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Effect of carbon emission regulations on transport mode selection under stochastic demand

K.M.R. Hoen*, T. Tan, J.C. Fransoo, and G.J. van Houtum
School of Industrial Engineering, Eindhoven University of Technology,
P.O. Box 513, 5600 MB Eindhoven, the Netherlands

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Abstract

Companies are experiencing new and more important reasons to pay attention to their carbon footprint. In this work we consider a ‘carbon-aware’ company (either by choice or enforced by regulation) that is reconsidering the transport mode selection decision. Traditionally the trade-off has been between lead time (and corresponding inventory costs) and unit transportation costs but now emission costs come into the equation. We use a carbon emission measurement methodology based on real-life data and incorporate it into an inventory model. We consider the results for different types of emission regulation (including voluntary targets). We find that even though large emission reductions can be obtained by switching to a different mode, the actual decision depends on the regulation and other practical issues.

Keywords: green supply chains, carbon emissions, inventory model, transport mode selection, newsvendor.

1 Introduction

Over the last few decades global warming has received increasing attention. In 1995 the Intergovernmental Panel on Climate Change (IPCC) (set up by World Meteorological Organization and United Nations Environment Programme) published an assessment which states that the increase in greenhouse gas concentrations tends to warm the surface of the earth and leads to other climate changes, IPCC (1995). Greenhouse gases is a term which is used to refer to a collection of gases among which are carbon dioxide (or carbon), methane, and CFCs. The assessment of the IPCC was used to formulate an important international commitment to reduce greenhouse gas emissions in 1997: the Kyoto protocol. Besides the reduction target the protocol offers three market-based mechanisms to meet the targets: Emissions Trading, Clean Development Mechanism and Joint Implementation. The European Union has already implemented an emission trading scheme (EU ETS) for the energy-intensive industries, which

* Corresponding author, E-mail: k.m.r.hoen@tue.nl

currently account for almost 50% of Europe's carbon emissions, European Commission (2008). Under the ETS, each company is allowed to emit a certain amount of carbon (based on past emissions) and receives that amount of allowances. If the emissions of a company are lower than the allowed amount, they can sell the allowances. If the emissions are higher, they have to buy allowances. A trading market for allowances has been created and the market determines a price for emissions. Since the introduction the price of a carbon allowance has varied between € 0 and € 30 per tonne of CO_2 , European Carbon Exchange (2011). In this research we focus on carbon dioxide emissions because it is an important greenhouse gas and all other greenhouse gases can be expressed in carbon dioxide equivalents (CO_2e).

Currently, no comprehensive regulations exist that impact carbon emissions resulting from all types of transport. However, in January 2009 the European Commission published a directive to include aviation in the EU ETS. From 2010 on, a few countries have adopted it already and it is likely to be included by all member states by 2013 at the latest, European Commission (2010). A study of the Organization for Economic Co-operation and Development OECD (2002) predicted that, without appropriate action, the carbon emissions resulting from transport will be doubled by 2020 (compared with 1990). This is not in line with the emissions of other areas, such as industry or power generation, which show a decreasing trend over the same period. Since 1990 the energy efficiency of transport has been increasing and is likely to continue increasing, European Commission (2007). The increase in emissions is due to the increase in demand for transportation and the existing trend in increased energy efficiency is not sufficient to balance this. It is important to reduce carbon emissions resulting from transport to meet the overall carbon emission target. In the (near) future governments are likely to develop regulations which restrict the emissions originating from transport activities. Companies need to seek opportunities to decrease the amount of energy (and emissions) required to transport 1 tonne of goods over 1 kilometer to make sure that the regulations will be met in the future. A possible way to reduce carbon emissions is to select transport modes which generate lower emissions per km traveled. A trade-off exists because slower transport modes generate lower transportation costs and fewer emissions at a cost of higher inventories (or lower service levels) to meet the demand during lead time.

The accurate measurement of carbon emissions is an essential requirement to ensure that the emission targets are met and for companies to reduce their carbon emissions. Several methodologies are available: Greenhouse Gas protocol (GHG), Greenhouse Gas Protocol (2011), Artemis, TRL Ltd (2004), EcoTransIT, ECOTransIT (2011), NTM, NTM (2011), and STREAM, Den Boer *et al.* (2008). GHG protocol contains a low level of detail, is a top-down calculation method

and the scope is worldwide but with a focus on the US. Artemis provides a very high level of detail and the scope is Europe. EcoTransIT has a moderate level of detail and also focuses on Europe. The NTM method has a high level of detail and focuses on Europe. Lastly, STREAM provides a medium level of detail and is focused on the Netherlands. For this research, the NTM method is selected because it provides a high level of detail and the methodology provides estimates for parameter values that are unknown to a company or logistics service provider. NTM is also involved with the European Committee for Standardization (CEN) in developing the European standard for emission calculation, NTM (2011).

A description and the objective of NTM can be found on their Website NTM (2011): “The Network for Transport and Environment, NTM, is a non profit organization, initiated in 1993 and aiming at establishing a common base of values on how to calculate the environmental performance for various modes of transport.” The objective of NTM is to “act for a common and accepted method for calculation of emissions, use of natural resources and other external effects from goods and passenger transport.” To the best of our knowledge, the explicit modeling of carbon emissions has not been studied in the operations management literature.

Several areas of literature are related to this research. First, the literature on global warming and the role of carbon emissions in this is relevant. The effect of emissions from human industry on global warming were first calculated by Arrhenius in the 19th century, Arrhenius (1895) and Callendar argued in 1938 that higher levels of carbon dioxide were causing an increase in the global temperature, Callendar (1938).

Second, green supply chains and green supply chain management (GSCM) literature is connected to our work. Green supply chain management is defined by Srivastava (2007) as “Integrating environmental thinking into supply chain management including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life”. Overviews of green supply chain management literature are given by Corbett & Kleindorfer (2001a), Corbett & Kleindorfer (2001b), Kleindorfer *et al.* (2005), Srivastava (2007), Sasikumar & Kannan (2009), and Gupta & Lambert (2009). Reverse logistics/closed-loop supply chains is an important part of green supply chain management and a lot of research has already been conducted in this field; see for example Blumberg (2005) and Pochampally *et al.* (2009). Literature reviews of the field are given by Atasu *et al.* (2008) and Fleischmann *et al.* (1997). More recently, the GSCM field has been extending to include green inventory models that link the inventory and ordering behavior and emissions. Bonney & Jaber (2010) elaborate on this development. Some other work in the field of green inventory management include Rosić & Jammernegg (2010),

Benjaafar *et al.* (2010), and Hua *et al.* (2009).

Finally, transport mode selection literature is related because situations similar to ours are analyzed. The approach of the articles is very different because the focus is on accurately describing transport (inventory is also included). Within the transport mode selection literature, articles which focus on the inventory-theoretic framework are relevant, see Tyworth (1991) for a literature review up to 1990. This topic is covered by a vast body of literature and it was studied for the first time by Baumol & Vinod (1970). Blauwens *et al.* (2006) investigate the effect of policy measures on modal shift, and the aim is to move away from road transport because of congestion. In Kiesmüller *et al.* (2005) the added value of using a slow mode in addition to a fast mode is considered. In some articles emissions are taken into account, for example Bauer *et al.* (2009) develop an integer linear programming formulation to determine the service network design that minimizes the emissions. Their work differs from ours as they focus on the design of the network, which is outside the scope of our article. Meixell & Norbis (2008) present an overview of all available literature on transportation mode selection and present directions for future research. They indicate that none of the articles they reviewed included energy consumption or emissions and that it is an important area to investigate. This is exactly what we do in this paper.

We consider a company that determines on a regular basis, e.g. yearly, which transport mode (or intermodal transport) to use for a particular product on a particular leg of the supply chain. They send out a request-for-quotation (RFQ) to third-party logistics service providers (3PL) and based on the offers they obtain, one mode is selected for that period. Traditionally, the decision for a transport mode has only been based on the lead time and the unit cost of transport. A trade-off exists because the longer the lead time, the higher the inventory required to deal with demand uncertainty, and the lower the transport cost. The company now has (more) incentives to focus on the emissions of transport as well. So an extended trade-off is sought among inventory costs, transportation costs and carbon emissions. We consider the design of the supply chain as fixed, which we have also observed in practice to be the preferred problem scope by many companies. The demand is stationary and stochastic. We consider a single product setting in order to focus on the interactions and the trade-offs between the relevant costs and carbon emissions. This set of assumptions is reasonable if, e.g., the transport activities are outsourced.

