Cost, carbon emissions and modal shift in intermodal network design decisions

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Abstract: Intermodal transportation is often presented as an efficient solution for reducing carbon emissions without compromising economic growth. In this article, we present a new intermodal network design model in which both the terminal location and the allocation between direct truck transportation and intermodal transportation are optimized. This model allows for studying the dynamics of intermodal transportation solutions in the context of hinterland networks from a cost, carbon emissions and modal shift perspective. We show that maximizing the modal shift is harmful for both cost and carbon emissions and that there is a carbon optimal level of modal shift. We also show that even if transportation cost and carbon emissions share the same structure, these two objectives lead to different solutions and that the terminal is located closer to the port when optimizing cost and further away when optimizing carbon emissions. The model also allows for studying the tradeoff between distance and volume, the impact of using aggregated models for estimating train transportation cost and carbon emissions as well as the potential policy measures that enable aligning cost and carbon emissions.

Keywords: Intermodal transportation, hinterland network design, cost, carbon emissions, modal shift.

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1. Introduction

Transportation is crucial for economic growth and for citizens' quality of life. On the other hand, several downsides such as congestion, safety issues, oil dependence and pollution are often associated to transportation. For example, transportation is recognized as one of the main contributors of carbon emissions (IPCC, 2007). In a roadmap toward a competitive and resource efficient transport system (EC, 2011), the European Commission states that the main objective related to transportation is to reduce the downsides without compromising mobility and economic growth. Among the downsides targeted by the European Commission, carbon emissions play an important role as the European Union is committed to reduce carbon emissions (UNFCC, 1997). Thus, The European targets its transportation sector to reduce carbon emissions by at least 60% by 2050 with respect to 1990 level (EC, 2011). When focusing on freight transportation, the main solution proposed by the European Commission is to promote intermodal transportation. Intermodal freight transportation is defined as the transportation of the load from origin to destination in the same transportation unit without handling of the goods themselves when changing modes (Crainic and Kim, 2007). Although the European Union is at the forefront in promoting intermodal freight transportation, other countries and regions are following the same objectives (GAO, 2006, 2007). This trend toward intermodal transportation is also supported by many leading companies (EDF, 2012). Thus, the logistics sector needs to take into account this new trend by proposing efficient intermodal transportation solutions.

The rationale behind promoting intermodal freight transportation as efficient in reducing carbon emissions without compromising economic growth can be explained as follows. Both trains and barges (the two most classical modes for the linehaul part of intermodal transportation) emit less carbon emissions than heavy duty trucks. Thus, if intermodal freight transportation networks can compete against road in terms of cost, then the economic growth would not be compromised and the carbon emissions would be reduced. The objective followed while promoting intermodal freight transportation is thus generally expressed in terms of modal shift, i.e., the number of ton.km shifted from the road (or equivalently the percentage of the total amount of ton.km shifted from the road). For example, the objective of the European Commissions is that "30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050" (EC, 2011). However, intermodal transportation induces an increase in the distance travelled due to origin and/or destination drayage compared with direct truck

transportation. For example, assume that the distance travelled for drayage is greater or equal to the distance travelled for direct shipment by trucks (if intermodal terminals are located very far away from origin and destination). In this case, the carbon intensity of intermodal transportation would be higher than for direct truck transportation. Accordingly, Craig et al. (2013) have shown that the carbon intensity of intermodal transportation can be higher than direct truck transportation in practice. Thus, there is a tradeoff between the efficiency gain in the linehaul and the increase in the distance traveled. This article aims at studying such a tradeoff to better understand the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions.

We refer to Bontekoning et al. (2004) for a review on the early development of the research on intermodal freight transportation and to Caris et al. (2013) and SteadieSeifi et al. (2014) for recent reviews. Most of the literature on intermodal freight transportation states that intermodal transportation is an ecoefficient and sustainable alternative to truck transportation. However, the majority of these articles focus on a pure cost minimization model to assess if intermodal transportation can compete against road transportation. The literature on intermodal transportation taking carbon emissions into account is quite scarce. Janic (2007) proposes a model for calculating the full costs of an intermodal and road transport network. This cost includes the impact of the networks on society and the environment. Winebrake et al. (2008) present an energy and environmental analysis model to explore the tradeoffs among alternative routes in an intermodal transportation network. Cholette and Venkat (2009) present a case study in which several modes of transportation are available in a wine supply chain context. Their analysis accounts for cost, carbon emissions and energy consumption. Craig et al. (2013) calculate the carbon emissions intensity of intermodal transportation in the USA, based on a data set of more than 400,000 intermodal shipments. They show that some huge variations in carbon intensity exist and they apply the market area concept to explain these variations. Pan et al. (2013) investigate how freight consolidation and intermodal transportation can help in curbing carbon emissions. They formulate a carbon emissions minimization model in which both road and rail transportation are available. The model is applied to optimize the carbon emissions of two large retail chains.

The articles mentioned above take the perspective of a shipper who needs to decide among several transportation options including intermodal transportation. They assume that the intermodal network has already been designed and that the shippers aim at identifying the most

efficient path in the network. Note that the comparison between direct shipment and terminal routing has also been extensively studied from a cost perspective (see e.g., Blumenfeld et al., 1985; Campbell, 1990; Daganzo, 1987; Hall, 1987a, 1987b). This stream of literature presents relevant and insightful results.

However, the increase in the distance travelled due to origin and destination drayage is determined at the design phase of the intermodal network when deciding on where to locate the intermodal terminals. Thus, considering network design decisions can be of great importance to better understand the tradeoff between efficiency gain in the linehaul and increase in distance traveled. To our knowledge, this problem has been considered in a single published article. Zhang et al. (2013) propose to include an environmental cost to the problem of optimally designing an intermodal network. They show in an example that the optimal layout of the network is sensitive to the carbon price. This demonstrates that taking carbon emissions into account at the design phase of an intermodal network may deserve attention. However, Zhang et al. (2013) primarily focus on solving a particular real life example. Their results provide limited insights into the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions.

Our work analyzes intermodal network design decisions from a cost, carbon emissions and modal shift perspective. We prove that maximizing the modal shift does not lead to the minimum level of carbon emissions and that there is a carbon optimal level of modal shift. Exceeding this optimal level of modal shift is harmful for both cost and carbon emissions. We also show that even if transportation cost and carbon emissions share the same structure, these two objectives lead to different solutions and that the terminal is located closer from the port when optimizing cost and further away when optimizing carbon emissions. The model also allows for studying the tradeoff between distance and volume. We show that intermodal transportation is feasible for short and medium distance if the volume is big and if the origin/destination drayage distances are low. We also prove that using an aggregated model for estimating train transportation emissions and cost negatively affects the performances of intermodal transportation and that this can lead to consider intermodal transportation as inefficient in situations in which such a solution could be implemented. We finally provide some insights on how to align cost and carbon emissions by using a tax scheme and/or subsidizing intermodal operations. We show that a well-chosen

combination of a tax on truck transportation, a train usage fee and a subsidy via investment on the train network enables aligning cost and carbon emissions in an effective way.

The remainder of this article is organized as follows. Section 2 is devoted to the description of the model. Then, the model is solved and an example is presented in Section 3. The results are used in Section 4 to propose a series of insights. Finally, Section 5 is devoted to the conclusion.

2. Model description

2.1 Hypotheses

In this article, we study an intermodal hinterland network design problem. Hinterland networks are connected to at least one deepsea port and are primarily intended for the transportation of import and export flows, i.e., flows to and from the deepsea port. Hinterland networks play an important role in global supply chains due to the trend toward globalization. Moreover, the share of hinterland costs in the total transportation costs of a container shipping typically range from 40% to 80% (Notteboom and Rodrigue, 2005). Hinterland networks are also critical when focusing on intermodal transportation for several reasons. First, the container is the most common transportation unit used in intermodal hinterland networks (Crainic and Kim, 2007) and containerization has primarily been promoted by the maritime industry. Second, container transportation is expanding at an enormous pace. Indeed, world container traffic has been growing at almost three times world gross domestic product growth since the early 1990s (UN-ESCAP, 2005). We refer to Fransoo and Lee (2013) for a discussion on the critical role of container transportation in global supply chains. Third, hinterland networks imply an important concentration of the flows in the port area. This creates some favorable conditions for intermodal transportation as volume is often presented as a key issue for efficient train and barge transportation. Hinterland networks thus have a strong potential for intermodal transportation.

