Iso-emission map: a proposal to compare short sea shipping with road transport

Jose Angel Vallejo-Pinto[a], Lorena Garcia-Alonso[b] *, Roberto Álvarez Fernández[c], Ingrid Mateo-Mantecón[d]

[a] Department of Computer Science, University of Oviedo. Campus de Viesques, Gijón. CP 33204, Spain.
[b] Department of Applied Economics, University of Oviedo. Avda. del Cristo s/n, Oviedo. CP 33006, Spain.
[c] Department of Engineering, Antonio de Nebrija University. Escuela Politécnica, C/ Pirineos 55, Madrid. CP 28040, Spain.
[d] Department of Economics, University of Cantabria. Avda. de los Castros s/n, Santander. CP 39005, Spain.

* Corresponding author.

E-mail addresses: vallejo@uniovi.es (J.A. Vallejo-Pinto), lorena@uniovi.es (L. Garcia-Alonso), ralvarez@nebrija.es (R. Álvarez Fernández), ingrid.mateo@unican.es (I. Mateo-Mantecón).

Abstract

Policy makers around the world are promoting different initiatives to face the threat of global warming. This work focuses on the transport sector. In particular, it focuses on those initiatives that promote the shift of traffic from road to sea by supporting short sea shipping services in order to reduce air emissions. The aim is to contribute to the debate about the desirability of this modal rebalance from an environmental point of view. To this end, the so-called *iso-emission map* is proposed. This new tool allows to identify the geographical scope where each transport alternative is more environmentally friendly. It is focused on physical emissions, therefore it provides an additional and complementary point of view about the suitability of any modal shift. To illustrate the proposal made, the *iso-emission map* is introduced through a case study: The motorway of the sea Gijón-St. Nazaire.

Keywords: greenhouse gas emissions; *iso-emission map*; motorway of the sea; road transport; short sea shipping.

Declarations of interest: none.

1. Introduction

There is an increasing social awareness about the negative effects of global warming acceleration. As a result, there is a growing interest from the academia and the administrations about how to deal with this threat, and the transport sector is focusing their attention in this sense. Almost a quarter of fuel-burn CO2 emissions globally come from this sector, and keep on rising (International Transport Forum, 2017). In the European Union (EU) context, this sector accounts for almost one third of total EU energy consumption, which generates high environmental costs. According to some forecasts, if the trend continues, they could reach 2% of Gross Domestic Product by 2050 (European Commission, 2011). Therefore, achieving the emission target set in international agreements, such as Kyoto, is a major challenge.

Regulations to control emissions sources are directly aimed at reducing total emissions and, in setting regulations, policy makers usually put the focus on the sources that cause the greatest impact or on those most cost-effective sources to be managed and controlled (i.e., the least regulated). A systematic literature review in environmentally sustainable freight transportation can be found in Ellram and Ueltschy Murfield (2017) and Ülengin *et al.* (2018). They can be consulted for a further exploration of current previsions about climate change and international agreements.

Within this general framework, an increasing interest has been paid to shipping and ports over the last decade (Gonzalez Aregall et al., 2018). It is commonly accepted that the maritime transport is more environmentally friendly than the road transport, although it is a significant source of air pollution too. In general terms, deep sea shipping services have a comparative advantage in atmospheric emissions per ton-km. Nevertheless, such comparative advantage is not so evident in the short see shipping (SSS), for which the consignments are smaller, the vessels operate at higher speeds and the routes are considerably shorter. Consequently, the Greenhouse Gas (GHG) emissions per ton-km resulting from both maritime transport services differ, in such a way that SSS is not always preferable to road transport (Hjelle, 2014, 2010; Hjelle and Fridell, 2012; Kotowska, 2016).

Nonetheless, short sea shipping is still considered an interesting alternative to be promoted as a step towards green logistics chains (Carballo-Penela et al., 2012; Lee et al., 2010) and, in this sense, the European authorities are fostering different initiatives trying to shift traffic from the road to the sea, as can be seen later.

The aim of this paper is to contribute to identify when the traffic shift from the road to the sea can actually help to reduce the air emissions. This is important because SSS services usually compete with road alternatives, and shippers make their choice mostly considering the service profitability (that is, assessing if there is sufficient market and analysing the corresponding generalized transport cost), but not the environmental performance of the alternatives (see Lupi *et al.* (2017) or Santos and Soares (2017)). Nevertheless, national, regional and even local governments are supposed to design their policies with particular concern for environmental damage (European Commission, 2018).

The existing literature usually faces the analysis of the suitability of SSS versus the "only road" transport alternative by comparing their full costs, both internal and external[1]. Commonly, GHG emissions are evaluated through a decision model that considers their contribution to marginal external costs (see, for instance, Ricci and Black (2005) or Schrooten *et al.* (2009)). However, there are two main concerns when estimating these costs: the factors to be considered and how to deal with them. This is very important because the assessment of the transport modes can be distorted when the external costs are not conveniently internalised (Suárez-Alemán et al., 2015).

On the one hand, the estimated external costs for road transport per ton and kilometre are considerable higher than those for SSS (García Menéndez and Feo-Valero, 2009). However, it is worth noting that the competitiveness of SSS and trucking cannot been properly compared if, for instance, users do not fully assume the cost of public investment in roads (Gesé Aperte and Baird, 2012). Furthermore, Medda and Trujillo (2010) identified three main barriers when assessing external costs regarding environmental issues: i) there is no market for air quality, as it is a pure public good;

[1] They depend on the network characteristics, such as distances, route design, type of flows or kind of services (Janic, 2007; Kotowska, 2016).

ii) there are no indexes/measurement principles to assess air pollution damage worldwide accepted, and iii) the air pollution depends on many factors and it is location-specific. On the other hand, the programs implemented to monetarily estimate the external costs contain significant constraints. As a result, even when similar case studies are considered, their findings can be different (see Lee *et al.* (2010) and Kotowska (2016) for a review of the literature on this issue).

This paper contributes to the literature by proposing a different and complementary approach to stablish a comparison between the SSS and the "only road" alternative: the *iso-emission map*. This tool provides two relevant advantages. Firstly, the air emissions are considered from the physical perspective instead of the monetary one. Therefore, no assumptions about their external costs are needed. Secondly, all the potential origin-destination pairs within a previously established radius are considered. Due to the scarcity of data concerning the SSS transport mode, it is difficult to predict and optimize freight flows between multiple origins and destinations (van den Bos and Wiegmans, 2018). However, the *iso-emission map* shows complete geographical areas. Thus, the analysis is not restricted to a few specific locations, as is usual in these studies, but it allows to identify all the production and consumption centres located within its borders.

For a better understanding of the methodological proposal made here, the *iso-emission* map is introduced through a case study, where GHG emissions from SSS and its equivalent "only road" service are compared. The remainder of this paper is organised as follows. Section 2 briefly introduces the motorways of the sea, the main European initiative developed to shift traffic from the road to the sea, and the case study selected to illustrate the methodological proposal made here. Section 3 presents the new tool: the *iso-emission map*. Section 4 is devoted to the quantification of the air particles emitted by the vehicles involved, both in the maritime and road transport services. Section 5 illustrates the steps followed to obtain the *iso-emission map* for the MoS Gijón-St. Nazaire and the result obtained for the case study carried out. Section 6 shows further possibilities for using the *iso-emission map* tool. Finally, the main conclusions are summarised in Section 7.

2. Motorways of the sea as an alternative mode to road transport in the European Union

European Commission aims to reduce GHG emissions by 60% by 2050 (European Commission, 2011). One of the proposed initiatives to achieve this target is to shift at least 30% of road freight transport over distances of more than 300 km to alternative modes by 2030, as it is responsible for the majority of the CO_2 emissions (and more than half of those of nitrogen oxides and solid particles). In this respect, in order to reinforce the use of more environmentally friendly transport alternatives, the European policy makers have focused on the short sea shipping[2] and, in particular, on the development of motorways of the sea (MoS) (European Commission, 2016).