Companies might have two main reasons to exert effort on carbon emission abatement, in addition to costs: The first one is voluntary commitment, as a response to customer preferences, pressure, environmental groups, organizations, initiatives (such as the Carbon Disclosure

Project), etc. Many companies have specified targets, even in their mission statement, to reduce emissions by a certain amount before a certain time (e.g., 20% by year 2020). This target can be converted to a department target and even a product target. The second reason is to comply with regulations, that are induced by governments to reduce emissions. As far as transportation is concerned, currently this is restricted to a cap-and-trade system for air transport in Europe, as described before, but it is likely to increase in the future. The most likely types of regulations are i) a (carbon or diesel) tax, ii) inclusion in or creation of a separate cap-and-trade system, or iii) a hard constraint on emissions. We formulate a model that can represent any of these three regulation types. The impact each of the regulation types would bring in are different, of course. We elaborate on this in Section 5. In emission (or even environment) regulation, the general principle is ‘the polluter pays’. In case of production, this is clear. However, when transport is concerned this is not as clear, because two parties are involved: the shipper and the shipping company. We assume that the shipper is solely responsible for the emissions resulting from transporting the items (even though they correspond to ‘Scope 3’ emissions of the GHG Protocol). We consider this assumption to be reasonable because the shipper creates the demand for transport. Moreover, it is in the best interest of the shipping company to make the execution of the transport as efficient as possible, because it reduces fuel consumption, and hence the costs.

This paper makes three contributions to the literature. First, we use a methodology based on empirical data to obtain accurate estimates for the carbon emissions for different modes of transport and specific parameter values. Second, we formulate a model which analyzes the trade-off between inventory, transport, and emission costs for transport modes. Finally, we investigate the effect of different types of regulations with respect to emissions on the selected transport mode and the corresponding emissions.

To be able to observe the effect of emission regulations on transport mode selection we need (i) a definition of the transport mode selection problem, (ii) a problem formulation with carbon emissions, and (iii) a methodology to calculate the emissions. We present these ingredients in the succeeding sections of the paper: our model and the Transport Mode Selection Problem are described in Section 2. In Section 3, we describe the Emission Transport Mode Selection Problem which extends the transport mode selection problem. Moreover, we describe the NTM method to calculate the emission estimates. In Section 4, we present the solution to the (Emission) Transport Mode Selection Problem. In Section 5, we calculate the actual emissions for a test bed and determine the preferred transport mode for the parameter settings. An approximate model is presented in Section 6 in which more analytical results are derived. In

Section 7, we draw conclusions.

2 Model without emissions

In this section we formulate our model and assumptions and the Transport Mode Selection Problem, in which the transport mode which minimizes the average cost is selected. We consider a single production facility of a company as part of a larger supply chain which uses a single product as input to the production process. The production facility orders units of the product from a (possibly internal) supplier and several (two or more) transport modes are available for transport. The producer has to select one mode which will be used for all transport. All units are shipped by a third party logistics service provider (3PL).

We assume that the production facility orders each period from its supplier and we assume an infinite horizon. We assume that the period of time for which the producer decides to use a particular mode is long enough that an infinite horizon model is a valid approximation. Demand per period for the product at the production facility follows a continuous distribution and is characterized by mean μ , standard deviation σ ($\mu, \sigma > 0$) and we denote the coefficient of variation of demand by $\psi = \frac{\sigma}{\mu}$. Demands in different periods are assumed to be independent identically distributed (i.i.d.).

The unit cost of the product is denoted by k ($k > 0$). The following physical characteristics of the product are specified: the product volume v ($v > 0$), and the product density ρ ($\rho > 0$). The amount of goods a vehicle can carry depends on the weight and the volume of the load. If an item is light yet large, not many items can be transported even though the weight is not restrictive. Logistics Service Providers therefore charge their customers based on the dimensional or volumetric weight of the shipment (NTM Air, 2008), (NTM Road, 2008). This means that if a product has a high density, the actual weight is taken for allocation. If a product has a low density, a weight is assigned which is the volume times a prespecified minimum density, this results in the following formula for weight:

$$w = v \max\{\rho, \bar{\rho}\}, \quad (1)$$

where ρ denotes the density of the product (in kg/m^3) and $\bar{\rho}$ the prespecified minimum density. Please note that $\bar{\rho}$ might be equal to 0 which implies that the actual weight of the product is used to determine the price.

Several transport modes are available to ship the product. Let $I = \{1, \dots, |I|\}$ denote the set of available transport modes (including intermodal transport). Let c_i ($c_i > 0$), $i \in I$, denote

the unit transportation cost for mode i charged by the 3PL which is based on the volumetric weight of the product and a cost factor per kilogram of product shipped over 1 kilometer (€/kg km) t_i : $c_i = t_i \max\{\bar{\rho}, \rho\}vd$, where d is the distance to be traversed. The deterministic supply lead time for mode i is denoted by L_i ($L_i \in \mathbb{N}_0$, where $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$). We assume that the supplier holds sufficient stock to satisfy the demand within the specified lead time. One transport mode is selected for all shipments.

When an item is required at the facility and there are no units on stock, the demand is backordered. A penalty cost p ($p > 0$) is incurred per unit on backorder at the end of a period for mode i . The average number of items backordered at the end of a period for mode i is denoted by $\mathbb{E}[B_i]$. The average penalty cost for mode i is then $p\mathbb{E}[B_i]$. The holding costs represent an opportunity cost because inventory ties up capital that might generate revenue otherwise. It is therefore a function of the expenses per unit of product once it is in inventory: the unit cost k and transport cost c_i associated with mode i . Holding costs are incurred for each unit on stock at the end of a period and is expressed as a holding cost rate r_h ($r_h > 0$) per monetary unit. The average number of items on stock at the end of a period (on-hand inventory) for mode i is denoted by $\mathbb{E}[X_i]$. The average holding cost for mode i is then $r_h(k + c_i)\mathbb{E}[X_i]$. The penalty costs per unit are typically 5-20 times as high as the holding costs.

The objective function is the average cost per period for transport mode i . The average number of units shipped per period is equal to the average demand μ . The average cost per period for mode i (C_i) consists of penalty cost, holding cost, and transportation cost.

$$C_i = p\mathbb{E}[B_i] + (k + c_i)r_h\mathbb{E}[X_i] + c_i\mu. \quad (2)$$

The cost term $k\mu$ is not relevant since it is not influenced by the inventory policy or the transport mode.

In each period first an order is placed (and earlier placed orders may arrive) and after that demand occurs. We assume that an order-up-to policy, or a base-stock policy, is used and we optimize the performance for this policy. Let S_i denote the order-up-to level for transport mode i . Our focus is not on determining an optimal inventory policy for the system and moreover an order-up-to policy is often used in practice.

We use the solution of a single-period Newsboy problem to find the optimal solution to our problem (Axsäter, 2006). To optimize the system, we need the distribution of the demand during lead time plus the review period which we denote by $D(L_i + 1)$ with parameters $\mu_i = (L_i + 1)\mu$ and $\sigma_i = \sqrt{L_i + 1}\sigma$ (follows from the i.i.d. assumption). Let $f_i(x)$ and $F_i(x)$ denote the probability density function and cumulative distribution function of $D(L_i + 1)$ (for mode i).

The expected cost per period, given order-up-to level S_i , is denoted by $C_i(S_i)$ and is calculated as follows:

$$\begin{aligned}
C_i(S_i) &= \mathbb{E}[C_i(S_i, x)] \\
&= (k + c_i)r_h \int_{-\infty}^{S_i} (S_i - x)f_i(x)dx + p \int_{S_i}^{\infty} (x - S_i)f_i(x)dx + c_i\mu \\
&= (k + c_i)r_h(S_i - \mu_i) + ((k + c_i)r_h + p)G_i(S_i) + c_i\mu,
\end{aligned} \tag{3}$$

where $G_i(y) = \int_y^{\infty} (x - y)f_i(x)dx$.

