea region})$$  \hspace{1cm} (7)

The type of ship and DWT must be in the path definition. Container ships, Ro-Ro and Ro-Pax ships are considered to fall into the general cargo vessel type. For bulk carriers, feeder size is considered as up to 15kt DWT, handysize from 15kt to 40 kt and handymax greater than 40 kt. The cost is divided by the vessel’s capacity in trailers $SssCap_{ij}$ multiplied by the capacity utilization factor $SssUt_{ij}$ in order to obtain the values per trailer carried onboard. These variables are defined in the path definition. The central value of the carbon price used in Korzhenevych et al. (2014) is 90€ and a recommendation is put on the update of the unit costs proportional to the variation of the estimates on the carbon price. In the most recent version of the handbook the recommended price is 100 €/ton CO₂.

2.3. Activity-based emissions and external costs

The lack of consistence between the different sources of air pollutant emissions related external costs factors, especially in the case of ships, supports in many studies the use of an activity based methodology to calculate those costs. This alternative methodology is based on an estimate of the actual quantity of pollutant emissions in a trip through the calculation of the vehicle’s fuel consumption combined with emission factors. In the end, the damage costs per quantity of pollutant are used to evaluate the external costs. This can be done for all transport modes considering that either engine load or consumption characteristics and fuel are known, and emission factors or vehicle standards are available. For the case of short sea shipping, first, the vessel’s fuel consumption must be calculated, it should include main and auxiliary engine(s) consumption. The vessel’s main engine fuel consumption $FC_{ME}$ per link, in g, can be calculated according with:

$$FC_{ME\_ijk} = \frac{SFOC_{ME} \times P_{EF\_ijk}}{s_{ijk}} \times d_{ijk}$$  \hspace{1cm} (8)

where $P_{EF}$ is the effective capacity of the main engine, in kW, $SFOC_{ME}$ is the specific fuel oil consumption of the main engine in g/kWh and $s_{ijk}$ is the travel speed within the link in km/h.

The effective output at a given link speed $s_{ijk}$, in kW, can be estimated using the brake power-speed relation in (9), assuming an engine load factor at design speed with clean hull and in calm weather of 0.9. The factor 1.09 accounts for hull roughness and 1.15 for wave resistance in average conditions as per EcoTransIT World Initiative (EWI 2018) . $P_{ME}$ is the nominal power of the main engine, in kW, and $SssSpeed_i$ is the design speed of the vessel (without sea margin):

$$P_{EF\_ijk} = 0.9 \times 1.09 \times 1.15 \times SssP_{ME\_ijk} \times \left(\frac{s_{ijk}}{SssSpeed_i \times 1.852}\right)^3$$  \hspace{1cm} (9)

The main engine fuel oil consumption factors for engines as old as 2001 (IMO 2015) assumed in this model are 175 g/kWh, 185 g/kWh and 195 g/kWh, for, respectively, slow speed, medium speed and high speed engines.

Similarly, the fuel consumption in g of the auxiliary engines (and/or boilers) can be calculated as follows:

$$FC_{AE\_ijk} = SFOC_{AE} \times P_{AE} \times \frac{d_{ijk}}{s_{ijk}}$$  \hspace{1cm} (10)

depending on the time and engine load at sea $P_{AE}$ in kW. No emissions in port are being accounted for. The engine load at sea is assumed to be 30 % of engine MCR according to Whall et al. (2002). For auxiliary engines and boilers, the specific fuel oil consumption factor, $SFOC_{AE}$, is 225 g/kWh for medium speed engines operating on either HFO or MDO.
Next, the amount of emissions per pollutant is obtained by multiplying the fuel consumption by the emission factors in g/g fuel:

\[ g \text{CO}_{2,ijk} - \text{eq} = FC_{\text{ME,ijk}} \times e_{\text{CO}-\text{eq,ME}} + FC_{\text{AE,ijk}} \times e_{\text{CO}-\text{eq,AE}} \]  
\[ g \text{SO}_{x,ijk} = FC_{\text{ME,ijk}} \times e_{\text{SO}_x,\text{ME}} + FC_{\text{AE,ijk}} \times e_{\text{SO}_x,\text{AE}} \]  
\[ g \text{NO}_x,ijk = FC_{\text{ME,ijk}} \times e_{\text{NO}_x,\text{ME}} + FC_{\text{AE,ijk}} \times e_{\text{NO}_x,\text{AE}} \]  
\[ g \text{PM}_{ijk} = FC_{\text{ME,ijk}} \times e_{\text{PM},\text{ME}} + FC_{\text{AE,ijk}} \times e_{\text{PM},\text{AE}} \]  

(11)  
(12)  
(13)  
(14)

The most important air pollutants impacting human health are particulate matter (PM) (mostly fine PM$_{2.5}$ from exhaust emissions), nitrogen oxides (NO$_x$) and sulphur oxides (SO$_2$).