The main objective is to shift traffic from the road to the sea in order to achieve a modal rebalancing[3]. This modal shift is expected to have positive effects on both the environment and the society as a whole, by mitigating certain negative externalities (such as congestion, pollution or traffic accidents). However, shippers remain reluctant to shift traffic from the road to the sea (see Paixão Casaca and Marlow (2002), Medda et al. (2010) or Triunfante Martins et al. (2010))[4]. In an attempt to modify this perception, the first White Paper on Transport (European Commission, 2001) introduced the concept of MoS: a Ro-Ro SSS service integrated in a logistic chain with specific characteristics about frequency and quality connecting Member States[5]. It is expected that these features will enable MoS to offer a door-to-door service at similar cost and quality conditions to those

---

[2] Following the European Commission, the SSS refers to "the movement of cargo and passengers by sea between ports situated in geographical Europe or between those ports situated in non-European countries having a coastline on the enclosed seas bordering Europe" (European Commission, 1999), According to Douet and Cappuccilli (2011), this definition (primarily geographical) has consequences in terms of policy-making, as it does not allow for the identification of which flows should be shifted from road to sea. However, the analysis of that problem is beyond the scope of this paper.

[3] Nowadays, the SSS serves approximately one third of intra-EU trade (ton-km), being the second transport mode (behind the road only) for the intra-EU flows (European Commission, 2017b).

[4] Paixão Casaca and Marlow (2002) analysed the main strengths and weaknesses of SSS, and Morales-Fusco et al. (2013) pointed out its advantages and drawbacks concerning several supply chain strategies. The main factors influencing this transport alternative in EU were stressed in van den Bos and Wiegmans (2018).

[5] See Paixão Casaca (2008), Gesé Aperte and Baird (2012, 2013), Suárez-Alemán (2016) and Freire Seoane et al. (2017) for more detailed knowledge on the development of MoS in the EU.

of the road alternative, which is key to MoS's competitiveness and success (Paixão Casaca et al., 2010) [6].

After including the MoS projects in the Trans-European Transport Network (TEN-T) (European Commission, 2004)[7], it was proposed to develop four corridors by 2020 (Project 21): i) the Baltic Sea Motorway (links the Baltic members with those of the centre and west including a route through the North Sea/Baltic Sea channel); ii) Western European Sea Motorway (from Portugal and Spain through the Atlantic arch to the North Sea and the Irish Sea); iii) South-Eastern European Sea Highway (connecting the Adriatic with the Ionian Sea and the Eastern Mediterranean, including Cyprus); and iv) South-West European Sea Highway (West Mediterranean connecting Spain, France, Italy, including Malta and connecting with the South-East European Sea Highway, including connections to the Black Sea).

This amendment to the TEN-T led to a bilateral agreement between Spain and France in 2006 to promote the implementation of sea motorway projects. Through this bilateral agreement, the selected projects would receive finantial support subject to the following requirements (see Baird and Gesé Aperte (2010)): i) a service frequency of at least four departures per week in each direction for the first two years of operation; ii) a frequency of at least seven departures per week in each direction after these two years; iii) annual traffic of at least 350,000 semi-trailers should have been reached within five years; and iv) reaching 850,000 after ten years. The MoS chosen as case study in the present work, the MoS Gijón (Spain)-St. Nazaire (France), was approved following these requirements.

This MoS was operated from 2010 by the shipping company LD Lines, mainly with the vessels "Norman Asturias" and “Norman Atlantic”, with capacity for 500 passengers and 120 trucks. The

[6] MoS have recently been redefined as the maritime pillar of the Trans-European Transport Network as they contribute very positively for connecting many European regions to the core network (European Commission, 2018).

[7] The concept of MoS was introduced within the TEN-T to provide a legal framework for funding projects aimed to promote maritime connections (Morales-Fusco et al., 2018). The effect of the TEN-T on the development of SSS was analysed by Paixão Casaca and Marlow (2007).

route was stablished with three stopovers a week per direction and a sailing time of 15 hours, and it was expected to absorb between 3 and 5% of the heavy traffic crossing the Pyrenees in the first five years (Zamora, 2010). Nevertheless, the MoS stopped in 2014. Unfortunately, the demand for the service from Nantes to Gijón was insufficient, both for passengers and loaded trucks, which led to the closure of the line.

The MoS Gijón-St. Nazaire has been chosen to illustrate the potential of the *iso-emission map* because a renewed project is currently under discussion in relation to this route. The shipping company Balearia is planning to offer a new MoS service with Ro-Ro and passenger ships (Ro-Pax), like those used on the Mediterranean coast (with capacity for 850 passengers and 150 trucks). Thus, public resources could be compromised to support a route failed time ago due to a lack of profitability. Therefore, additional arguments beyond economic ones are needed to assess the suitability of this initiative, such as environmental considerations. The use of the *iso-emission map* can help in this respect. How to deal with this tool is explained in the following section.

3. Methodological proposal: the *iso-emission map*

As mentioned above, many research studies comparing the transport services provided by SSS with an equivalent road transport alternative can be found. Regardless of their approach, two common characteristics can be found among them: i) they use a monetary perspective and ii) they previously establish and restrict the origin-destination pairs considered.

This paper contributes to the literature by proposing the *iso-emission map*, inspired by the concept of the isochrone curves, which in science and urban planning are used to show on a map the points at which something occurs or arrives at the same time (Kirk, 2016). This kind of maps have been used in city and transportation planning for more than forty years.

Similarly, the *iso-emission map* shows the geographical regions that can be connected by SSS and road with the same level of emissions. As stated before, this methodological proposal provides a very different perspective regarding those previous aspects: i) it assesses the air emissions in physical terms and, additionally, ii) it allows identifying the complete inland geographical scope where the SSS is preferable in terms of air emissions. Therefore, once the border is identified, the potential demand could be estimated more accurately.

The *iso-emission map* combines two different perspectives: that of the SSS and that of the "only road" alternative. Each one generates its own elements on the map:

1. The SSS: a set of coloured bands defined from the ports under study, showing the geographical areas that can be connected by SSS with similar emissions.
2. The "only road" service: a set of lines showing the maximum distance that can be reached from a specific location and with identical emissions than the SSS option.

Once both elements are obtained, their superposition in the map allows to identify the geographical scope where SSS is more environmentally friendly than the "only road" alternative. In terms of the case study that has been chosen to illustrate the potential of the *iso-emission map*, the MoS Gijón-St. Nazaire, the result is anticipated in Figure 1.

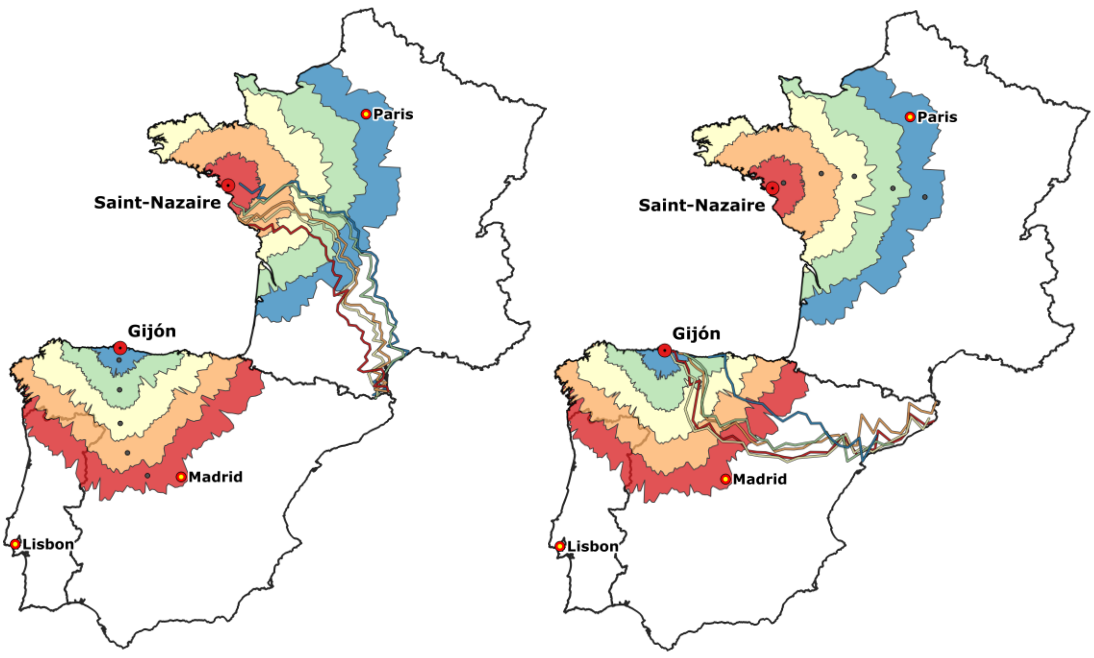

Figure 1. The *iso-emission map* for the MoS Gijón-St. Nazaire.