Let the *Cost-Minimization Problem* for transport mode i be defined as follows:

$$C_i^* = \min_{S_i} C_i(S_i), \tag{4}$$

and S_i^* denotes the optimal order-up-to level for mode i .

The *Transport Mode Selection Problem* (TMSP) is formulated as follows:

$$C^* = \min_{i \in I} C_i^*. \tag{5}$$

In the TMSP the transport mode with the lowest minimum average cost per period is selected.

3 Emissions

In this section we describe how carbon emissions are incorporated into our model and the methodology to calculate the emissions. In Section 3.1 we define the Emission Transport Mode Selection Problem in which an emission price per unit of emissions is charged. After that, in Section 3.2, we introduce the NTM method which enables us to calculate the emissions resulting from transportation.

3.1 Emission Transport Mode Selection Problem

In Section 1 we have described several possible ways in which carbon emissions might influence the transport mode selection problem. We consider a model with an emission cost that can represent any of the emission regulations, which represents an emission tax or the price of a carbon allowance in a cap-and-trade system. Our model can also represent other regulation types. The internal motivation, i.e. a self-imposed emission target, will translate to a constraint on the maximum amount of emissions. This constraint is a hard constraint, it can not be violated. The constrained problem can be translated into an unconstrained problem with a Lagrange multiplier with infinite value. In Section 5 we will comment on the difference in impact of these different types of (internal) regulation.

The Emission Transport Mode Selection Problem (ETMSP) extends the TMSP by adding a carbon emissions cost. We only consider variable emissions (so independently of the amount of products ordered at the same time). The reason for this is that transport is outsourced to a Logistic Service Provider and the shipper has no control over the actual shipping. We therefore assume, in accordance with NTM, that each product is shipped with an averagely loaded vehicle. This is explained in more detail in Section 3.2. Let e_i ($e_i > 0$) denote the emissions associated with shipping 1 unit of the product with mode i . Moreover c^e ($c^e \geq 0$) denotes the emission cost per unit of emissions (e.g. tonne). The tied-up capital per product on stock changes as well, the holding cost (for mode i) are defined by the following equation: $r_h(k + c_i + c^e e_i)$.

Let C_i^e denote the average cost per period, including the emission cost, for order-up-to level S_i^e .

$$C_i^e(S_i^e) = r_h(k + c_i + c^e e_i)(S_i^e - \mu_i) + (r_h(k + c_i + c^e e_i) + p)G_i(S_i^e) + (c_i + c^e e_i)\mu, \quad (6)$$

where $G_i(y)$ is defined as before.

The *Emission Cost-Minimization Problem* for transport mode i is defined as follows:

$$C_i^{e,*} = \min_{S_i^e} C_i^e(S_i^e). \quad (7)$$

The *Emission Transport Mode Selection Problem* (ETMSP) is formulated as follows:

$$C^{e,*} = \min_{i \in I} C_i^{e,*}. \quad (8)$$

As in the TMSP the transport mode with the lowest minimum average cost per period is selected.

3.2 Emission calculations

The NTM method specifies emissions for four types of transport: air, rail, road and water, which are described in Sections 3.2.1 - 3.2.4, respectively. The two main steps in determining the emissions for a unit transported with a vehicle are: determine the emissions for a vehicle with an average load and then allocate the emissions of the averagely-loaded vehicle to one unit of the product based on weight. The general structure for the unit emissions are then:

$$e_i = (f^c + f^v d) \frac{w}{\hat{l}_o \cdot l}, \quad (9)$$

where d denotes the traveled distance (in km), f^c a constant emission factor (in kg), f^v a variable emission factor (in kg/km), w the weight of 1 product (in kg), \hat{l}_o the maximum load

of the vehicle (in kg) and l the average load factor of the vehicle. The load factor of a vehicle is defined as the actual load as a fraction of the maximum load. NTM uses the emissions of an averagely loaded vehicle because in general no better information is available to the shipper. In the following sections we describe the mode-specific assumptions and issues.

3.2.1 Air transport

All details are taken from NTM Air (2008).

Emission factors: In air transport the constant emission factor corresponds to the emissions during take-off and landing, which are a significant part of the total emissions for short distances. NTM provides the emission factors for load factors of 50, 75 and 100 %. The emission factors for different load factors are found by interpolation.

Distance: The flight distance is calculated with the method used by the International Civil Aviation Organization (ICAO): the Great-circle distance formula. The Great-circle distance formula gives the shortest distance between two locations on a sphere by following a path on the surface of the sphere.

Unit Emissions: The prespecified minimum density for air transport is $167 (kg/m^3)$, which is a density commonly used by transport companies.

3.2.2 Rail transport

Two types of rail transport are distinguished; electrical and diesel. Let their unit emissions be denoted by e_e and e_d , respectively. For rail transport, the distance is divided into distances per country because the emissions to generate 1 kWh , and the fuel content, differ per country. Define the set of countries through which the train travels as Z and $z \in Z$. All details are taken from NTM Rail (2008).

Emission factor (including allocation): Only a variable emission factor is used for rail transport. It depends on the gross weight of the train, an emission constant, a correcting factor for the terrain, the load factor, energy (cq. fuel) efficiency factor, and a transfer loss (for electrical only). The gross weight of the train (W_{gr} in *tonne*) includes the weight of the locomotive and the carriages. The topography of country z is classified as one of three types ($tf_z \in \{flat, hilly, mountainous\}$). Let $T(tf_z)$ define the energy (cq. fuel) consumption for a country with topography type tf_z . It holds that $T(mountainous) > T(hilly) > T(flat)$. Let l denote the load factor of the train (equals the ratio of net and gross weight of the train). Let EE^z denote the energy efficiency in country z , the emissions for producing 1 kWh of energy, and let FE^z denote the fuel emissions in country z , the emissions per liter of fuel burnt. Moreover, a

loss of energy TL (fraction) is taken into account during energy transfer from the power plant to the train.

Combining these factors yields the following equations for the emission factors for electrical and diesel rail transport f_e^z and f_d^z (in $kg CO_2$ /net tonne km):

$$\begin{aligned} f_e^z &= \frac{T(tf_z) \cdot EE^z}{10^3 \sqrt{W_{gr}} \cdot l \cdot (1-TL)}, \\ f_d^z &= \frac{T(tf_z) \cdot FE^z}{10^6 \sqrt{W_{gr}} \cdot l}. \end{aligned} \quad (10)$$

Distance: The distance traveled in country z , d^z , (in km) can be calculated from for example the EcoTransIT web page (ECOTransIT, 2011).

Unit emissions: The unit emissions are calculated per country and then summed over the countries traversed.

$$e_j = \sum_{z \in Z} f_j^z d^z w, \quad (11)$$

for $j \in \{d, e\}$. This equation applies to electrical and diesel rail transport.

3.2.3 Road transport

All details are taken from NTM Road (2008).

Emission factor: For road transport the emission factor is determined by the fuel consumption (FC in l/km) and the fuel emissions (FE). The fuel consumption depends on the load factor (l) and vehicle type. It is calculated with the following formula:

$$FC = FC_{empty} + (FC_{full} - FC_{empty})l. \quad (12)$$

The fuel emissions factor is defined as gram of CO_2 emitted per liter of fuel (diesel). The emission factor is determined by the product: $f^v = FC \cdot FE$.

Unit Emissions: For road transport the volumetric weight is used and the prespecified minimum density is $250 kg/m^3$, where 250 is a default density commonly used by transport companies.

3.2.4 Water transport

Water transport covers short-sea transport and inland transport with diesel oil-powered vessels. All details are taken from NTM Water (2008).

Emission factor: As for road transport, the emission factor is determined by the fuel consumption (FC) and the fuel emissions (FE).

Distance: The distance d in km can be obtained from, for example the PortWorld Distance

calculator website (PortWorld Distance Calculator, 2011).