For the sake of clarity, we focus on import flows from a single port to various destinations. The problem could be reversed by considering export flows from various origins to a single port. Our results hold in that case. The flows under consideration are assumed to be containerized. As the dimension of containers have been standardized (Agarwal and Ergun, 2008), the proposed model takes only one type of container into account. Two options are available for delivering a container from origin to destination, i.e., direct shipment by truck and intermodal transportation.

In the latter case, we assume that the containers are loaded on a train from the port to an inland terminal. We focus on train transportation because this is the most developed intermodal transportation solution worldwide. However, the model is also valid for road/barge and road/short sea intermodal transportation systems. Upon arrival at the terminal, the containers are transshipped to trucks to reach their final destination. The destination drayage distance is determined by the location of the inland terminal. We consider a single inland terminal to locate. This problem setting enables evaluating the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions and is in link with Campbell and O'Kelly (2012) who argue that, "new single hub model formulations continue to provide intriguing formulation issues".

The literature on transportation network design problems can be divided into two classes depending on how the demand is modeled. The first class considers discrete demand while the models in the second class approximate the demand as continuous. We refer to Langevin et al. (1996) for a review of models with continuous demand approximation. Even if approximating the demand for transportation as continuous over a region (by using density) can be viewed as unrealistic, these models are primarily used to provide insights and guidelines (Geoffrion, 1976). Moreover, these models are proved to be robust when used to approximate the optimal transportation cost for discrete demand hub location problems (Campbell, 1993). Thus, numerical optimization and continuous approximation methods could be viewed as complementary and should be used together (Langevin et al., 1996). Continuous demand approximation techniques have been recently used for modeling airline hub location (Saberi and Mahmassani, 2013), for designing integrated package distribution systems (Smilowitz and Daganzo, 2007), for designing a time definite freight transportation network (Campbell, 2013), for hub-and-spoke network design (Carlsson and Jia, 2013) and for retail store network design (Cachon, 2014). In accordance to this stream of literature, we approximate the demand as continuous in this article because our main objective is to provide insights into the dynamics of intermodal freight transportation with respect to cost, modal shift and carbon emissions.

Finally, the model presented in the subsequent section accounts for train transportation economies of scale. Intermodal transportation indeed implies concentrating several shipments in the linehaul. Moreover, the total volume shipped by train is directly related to the decisions considered in the terminal location problem. Thus, the train transportation cost per kilometer is modeled with a fixed term (independent of the load factor) and a linear term in the amount of

containers shipped. This feature is in line with the literature on hub-and-spoke network design as economies of scale is the "raison d'être" of any hub-and-spoke network (Campbell and O'Kelly, 2012). The same reasoning is applied for modeling carbon emissions from train transportation. As mentioned by Velázquez-Martínez et al. (2014), a variety of activity-based methods are available for estimating carbon emissions from transportation. These methods differ in terms of their aggregation level, some being more detailed. For example, some methodologies assume an average load factor and derive an average level of carbon emissions per container.km. In more detailed approaches, the level of carbon emissions is considered as dependent of the load factor. Velázquez-Martínez et al. (2014) have shown that the magnitude of error can be substantial when using too aggregated carbon emissions estimation models. Acknowledging this, we propose to use the same structure as for the cost to model the carbon emissions from train transportation. This modeling approach is in accordance with the NTM methodology (NTM, 2008). The impacts of using an aggregated model for evaluating carbon emissions are discussed in Section 4.

2.2 Model formulation

We refer to Figure 1 for a visualization of the problem setting.

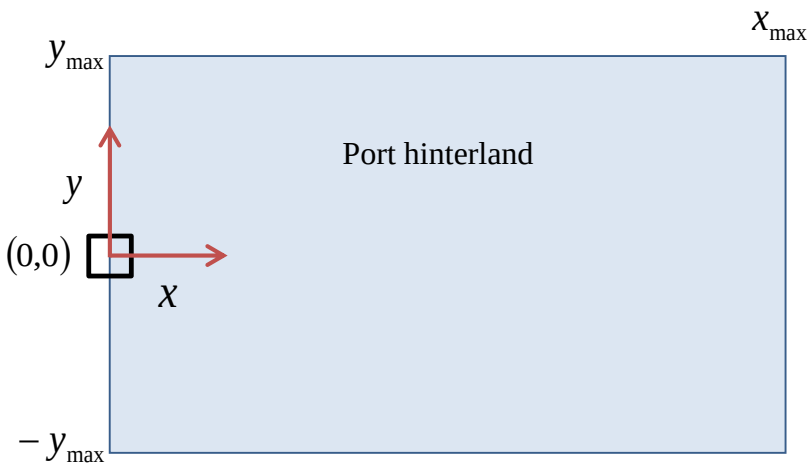

Figure 1: Problem setting

The demand is uniform and is approximated as continuous over a rectangle region representing the hinterland of the port under consideration. The density of the demand is equal to ρ containers per km^2. The rectangle's width is x_{max} and its height is equal to $2y_{max}$. The port is located at $(0,0)$

, in the middle of the rectangle's height. All the containers originate from the port as the model is expressed in terms of import flow.

Truck transportation is used for direct shipment and for the destination drayage in case of intermodal transportation. The truck transportation cost Z_1 is assumed to be linear in the distance traveled and in the number of containers shipped. The cost of serving a demand region i of size A_i by using direct shipment is expressed as follows:

$$Z_{0,i}^{DS} = \delta_{0,i} \rho A_i Z_1, \tag{1}$$

where:

$\delta_{0,i}$ = the distance from the port to the gravity center of demand zone i (expressed in km),

ρ = the demand density (expressed in containers per km^2),

A_i = the size of region i (expressed in km^2),

Z_1 = the truck transportation cost per container.km (expressed in € per container.km).

The carbon emissions associated to truck transportation E_1 are assumed to be linear in the distance traveled and in the number of containers shipped. The carbon emissions associated to the direct delivery of a demand region i of size A_i are calculated with the following equation:

$$E_{0,i}^{DS} = \delta_{0,i} \rho A_i E_1. \tag{2}$$

where:

E_1 = the carbon emissions from truck transportation (expressed in kgCO_2 per container.km).

When intermodal transportation is used for delivery, the containers are first shipped by train from the port to the inland terminal located at (x, y) with $0 \le x \le x_{\max}$ and $-y_{\max} \le y \le y_{\max}$. Train transportation cost is composed by two terms. The first term ZF_2 is linear in the distance and independent of the amount of containers shipped. This term represent the cost of the train when traveling empty. The second term Z_2 is linear in the distance and in the number of containers shipped. Z_2 is associated to the cost per kilometer of shipping one extra container by train. The total cost of serving a region i of size A_i by using intermodal transportation can be expressed as follows:

$$Z_{0,i}^{IT} = \delta_{0,T}(ZF_2 + \rho A_i Z_2) + \delta_{T,i}\rho A_i Z_1, \quad (3)$$

where:

$\delta_{0,T}$ = the distance from the port to the inland terminal (expressed in km),

$\delta_{T,i}$ = the distance from the terminal to the gravity center of demand zone i (expressed in km),

ZF_2 = the fixed train transportation cost per km (expressed in € per km),

Z_2 = the linear train transportation cost per container.km (expressed in € per container.km).