In order to interpret the map properly, it is necessary to understand how it is obtained. To this end, the following sections provide a detailed description of all the steps taken to carry out this particular case study which, of course, can be replicated for any other. Firstly, how emission levels are obtained in physical terms is explained. Secondly, it is detailed how the geographical areas reached by both transport alternatives with the same level of emissions are identified.

4. Quantification of greenhouse gas emissions

The concern about the air emissions of the transport sector has traditionally focused on the carbon dioxide (CO_2), considered the main responsible of the greenhouse gas emissions. Nonetheless, additional pollutants are also emitted from vessels and trucks, causing a negative impact not only at local, but also at planetary level, contributing to global warming[8]. In this sense, the Intergovernmental Panel on Climate Change has defined the Global Warming Potential (GWP) index, trying to reflect the warming effect of each GHG over a prevalence time (usually 100 years) in comparison to the effects of CO_2, so all the GHG can be expressed in CO_2 equivalent units. Therefore, when referring to GHG here, the global emissions are considered expressed as CO_{2eq}.

In this section, a simplified procedure has been established for evaluating GHG emissions inventory for both, SSS through MoS and truck transport. In general terms, each journey concerning SSS can be classified according to four basic phases: i) driving trucks from origin points to port A, ii) manoeuvring in the harbour area, iii) cruising between ports, and iv) driving trucks from port B to final destination (Hickman et al., 1999) as can be seen in Figure 2.

[8] In the maritime context, the European Commission adopted the COM (2013) 479, focused on the harmonization of the maritime transport greenhouse gas emissions with the CO2 emissions targets collected in the White Paper on Transport (European Commission, 2011). The first step sought to monitor the CO2 emissions of vessels operating in the ports of Member States. This step was finally collected in Regulation (EU) 2015/717 of the European Parliament. Additionally, the Directive (EU) 2016/802 drastically limit Sulphur emissions in all European territorial seas and Exclusive Economic Zones from 2020, according to the International Maritime Organization requirements, and because of their impact on health (Gonzalez Aregall et al., 2018; Hjelle, 2014). The potential effects of the designation of the Mediterranean, the North Sea and the Baltic Sea as Sulphur Emission Control Areas (SECA) can be found in Panagakos et al. (2014) and Svindland (2018).

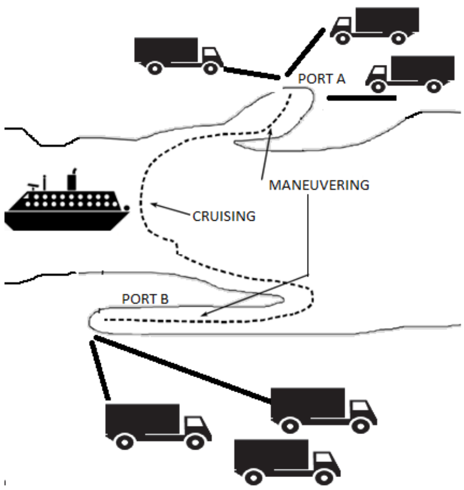

Figure 2. Scheme of journey phases

All these stages carry out GHG emissions, because the propulsion and manoeuvring of the vessel, and also the generation of the electricity necessary on board (required for pumping and heating water, lighting, electronic and other equipment feed), take place primarily with the aid of diesel engines (other engines which are based on the combustion of fossil fuels are gas turbines and steam engines i.e.). The combustion processes that take place in all these engines cause emissions of different types of pollutants that implies a global level of emissions of CO_{2eq}. In the same way, truck transportation from origin points to port A, and also from port B to destination, account a second amount of CO_{2eq} to be added.

Most of studies try to find a global figure for a fleet of different types of ships, but in this work we are going to focus on RO/PAX[9] ships with high speed motor engines fuelled with marine diesel oil and the analysed operating modes are cruising and manoeuvring. The first requirement for a calculation of emissions is to determine the fuel consumption of the ship[10]. In this sense, it is going

[9] RO-PAX vessels are suitable for SSS, but their environmental performance is very different from that of other vessels for several reasons. Firstly, the payload capacity relative to their size is significantly lower. Secondly, they can operate with higher speeds. And thirdly, they operate in liner services demanding consolidation activities in order to fill the available cargo capacity of the vessels. There is an additional factor, "the double load factor problem", because of the trailers transported within the ships. That means that the relevant load factor of such vessels is a multiple of two load factors (Hjelle and Fridell, 2012).

[10] Unlike for trucks, a particularity of ships is that they are unit products, thus they are never a case of large series or mass production, and a series of 20 equal ships is considered as a large series (Mandal, 2017).

to be considered the main factors that affect to energy consumption with the defined shipping activity and then to estimate the emissions using fuel specific emission factors for the different navigation phases where fuel consumptions are calculated. Lloyd's Maritime Information Services Ltd (Lloyds Register, 1995) is a trustable source for extracting data for this purpose. The daily RO/PAX average fuel consumption that may be used if no information on Gross Tonnage (GT) is available is 32.28 t/day. If GT is known, fuel consumption for each operation mode follows a linear regression (calculated from a database of 15,000 ships) reflected in Equation 1 (Trozzi and Vaccaro, 1999) as a function of GT and corresponding operating mode (k).

$$C_{mode\ k}(\frac{t}{day}) = (12.834 + 0.00156 * \mathrm{GT}) * k \qquad [1]$$

Where k represents the fraction of full power consumed in each operation mode. This value is 0.8 and 0.4 for cruising and manoeuvring mode respectively. If the number of days in navigation are not known, they can be estimated from the speed of the ship and the distance covered. Therefore, in cruising mode, and taking into account that 1.852 km is the equivalence in kilometres of a nautical mile (nm), fuel consumption follows Equation 2. A similar one would be obtained for manoeuvring mode with k=0.4.

$$C_{cruising}\left(\frac{t}{km}\right) = (12.834 + 0.00156 * \mathrm{GT}) * 0.8\ \frac{t}{day} * \frac{1\ day}{24\ h} * \frac{\mathrm{h}}{V_c nm} * \frac{1\ nm}{1.852\ km} \qquad [2]$$

Where Vc represents the constant speed for cruising mode in nautical miles per hour (knots). Simplifying (2), they are obtained (3) and (4), which represent the maximum fraction of fuel used. Manoeuvring speed V_m value is between $V_c/4$ and V_c (having used $V_c/4$ to get Equation 4), while hoteling could be considered as negligible in many cases (fuel used in this phase is lower than 3% of cruising phase).

$$C_{cruising}(\frac{t}{km}) = \frac{(0.23+0.0000280778*GT)}{V_c} \qquad [3]$$

$$C_{manoeuvring}(\frac{t}{km}) = \frac{4*(0.115+0.0000140389*GT)}{V_c} \qquad [4]$$

The expression for the global amount of fuel consumed (in tons) as a function of gross tonnage and cruising speed is obtained multiplying Equations 3 and 4 by the distance covered in each mode and adding both quantities, resulting in:

$$C_{global}(\mathrm{t}) = C_{cruising} * \mathrm{D}_{m1} + C_{manoeuvring} * D_{m2} \qquad [5]$$

Being D_{m1} and D_{m2} the distances covered (km) in cruising mode and manoeuvring mode, respectively.