Unit emissions: Define the allocation fraction $\beta \in (0, 1]$ as follows:

$$\beta = \frac{\text{unit capacity}}{\text{total capacity}}.$$

The unit of capacity is dependent on the type of ship used, it can be weight (for bulk vessels), TEU (twenty-foot equivalent units) (for container vessels) or lane meters (for roll-on, roll-off vessels, which transport trucks or rail carts). The allocation fraction α replaces $\frac{w}{l\sigma}$, in the Equation (9).

4 Analysis

We solve the Transport Mode Selection Problem and Emission Transport Mode Selection Problem to optimality in Sections 4.1 and 4.2, respectively.

4.1 Problem without emissions

It is known that (see, e.g., Axsäter (2006)) the optimal order-up-to level (S_i^*) satisfies the condition:

$$F_i(S_i) = \frac{p}{p + r_h(k + c_i)}. \quad (13)$$

The minimum average cost per period (C_i^*) associated with mode i is accordingly

$$C_i^* = r_h(k + c_i)(F_i^{-1}(\alpha_i) - \mu_i) + (p + r_h(k + c_i))G_i(F_i^{-1}(\alpha_i)) + c_i\mu, \quad (14)$$

where $\alpha_i = \frac{p}{p + r_h(k + c_i)}$.

To obtain more insight into the solution to the TMSP, we derive for a pair of modes a threshold value for one of the parameters that determines which mode has lower average period costs. For modes x and y , given the values of c_x , c_y and L_y , we derive an expression for the threshold value of L_x (\bar{L}_x) such that if mode x has a shorter lead time than \bar{L}_x , then its average cost is lower. For illustration purposes, we derive this equation if demand in $L_i + 1$ periods follows a Continuous Uniform distribution.

Special case: Continuous Uniform distribution Assume $D(L_i + 1) \sim U[0, b_i]$, where $b_i = 2(L_i + 1)\mu$ (which is not necessarily integer). The minimum average cost can then be found by applying Equation (13) to this case:

$$C_i^* = \mu \left((L_i + 1) \frac{pr_h(k + c_i)}{p + r_h(k + c_i)} + c_i \right). \quad (15)$$

This yields the following equation for \bar{L}_x :

$$\bar{L}_x = (L_y + 1) \frac{1 - \alpha_y}{1 - \alpha_x} + (c_y - c_x) \frac{1}{p(1 - \alpha_x)} - 1 \quad (16)$$

$$\frac{\partial \bar{L}_x}{\partial c_x} = \left((L_y + 1)(1 - \alpha_y) + \frac{c_y}{p} \right) \frac{-p}{r_h(k + c_x)^2} - \frac{1}{p} - \frac{k}{r_h(k + c_x)^2} < 0. \quad (17)$$

If $L_x > \bar{L}_x$, then $C_y^* < C_x^*$ and vice versa. \bar{L}_x is decreasing in c_x (increasing in c_y and L_y), implying that for higher values of c_x (smaller values of c_y and L_y) a shorter lead time is required to justify the use of mode x . If c_x grows too large, the transport costs of mode x alone are already more expensive than the total costs of mode y . As a result, the outcome of Equation (16) becomes negative for any positive value of L_x . The value of c_x for which $\bar{L}_x = 0$ is denoted by \hat{c}_x :

$$\hat{c}_x = \frac{r_h(A - p - k) - p + \sqrt{D}}{2r_h}, \quad (18)$$

where $A = \frac{C_y^*}{\mu}$ and $D = p^2 + r_h^2(p^2 + k^2 + A^2) - 2r_h^2(pA + pk - kA) + 2r_hp(k + p - A)$. This results in the following result regarding the solution of the TMSP: If $c_x > \hat{c}_x$, then $C_y^* < C_x^*$ for any value of L_x . If $c_x \leq \hat{c}_x$, then $C_x^* \leq C_y^*$ for $L_x \leq \bar{L}_x$.

4.2 Problem with emissions

For the Emission Cost-Minimization problem the total costs depend on the emission level. We determine the optimal order up-to level ($S_i^{e,*}$) for mode i with the following equation:

$$F_i(S_i^e) = \frac{p}{p + (k + c_i + c^e e_i)r_h}, \quad (19)$$

or correspondingly, $S_i^{e,*} = F_i^{-1}\left(\frac{p}{p + (k + c_i + c^e e_i)r_h}\right)$. The cost associated with the optimal order-up-to level $S_i^{e,*}$ ($C_i^{e,*}$) is:

$$C_i^{e,*} = r_h(k + c_i + c^e e_i)(F_i^{-1}(\alpha_i^e) - \mu_i) + (p + (k + c_i + c^e e_i)r_h)G_i(F_i^{-1}(\alpha_i^e)) + (c_i + c^e e_i)\mu, \quad (20)$$

where $\alpha_i^e = \frac{p}{p + (k + c_i + c^e e_i)r_h}$. In the ETMSP we select the mode with the lowest cost and the solution depends on the value of c^e . The average backorder and the on-hand inventory at the end of a period for the optimal order-up-to level ($\mathbb{E}[B_i^{e,*}]$ and $\mathbb{E}[X_i^{e,*}]$) are determined by the following equations:

$$\begin{aligned} \mathbb{E}[B_i^{e,*}] &= G_i(S_i^{e,*}) &= G_i(F_i^{-1}(\alpha_i^e)), \\ \mathbb{E}[X_i^{e,*}] &= S_i^{e,*} - \mu_i + G_i(S_i^{e,*}) &= F_i^{-1}(\alpha_i^e) - \mu_i + G_i(F_i^{-1}(\alpha_i^e)). \end{aligned} \quad (21)$$

We derive the following monotonicity results for the model:

Theorem 4.1 a $S_i^{e,*}$ is decreasing in c^e ,

b $\mathbb{E}[B_i^{e,*}]$ is increasing in c^e ,

c $\mathbb{E}[X_i^{e,*}]$ is decreasing in c^e ,

d $C_i^{e,*}$ is increasing in c^e .

Proof:

Proof in Appendix A.3. □

This implies that if the emission cost increases, the order-up-to level decreases and therefore the average end of period on-hand inventory decreases and the average backorder increases. The total average period costs increase as a result. The reason behind this is the additional cost that is induced in the system.

For illustration purposes, we now assume that demand follows a Normal distribution to derive more insight in the effect of parameters on the minimum average period cost. Let the standard probability density function be denoted by $\phi(x)$ and the standard cumulative distribution function $\Phi(x)$. The minimum cost for the Emission-Cost minimization problem is given by the following equation:

$$C_i^{e,*} = (p + r_h(k + c_i + c^e e_i))\sqrt{L_i + 1}\sigma\phi(\Phi^{-1}(\alpha_i^e)) + (c_i + c^e e_i)\mu, \quad (22)$$

where $c_i + c^e e_i = v \max\{\rho, \bar{\rho}\}(d(t_i + c^e f^v) + c^e f^c)$, and $\alpha_i^e = \frac{p}{p + r_h(k + c_i + c^e e_i)}$. If we furthermore assume that each vehicle of a certain transport type travels a fixed maximum distance per day, the lead time becomes a function of distance and the speed (s_i): $L_i = \frac{d}{s_i}$. From this equation it is clear that $C_i^{e,*}$ is increasing in v , ρ , and d , where we use the fact that an increase in the holding cost leads to an increase in $\phi(\Phi^{-1}(\alpha_i^e))$.

4.2.1 Emission Transport Mode Selection Problem

We now use the output of the Emission-cost Minimization problem to derive insight in the solution of the ETMSP. The solution to the ETMSP consists of a set of modes which are preferred for a certain range of c^e . A subset of I can be considered which consist of only those modes which are preferred. Consider for all modes the minimum average period cost for the TMS (C_i^*) and the unit emissions (e_i). If for mode i there exists a mode which results in lower expected costs *and* is greener, then mode i is excluded from the analysis. The reason is that for two modes x and y if $C_x^* > C_y^*$ and $e_x > e_y$, $C_x^{e,*} - C_y^{e,*}$ only increases as a function of c_e and the two lines therefore do not intersect at a positive value of c_e . The remaining modes are so-called efficient modes, which may be the preferred transport mode for a range of c^e . A

further reduction of the set of modes is required to end up with a set in which *all* modes are preferred for a range of c^e . This reduction cannot be executed analytically for this model. In Section 6 the reduction is executed for an approximate model.