As stated in the previous section, we assume the same structure for the carbon emissions associated to intermodal transportation. Thus, the carbon emissions associated to the delivery of a demand region i of size A_i by intermodal transportation are calculated with the following equation:

$$E_{0,i}^{IT} = \delta_{0,T}(EF_2 + \rho A_i E_2) + \delta_{T,i}\rho A_i E_1, \quad (4)$$

where:

EF_2 = the fixed emissions associated to train transportation (expressed in $kgCO_2$ per km),

E_2 = the linear train transportation emissions per container.km (expressed in $kgCO_2$ per container.km).

The demand over the entire hinterland region has to be satisfied. The model aims at finding the optimal location of the terminal with respect to cost, carbon emissions and modal shift. We assume that the routing decisions, i.e., deciding between direct shipment and intermodal transportation, are made optimally in accordance with the objective followed. The cost optimal terminal location is (x_Z, y_Z), the carbon optimal terminal location is (x_E, y_E) and the optimal terminal location in terms of modal shift is (x_M, y_M). We can notice that maximizing the modal shift is equivalent to minimize the distance traveled by truck for this problem. This corresponds to the special case in which the cost is minimized with $ZF_2 = 0$ and $Z_2 = 0$. We can also directly state that $y_Z = y_E = y_M = 0$ for symmetry reasons. In the next section, the problem is solved based on two estimations of the distance. The first one corresponds to the Manhattan distance (norm L_1) and the second corresponds to the Euclidean distance (norm L_2).

3. Model analysis

3.1 Manhattan distance

In this section, the distance between two points (x_i, y_i) and $(x_j; y_j)$ is evaluated by using the Manhattan distance:

$$\delta_{i,j} = |x_i - x_j| + |y_i - y_j|, \tag{5}$$

The first step in the analysis consists in identifying the region that is served by intermodal transportation and the region that is served by direct shipment in function of the terminal location $(x,0)$. The analysis is performed for the cost minimization problem first and the results are adapted to the carbon emissions minimization and the modal shift maximization problems as a second step. Let (x_{BZ}, y_{BZ}) be a point of the border between direct and intermodal shipments. Then, this point has to satisfy the following condition:

$$Z_1\delta_{0,BZ} = Z_1\delta_{T,BZ} + Z_2\delta_{0,T}, \tag{6}$$

By applying Equation 5, this condition translates into the following:

$$Z_1 x_{BZ} = Z_1|x - x_{BZ}| + Z_1 x, \tag{7}$$

We can notice that the border is a straight line parallel to the y-axis because the condition is independent of y_B. Condition 7 can lead to two different situations. If $x > x_{BZ}$, then:

$$x_{BZ} = \frac{Z_1 + Z_2}{2Z_1} x, \tag{8}$$

And the necessary condition for having $x > x_{BZ}$ is that $Z_2 < Z_1$. If $x \le x_{BZ}$, then Condition 7 leads to $x = 0$, thus the delivery of the port's hinterland is done only by direct shipment. Let:

$$B_Z = \frac{Z_1 + Z_2}{2Z_1}, \tag{9}$$

We can notice that $1/2 \le B_Z < 1$ if intermodal transportation is used. For a given terminal location at $(x,0)$, the total cost for hinterland delivery can be expressed as follows:

$$Z(x) = ax^2 + bx + c, \tag{10}$$

where:

$a = 2\rho y_{\max}\left((B_Z - 1)^2 Z_1 + B_Z(Z_1 - Z_2)\right)$,

$b = 2\rho x_{\max} y_{\max}(Z_2 - Z_{1)} + ZF_2$,

$c = \rho(x_{\max} y_{\max}^2 + x_{\max}^2 y_{\max})Z_1$.

$Z(x)$ is convex on $[0; x_{\max}]$ because $a > 0$. The cost optimal location for the inland terminal is:

$$x_Z = \begin{cases} 0 & \text{if } Z_2 \geq Z_1 \text{ ,} \\ 0 & \text{if } ZF_2 \geq 2\rho x_{\max} y_{\max}(Z_1 - Z_2) \text{ ,} \\ \dfrac{x_{\max}(Z_1 - Z_2)}{2((B_Z - 1)^2 Z_1 + B_Z(Z_1 - Z_2))} - \dfrac{ZF_2}{4\rho y_{\max}((B_Z - 1)^2 Z_1 + B_Z(Z_1 - Z_2))} & \text{else.} \end{cases} \quad (11)$$

In addition of having $Z_2 < Z_1$, the second necessary condition for using intermodal transportation is that $ZF_2 < 2\rho x_{\max} y_{\max}(Z_1 - Z_2)$. Otherwise, the fixed cost associated with train transportation is too high and only direct shipments take place. In the case in which intermodal transportation is used, x_Z is increasing in $x_{\max}$, in $y_{\max}$, in Z_1 and in ρ. Moreover, x_Z is decreasing in Z_2 and in ZF_2. We can also notice that $x_Z \leq 2x_{\max}/3$ and that the equality is obtained when both $Z_2 = 0$ and $ZF_2 = 0$. This directly leads to the optimal location of the inland terminal when the objective is to maximize the modal shift:

$$x_M = \frac{2}{3} x_{\max} \text{ .} \quad (12)$$

Equation 12 shows that x_M only depends of $x_{\max}$. Moreover, the corresponding modal shift, expressed in ton.km shifted from the road divided by the total amount of ton.km traveled when only considering direct shipment can be expressed as follows:

$$MS = \frac{2x_{\max}}{3(x_{\max} + y_{\max})} \text{ .} \quad (13)$$

Finally, the cost analysis can be translated into a carbon emissions analysis because these two objectives share the same structure. We can deduce that:

$$x_E = \begin{cases} 0 & \text{if } E_2 \geq E_1 , \\ 0 & \text{if } EF_2 \geq 2\rho x_{\max} y_{\max} (E_1 - E_2), \\ \dfrac{x_{\max}(E_1 - E_2)}{2((B_E - 1)^2 E_1 + B_E (E_1 - E_2))} - \dfrac{EF_2}{4\rho y_{\max}((B_E - 1)^2 E_1 + B_E (E_1 - E_2))} & \text{else,} \end{cases} \quad (14)$$

where:

$$B_E = \frac{E_1 + E_2}{2E_1}.$$

In the case in which intermodal transportation is used, x_E is increasing in $x_{\max}$, in $y_{\max}$, in E_1 and in ρ. Moreover, x_E is decreasing in E_2 and in EF_2. Finally, as for the cost optimal location, $x_Z \leq x_M$ and the equality is obtained in the case in which both $E_2 = 0$ and $EF_2 = 0$. This means that unless train transportation is carbon-neutral, the modal shift optimal and the carbon optimal solution are different. We further elaborate on this issue in Section 4.1.

3.2 Euclidean distance

In this section, the distance between two points (x_i, y_i) and $(x_j; y_j)$ is evaluated by using the Euclidean distance:

$$\delta_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, \quad (15)$$

The reasoning followed for solving the problem with the Manhattan distance can be directly applied. However, the analysis with the Euclidean distance is more complex as shown below. The analysis is performed for the modal shift problem first. Let $(x_{BM}; y_{BM})$ be a point of the border between direct and intermodal shipments. Condition 6 is applied with $Z_2 = 0$ and we obtain that the border is a straight line parallel to the y-axis with:

$$x_{BM} = \frac{x}{2}. \quad (16)$$

Minimizing the number of container.km traveled by truck is equivalent to maximizing the modal shift. The following expression provides the number of container.km traveled by truck for hinterland delivery, for a given terminal location at $(x,0)$:

$$M(x) = \rho y_{\max}\left(x\sqrt{x^2/4 + y_{\max}^2} + (x_{\max} - x)\sqrt{(x_{\max} - x)^2 + y_{\max}^2} \right). \quad (17)$$