Emissions from use of different transport fuels are reported as specific Emission Factors (EF), in units of $kgCO_{2eq}$ per ton of fuel burned. Finally, Equation 6 represents the influence of specific emission factor for each type of pollutant or the global equivalence in CO_{2eq}.

$$Emissions_{global}(kg) = C_{global}\ (t) * EF(\frac{kg}{t}) \qquad [6]$$

Now it is the time to examine real situations. Table 1 shows the basic data needed to apply the simplified method described. The distance between the sea ports of Gijón and Nantes is 507.5 km, being the manoeuvring distances of 6.48 and 7.42 km respectively. We consider the Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) as fuel combination for high speed diesel engines and its corresponding emissions, knowing that there can be quite large variations in the emission factors depending on the engine loading (Trozzi et al., 2013). The emission factor used is taken from Mulligan and Lombardo (2006), that estimate the fuel consumption for different combinations of speed and vessel size, finding a strong linear relationship (3.1683) between CO_{2eq} emissions (kg) and fuel consumption (kg). Whall et al. (2002) estimated a similar value (3.172) but including an interesting analysis of the uncertainty of this value and its correction. This uncertainty arises primarily from the number of measurements used in comparison to the total number and types of marine engines in use; the different measurement techniques and thus pollutants, and even the applicability of a universal factor for a given ship category. These levels of uncertainly could cause variations up to ±30% in cruising mode.

The characteristics and results in fuel consumption (in tons) and CO_{2eq} (in kg) for a ship commonly used in MoS are displayed on Table 1.

Max speed (knots)	**Gross tonnage**	**Trucks**	**Fuel (t)**	**kgCO_{2eq}**
22.5	22,152	144	19.77	62,625

Table 1: RO/PAX datasheet (Navi e Capitani, 2018), fuel consumption and CO_{2eq} performance.

In the case of trucks, emissions have been significantly reduced as a result of increasing fuel quality and a progressive tightening of emission legislation (European Commission, 2017a). The real world emissions will depend on several factors (Hjelle and Fridell, 2012), as the tonnage, the year of manufacture of the truck, the type of road and other specific and not always under control factors (as the driver behaviour or the quality of the road pavement i.e.). The consequence is a variation from standard homologation tests and real world driving consumption and emissions. Literature presents studies with reference high values of 3,000-4,000 gCO_{2eq}/km ((Alliance of Maritime Regional Interests in Europe (AMRIE), 2003; Luo and Grigalunas, 2003). Other test emissions ranges published (Oficina Catalana del Cambio Climático, 2013) go from a lowest value (rigid trucks, < 7.5 tons) of 402 gCO_{2eq}/km to a highest value (articulated trucks, 50-60 tons) of 1,749 gCO_{2eq}/km depending on the type of driving: urban, rural, or inter-urban. For the case study presented in the following section the reference truck chosen generates an average real world driving emissions of 1.248 kgCO_{2eq}/km (2.6 kg/l of standard fuel * 0.48 l/km of fuel consumption, according to the data provided by Volvo).

5. Drawing up of the iso-emission map for the MoS Gijón-St. Nazaire

To calculate and draw the *iso-emission map* we have used a GIS software, specifically the open-source QGIS (QGIS Development Team, 2009), which allows to create custom scripts to perform alternative analysis tasks not covered by the tools included with the standard installation. This way, each parameter of the process (the maximum distance from the port, the number of bands or the angular and radial precisions, among others) can be easily changed, and the corresponding results displayed over a base map.

As stated in Section 3, the *iso-emission map* results from the superposition of the two elements conforming it: the bands and the lines. Both elements are obtained by following the steps indicated in the next subsections.

5.1 The bands for SSS

This element is used to identify the points within the area under study located at the same distance to the corresponding port. The way to present that information on the map in an easy to interpret way is to define a maximum distance to the port and split it in several bands, using a distinctive colour for each one of them, based on the QGIS "spectral" scale.

In both countries, a maximum distance of 500 km has been used from each one of the two ports concerned. This distance has been divided into five bands of 100 km each to allow easy visual interpretation[11]. Therefore, the maximum final distance travelled by road in the SSS option will be 600 km (100 km in one country and 500 km in the other one). That overall distance (600 km to be travelled by road) is in line with Martinez-Lopez et al. (2015). Additionally, a radius of 500 km allows to include Madrid and Paris in the influence scope of Gijón and Saint-Nazaire respectively.

The steps followed to obtain the bands are:

1.- Create an angle/radius grid from each port under study, as shown in Figure 3 for the ports of Gijón and St. Nazaire. The script created takes the angular and the radial steps as parameters, allowing to experiment with changes in those values. For a clearer view, the grids in Figure 3 were created with five degrees of angular step and 15 km of radial step, but in the calculations for the case study addressed a finer grid was used to get more accurate results.

[11] Obviously, the smaller the band width, the greater the accuracy.

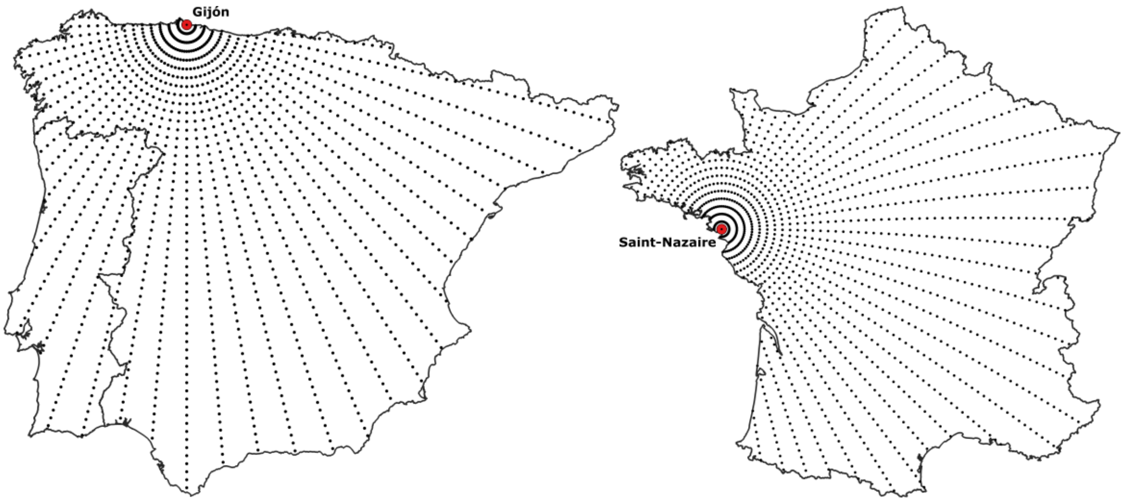

Figure 3. Angle/radius grids.

2.- Calculate the best route from the port to each point of the grid over the actual road network. The fastest route is considered the best, and the length of that route is used.

The road network used for the calculations is that of the OpenStreetMap Project (OpenStreetMap contributors, 2017), which provides accurate results for the Iberian Peninsula and France. For this study, a subset of the global road network covering the land territories of Portugal, Spain and France has been extracted and used to get the best routes.

A high-performance tool is needed to determine the best route, as it is necessary to calculate thousands of routes (for every point in the angle/radius grid) to create the *iso-emission map*. The OSRM (Open Source Routing Machine) project (Luxen and Vetter, 2011) provides such tool in the form of the “osrm-routed” application, that can be queried with an HTTP based API. Nevertheless, although the route calculation only takes a few milliseconds, the latency associated to the HTTP request makes it unpractical for massive calculations, as it takes about a second to return a single route response.

The solution to that performance bottleneck has been found through the use of OSRM as a library, creating a custom routing application that can process a batch of routing requests and return the results much faster than the HTTP API. With that application we have reached a rate of about 1,000 requests/minute, fast enough to experiment with changes in the parameters of the *iso-emission*.

Figure 4 shows an example of the best routes to the grid points for the Iberian Peninsula, calculated applying the same angle/radius precision than Figure 3 to avoid overloading the map. A similar procedure has to be conducted for France.