For a pair of transport modes say i and j , c_{ij}^e denotes the value of the emission cost for which the minimum average period costs are equal. We refer to this value as the indifference emission cost for mode i and j . If the realization of c^e is less than c_{ij}^e , the minimum costs of mode i are less than that of mode j thus mode i is preferred (and vice versa). This value (c_{ij}^e) can also be negative which implies that mode i is never results in lower minimum costs than mode j . For our model, c_{ij}^e can only be determined numerically. In the approximate model in Section 6, a closed-form expression is derived for c_{ij}^e .

In ecological economics marginal analysis is used to determine the effect of (a given value) of emission regulation, Pindyck & Rubinfeld (2009). In marginal analysis it is assumed that companies incur costs to reduce emissions and that these costs are in general increasing in the emission reductions. If e.g. a carbon tax is set to a value of \tilde{c}^e per unit of emissions, all companies will reduce their emissions until the point where the marginal cost of reduction is higher than the tax. It is then cheaper to pay the tax for the remaining emissions than to decrease the emissions further. In our case the emission reduction option is to switch to a less polluting mode. Hence, following the same logic, if $\tilde{c}^e > c_{i,j}^e$, i.e. the actual emission price is higher than the marginal cost of switching, then a switch to mode j from mode i leads to a cost reduction.

5 Numerical study

In this section we conduct a numerical study with the purpose to gain managerial insights from the transport mode selection problems. In Section 5.1 we specify the actual emission calculations for four specific transport modes and we apply them to the instances of a test bed. Next we analyze the effect of parameters on the solution to the ETMSP in Section 5.2.

5.1 NTM emission calculations

In this section we apply the NTM methodology and describe the additional assumptions that were made. The details and parameter values can be found in Appendix A.1. The unit emission is expressed in kg of CO_2 and is a function of the volume of the product in m^3 , the density in kg/m^3 , and the distance in km . We determine the emissions for each of the transport types for a given origin and destination. For non-road transport we only consider the distance between

the two terminals (and not the first and last leg which is typically done by road transport). Unless indicated otherwise in this section, all assumptions are taken from the NTM methodology (NTM Air (2008),NTM Rail (2008),NTM Road (2008),NTM Water (2008)).

Air transport We select an aircraft type whose emission factors represent an average-sized (dedicated cargo) airplane. Van den Akker (2009) has found in a practical study that a dedicated cargo aircraft has on average a load factor of 80 %. To correct for the fact that the distance between two locations over the road is longer than through the air, we investigated for several routes in Europe the air and road distance. For the origin-destination pairs we considered, we found that the distance through the air is about 80% of the road distance and this is the factor that we use. As a result, we have the following equation for unit emissions e_a (in kg):

$$e_a \approx (0.1783 + 0.0005295d)v \max\{167, \rho\}. \quad (23)$$

Rail transport It is estimated that in Europe 75.4% of the rail network is designed for electrical trains and 24.6% for diesel trains (EUrostat, 2010). The emission factor of diesel and electrical rail transport are determined and weighed according to these fractions. In line with NTM, we take a 50 % load factor. We do not distinguish between distances traveled in countries but rather take the average values for Europe, to be more generic. We assume that the entire track is hilly and that the rail distance between two locations is equal to the road distance. Let e_t (in kg) denote the unit emissions for the average rail transport:

$$e_t \approx 2.223 \cdot 10^{-5} \cdot d \cdot v \rho. \quad (24)$$

Road transport We assume that road transport takes place via integrating terminals, for which NTM suggests a load factor of 70%. Hence, we assume no positioning distance or empty returns. A route from the origin to its destination mainly consists of motorway but some distance has to be traveled on urban roads. To obtain an estimate for this distance, we analyzed for the same origin-destination pairs as before the average distance traveled on urban roads, which was estimated at 8.9 km (17.8 km for a route). We again assumed that the terrain was hilly. The equation to calculate the unit emissions (e_r in kg) is then:

$$e_r \approx (0.0002089 + 0.00003143d)v \max\{250, \rho\}. \quad (25)$$

Water transport We assume that inland waterways are used for transport and that a general cargo vessel is used. For inland waterways a load factor of 50% is assumed. This factor is relatively low since in inland waterways the transport is shuttle-like. We assume that the distance between two locations over inland waterways is larger than the distance over road: 1.2

times as large. This value is an educated guess since distance information for water transport is not accessible. These assumptions yield the following equation for the unit emissions for water transport (e_w in kg):

$$e_w \approx 1.3904 \cdot 10^{-5} \cdot d \cdot v \rho. \quad (26)$$

Comparing the unit emission equations (Equations (23)-(26)) for the different types of transport reveals the ordering of the emissions. The unit emissions for air transport are always higher than for road transport, the difference in the standard density does not compensate the big difference in the emission factor. It is evident that $e_r > e_t$ and $e_t > e_w$. Hence, the following ordering exists in the unit emissions: $e_a > e_r > e_t > e_w \forall v, \rho, d \geq 0$.

We now describe the test bed we developed to obtain insight into the range of unit emissions and the indifference emission cost for the different transport modes. We vary the distance between two locations (in km), the density (in kg/m^3) and volume (in l) of the product. Each variable has a high and a low value denoting a medium and long distance, a low and high density and a small and relatively large product. In total the test bed consists of $2^3 = 8$ instances. The values are given in Table 1. If we apply the equations and the assumptions mentioned before,

Table 1: *Parameter settings*

Parameter	Number of values	Values
Distance (D) in km	2	800, 2000
Density (ρ) in kg/m^3	2	100, 1000
Volume (v) in l	2	1, 500

we obtain the unit emissions (in kg) in Table 2.

Table 2: *Unit emissions road and air transport (in kg)*

v [l]	D	800				2000			
		ρ [kg/m^3]	Air	Rail	Road	Water	Air	Rail	Road
1	100	0.101	0.002	0.006	0.001	0.207	0.004	0.016	0.003
1	1000	0.602	0.018	0.025	0.011	1.237	0.044	0.063	0.028
500	100	50.259	0.889	3.169	0.556	103.321	2.223	7.884	1.390
500	1000	300.950	8.890	12.677	5.562	618.686	22.225	31.537	13.904

From Table 2 we notice the large difference in emissions. The ratio of the emissions of two modes also differs significantly, for air and road it is in the range 12-24 and for road and rail 1-4. The reason for this difference is that the emissions for air and road transport do not converge to 0 as ρ and d go to 0, because of the volumetric weight and the constant emission

factor. The ratio is highest for the small distance and high density (and smallest for the large distance and density) instance. The prespecified density of road transport is higher than that of air transport, so road has higher emissions for low values of the density. Because of the large constant emission factor of air transport, air transport has relatively higher emissions for small distances. Table 2 also shows that the unit emissions can be as high as 619 *kg*! If the carbon price is € 15 /tonne, the average costs per period increase with up to € 15 · 0.619 = € 9.90 per item, which can be a large part of the total costs depending on the value of the product.

5.2 Results of the Emission TMSP

In this section we describe the effect of parameters on the solution of the ETMSP and the indifference emission cost. We assume that demand follows a Normal Distribution to allow for fast calculation times.

We assume that L_a is fixed at one day and that L_r , L_t and L_w depend on the distance; the speed is 400, 240, and 160 *km* per day for road, rail and water, respectively. We select the test bed of Section 5.1 and we specify in addition the following (realistic) parameter values: $\psi = \frac{\sigma}{\mu} = 0.2$, $L_a = 1$, $L_r = \frac{D}{400}$, $L_t = \frac{D}{240}$, $L_w = \frac{D}{160}$, $t_a = 3.125 \cdot 10^{-5}$, $t_r = 1.250 \cdot 10^{-5}$, $t_t = 1.000 \cdot 10^{-5}$, $t_w = 7.5 \cdot 10^{-6}$ and, $r_h = \frac{0.25}{300}$, and $r_p = 10r_h k$. According to us, these values are a good representation of reality. We have selected two values of k that yield results that are interesting enough to compare. For small values of k , water transport is always preferred, therefore, we have selected two large values of k (2000 and 9000). In this particular case the transport modes are ordered; $e_a > e_r > e_t > e_w$. If the costs deviate from the following ordering $C_a^* < C_r^* < C_t^* < C_w^*$, one or more modes are not efficient and are not the preferred mode (for any positive value of c^e). In total, the test bed consists of 16 instances and the indifference emission cost $c_{i,j}^e$ is calculated for each of the instances; the results are in Table 7 in Appendix A.4.