The most recent emission factors available for maritime transport come from (IMO 2015), differentiated by main engine and auxiliary engine, fuel type, engine rating and IMO tier for NO$_x$ emissions. The sulphur content of HFO is assumed to be 2.51% and for MDO 0.1% according with the latest regulations. Tier 3 emission factors are deducted from Tier 1 with an 80% reduction.

Finally, the damage cost factors of exhaust emissions in €/ton of emitted pollutant differentiated per sea area from the NEEDS project can be used to estimate air pollution external costs due to exhaust emissions from maritime transport $c_{\text{air,mar},ijk}$ € per trailer according to:

\[ c_{\text{air,mar},ijk} = c_{\text{ton,SO}_x} \times g \text{SO}_{x,ijk} + c_{\text{ton,NO}_x} \times g \text{NO}_x,ijk + c_{\text{ton,PM}} \times g \text{PM}_{ijk} \times 10^6 \times Sss\text{Cap}_{ij} \times Sss\text{Ut}_{ij} \]  

(15)

For climate change costs, the amount of emitted CO$_2$ equivalent gases (GHG) is multiplied by the estimate of the carbon price to calculate the climate change external costs, given in € per trailer:

\[ c_{\text{CC,mar},ijk} = c_{\text{ton,CO}_2} \times g \text{CO}_2,ijk - \text{eq} / 10^6 \times Sss\text{Cap}_{ij} \times Sss\text{Ut}_{ij} \]  

(16)

For those alternative fuel technologies other than the use of MDO or HFO for which emissions factors are known, the external cost reduction factors in Table 2 can be applied.

3. NUMERICAL RESULTS

3.1. Road and intermodal routes in Greece

The numerical methods above will now be illustrated in a case study where a comparison is made with the results published in a paper by Tzannatos, Papadimitiou and Katsouli (2014). This paper reports a study of intermodal transport (road haulage plus short sea shipping) versus unimodal transport (fully road based), along the corridor between Athens and Thessaloniki freight centres. Cargo units considered in that study are trucktainers (12m in length), implying unaccompanied traffic. SSS is carried out using a cargo Ro-Ro ship with 20070 kW of main engine power and 4 x 1720kW auxiliary power. The assumed cargo utilization factor of the ship is 62.5%, equivalent to carrying 200 trucktainers in each direction. At sea, the main engine operates at 80% load and the auxiliary engines at 30% load, while in port the main engine operates at 20% load for 20% of the time and is turned off for the remaining 80% of time.

In what concerns the road leg associated with the intermodal transport, a 5 axles EURO 5 truck is considered, and it is assumed that 55% of the distance is driven along a motorway. This motorway section is driven along for 40% of the overall travel time with a truck engine load of 60%, while the road section takes 60% of the overall travel time at 30% engine load. When unimodal transport is used it is assumed that the truck engine load factor is 60% for 90% of the overall travel time, when driving along a motorway. When driving in other roads the engine load is 30% and this takes 10% of the overall travel time.

In this paper a further study is carried out based on the main features of the Tzannatos, Papadimitiou and Katsouli (2014). Given that this author found out that external costs were actually higher in the intermodal transport solution than in the unimodal solution, for the utilization factor of 62.5%, it was decided to investigate how such a situation could be improved, using the numerical methods and route network model explained above. The utilization factor was set at 80% of the ship’s cargo capacity as most owners will not operate ships in routes with low utilizations for long without subsidies, as experiences with Marco Polo programme clearly indicate. A set of alternative scenarios is considered in this chapter, exploring three different sea routes, as shown in Figure 1.
similar to the one used in road transport, is considered, this having a sulphur content of 0.005% by mass (50 ppm).

The two first scenarios shown in Table 3 are identical to the ones studied in the paper. In addition to these scenarios, new ones are developed using the ports of Agii Apostoli and Kimasi, which are much closer to Thessaloniki than Lavrio is, as shown in the fourth column of Table 3, and, therefore, allow ship speed to be decreased from 25 knots, which is a very high speed for a Ro-Ro cargo ship and leads to very high emissions, to 19 knots, while slightly decreasing the sailing time to 8.7 hours, in the case of Agii Apostoli, and 6.7 hours, in the case of Kimasi. The use of these two ports is tested in scenarios 3 and 4, while in scenario 5 the ship’s speed is further decreased to 15 knots (probably the lower limit for typical sailing speeds of Ro-Ro cargo ships in EU short sea routes) and an emission control area (ECA) is put in place, implying that the ship’s main engines and generators both run on low sulphur (0.1%S) fuel.