By taking the second derivative of $M(x)$, we can show that this one is positive on $[0; x_{\max}]$ thus $M(x)$ is convex on $[0; x_{\max}]$. Moreover, we obtain that:

$$x_M = \frac{2}{3} x_{\max}, \quad (18)$$

This result is similar to the one obtained for the Manhattan distance. When focusing on cost minimization, we start studying the special case in which $Z_2 = 0$. In this case, the border is still a straight line parallel to the y-axis with:

$$x_{BZ} = \frac{x}{2}. \quad (19)$$

The related cost in function of the terminal location is as follows:

$$Z(x) = Z_1 \rho y_{\max}\left(x\sqrt{x^2/4 + y_{\max}^2} + (x_{\max} - x)\sqrt{(x_{\max} - x)^2 + y_{\max}^2} \right) + ZF_2 x. \quad (20)$$

This function is convex and x_Z is obtain by solving:

$$\sqrt{x_Z^2/4 + y_{\max}^2} + \frac{x_Z^2}{4\sqrt{x_Z^2/4 + y_{\max}^2}} - \frac{2(x_{\max} - x_Z)^2 + y_{\max}^2}{\sqrt{(x_{\max} - x_Z)^2 + y_{\max}^2}} = -\frac{ZF_2}{Z_1 \rho y_{\max}}. \quad (21)$$

This special case can be viewed as a relevant approximation for practical cases because the marginal cost associated to transporting an additional container by train is often quite small compared with the other costs considered in the model. The same analysis holds when aiming at minimizing carbon emissions and this special case is also relevant for carbon emissions based on the same argument.

Finally, we determine the border equation in the case in which $Z_2 \neq 0$. Condition 6 can be expressed as:

$$\delta_{0,BZ} - \delta_{T,BZ} = \frac{xZ_2}{Z_1}, \quad (22)$$

As the terminal location is fixed, this equation corresponds to a fixed difference of the distance to the two foci, i.e., to one branch of a hyperbola. The border between direct shipment and intermodal transportation can be found by using the following equation:

$$x_{BZ} = a\sqrt{1+\frac{y_{BZ}^2}{b^2}} + \frac{x}{2}, \tag{23}$$

where:

$e = \frac{Z_1}{Z_2}$,

$a = \frac{x}{2e}$,

$b = a\sqrt{e^2 - 1}$.

Based on Equation 23, the total transportation cost can be calculated and the optimal terminal location can be obtained. In what follows, we propose an approximation of the border that allows simplifying the analysis.

We can notice that vertex's coordinates are $(B_Z x; 0)$. Moreover e is generally quite big for practical applications as Z_2 is generally small compared with Z_1. As the hinterland is classically such that $x_{\max} >> y_{\max}$, we can approximate the border for the Euclidean distance by the border defined in the Manhattan distance case. Thus, the total transportation cost can be approximated with the following expression:

$$\begin{aligned} Z(x) = {} & \rho y_{\max}\left(Bx\sqrt{B^2x^2 + y_{\max}^2} + (1-B)x\sqrt{(1-B)^2x^2 + y_{\max}^2} + (x_{\max} - x)\sqrt{(x_{\max} - x)^2 + y_{\max}^2}\right)Z_1 \\ & + ZF_2 x + 2\rho y_{\max}(x_{\max} - Bx)Z_2 x \end{aligned} \tag{24}$$

By taking the second derivative of $Z(x)$, we can show that this one is positive if $Z_1 \geq 4Z_2$ (equivalent to $e \geq 4$) and if $x_{\max} \geq 3y_{\max}$. These conditions are reasonable in practice and they are only sufficient ones, thus $Z(x)$ may be convex even if these conditions are violated. An approximation of the optimal terminal location can be obtained easily. This analysis can be directly applied to the carbon emissions minimization problem because the arguments supporting the approximation made are also valid for carbon emissions parameters.

3.3 Application

The data considered in this example are based on a discussion with experts and are in line with transportation cost and carbon emissions in Europe. We refer to Table 1 for more details.

ρ	0,0005	*containers/km²*
x_{max}	500	*km*
y_{max}	100	*km*
E_1	0,90	*kgCO2/cont.km*
E_2	0,22	*kgCO2/cont.km*
EF_2	8,80	*kgCO2/km*
Z_1	1,50	*€/cont.km*
Z_2	0,30	*€/cont.km*
ZF_2	35,00	*€/km*

Table 1: Application data

First, we focus on the Manhattan distance case. By applying Equations 11, 12 and 14, we obtain that x_Z = 130 km, x_E = 228 km and x_M = 333 km. This means that intermodal transportation is feasible from a cost, carbon emissions and modal shift perspective but the optimal terminal location is very different depending on the objective followed. Table 2 provides the total cost (Z), total carbon emissions (E) and modal shift (M) for x_Z , x_E and x_M . Surprisingly, maximizing the modal shift performs worse than minimizing the cost when focusing on carbon emissions. This example proves that the common trend toward focusing on the modal shift as a proxy for carbon emissions may fall short when focusing on intermodal network design decisions. The modal shift optimal solution generates 18% increase in cost compared with the cost optimal terminal location. On the other hand, the carbon emissions optimal terminal location generates less than 5% increase in total cost. Moreover, the convexity of both the total cost and the carbon emissions functions proved in Section 3.1 enables finding efficient tradeoffs. For example, locating the terminal at x = 170 km, enables more than 3% reduction in carbon emissions (compared with the cost optimal solution) with less than 0.75% increase in cost.

		Z	E	M
x_Z	130	20.872	11.156	35%
x_E	228	21.828	10.622	50%
x_M	333	24.704	11.190	56%

Table 2: Cost, carbon emissions and modal shift for the optimal locations

When focusing on the Euclidean distance, Figure 2 shows the exact cost border between direct shipment and intermodal transportation for several terminal locations. We can see that the approximation proposed in Section 3.2 performs reasonably well for this example. Moreover, we can observe that $x_{\max} = 5y_{\max}$ and that $Z_1 \geq 4Z_2$. The total transportation cost function approximated by Equation 24 is thus convex and we obtain that $x_Z \approx 120$ km. By performing the same analysis for carbon emissions, we can observe that $E_1 \geq 4E_2$ and we obtain that $x_E \approx 225$ km. These results are quite similar to the ones obtained with the Manhattan distance. Thus, the insights and discussions presented in the next section are based on the Manhattan distance case.

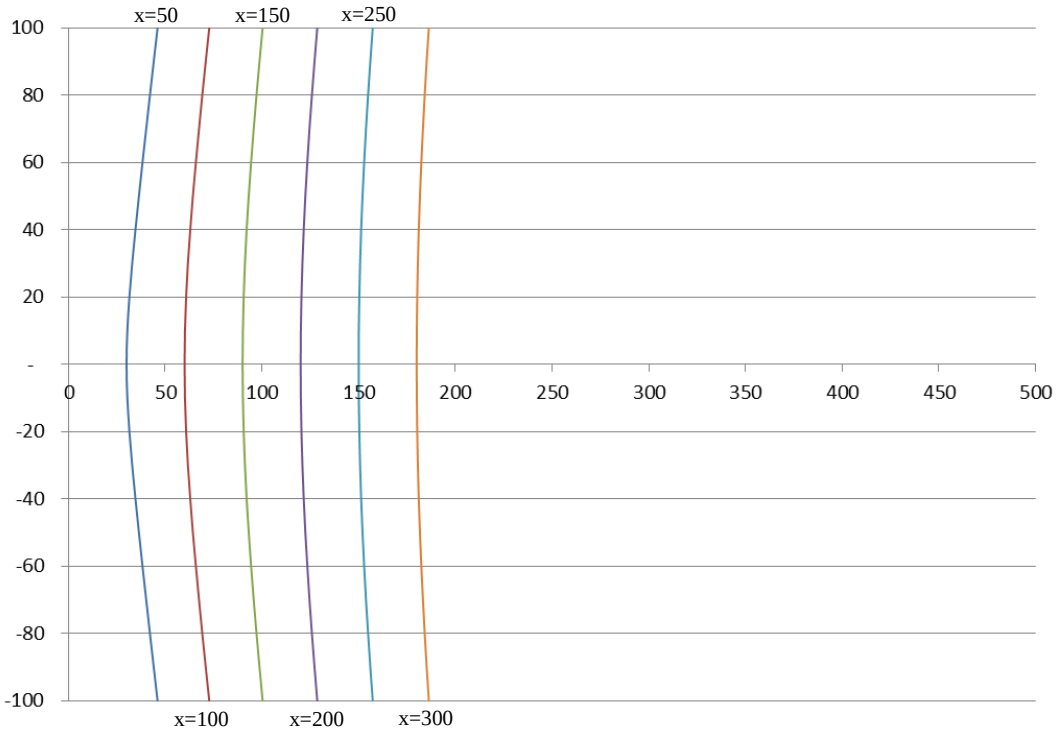

Figure 2: Border analysis

4. Insights and discussions

4.1 Optimal terminal location

Figure 3 and Figure 4 enable us to analyze the cost and carbon emissions structures as well as the variation of the different terms in function of the terminal location.