The indifference emission cost decreases in v and ρ , because e_i and c_i increase in these factors and it increases faster for more polluting and expensive modes. The impact of an increase of d is increasing or decreasing, depending on the pair of modes considered: $c_{a,r}^e$ is increasing in d and $c_{r,t}^e$ and $c_{t,w}^e$ are decreasing in d . The fact that air transport has a significant constant emission factor is the reason for this difference.

The effect of some of the parameter effects on the value of $c_{i,j}^e$ is shown graphically. Recall that the values of $c_{i,j}^e$ are determined numerically. Figure 1 shows the values of the emission price for which the average costs for two modes are equal as a function of the volume of the product. We see from this graph that air transport is only selected for low volume products. If

the volume is 0.08 m^3 or more, it is never selected (because $C_a^* > C_r^*$). For a product volume of 0.47 m^3 or larger, water transport is always the preferred mode (because $C_w^* < C_t^*$). For a given volume, the distance between $c_{i-1,i}^e$ and $c_{i,i+1}^e$ indicates the range of c^e for which that mode presents the solution to the ETMSP. For road transport, this range is quite large for small values of the volume. The range for rail transport is small, for any value of the volume. This is caused by the fact that rail and water transport are quite similar in terms of unit costs, lead time, and emissions. Because water transport has lower unit emissions it is always preferred for higher values of c^e .

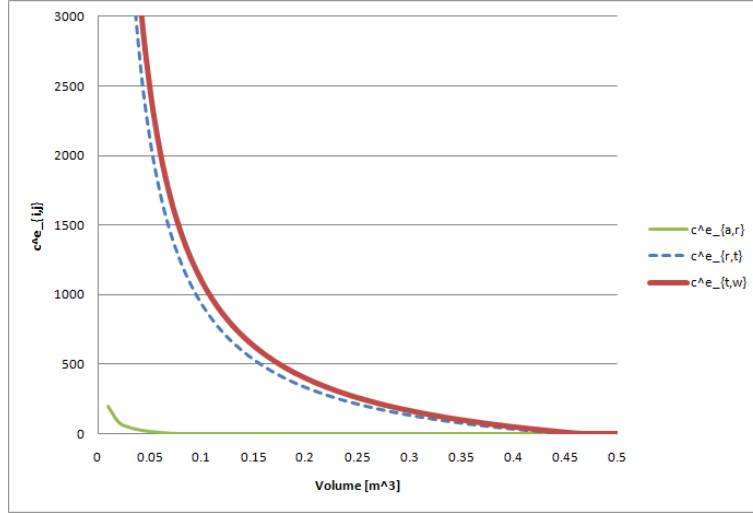


Figure 1: Indifference emission cost as a function of the product volume $\mu = 10, \sigma = 2, k = 5000, L_a = 1, t_a = 3.125 \cdot 10^{-5}, t_r = 1.250 \cdot 10^{-5}, t_t = 1.000 \cdot 10^{-5}, t_w = 7.5 \cdot 10^{-6}, r_h = \frac{0.25}{300}, r_p = 10r_h k, d = 1200, \rho = 500$

This result also has a practical implication for companies: given that the volume of an actual product is fixed, the volume of the packaged product is something that companies can change. A decrease in the volume of the packaged product leads to a cost reduction, because both the unit transportation costs and the (allocated) emissions decrease.

A similar graph can be constructed for the distance (Figure 2). It can be seen that the indifference emission cost is decreasing as a function of distance. The indifference emission cost for road and rail transport is increasing for small distances (up to 100 km) due to the small fixed emission factor of road transport. The indifference emission cost for air and road transport is always negative, because air transport is always more expensive, for the given setting.

A similar graph can be constructed for the density (Figure 3). It can be seen that the indifference emission cost is decreasing as a function of density. Only for the line relating road and rail transport, we observe an interesting shape. The function is first increasing and then

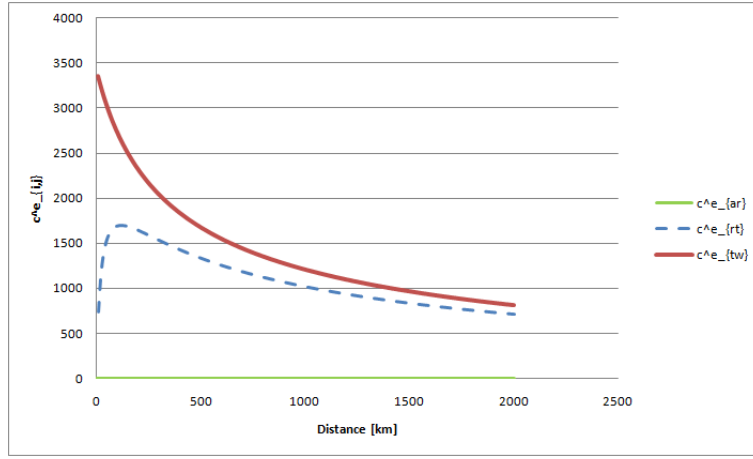


Figure 2: Indifference emission cost as a function of the product distance $\mu = 10, \sigma = 2, k = 5000, L_a = 1, t_a = 3.125 \cdot 10^{-5}, t_r = 1.250 \cdot 10^{-5}, t_t = 1.000 \cdot 10^{-5}, t_w = 7.5 \cdot 10^{-6}, r_h = \frac{0.25}{300}, r_p = 10r_h k, v = 0.1, \rho = 500$

decreasing. This is caused by the prespecified density for road transport. The emissions (and transport costs) for road transport do not increase if the density is less than this prespecified density (250). As a consequence rail transport becomes relatively more expensive if the density approaches 250. Only for low values of the density (up to 400 kg/m^3) is air transport preferred over road transport for low values of the emission cost.

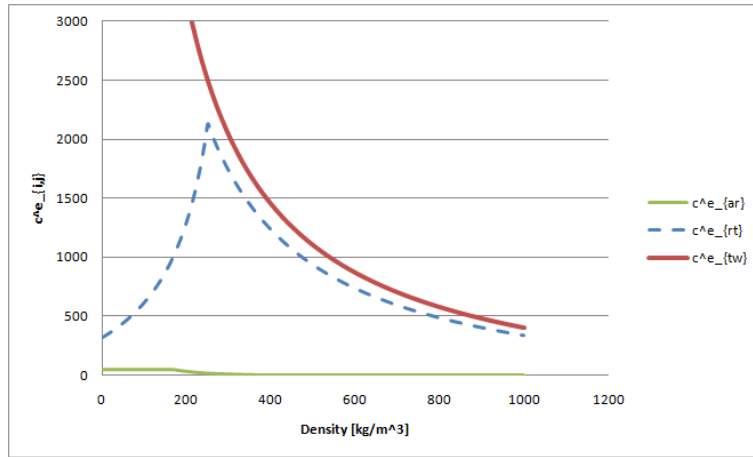


Figure 3: Indifference emission cost as a function of the product volume $\mu = 10, \sigma = 2, k = 5000, L_a = 1, t_a = 3.125 \cdot 10^{-5}, t_r = 1.250 \cdot 10^{-5}, t_t = 1.000 \cdot 10^{-5}, t_w = 7.5 \cdot 10^{-6}, r_h = \frac{0.25}{300}, r_p = 10r_h k, d = 1200, v = 0.1$

We now select four particular products and determine the solution to the ETMSP for any value of c^e for each of the products. The products and their characteristics are: sugar (product 1: $k = 1, v = 6.4 \cdot 10^{-3}$ and $\rho = 1586.2$), a gold bar (product 2: $k = 9635, v = 6.4 \cdot 10^{-3}$ and $\rho = 19320$), insulation material (product 3: $k = 12.50, v = 0.3375$ and $\rho = 141.3$), and a

high-end television (product 4: $k = 4000, v = 0.3375$ and $\rho = 145.8$). Two products have low value-density and the other two have high value-density, one of each with low volume and one with high volume. We have determined for each mode the costs for each value of c^e and used that to construct the solution to the ETMSP for each value of c^e , the result is in Figure 4.