In the other scenarios, the main engines run on HFO (2.7%S) and the generators on low sulphur MDO (0.1%S). Scenario 6 comprises the utilization of the TRAINOS railway line which offers rail freight transport in the corridor Athens-Thessaloniki. This last scenario already runs as a competitive alternative to both sea and road freight transport in this region.

Table 3: Characteristics of the different scenarios studied in the corridor Athens-Thessaloniki

<table>
<thead>
<tr>
<th>Identification</th>
<th>Name</th>
<th>Description</th>
<th>Distances</th>
<th>Number of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Direct ferry</td>
<td>Ro-Ro cargo ship Lavrio-Thessaloniki + Short range road haulage</td>
<td>Road distance: 68 km Sea distance: 418 km</td>
<td>15</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Road direct</td>
<td>Long range haulage</td>
<td>Road distance: 489 km</td>
<td>17</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Agii Apostoli ferry</td>
<td>Ro-Ro cargo ship Agii Apostoli-Thessaloniki + Short range road haulage</td>
<td>Road distance: 97 km Sea distance: 299 km</td>
<td>16</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Kimasi ferry</td>
<td>Ro-Ro cargo ship Kimasi-Thessaloniki + Medium range road haulage</td>
<td>Road distance: 188.5 km Sea distance: 227 km</td>
<td>14</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>Kimasi ferry (ECA)</td>
<td>Ro-Ro cargo ship Kimasi-Thessaloniki (within ECA) + Medium range road haulage</td>
<td>Road distance: 188.5 km Sea distance: 227 km</td>
<td>14</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>Rail</td>
<td>Long-haul freight train Athens (Thriasion) – Thessaloniki (Trigonos) + Short range road haulage</td>
<td>Road distance: 14 km Rail distance: 471.5 km</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 2 shows the air pollutant and climate change emissions for the various scenarios, calculated using the activity-based methodology detailed above, on a per trailer basis. It may be seen that scenario 1 is by far the worst case for all types of emissions, except for CO$_2$ emissions which are larger in the road direct scenario. When the two other ports are used the emissions drop severely because of the shorter distance travelled by ship and the lower speed used (19 knots). The air pollutant emissions remain still much higher than those of the road direct scenario, but CO$_2$ are more than 40% lower than those for the road direct service. Finally, if the Kimasi port is used but the ferry runs on low sulphur fuel only and at a reduced speed of 15 knots (due to a fictitious ECA zone in the Aegean Sea) the SO$_2$ and PM emissions are severely decreased, while NO$_x$ decreases moderately. Overall, this last scenario emission levels are like those of the road direct service other than the level of CO$_2$ emissions which are decreased by the sea leg. Furthermore, the use of emission abatement technologies on-board or of cleaner fuel types would be able to make all SSS alternatives superior to the road alternative emissions-wise. Finally, the rail alternative is competitive in terms of CO$_2$, PM and SO$_2$ emissions but produces large quantities of NO$_x$.

Figure 3 shows the total external costs per trailer for the six different scenarios. It is evident that the situation is more evenly balanced than that seen for the emissions. This is because the road direct scenario presents much more external costs related with congestion (39%), accidents, noise, infrastructure and up and downstream costs, and these compensate for the lower emissions related external costs.
Overall, the first scenario presents the largest external costs per trailer. When measures are taken to decrease emissions, namely using the two other ports, decreasing the ship speed or using low sulphur fuel, the external costs of the door-to-door intermodal transport solution decrease significantly and become lower than that of the road direct scenario. The rail direct scenario shows to be a competitive alternative with similar total external costs to the alternative scenarios 3 to 5.

3.2. Intermodal routes in the corridor Valongo-Paris

Portugal and Spain have significant volumes of trade in goods with central European countries, as France, and could therefore benefit from the use of Ro-Ro based SSS services as an alternative to routes that are taken mainly by road (Santos & Guedes Soares 2017). Therefore, in this subchapter a study of intermodal transport solutions in this corridor is reported. Different transport scenarios are chosen involving all transport modes considered in the model as represented in Figure 4, and its characteristics are presented in Table 4.