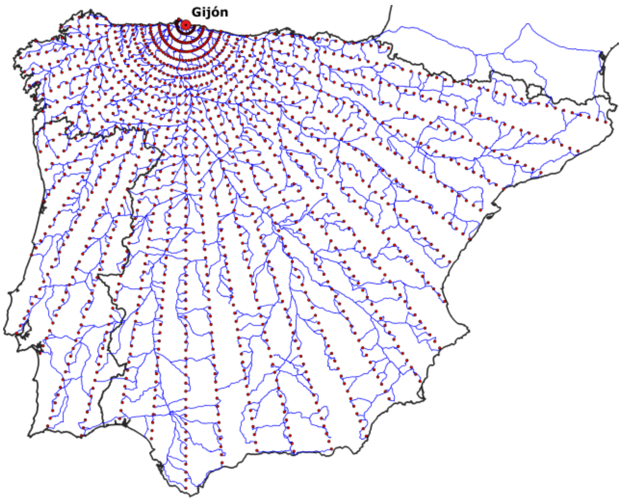

Figure 4. Best routes to the grid points for the Iberian Peninsula.

3.- For each angle, the grid point closest to each of the bands limits (100, 200, 300, 400 and 500 km in this case) must be found. As it is possible that none of the grid points for that angle will fall exactly at the required distance value, a configurable tolerance value will be used. Initially it is set to half the radial step of the grid, to avoid gaps or missing points in the iso-emission band. The resulting points are shown in Figure 5, again with the same angle/radius precision than in Figure 3.

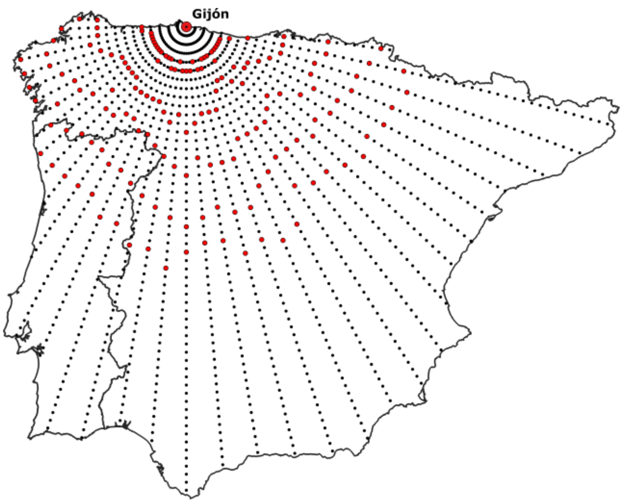

Figure 5. Closest points to the bands limits for the Iberian Peninsula.

4.- In the last step those points must be converted to bands. That process is carried out using some of the standard QGIS procedures, like converting from points to polygons, calculating the intersection between the polygons and the map contour and calculating the symmetrical difference between each area and the previous one to obtain the final bands.

The result of those operations is presented in Figure 6, both for the port of Gijón and St. Nazaire. From each point in the same band, a similar volume of emissions is generated to reach the corresponding port (and vice versa). The colours of the bands are assigned to Saint-Nazaire in reverse order to those used previously for the port of Gijón. It is a visual representation of the area of one country that can be reached from the area of the same colour in the other country with the same level of CO_{2eq} emissions[12].

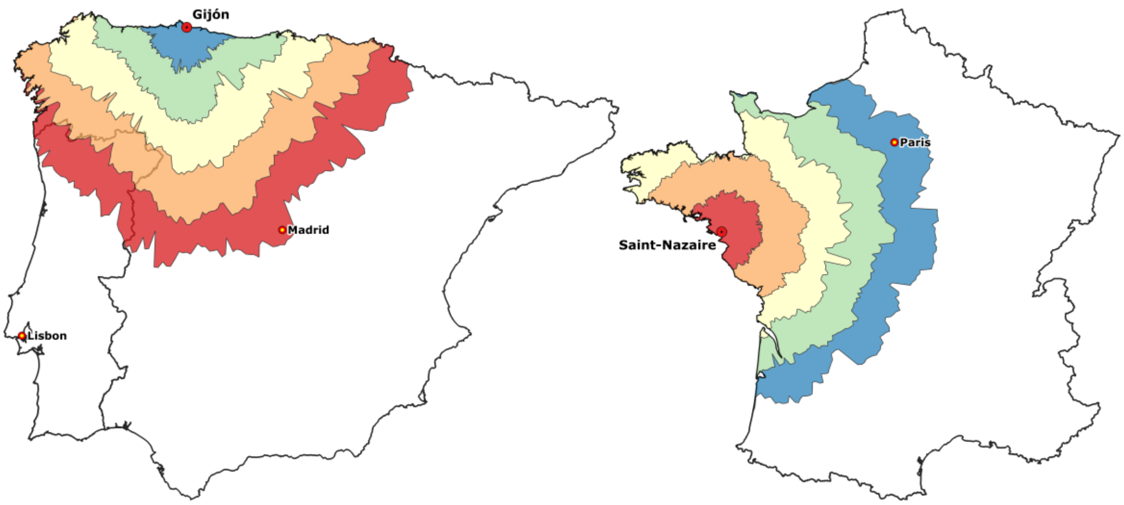

Figure 6. Areas reached through MoS with the same volume of CO_{2eq} emissions.

5.2 The lines for "only road"

The lines indicate the geographical scope that can be reached with the "only road" alternative given a physical emission level. To compare these reachability areas, a representative point is chosen in each area of each country. The geometrical centroid of the area is used as an illustration but, as stated before, any other location could be considered. From each of those representative points a process similar to that used for the calculation of the iso-emission bands is executed, with the only

[12] Of course, areas closer to the port can be reached with a lower level of emissions.

difference being that only one line will be calculated for each area (in order to distinguish these iso-emission curves from those linked to the MoS alternative).

The physical amount of GHG emissions was obtained (both for the trucks and the vessel) as indicated in Section 4. As Aregall et al. (2018) pointed out, SSS requires land transport services that must also be taken into account when assessing its environmental performance[13]. The three segments considered here are: road1 + ship + road2, of which the maritime one is fixed (the route linking the ports of Gijón and Saint-Nazaire, in this case). For the calculations and figures presented here, and to be able to compare both transport modes, we have used the reference ship and truck[14] indicated in Section 4.

The first part of the case study assumes that the ship is loaded to its full capacity (144 trucks). Therefore, the emissions generated by SSS for the reference truck and ship, loaded to its full capacity, will be:

$$CO_{2eq}\ (SSS) = \ 62{,}625\ kg + (d1 + d2) * (1.248\frac{kg}{km} * 144\ ) \qquad [8]$$

Where:

- 62,625 kg is the total amount of CO_{2eq} emitted by the reference ship, whose calculation has already been explained.
- d1 and d2 are the road distances in km from the origin-destination of the vehicles to the corresponding port.
- 1.248 are the emissions of one truck, that gives 179.7 kg/km for the 144 trucks.

As previously indicated, the maximum final distance travelled by road in the SSS option considered here is 600 km. That gives us a maximum of ≈ 170,452 kgCO_{2eq} emitted. With that

[13] Emissions from port activities are not considered.
[14] Obviously, the same methodology can be applied to any combination of ship and truck.

maximum level of emissions, the "only road" option could cover a maximum distance from origin to destination of ≈ 948 km (170,452 / 179.7).

5.3 Combined map

Once the bands and the lines are drawn on the map, the alternative transport modes can be compared from the environmental perspective. The resulting map for the case study combines the Iberian Peninsula and France, and it is shown in Figure 7. As stated before, the lines indicate the geographical scope that can be reached with the "only road" alternative given an overall emission level of 170,452 $kgCO_{2eq}$ (≈ 948 km). The borders of the trips originating in the centres of the Spanish and French bands are respectively shown on the left and right maps. In these maps, the line colour corresponds to that of the iso-emission band from whose centroid the trips originate.