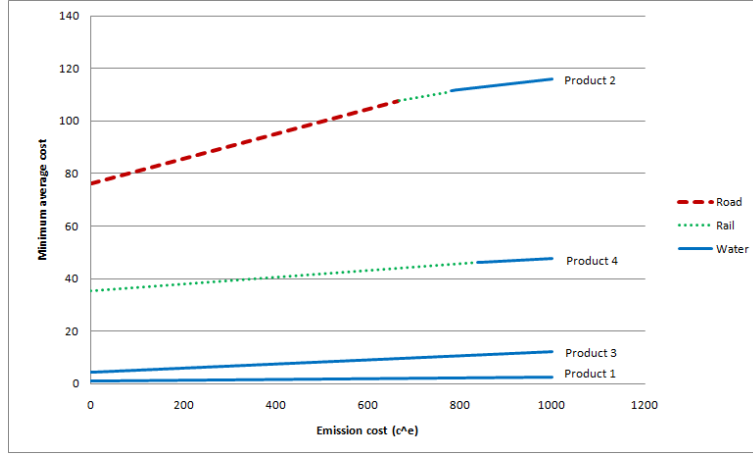


Figure 4: The solution to the ETMSP for four products

$\mu = 10, \sigma = 2, L_a = 1, t_a = 3.125 \cdot 10^{-5}, t_r = 1.250 \cdot 10^{-5}, t_t = 1.000 \cdot 10^{-5}, t_w = 7.5 \cdot 10^{-6}, r_h = \frac{0.25}{300}, r_p = 10r_h k, d = 1200$

The lines represent the solution to the ETMSP for any value of c^e for each product. For product 1 and 3 water transport is optimal for any value of c^e . For product 4 rail transport is preferred for small values of c^e and for product 2 the preferred modes are road, rail and water transport in increasing values of c^e . The fact that k is high for products 2 and 4 is the reason that road and rail transport are the preferred modes for a range of c^e (because modes with longer lead times have relatively higher inventory costs for higher values of k). The values for $c^e = 0$ correspond to the solutions of the TMSP, which is water for product 1 and 3, road for product 2 and rail for product 4.

We conclude this section with an analysis of the preferred transport mode for each of the four products just described for several emission regulation alternatives. Assume that in a situation without emission regulation the mode with the lowest value of C_i^* (of for $c^e = 0$) is selected for each product. This implies that no emission reductions can be obtained by switching transport modes for product 1 and 3, because water transport (with the lowest unit emissions) is already used. Moreover, note that the value of c^e for which a switch occurs for product 2 and 4 is rather high: around 700 and 800. This implies that the value of a carbon tax or the price of a carbon allowance needs to be at least 700 €/tonne CO_2 to lead to a switch in transport mode. In the EU ETS the value of emission allowances to date has varied between € 0 and € 30/tonne CO_2 . If an emission price in that range would apply to transport, it

would not lead to reductions in emissions (provided that the decision is only made base on the variables in our model). If, on the other hand, a fuel tax would be implemented, then the price of carbon emission can take much higher values, which might be high enough to lead to a switch in transport modes and in turn lead to emission reductions. Lastly, if the company decides to impose an emission reduction target (in the absence of emission regulation), then large emission reductions are possible at a cost increase (up to 55 % for product 2 at 24 % cost increase). A self-imposed emission reduction target may lead to the lowest emissions.

6 Approximate model

In this section we approximate the emission cost model with a model in which the holding costs only depend on the value of the product, k . We believe that this approximation is relatively accurate because the impact of c^e on the holding costs is relatively low. We moreover assume that demand follows a Normal distribution. As before, denote the standard probability density function by $\phi(x)$ and the standard cumulative distribution function by $\Phi(x)$. The minimum average costs are then:

$$C_i^{e,*} = \sqrt{L_i + 1}\sigma(p + r_h k)\phi(\Phi^{-1}(\alpha)) + \mu(c_i + c^e e_i). \quad (27)$$

where $\alpha = \frac{p}{p+r_h k}$. Let $c_{i,j}^e$ denote the indifference emission cost for mode i and j , as before. In this case the critical fractile (α) does not depend on a mode-specific variable which allows us to give a closed form expression for $c_{i,j}^e$:

$$c_{i,j}^e = \frac{c_i - c_j - \frac{\sigma}{\mu}(\sqrt{L_j + 1} - \sqrt{L_i + 1})R}{e_j - e_i}, \quad (28)$$

where $R = (p + r_h k)\phi(\Phi^{-1}(\alpha))$.

In addition to excluding non-efficient modes, a further reduction on the possible set of transport modes can be made, since being an efficient mode is a necessary but not a sufficient condition. Theorem 6.1 describes the condition that needs to be met for a mode to be ‘superefficient’.

Theorem 6.1 Consider three transport modes x, y and z such that $C_x^* < C_y^* < C_z^*$,

$e_x > e_y > e_z$, and x, y, z are efficient modes in I .

a If $C_y^* > \bar{C}_y$, then transport mode y is not the preferred transport mode for any $c^e \geq 0$ ($C_y^{e,*} > \min\{C_x^{e,*}, C_z^{e,*}\}$),

b If $C_y^* \leq \bar{C}_y$, then transport mode y is the preferred transport mode for $c^e \in [c_{x,y}^e, c_{y,z}^e]$,

where

$$\bar{C}_y = C_x^* + (C_z^* - C_x^*) \frac{e_x - e_y}{e_x - e_z}. \quad (29)$$

Proof:

In Appendix A.3 □

The interpretation of this theorem is that not only need transport modes be efficient, but they need to be ‘superefficient’, i.e. they need to outperform the convex combination of modes x and z . As a result, the remaining modes form a convex hull. Any mode y which meets $C_y^* > \bar{C}_y$ is removed from the analysis. Let $\hat{I} = \{1, \dots, |\hat{I}|\}$ denote the set of remaining transport modes. Without loss of generality, we sort all modes in \hat{I} in increasing minimum average period cost (C_i^*), as a consequence the modes are also ordered in decreasing emissions (e_i). The following corollary follows from Theorem 6.1b.

Corollary 6.2 Transport mode i is the preferred transport mode for

$$c^e \in [c_{i-1,i}^e, c_{i,i+1}^e] \text{ for } i \in \hat{I}, \text{ and } c_{0,1}^e = 0 \text{ and } c_{|\hat{I}|,|\hat{I}+1}^e = \infty.$$

The realization of c^e determines the solution to the Emission Transport Mode Selection Problem. Let us now consider only two available transport modes x and y . We further assume (without loss of generality) that $C_x^* < C_y^*$. Equation (28) can now be used to examine the impact of parameters on the indifference emission price ($c_{x,y}^e$). If $c_{x,y}^e < 0$, mode y is always preferred over mode x which is less interesting to assume. We therefore assume that $c_{x,y}^e$ is positive, and since $c_x - c_y - \frac{\sigma}{\mu}(\sqrt{L_y + 1} - \sqrt{L_x + 1})R < 0$ (because $C_x^* < C_y^*$), we further require $e_y - e_x < 0$. We observe the following effects of the parameters. A parameter can be increased or decreased up to the point where $C_x^* = C_y^*$.

Emissions: If $e_y - e_x$ increases (up to $e_y = e_x$), $c_{x,y}^e$ increases (to infinity). This implies that mode x is preferred for a larger range of c^e (because its emission decreases or the emission of mode y increases).