![Figure 4: Transport network supporting the intermodal and unimodal routes in the corridor Valongo -Paris](image)

The objective of this study is also to include paths with all transport modes being tested. For the road links, a 5 axles 40t EURO 5 articulated truck is considered at 85% of loading capacity and having an engine with a power of 365 kW and a specific fuel oil consumption of 215 g/kWh. For the rail links, a diesel train with a capacity of 40 FEU’s utilized at 75% is considered, having an installed power of 2240 Kw and a SFOC of 236 g/kWh. A vessel with 737 kW of installed power is considered for inland waterways links, having a capacity of 50 FEUs utilized at 60%. Two reference cargo ships are considered for maritime links: a containership having a deadweight of 11200 t, a capacity of 306 FEUs/trailers @14 tons utilized at 70%, an installed power for the main engine of 8400 kW and two auxiliary generators at 500 kW each; a ro-ro cargo ship having a deadweight of 13535 t, a capacity of 239 FEUs/trailers utilized at 80%, an installed power for the main engine of 12000 kW and 1270kW of auxiliary power.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Name</th>
<th>Description</th>
<th>Distances</th>
<th>Speed average</th>
<th>Number of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Road direct</td>
<td>Long range road haulage</td>
<td>Road distance: 1628 km</td>
<td>Road: 80 km/h</td>
<td>54</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Rail</td>
<td>Long haul freight train Valongo-Paris + Short range road haulage</td>
<td>Road distance: 47.5 km</td>
<td>Railway distance: 1745 km</td>
<td>Road: 50 km/h</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>SSS LeHavre (Ro-Ro)</td>
<td>Ro-Ro cargo ship Leixões-Le Havre + Medium range road haulage</td>
<td>Road distance: 246 km</td>
<td>Sea distance: 836 km</td>
<td>Road: 80 km/h</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>IWW</td>
<td>Short range road haulage + Containership Matosinhos-Le Havre + Inland vessel Le Havre-Paris</td>
<td>Road distance: 38 km</td>
<td>Inland distance: 343 km</td>
<td>Sea distance: 841 km</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>SSS St.Nazaire (Ro-Ro)</td>
<td>Medium range road haulage + Ro-Ro cargo ship Leixões-St. Nazaire</td>
<td>Road distance: 460 km</td>
<td>Sea distance: 1086 km</td>
<td>Road: 80 km/h</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>SSS Gijon (Ro-Ro)</td>
<td>Long range road haulage + Ro-Ro cargo ship Gijon-St. Nazaire</td>
<td>Road distance: 988 km</td>
<td>Sea distance: 482 km</td>
<td>Road: 80 km/h</td>
</tr>
<tr>
<td>Scenario 7</td>
<td>SSS Gijon &amp; Rail St. Nazaire</td>
<td>Medium range road haulage + Ro-Ro cargo ship Gijon-St. Nazaire + Freight train St. Nazaire-Paris</td>
<td>Road distance: 585.5 km</td>
<td>Railway distance: 507 km</td>
<td>Sea distance: 482 km</td>
</tr>
</tbody>
</table>

3 Reference vessel: WEC VERMEER IMO 9237371
Figure 5 shows the air pollutant and climate change emissions for the various transport alternatives, calculated using the methodology described in 3.4, in quantities per trailer, using a carbon price of 100 €/tCO₂. As expected, the road direct option is clearly the worst alternative regarding carbon-based emissions. This footprint of the road service is also noticed in scenario 6 with road haulage corresponding to two thirds of the distance travelled. CO₂ emissions can drop to less than one third when a SSS based alternative is preferred as it is the case with scenarios 3 and 4. The alternatives that include SSS consider the English Channel ECA with the use of low sulphur oil in those links but heavy fuel oil with sulphur 2.5% outside. This is the reason for the higher air pollutant emissions in those alternatives. Although NOₓ remains an issue when no emission control options are considered, the least pollutant alternative is the SSS based route to Le Havre (Ro-Ro) represented by scenario 3. In scenario 4, while the maritime distance is the same as in scenario 3, NOₓ emissions are more than double. This is due to the inland waterways leg, which is using low sulphur oil but no emissions abatement technology, resulting in much higher external costs than when the leg Le Havre-Paris is done by road.

The results on the external costs of this transport scenarios were added to its internal costs (Santos & Guedes Soares, 2017), resulting in Figure 7. This means that Figure 7 shows the results of a full internalization of the external costs. Considering this, the unimodal solution becomes more attractive compared to scenario 6 using SSS contrary to what happens when only external costs are considered. Even so, the superiority in terms of total costs of SSS routes in this corridor is noticeable at least for scenarios making use of the ports of Le Havre and Saint Nazaire (the ones leading to less road distances).
Even without any emission control option considered and using H FO in the sea links outside the English Channel, SSS alternatives prove to be very competitive in this corridor. By 2020 the compliance with the sulphur limit of 0.5% should be mandatory in all sea areas and will further benefit the competitiveness of those (in the same travelling conditions). Let us then assume alternatively the use of a seawater scrubber and LNG/methanol in the maritime links in scenarios 3, 5 and 6, reducing air pollution abatement costs in 58% and more than 90% (Table 2), respectively. The comparison of total external costs when those emission abatement and fuel technologies are considered is in Figure 8. Because the road leg is dominant in terms of external costs share in those routes, the use of a scrubber represents in all scenarios less than a 10% reduction in total external costs, and the use of LNG at most 22% reduction in scenario 5.