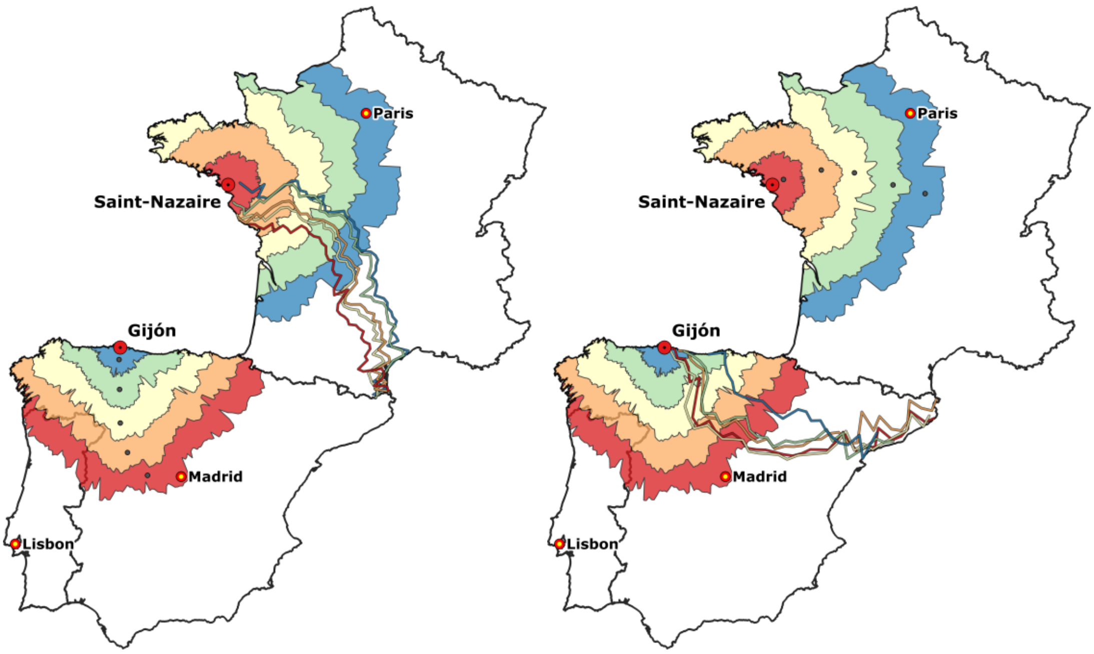

Figure 7. Borders for the trips originating in the centroids of the bands (left: Spain, right: France).

6. Additional applications

6.1 Map for a specific location

The methodology can be also applied to specific locations to identify the boundary of the geographical scope for which each alternative is preferable in terms of CO_{2eq} emissions, as shown in Figure 8 for Madrid (left) and Paris (right).

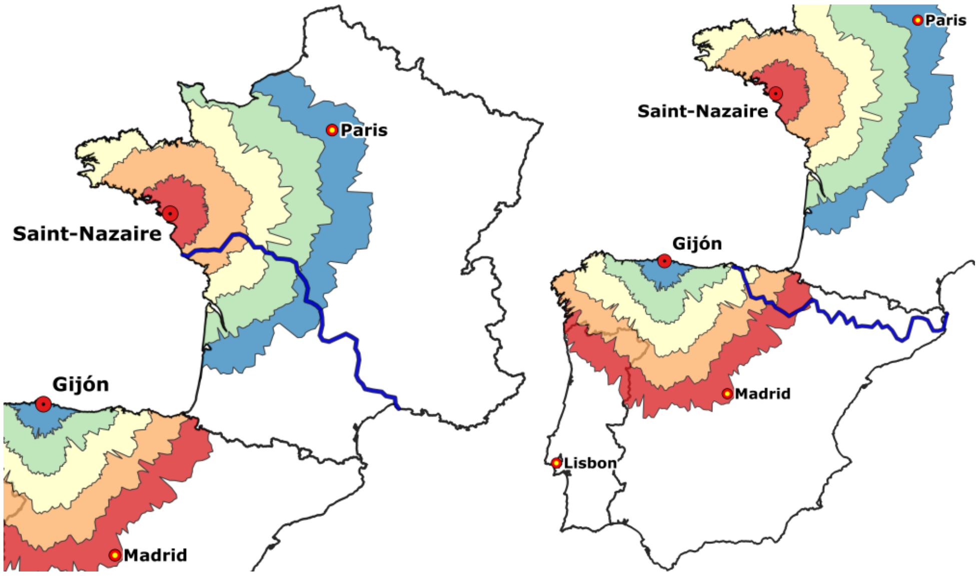

Figure 8. Boundary between the two alternatives (left: for Madrid, right: for Paris).

For an easier understanding of this representation, in Figure 9 the previous map for Madrid has been labelled with two different zones: the one for which the MoS is preferable (A) and the one for which the "only road" is preferable (B).

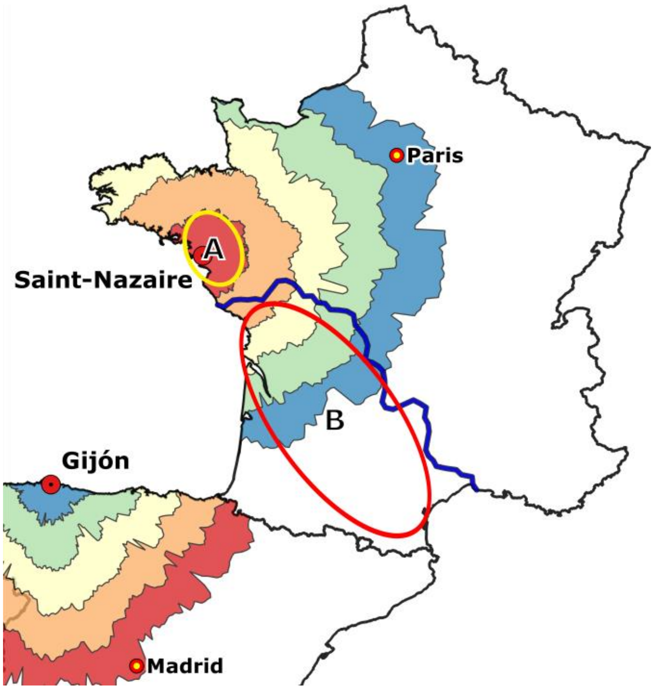

Figure 9. Eligibility zones.

6.2 Experiments with different ship load levels

In Section 5 it was assumed that the ship was loaded to its full capacity but, in the real world, this situation is not always possible. In the following set of tests, the calculations and maps have been repeated for the same ship and different load levels (2/3 and 1/2) to show how the proposed tool can be used to assess different scenarios. Table 2 presents a summary of these calculations changing the ship load.

Ship load	Trucks	SSS $kgCO_{2eq}$	"Only road" distance
full	144	170,452	948 km
2/3	96	130,354	1,088 km
1/2	72	110,305	1,228 km

Table 2: Calculations for different ship load levels.

A lower load (number of trucks) has two consequences that have been accounted to obtain the previous figures: i) a small reduction in the GT of the ship and ii) less emissions in the road segment. Figure 10 shows the results of the maps obtained: left for 2/3 of ship load and right for 1/2 of ship load, highlighting the eligibility zones in Figure 10 as in Figure 9. Here, a new zone (C) appears, representing the area for which both transport options generate a similar amount of emissions. It is worth noting that zone (A) disappears in the right map, meaning that the SSS alternative is not better than the "only road" for any region of the destination country for a ship load of 1/2.