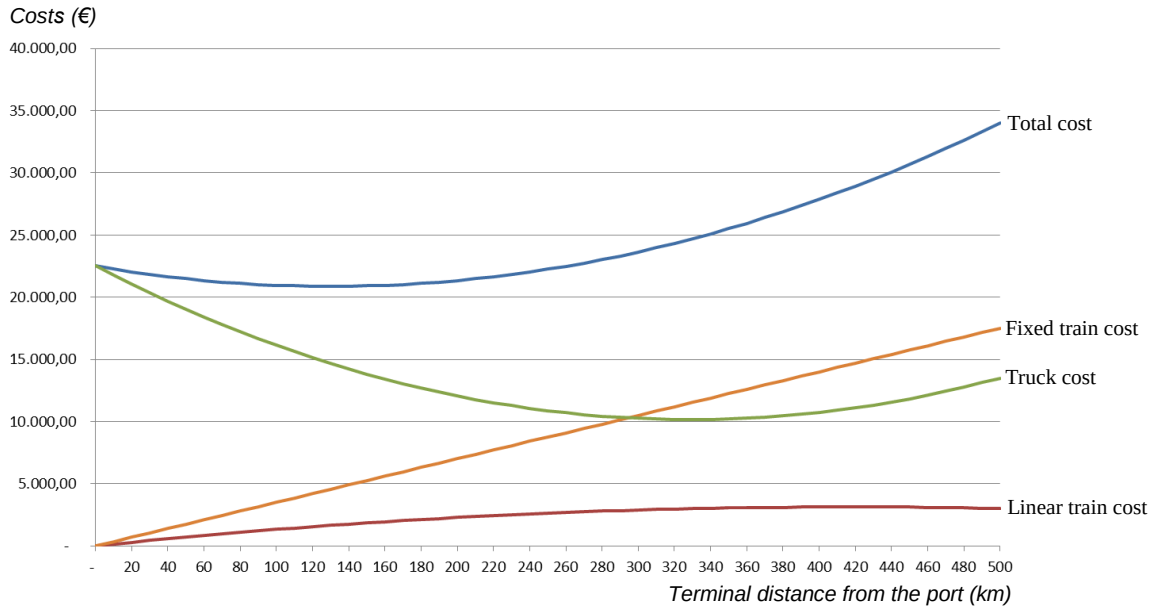

Figure 3: Cost analysis

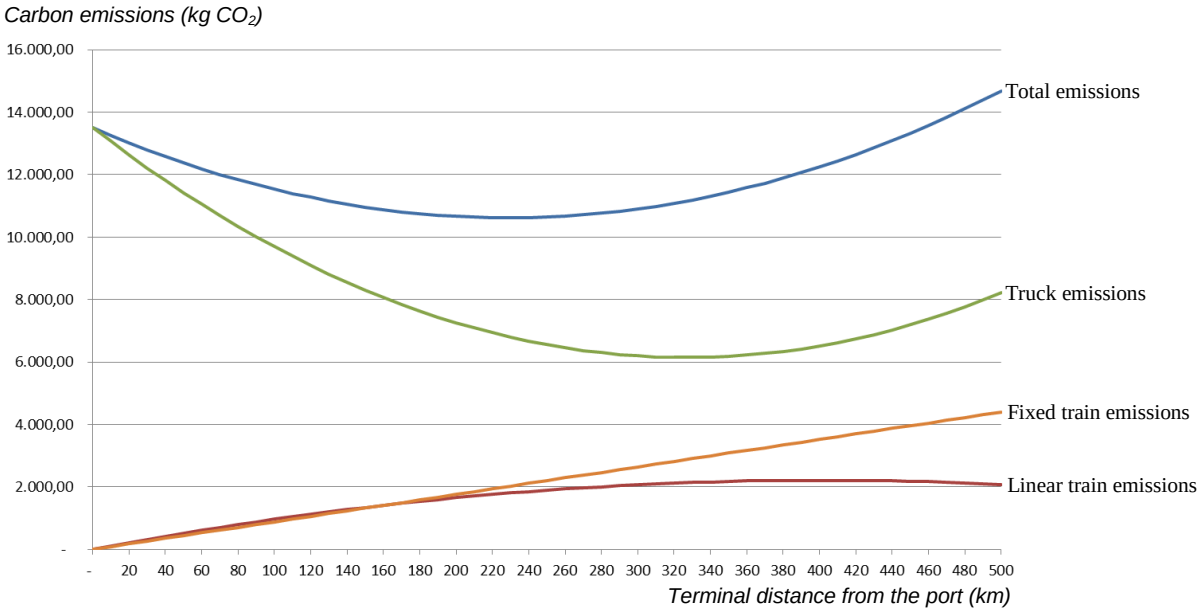

Figure 4: Carbon emissions analysis

The main difference between the cost and the carbon emissions optimal location is related to the fixed train parameter. To make this feature more visible, the carbon emissions functions have been put to cost scale by multiplying by $\frac{Z_1}{E_1}$. The results are represented in Figure 5 by the dashed lines while the solid lines represent cost functions.

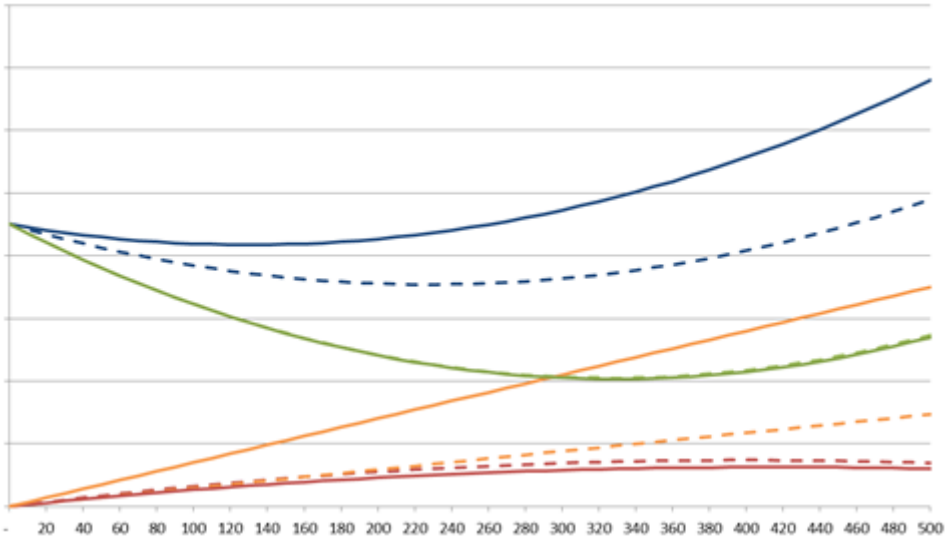

Figure 5: Comparison between cost and carbon emissions

First, we can observe that the truck contributions to the total functions are almost similar. This result comes from the fact that the cost and the carbon emissions borders between direct shipment and intermodal transportation are almost similar because $B_Z = 0.6$ and $B_E = 0.62$. Second, we can observe that the difference between the two linear train functions is very small due to the same argument. Thus, the main difference in the total cost and carbon emissions functions comes from the difference in the fixed train parameters. Indeed, $ZF_2 > 3EF_2 \frac{Z_1}{E_1}$ in the proposed example. This analysis enables explaining why $x_Z < x_E$.