Figure 8: External costs per trailer comparison of the different routes Valongo-Paris – seawater scrubbing and LNG

4. CONCLUSIONS

An extensive literature review was done on the definition and application of the concept of external costs of transport to different modes of transportation, including the waterborne modes. Right after it, the need for an activity-based evaluation of polluting emissions for the various transport modes was shown, supported by a further review of literature on the estimates of emission factors, damage costs and emissions abatement solutions for the case of waterborne transport. All this served as a basis for building a methodology by which the various cost components are calculated using a detailed database of transport networks that includes both roads, rail, inland and sea routes.

This methodology has been applied in a case study in Greece, building upon an already existing study, which was used for validation of the program results. For the carriage of cargo units from Athens to Thessaloniki, various scenarios were built for different land-sea routes, ship speeds and types of fuel (lower sulphur content), aiming at improving the environmental sustainability, but also the economic performance, of short sea shipping in the context of intermodal transport chains. External costs associated with a direct ferry scenario proved to be higher than in the road transportation scenario. Making the sea route shorter by using other ports, allows a decrease of the ship’s speed and this leads to a decrease in the external costs, as less speed over smaller distances implies a much lower level of polluting emissions. In fact, it was demonstrated that direct shipping from Athens (round voyage performed within a single day) requires a very high ship speed (25 knots) leading to a very large volume of emissions, most notably of NOx, SO2 and PM, as compared to a fully road based transport. However, using these alternative ports and less speed decreases significantly emissions and external costs. The analysis also shows that if, in addition, an emission control area is in place, a further decrease of the emissions would occur and transport chains resorting to SSS would have a level of emissions comparable with fully road based transport. This causes fewer external costs, which in conjunction with the reduced freight rate due to a shorter sea distance, leads to a significant increase in the competitiveness of SSS-based intermodal transport chains.

Another case study was dedicated to the study of transport operations in the corridor Portugal – Northern Europe, chosen due to its interest for the Portuguese freight market. Again, various scenarios were built for different land/sea routes and varying ship speeds and fuel technologies were chosen. Regarding the performance of different transport modes compared within the same transport corridor, road transport is, as expected, responsible for most external costs of transport and loses its competitiveness over CO2 emissions costs. In comparison, SSS services are greener with respect to climate change costs but not when other air pollutant emissions are considered. The change on air pollution and climate change costs with the use of alternative fuel technologies and when in slow steaming was demonstrated. In this corridor, SSS base routes seem to be the most competitive alternatives at least while there are no changes in the road and rail sectors.

In the future, with new engines and exhaust emissions cleaning technologies encouraged by regulations in force among all transport modes, these conclusions may well be changed. This means that a quick transition into green shipping could stand for a peak in the sector's economy. As shown, damage costs and the avoidance costs of carbon play a big role in the valuation of respectively, air pollution and climate change costs and need always to be updated along with the most recent estimates, before quantitative evaluations are carried out.

The results in this paper demonstrate how this methodology, building also upon the availability of a comprehensive transport network model, may be used to obtain results which may assist shipping companies, ports and national authorities in the development and promotion of more sustainable transport chains.

On a general note, for vessels the emission factors and load factors are not reported in a way that makes a
generalization reliable. On a case by case basis it is recommended the use of the results of a more accurate calculation method for fuel consumption. Also, emissions from ships when manoeuvring and hotelling and related external costs are not yet considered, but those should have a significant impact because of the increased damage costs in port areas. At the same time, deeper studies on fuel consumption and emission factors of other transport modes would give better results for analysis of intermodal routes.

REFERENCES


Department of Transport (2005), National Transport Model FORGE - The Road Capacity & Costs Model, Research Report.

EcoTransIT World Initiative (EWI) (2019), Ecological Transport Information Tool for Worldwide Transports, Methodology and Data Update, s.n., Berne-Hannover-Heidelberg


Lloyd's Register Marine (2015). Your options for emissions compliance - Guidance for shipowners and operators on the Annex VI SOx and NOx regulations


ANNEX A– Subroutine External Costs 2019