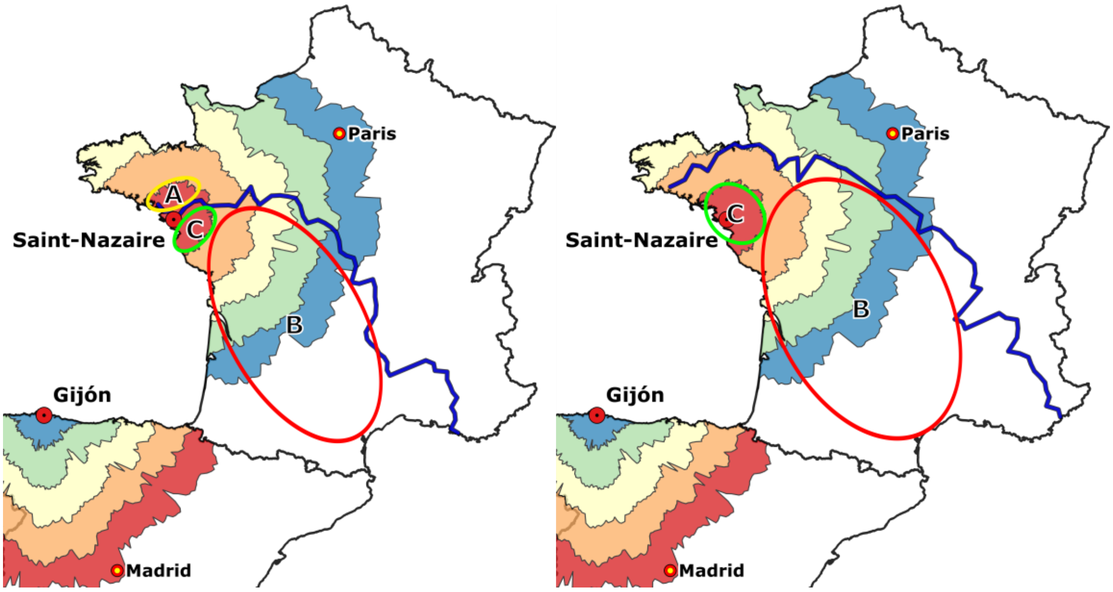

Figure 10. Experiments with other ship loads (left: 2/3, right: 1/2).

7. Conclusions

With respect to environmental concerns, Brooks *et al.* (2006) stated that "it is unrealistic for government to expect shippers to move to a more environmentally friendly, modally integrated transport choice if, in so doing, it results in additional costs and reduced competitiveness for them". This is why the EU provides financial support to encourage the opening of new routes of MoS within the TEN-T context. Nevertheless, despite the initiatives promoted, less than 1% of road transport has shifted to other transport modes from 2010 to 2016 (Eurostat, 2018), and remains by far the most widely used transport service in the EU, with more than 50% of the share. However, following Aregall et al. (2018), it should be noted that the goal must not be confused with the means to achieve it; that is, the modal shift to the Ro-Ro SSS is not an objective in itself, but the way to achieve a reduction in air emissions and road congestion.

The proposal made in this paper contributes to assessing the achievement of that goal. It contributes to the literature by offering a new perspective for the environmental comparison between alternative transport modes. Instead of an analysis in which the damage caused by the air emissions is measured in monetary terms, the distance reached by each mode is compared for the same amount of air emissions. This is of interest in two ways. Firstly, the assumptions made to monetarise external costs are not needed here, as the *iso-emission maps* are defined from units of physical variables. Secondly, as the proposed tool provides an *iso-emissions map* showing the geographical scope for which each alternative is preferable, all possible origin-destination pairs are identified for each case. Therefore, the potential profitability of a MoS more environmentally friendly than the "only road" transport service can be more easily assessed. Consequently, policy makers could better evaluate when a particular route deserves to be promoted when the objective is to reduce the air emissions. Besides, an additional advantage of the proposed tool is that it can be applied to any case and context just modifying the route, the vehicles characteristics or the type of air emissions considered.

As a result, the use of *iso-emission maps* makes it easier to answer some relevant questions. For instance, what is the geographical scope in which MoS are preferable to road in terms of air emissions? Within this area, is there enough traffic to make a potential MoS profitable? What type of vessel (in terms of capacity, speed and energy consumption) should be used to link some specific origins-destinations under better environmental conditions than the "only road" service? In short, for each particular case study, does the potential shift of traffic from road to sea really contribute to reducing the air emissions?

Regarding the case study presented to illustrate the methodological proposal, the following can be concluded: from many different origins in the Iberian Peninsula, some important French destinations can be reached with fewer air emissions by shifting traffic from the road to the MoS, and vice versa. Additionally, as expected, the higher the load factor of the ship, the wider the geographical scope for which the SSS is preferable. That depends on the existing flows between all the origin-destination pairs involved. Further analysis would be needed to assess the potential volume of traffic that could be shifted from road to sea. However, this is beyond the scope of this paper and will be addressed in future research.

Acknowledgements

Garcia-Alonso and Álvarez Fernández acknowledge respectively the financial support provided by the Government of Spain (Project Number MTM2014-54199-P) and the Cátedra Santader Nebrija en Transporte Sostenible.

References

Alliance of Maritime Regional Interests in Europe (AMRIE), 2003. Intermodal Comparative Framework. Regional Action for Logistical Integration of Shipping across Europe (REALISE). Brussels.

Brooks, M.R., Hodgson, J.R., Frost, J.D., 2006. Short Sea Shipping on the East Coast of North America: An analysis of opportunities and issues. Halifax.

Carballo-Penela, A., Mateo-Mantecón, I., Doménech, J.L., Coto-Millán, P., 2012. From the motorways of the sea to the green corridors' carbon footprint: the case of a port in Spain. J. Environ. Plan. Manag. 55, 765–782.

Douet, M., Cappuccilli, J.F., 2011. A review of Short Sea Shipping policy in the European Union. J. Transp. Geogr. 19, 968–976. https://doi.org/10.1016/j.jtrangeo.2011.03.001

Ellram, L.M., Ueltschy Murfield, M.L., 2017. Environmental Sustainability in Freight Transportation: A Systematic Literature Review and Agenda for Future Research. Transp. J. 56, 263–298.

European Commission, 2018. CEF Support to the Motorways of the Sea. Innovation and Networks Executive Agency.

European Commission, 2017a. Regulation of the European Parliament and of the Council on the monitoring and reporting of CO2 emissions from and fuel consumption of new heavy-duty vehicles. Brussels.

European Commission, 2017b. EU transport in figures, Statistical pocketbook 2017. Luxembourg.

European Commission, 2016. SWD (2016) 140 Final Commission staff working document refit ex-post evaluation of Combined Transport Directive 92/106/EEC. Final Report. SWD (2016, 141 final).

European Commission, 2011. White Paper. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Brussels.

European Commission, 2004. Motorways of the sea, implementation through Article 12a TEN-T, Consultation document D(2004), 30 July, Directorate G, CEC. Brussels.

European Commission, 2001. Libro Blanco. La política europea de transportes de cara al 2010: la hora de la verdad. COM (2001, 370 final). Bruselas.

European Commission, 1999. The development of short sea shipping in Europe: a dynamic alternative in a sustainable transport chain. Second two-yearly progress report. COM (1999, 317 final).

Eurostat, 2018. User guide on European statistics on international trade in goods [WWW Document]. Comext database.

Freire Seoane, M.J., González Laxe, F., Pais Montes, C., 2017. Short sea shipping in the Atlantic Arc: a spatial shift-share approach. Int. J. Shipp. Transp. Logist. 9, 323–370.

García Menéndez, L., Feo-Valero, M., 2009. European Common Transport Policy and Short-Sea Shipping: Empirical Evidence Based on Modal Choice Models. Transp. Rev. 29, 239–259.

Gesé Aperte, X., Baird, A.J., 2013. Motorways of the sea policy in Europe. Marit. Policy Manag. 40, 10–26. https://doi.org/10.1080/03088839.2012.705028

Gesé Aperte, X., Baird, A.J., 2012. European motorways of the sea: lessons from the Spanish experience. Int. J. Ocean Syst. Manag. 1, 395–419.

Gonzalez Aregall, M., Bergqvist, R., Monios, J., 2018. A global review of the hinterland dimension of green port strategies. Transp. Res. Part D Transp. Environ. 59, 23–34. https://doi.org/https://doi.org/10.1016/j.trd.2017.12.013

Hickman, J., Hassel, D., Joumard, R., Samaras, Z., Sorenson, S., 1999. Methodology for Calculating Transport Emissions and Energy Consumption. Crowthorne, United Kingdom.