Having $B_Z \approx B_E$ and $ZF_2 > EF_2 \frac{Z_1}{E_1}$ is a very general feature for intermodal transportation. Indeed, both Z_2 and E_2 are related to the energy consumption associated with transporting an extra container by train. These parameters are generally quite low compared with Z_1 and E_1 respectively. Moreover, train transportation is recognized as being more efficient in terms of carbon emissions than in terms of cost when being compared to truck transportation. This difference in efficiency is necessarily explained by a difference in fixed train parameters because the impacts of Z_2 and E_2 can be considered as marginal. Note that the same argumentation holds for barge transportation. We derive the following insight from this analysis.

Insight 1: *The terminal is located closer to the port when optimizing cost and is located further away from the port when optimizing carbon emissions.*

Insight 1 shows that even if the cost and the carbon emissions from transportation share the same structure, the variation of the underlying parameters (and especially the fixed train parameters) can lead to huge differences in optimal solutions. For example, the distance from the port to the inland terminal is almost doubled in the example proposed in Section 3.3 when carbon emissions are minimized.

Moreover, the results from Section 3 in addition to Insight 1 enable building the following relationship:

$$x_Z < x_E < x_M \,. \tag{25}$$

This shows that the terminal is located too far away when maximizing the modal shift. However, the accurate evaluation of carbon emissions from transportation is recognized as a difficult task. Thus, using a simple proxy for carbon emissions to derive some guidelines can be advantageous. In this sense, using the modal shift as a proxy for carbon emissions allows indicating the right direction from the cost optimal solution. However, keeping the goal of constantly increasing the modal shift can be harmful for both cost and carbon emissions. Let us assume that the results of the model presented in Section 3.3 are representative of the overall situation in Europe. The current level of modal shift in Europe is about 25% (Eurostat, 2012), i.e., lower than the cost optimal level of modal shift of the proposed example. However, we may argue that the current situation is not totally optimized from a cost perspective due to resistance to change. Then the objective of the European commissions of exceeding 50% of modal shift by 2050 would not be accurate because the carbon optimal level of modal shift is exactly 50%. This article shows that there is a carbon optimal level modal shift. The prerequisite for focusing on modal shift as a proxy for carbon emissions consists of identifying the carbon optimal level of modal shift.

Insight 2: *Modal shift can be viewed as a good proxy for carbon emissions if the carbon optimal level of modal shift can be identified.*

4.2 Distance versus volume

In the previous section, we have shown that the difference in fixed train parameters is the key driver of the analysis. This result proves that volume has to be considered as a main driver for efficient intermodal transportation. On the other hand, intermodal transportation is often presented as a viable option only for long distances. For example, the European Commission considers that "freight shipments over short and medium distances will to a considerable extent remain on trucks" (EC, 2011). Long distances induce reducing the effects of the origin and destination drayage thus this reduces the relative increase in the distance traveled compared with direct truck shipment. This helps explaining why intermodal transportation is generally viewed as efficient in reducing carbon emissions without compromising economic growth. However, focusing exclusively on long distances for intermodal transportation creates a big tension with the volume issue discussed above. Indeed, Tavasszy and van Meijeren (2011) show that only 11% of the volume is transported over a distance greater than 300 km for road transport in Europe.

The model presented in this article enables taking the tension between distance and volume into account. Indeed, the total volume shipped by intermodal transportation is decreasing in the distance from the port to the terminal. In addition, the fixed train parameters enable modeling flow dependent economies of scale. We prove that intermodal transportation can be viable for short and medium distances if two conditions are satisfied, i.e., the volume is big and the increase in traveled distance compared with direct shipment is low. This insight is also supported by several industrial examples. For example, eleven traders in the region of Westland in the Netherlands (situated at less than 100 km of the port of Rotterdam) have signed an agreement to transport 10,000 to 15,000 containers per year by barge/road intermodal transportation from the port of Rotterdam (project Fresh Corridor 7).

Insight 3: *Intermodal transportation is viable for short and medium distances if the volume is big and the origin/destination drayage distances are low.*

By using Insight 1, we can state that volume is more important than distance for efficient intermodal transportation because the terminal is located closer form the port when optimizing cost. Focusing primarily on volume instead of restricting the scope of intermodal transportation to long distances shipments can also help preventing some other externalities associated with road

transportation such as congestion. Congestion is indeed recognized as a key problem in most of the ports hinterlands (OECD/ITF, 2013).

Insight 4: *The scope of application of intermodal transportation solution should not be restricted to long distances shipments as volume is more important than distance for efficient intermodal transportation.*

Insights 3 and 4 show that the hinterland context is very favorable for efficient intermodal transportation even for short and medium distances as volumes are huge and that there is no origin drayage.

4.3 Aggregated cost and carbon emissions estimation models

We have proved in Section 3 that the shippers' optimal decisions between direct shipment and intermodal transportation do not depend on the fixed train parameters. Only the marginal contribution of adding an extra container on the train should be taken into account. However, the common practice for estimating cost and carbon emissions consists in sharing the fixed impacts of the train while running empty between the users by dividing the fixed train parameter by the average number of container shipped. This practice leads to express the train transportation cost per container.km (equivalent to per ton.km in our analysis). When focusing on carbon emissions, the methodologies for estimating carbon emissions from transportation typically accounts for an average load factor and end up with average carbon emissions intensity per container.km (equivalent to per ton.km in our analysis). In what follows, we discuss the implications of such estimations for both cost and carbon emissions calculations. We focus on carbon emissions but the same reasoning applies to cost. Assume that the average number of containers considered is α. Then the border between direct shipment and intermodal transportation is modified as follows:

$$B_{E\alpha} = B_E + \frac{EF_2}{2\alpha E_1}. \tag{26}$$

A necessary condition on α to make use of intermodal transportation is to have $B_{E\alpha} < 1$, this condition implies:

$$\alpha > \frac{EF_2}{E_1 - E_2}. \tag{27}$$

We discuss several ways of taking α into account in the decision making process in what follows. Indeed, the load factor can be considered as exogenous to the decisions made by the shippers. However, the number of containers shipped by intermodal transportation can also be calculated from the model. Moreover, we can consider that the practice of replacing E_2 by $E_2 + EF_2/\alpha$ affects the shippers' decisions but this can also affect the optimal terminal location.

First, assume that α is considered exogenously in the model and that the estimation affects only the routing decisions. Moreover, we focus on the case in which α satisfies Condition 27, otherwise, intermodal transportation is not used even if $x_E > 0$ based on Equation 14. The volume lost for intermodal transportation is:

$$V = \rho y_{\max} x_E \frac{EF_2}{\alpha E_1}, \tag{28}$$

and the impact in terms of carbon emissions is:

$$E_\alpha = V x_E \left(\left(2B_E - 1 + \frac{EF_2}{2\alpha E_1} \right) E_1 - E_2 \right). \tag{29}$$

For example, let consider that $\alpha = 30$. Based on the parameters of the example proposed in Section 3.3, this leads to $V \approx 4$ containers and $E_\alpha \approx$ 125 $kgCO_2$ i.e., an increase of 1.2% in carbon emissions.

Insight 5: *The common practice of using an aggregated model for train transportation emissions estimations (respectively cost) negatively affects the performance of intermodal transportation.*

Second, assume that α is considered endogenously in the model and that the estimation affects only the routing decisions. Then the following condition holds:

$$\alpha = 2\rho y_{\max} (x_{\max} - B_{E\alpha} x_E). \tag{30}$$

This condition can be expressed as $a\alpha^2 + b\alpha + c = 0$ with $a = 1$, $b = \rho y_{\max} \left(x_E \left(1 + \frac{E_2}{E_1} \right) - 2x_{\max} \right) < 0$ and $c = \rho y_{\max} \frac{EF_2}{E_1} x_E > 0$. This second degree polynomial possesses at most one positive root. By using the data from the example of Section 3.3, we obtain

that Condition 30 is equivalent to $a \approx 3.45$. The necessary condition stated by Equation 27 (i.e., $a \geq 13$ for this example) is not satisfied thus intermodal transportation is not used.

Insight 6: *The common practice of using an aggregated model for estimating train transportation emissions (respectively cost) can lead to misleadingly consider intermodal transportation as ineffective.*

Finally, let consider that the terminal location decision is made accordingly to $B_{E\alpha}$ and let consider α as exogenous. Equation 14 can be used to find the new terminal location by replacing B_E by $B_{E\alpha}$ and E_2 by $E_2 + EF_2/\alpha$ and by taking $EF_2 = 0$. Let consider that $\alpha = 30$. Based on the data from the example of Section 3.3, we obtain that the new terminal location is $x_{E\alpha} = 280$ km. Indeed, we have proved in Section 4.1 that the optimal terminal location decision was primarily driven by the fixed train parameters. Thus, it is not surprising to get the terminal located closer from the modal shift optimal location. This inefficient way of approximating carbon emissions from train transportation is at the foundation of the common assessment of intermodal transportation. This practice leads to consider modal shift as a proxy for carbon emissions as $x_{E\alpha}$ is closed from x_M. Moreover, this leads to focus primarily on long distances shipments as $B_{E\alpha} x_{E\alpha} >> B_E x_E$.

Insight 7: *The common practice of using an aggregated model for estimating train transportation emissions (respectively cost) leads to the biased perception of intermodal transportation consisting in focusing on long distances and maximizing modal shift.*

4.4 Influencing the tradeoff by public policy

In this section, we focus on analyzing how cost and carbon emissions performance can be aligned in intermodal transportation. First of all, we can notice that the cost optimal solution performs quite well in terms of carbon emissions in the example discussed in Section 3.3. Indeed, the total carbon emissions for the cost optimal terminal location are only 5% higher than the minimum level of carbon emissions achievable. Moreover, using intermodal transportation with a cost perspective

enables us to reduce the carbon emissions by 17% compared with the situation in which only direct truck shipments are used. This satisfactory performance of the cost optimal solution is explained by the following two considerations. First, the border between selecting direct shipment and selecting intermodal transportation is approximately the same for cost and carbon emissions because they are based on almost the same ratio. Second, the total amount of carbon emissions is quite insensitive to the terminal location under reasonable variations for convexity reasons. Thus, we can expect that the results obtained for the discussed example are quite general.

However, the total amount of carbon emissions could still be reduced as compared with the cost optimal location, which public authorities in many European countries are targeting. To further decrease carbon emissions for freight transportation, several policy measures mainly based on taxing and/or subsidizing are commonly implemented to influence the cost evaluation. We refer to Blauwens et al. (2006) for an example exploring the impacts of such policy measures from the shipper's perspective. The model we present here can also help elaborating on the advantages and drawbacks of several types of policy measures. By taking into consideration the intermodal network design decisions, we expect to develop new insights into the impact of taxing and/or subsidizing the logistics sector.

4.4.1. Taxation on road

We focus first on the situation in which road transportation cost is increased through a taxation scheme for road transportation. We can notice that an increase in Z_1 could favor intermodal transportation in situations such that using only direct shipment is economically preferable because the first two conditions in Equation 11 will be harder to satisfy. Moreover, if intermodal transportation is already feasible, the cost optimal terminal location will be situated further away from the port under a tax on truck transportation because x_Z is increasing in Z_1. By using the results proposed in insight 1, this proves that a well-chosen level of tax on truck transportation can help aligning cost and carbon emissions.

Let us assume that Z_1 is replaced by $\beta.Z_1$ due to a tax on truck transportation, with $\beta > 1$. We can first notice that an increase in truck transportation cost leads to a decrease in B_Z. However, we have shown that B_Z and B_E are almost similar in practice, thus implementing only a tax on truck transportation leads to an allocation between direct shipment and intermodal transportation

which is not carbon optimal. We neglect this difference here and we aim at finding the value of β leading to locate the terminal at x_E. We can express Equation 11 as follows:

$$x_{Z\beta} = \begin{cases} 0 & \text{if } Z_2 \geq \beta Z_1 \ , \\ 0 & \text{if } \ ZF_2 \geq 2\rho x_{\max} y_{\max} (\beta Z_1 - Z_2) \\ \dfrac{x_{\max}(\beta Z_1 - Z_2)}{2G} - \dfrac{ZF_2}{4\rho y_{\max} G} & \text{else,} \end{cases} \quad , \tag{31}$$

where:

$$G = \frac{3\beta^2 Z_1^2 - 2\beta Z_1 Z_2 - Z_2^2}{4\beta Z_1}.$$

We can reasonably approximate G by the following expression because we have already mentioned that Z_2 has a marginal impact in the analysis:

$$G \approx \frac{3\beta Z_1}{4}. \tag{32}$$

This approximation of G allows for the following approximation:

$$Z_1 \approx \frac{2\rho x_{\max} y_{\max} Z_2 + ZF_2}{(2x_{\max} - 3x_Z)\rho y_{\max}}. \tag{33}$$

By solving $x_{Z\beta} = x_E$ and by considering approximations 32 and 33, we obtain that:

$$\beta \approx \frac{x_M - x_Z}{x_M - x_E}. \tag{34}$$

By using insight 1, we obtain that $\beta > 1$ because $x_E > x_Z$ and we can observe that the increase in truck transportation cost has to be substantial to align cost with carbon emissions because $x_M - x_Z >> x_M - x_E$. For the example provided in Section 3.3, the tax on truck transportation leading to the carbon optimal terminal location consists in increasing truck transportation cost by 81% (β=1.81). This solution leads to a total carbon emissions of 10,643 kg CO_2, only 0.20% higher than the carbon optimal solution. This small difference comes from the carbon suboptimal allocation between direct shipment and intermodal transportation. Indeed, $B_{Z\beta}$ is equal to 0.56 while B_E is equal to 0.62. Note that Approximation 34 leads to $\beta \approx 1.94$ and to almost the same level of carbon emissions with 10,650 kg CO_2, proving that this approximation performs fairly

well. This substantial increase in truck transportation has also a strong impact on the total transportation cost for the entire system as this one is increased by almost 50% in the example of Section 3.3.

Insight 8: *Taxing truck transportation solely enables aligning cost and carbon emissions but the increase in truck transportation cost needs to be substantial beyond reason.*

The way to implement such an increase in truck transportation cost in practice is also challenging. Indeed, one of the most common practices for taxing truck transportation is to adapt the level of fuel tax. However, even with a fuel tax representing 62% to 83% of the total fuel cost in European countries, the fuel cost amounts only for 19% to 25% of the total truck transportation cost (Delsalle, 2002). This means that this fuel cost needs at least to be quadrupled to increase the total truck transportation cost by 81%. This solution does not seem reasonable for practical purposes.

4.4.2 Subsidies on trains

We now analyze the impacts of subsidizing train transportation. In the proposed model, this can be obtained by decreasing Z_2 and/or by decreasing ZF_2.

We first consider a decrease in Z_2. We do not expect such a regulatory policy to be very effective because the impact of Z_2 is marginal in the analysis. In the example proposed in Section 3.3, taking $Z_2 = 0$ does not allow for locating the terminal at the carbon optimal location because we obtain that x_Z = 174 km. This solution results in a total amount of carbon emissions of 10,783 kg CO2, i.e., 1.52% higher than the carbon optimal solution. Moreover, the daily cost of subsidizing train transportation is equal to €2,047. Thus, this solution is costly and not very effective.