Hjelle, H.M., 2014. Atmospheric Emissions of Short Sea Shipping Compared to Road Transport Through the Peaks and Troughs of Short-Term Market Cycles. Transp. Rev. 34, 379–395. https://doi.org/10.1080/01441647.2014.905649

Hjelle, H.M., 2010. Short Sea Shipping's Green Label at Risk. Transp. Rev. 30, 617–640.

Hjelle, H.M., Fridell, E., 2012. When is short sea shipping environmentally competitive?, in: Jacques Oosthuizen (Ed.), Environmental Health - Emerging Issues and Practice. InTech Europe, Rijeka, Croatia, pp. 3–20.

International Transport Forum, 2017. ITF Transport Outlook 2017. Paris.

Janic, M., 2007. Modelling the full costs of an intermodal and road freight transport network. Transp. Res. Part D Transp. Environ. 12, 33–44. https://doi.org/http://dx.doi.org/10.1016/j.trd.2006.10.004

Kirk, A., 2016. Data Visualisation: A Handbook for Data Driven Design. SAGE Publications Ltd.

Kotowska, I., 2016. Method of assessing the role of short sea shipping in sustainable development of transport. Int. J. Shipp. Transp. Logist. 8, 687–704.

Lee, P.T., Hu, K.C., Chen, T., 2010. External costs of domestic container transportation: short-sea shipping versus trucking in Taiwan. Transp. Rev. 30, 315–335.

Lloyds Register, 1995. Marine Exhaust Emissions Research Programme. London.

Luo, M., Grigalunas, T., 2003. A Spatial-Economic Multimodal Transportation Simulation Model For US Coastal Container Ports. Marit. Econ. Logist. 5, 158–178.

Lupi, M., Farina, A., Orsi, D., Pratelli, A., 2017. The capability of Motorways of the Sea of being competitive against road transport. The case of the Italian mainland and Sicily. J. Transp. Geogr. 58, 9–21. https://doi.org/http://dx.doi.org/10.1016/j.jtrangeo.2016.11.002

Luxen, D., Vetter, C., 2011. Real-time routing with OpenStreetMap data, in: Proceedings of the 19th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems - GIS '11. ACM Press, New York, New York, USA, pp. 513–516. https://doi.org/10.1145/2093973.2094062

Mandal, N.R., 2017. Characteristics of Shipbuilding Industry, in: Ship Construction and Welding. Springer International Publishing, Singapure.

Martinez-Lopez, A., Munín-Doce, A., Garcia-Alonso, L., 2015. A multi-criteria decision method for the analysis of the Motorways of the Sea: the application to the case of France and Spain on the Atlantic Coast. Marit. Policy Manag. 42, 608–631. https://doi.org/10.1080/03088839.2015.1039091

Medda, F., Trujillo, L., 2010. Short-sea shipping: an analysis of its determinants. Marit. Policy

Manag. 37, 285–303. https://doi.org/10.1080/03088831003700678

Morales-Fusco, P., Grau, M., Saurí, S., 2018. Effects of RoPax shipping line strategies on freight price and transporter's choice. Policy implications for promoting MoS. Transp. Policy 67, 67–76.

Morales-Fusco, P., Saurí, S., De Melo, G., 2013. Short Sea Shipping in Supply Chains. A Strategic Assessment. Transp. Rev. 33, 476–496. https://doi.org/10.1080/01441647.2013.786765

Mulligan, R.F., Lombardo, G.A., 2006. Short sea shipping. WMU J. Marit. Aff. 5, 181–194. https://doi.org/10.1007/BF03195103

Navi e Capitani, 2018. No Title [WWW Document]. URL http://www.naviecapitani.it/Navi e Capitani/gallerie navi/Ro-Ro e Ro-Pax ---- Ro-Ro and Ro-Pax/Indice.html (accessed 7.20.18).

Oficina Catalana del Cambio Climático, 2013. Guía práctica para el cálculo de emisiones de gases de efecto invernadero (GEI).

OpenStreetMap contributors, 2017. Planet dump retrieved from https://planet.osm.org .

Paixão Casaca, A.C., 2008. Motorway of the sea port requirements: the viewpoint of port authorities. Int. J. Logist. Res. Appl. 11, 279–294. https://doi.org/10.1080/13675560801912254

Paixão Casaca, A.C., Carvalho, S., Oliveira, M., 2010. Port choice in the European short sea shipping market: the view of point of port authorities, in: International Association of Maritime Economists Conference. Lisbon.

Paixão Casaca, A.C., Marlow, P.B., 2007. The Impact of the Trans-European Transport Networks on the Development of Short Sea Shipping. Marit. Econ. Logist. 9, 302–323. https://doi.org/10.1057/palgrave.mel.9100184

Paixão Casaca, A.C., Marlow, P.B., 2002. Strengths and weaknesses of short sea shipping. Mar. Policy 26, 167–178. https://doi.org/http://dx.doi.org/10.1016/S0308-597X(01)00047-1

Panagakos, G.P., Stamatopoulou, E. V, Psaraftis, H.N., 2014. The possible designation of the Mediterranean Sea as a SECA: A case study. Transp. Res. Part D Transp. Environ. 28, 74–90. https://doi.org/https://doi.org/10.1016/j.trd.2013.12.010

QGIS Development Team, 2009. QGIS Geographic Information System.

Ricci, A., Black, I., 2005. The Social Costs of Intermodal Freight Transport. Res. Transp. Econ. 14, 245–285. https://doi.org/http://dx.doi.org/10.1016/S0739-8859(05)14009-8

Santos, T.A., Soares, C.G., 2017. Modeling transportation demand in short sea shipping. Marit. Econ. Logist. 19, 695–722. https://doi.org/10.1057/mel.2016.9

Schrooten, L., De Vlieger, I., Int Panis, L., Chiffi, C., Pastori, E., 2009. Emissions of Maritime Transport: a Reference System. J. Marit. Res. 6, 43–52.

Suárez-Alemán, A., 2016. Short sea shipping in today's Europe: A critical review of maritime transport policy. Marit. Econ. Logist. 18, 331–351. https://doi.org/10.1057/mel.2015.10

Suárez-Alemán, A., Campos, J., Jiménez, J.L., 2015. The economic competitiveness of short sea shipping: an empirical assessment for Spanish ports. Int. J. Shipp. Transp. Logist. 7, 42–67.

Svindland, M., 2018. The environmental effects of emission control area regulations on short sea shipping in Northern Europe: The case of container feeder vessels. Transp. Res. Part D Transp. Environ. 61, 423–430. https://doi.org/https://doi.org/10.1016/j.trd.2016.11.008

Trozzi, C., Lauretis, R., Rypdal, K., Webster, A., Fridell, E., Reynolds, G., Fontelle, J.P., Lavender, K., Kilde, N., Hill, N., Thomas, R., 2013. International navigation, national navigation, national fishing and military (shipping).

Trozzi, C., Vaccaro, R., 1999. Ships transport. Methodologies for calculating transport emissions and energy consumption.

Ülengin, F., Işık, M., Ekici, Ş.Ö., Özaydın, Ö., Kabak, Ö., Topçu, Y.İ., 2018. Policy developments for the reduction of climate change impacts by the transportation sector. Transp. Policy 61, 36–50. https://doi.org/https://doi.org/10.1016/j.tranpol.2017.09.008

van den Bos, G., Wiegmans, B., 2018. Short sea shipping: a statistical analysis of influencing factors on SSS in European countries. J. Shipp. Trade 3. https://doi.org/10.1186/s41072-018-0032-3

Whall, C., Cooper, D., Archer, K., Twigger, L., Thurston, N., Ockwell, D., Ritchie, A., 2002. Quantification of emissions from ships associated with ship movements between ports in the European Community. Northwich, Great Britain.

Zamora, M.R., 2010. Reflexiones en torno a las autopistas del mar, in: X Congreso Nacional de Medio Ambiente.