The main parameter explaining the variation of optimal terminal location from a cost and a carbon emissions perspective is the fixed train parameter. Thus, a decrease in ZF_2 should be efficient in aligning cost and carbon emissions. We express the fixed train cost leading to locate the terminal at the carbon optimal location by using the following equation:

$$ZF_2 = \rho y_{\max}\left(2(Z_1 - Z_2)x_{\max} - x_E\,\frac{3Z_1^2 - 2Z_1Z_2 - Z_2^2}{Z_1}\right). \qquad (35)$$

By using Equation 35 with the parameters of the example of Section 3.3, we obtain that ZF_2 is equal to €16.14 per km. This solution leads 10,624 $kgCO_2$, i.e., a solution very close to carbon optimality. The small difference in carbon emissions compared to the carbon optimal solution is due to the fact that the border between direct shipment and intermodal transportation is calculated based on B_Z instead of B_E. This solution can be implemented in practice by financing the construction of the network as a substantial part of the fixed train cost comes from the network cost. However, the cost for the society is not negligible. Indeed, this policy measure leads to a daily bill of €4,309 for governmental and/or local authorities. This represents about 20% of the total logistic costs.

Insight 9: *Subsidizing train transportation by investing in the construction of the network enables aligning cost and carbon emissions. However, the social cost of this policy measure can be substantial.*

4.4.3 Subsidies on trains, train usage fee and taxation on road

An option to reduce the impact of subsidizing the fixed train cost consists in increasing the linear train parameter by charging a usage fee. This idea of making fixed costs variable is very attractive for intermodal transportation projects. However, we have shown that B_Z and B_E are almost similar in practice. If Z_2 is increased through applying a train usage fee, B_Z would increase and this would lead to an allocation between direct shipment and intermodal transportation which is not carbon optimal. An option to keep the border between direct shipment and intermodal transportation accurate consists of increasing Z_1 at the same time as Z_2 increases through a tax on truck transportation by using the following equation:

$$Z_1 = \frac{Z_2}{2B_E - 1}. \tag{36}$$

Conditions 35 and 36 ensures that the solution obtained is carbon optimal as the terminal is located in x_E (Condition 35) and the border between direct shipment and intermodal transportation is based on B_E (Condition 36). Moreover, subsidizing the fixed train transportation cost, charging a train usage fee and applying taxation on road leads to three degrees of freedom while only two conditions need to be satisfied. Thus, Z_2 can be considered as a free parameter. Z_1 and ZF_2 are

strictly increasing in Z_2, and the total transportation cost is strictly increasing in Z_2. This means that the total transportation cost can be controlled by setting Z_2 at the accurate level. For example, the policy makers may aim for a solution which is cost neutral for the logistics sector. This solution is obtained by setting Z_2 such that the total cost is the same as for the cost optimal location. Note that the resulting value for Z_2 can be obtained by the bisection method. For the example of Section 3.3, we obtain that Z_2 is equal to €0.43 per container.km, Z_1 is equal to €1.77 per container.km and ZF_2 is equal to €17.29 per km by applying Conditions 35 and 36. In this case, the cost for the society is equal to the difference in cost between the cost optimal and the carbon optimal solutions i.e., €956. This represents less than 5% of the total logistic costs, i.e., 4 times less than when subsidizing only. This relatively limited cost for the society results from the fact that B_Z and B_E are quite similar and that the total transportation cost is quite insensitive to the terminal location under reasonable variations due to convexity reasons. Moreover Z_2 may be chosen such that the solution is cost neutral for the society. In this case, we obtain that Z_2 is equal to €0.45 per container.km, Z_1 is equal to €1.85 per container.km and ZF_2 is equal to €18.08 per km by applying Conditions 35 and 36. The increase in truck transportation cost by 23% seems reasonable in practice.

Insight 10: *Subsidizing train transportation in addition to a tax on truck transportation as well as a train network usage fee enables aligning cost and carbon emissions. The values of the tax, the usage fee and the subsidy can be chosen such that the solution is cost neutral either for the logistic sector or for the society.*

The main results of this section are summarized in Table 4.

Policy measure	Impact in the model	Optimal parameters value	Carbon emissions (kg CO_2)	Cost for the logistics sector (€/day)	Cost for the society (€/day)
taxation on road	increase in Z_1	Z_1=2.72	10,643	30,936	-9,125
subsidies on train	decrease in Z_2	Z_2=0	10,783	19,014	2,047
subsidies on train	decrease in ZF_2	ZF_2=16.14	10,624	17,490	4,309
subsidies on train, train usage fee and taxation on road	decrease in ZF_2 increase in Z_2 increase in Z_1	ZF_2=17.29 Z_2=0.43 Z_1=1.77	10,622	20,872	956
subsidies on train, train usage fee and taxation on road	decrease in ZF_2 increase in Z_2 increase in Z_1	ZF_2=18.08 Z_2=0.45 Z_1=1.85	10,622	21,828	0

Table 4: Summary of the different policy measures

5. Conclusion

This article studies the dynamics of intermodal transportation in the context of hinterland networks. We present a new intermodal network design model in which both the terminal location and the allocation between direct truck transportation and intermodal transportation are optimized. We indeed consider that intermodal transportation inherently induces a tradeoff between the efficiency gain in the linehaul and the increase in the distance traveled and that this tradeoff needs to be studied from a network design perspective. The model accounts for cost, carbon emissions and modal shift and enables analyzing the relationship between these different objectives. The optimal solutions are identified for two measures of the distance, i.e., the Manhattan distance and the Euclidean distance. In the Manhattan distance case, we prove that the border between direct truck transportation and intermodal transportation is a straight line. In addition, we show that both the cost function and the carbon emissions function are convex whereas the modal shift function is concave. In the Euclidean distance case, we prove that the modal shift function has the same properties as for the Manhattan distance. However, we characterize the border between direct truck transportation and intermodal transportation as one branch of a hyperbola for cost and carbon emissions. We derived efficient approximations for optimizing the cost and the carbon emissions functions and we show that these approximations are relevant for practical applications.

Several insights are derived from the analytical results. We show that the terminal is located closer from the port when optimizing cost compared to the carbon optimal terminal location.

Moreover, some limitations of using the modal shift as a proxy for carbon emissions are highlighted. Indeed, we prove that maximizing the modal shift is harmful for both cost and carbon emissions. We subsequently show that there is an optimal level of modal shift and we conclude that modal shift can be a good proxy for carbon emissions only if the optimal level of modal shift is identified. This insight is in opposition with the current practice which consists in trying to constantly increase the level of modal shift.

The model also allows for studying the tradeoffs between distance and volume. The model indeed allows for flow dependent economies of scale for train transportation cost and carbon emissions. Moreover, the total volume shipped by intermodal transportation is decreasing in the distance from the port to the terminal. We show that intermodal transportation is feasible for short and medium distance if the volume is big and if the origin/destination drayage distances are low. This insight is in opposition to the common practice of focusing on long distance for intermodal transportation. The model also shows that volume is more important than distance for efficient intermodal transportation. This insight leads us to consider hinterland networks as a very promising context for implementing intermodal transportation solutions even if the distances traveled are not necessarily long.

The implications of the current estimations practice for train transportation cost and carbon emissions are also evaluated. We prove that using an aggregated model for estimating train transportation cost and emissions negatively affects the performances of intermodal transportation and that this may lead to consider intermodal transportation as inefficient in situations in which such a solution could be implemented. We also show that these estimations are in the foundation of the biased perception of intermodal transportation, i.e., focusing on long distances and using modal shift as a proxy for carbon emissions.

Finally, we analyze several policy measures aiming at aligning cost and carbon emissions. We prove that a tax on truck transportation enables aligning cost and carbon emissions but that the increase in truck transportation cost has to be substantial, leading to an unfeasible solution for practical applications. We also prove that subsidizing train transportation by investing in the network enables aligning cost and carbon emissions but that the cost of such a policy measure can be substantial for the society. Thus, we propose to combine this train transportation subsidy with a train network usage fee as well as an appropriate tax on truck transportation. We show that

accurate values for the tax, the usage fee and the subsidy enable aligning cost and carbon emissions while being cost neutral either for the logistic sector or for the society.

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