Transport cost and Lead time: If $c_x - c_y$ increases (until the point that mode y always results in lower costs), $c_{x,y}^e$ decreases (to zero). This implies that mode x is preferred for a smaller range of c^e (because its transport cost increases or the transport cost of mode y decreases). The opposite effect is true for $\sqrt{L_y + 1} - \sqrt{L_x + 1}$: it leads to an increase in $c_{x,y}^e$. This implies that mode x is preferred for a larger range of c^e (because its lead time decreases or the lead time of mode y increases).

Cost parameters and Demand variation: In Appendix A.2 it is shown that

$\phi(\Phi^{-1}(\alpha))$ is decreasing in α for $\alpha \geq 0.5$. Since we assume that the penalty costs are at

least as expensive as the holding costs, $\alpha \geq 0.5$ holds for all our cases. If r_h or k increases in value, α decreases, $\phi(\Phi^{-1}(\alpha))$ increases and therefore R increases. If p increases in value, α increases, $\phi(\Phi^{-1}(\alpha))$ decreases, however we have observed that R increases. An increase in demand variation ($\frac{\sigma}{\mu}$) or the cost parameters can lead to an increase or decrease of $c_{x,y}^e$: if $L_x < L_y$, an increase in R (or $\frac{\sigma}{\mu}$) affects y more than x so $c_{x,y}^e$ increases, and vice versa.

7 Conclusion

Since transport emissions account for a substantial share of total carbon emissions, and an even larger share of the expected growth in carbon emissions, policy makers are developing regulation mechanisms that are expected to drive down emissions. Policy makers expect that for instance the transportation mode selection decision will be affected by regulatory frameworks that essentially charge for or limit the emission quantity. It is, however, unclear to what extent emission related costs will play a role in the transportation mode selection problem, since it is obvious that emission costs are only a part of the total costs involved. Therefore, in this paper we have analyzed the effect of (self-imposed) emission regulations on the transport mode selection problem in terms of cost and emissions of the solution. Our focus is on a decision maker who has to select one out of several available modes of transportation for a given product. Note that our analysis can be repeated for each product-lane combination, as an LSP is in charge of transportation and hence there is no significant set-up cost that trigger joint transportation for the shipper. We use an order-up-to policy and the solution of the single-period Newsboy problem is used to solve the Transport Mode Selection Problem (TMSP) and yields the optimal average cost. The TMSP has been extended which resulted in the Emission TMSP.

We used the NTM methodology, which is based on empirical data of activities in transportation that cause carbon emissions, to provide formulas and parameter estimates to determine the carbon emissions. We analyze four classes of transport: air, rail, road and water. We have selected a representative vehicle for each of the four classes and derived equations for the emissions in terms of distance, volume and density (of the product). For these vehicles it holds that the emissions for air transport are highest, followed by road transport, rail transport and water transport.

For the Emission TMSP we were able to determine for a pair of transport modes for which emission cost the expected total cost is equal. This in turn enables us to determine which mode is preferred for which range of c_e , given distance, cost and product characteristics. Our

numerical results clearly show that the impact of emission related charges is small: the emission related charges or the values of one or more of the parameters (volume or unit cost) needs to be extremely high in order for a decision maker to select a different transportation mode. So, adding emission costs leads rarely to a change in the selected transport mode. This in turn implies that water transport is already the preferred mode for most/many products. This would be a positive message but is also implies that for not too many products emission reductions from changing transport mode are possible.

In practice, however other factors play a role as well that make the actual selected mode different from the optimal solution to the Emission TMSP. Factors that influence the decision, that we did not take into account are: required customer lead time (favoring faster transport modes), frequency at which the required mode can be executed for a given route (especially for rail transport), and others. Also, we have only calculated the emissions from terminal to terminal and have not considered the distance from the origin and destination to the terminal. For example, water transport will not be optimal if the nearest harbor is hundreds of kilometers away from the origin or destination. Extending our model to include one or more of these factors would ensure that the solution of the model coincides more often with the transport mode which is preferred in practice.

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A Appendix

A.1 Detailed NTM calculations

Air transport All assumptions are taken from NTM Air (2008) unless indicated otherwise. NTM has determined the emission factors (constant and variable) for 31 combinations (dedicated cargo aircrafts). We calculate the emission factors per *kg* of the maximum load and the minimum, average and maximum corrected emission factors over all combinations, to allow for a fair comparison between combinations. We select an aircraft type whose emission factors are most similar to the average values. The emission factors of the selected aircraft can be found in Table 3.

Table 3: *Emission factors*

Load Factor [%]	CEF [kg]	VEF [kg/km]
50	3583.901	15.307
75	4041.709	15.351
100	4531.182	15.363

In an applied study (Van den Akker, 2009) the NTM methodology was applied to a particular company to estimate the emissions resulting from transport. They studied the average load factor for cargo aircrafts and found an average load factor of 80% for dedicated cargo aircrafts. We, therefore, assume a load factor of 80% ($l = 0.80$). Hence, the emission factors are $f^c = 4139.6$ and $f^v = 15.353$.

To compare the road and air distance, we calculated for several routes in Europe the road distance and the distance obtained with the great-circle distance formula (values obtained through a routeplanner (Google Maps, 2011) and Distance Calculator (Distance calculator, 2011)). For the routes we investigate that the air distance is 80.1% of the road distance on average, as can be seen in Table 4.

Table 4: *Air and road distances*

Route	Road distance [km]	Air distance [km]	Ratio [%]
Amsterdam - Berlin	661	577	87.3
Amsterdam - Lisbon	2241	1864	83.2
Amsterdam - Madrid	1772	1482	83.6
Amsterdam - Vienna	1149	936	81.5
Berlin - Lisbon	2788	2315	83.0
Berlin - Madrid	2319	1871	80.7
Berlin - Vienna	759	524	69.1
Lisbon - Madrid	629	504	80.1
Lisbon - Vienna	2965	2302	77.6
Madrid - Vienna	2422	1812	74.8

For the aircraft we select the maximum load \hat{l}_0 is 29029 kg. The equation for the unit emissions (e_a in kg) is then in this case:

$$\begin{aligned}
 e_a &= (4139.6 + 15.353 \cdot 0.801d) \frac{v \max\{\rho, 167\}}{23223.2} \\
 &\approx v \max\{167, \rho\} (0.1783 + 0.0005295d).
 \end{aligned}$$

Rail transport All assumptions are taken from NTM Air (2008) unless indicated otherwise. We assume that the gross weight of the train is 1000 tonne ($W_{gr} = 1000$), which is the average value specified by NTM.

For a diesel train we take the following parameter values. The fuel consumption factor ($T(\text{hillly})$) is 153.08. The fuel emissions (FE) are 3175 g/kg .

For an electrical train we assume that the energy consumption factor ($T(\text{hillly})$) is 675 and a 10% loss of energy due to energy transfer ($TL = 0.10$).

The average emissions to air when generating 1 kWh in Europe (EE) is 0.41 kg/kWh .

The emission factor (EF_e in $kg/net\ tonne\ km$) for an electrical train with these parameter values is then:

$$EF_e = \frac{675 \cdot 0.41}{1000\sqrt{1000} \cdot 0.5 \cdot 0.9} \approx 0.01945.$$

The emission factor (EF in $kg/net\ tonne\ km$) for a diesel train with these parameter values is then:

$$EF_d = \frac{1.25 \cdot 153.08 \cdot 3175}{10^6\sqrt{1000} \cdot 0.5} \approx 0.03074.$$

If we combine this with the average fraction of diesel and electrical railway in Europe, we obtain the average emission factor (\bar{EF} in $kg/net\ tonne\ km$):

$$\bar{EF} = 0.754 \cdot 0.01945 + 0.246 \cdot 0.03074 \approx 0.02223.$$

We assume that the rail distance between two locations is equal to the road distance. Let e_t denote the unit emissions for the average rail transport. If we implement this, we obtain the following formula for the unit emissions (e_t in kg):

$$e_t \approx 2.223 \cdot 10^{-5} \cdot d \cdot w.$$

Road transport All assumptions are taken from NTM Road (2008) unless indicated otherwise. We assume that a Tractor + Semi-trailer is used, because it is a common type to use for longer distances. The fuel consumption depends on the road type and the values are given in Table 5. For a load factor of 70%, the fuel consumption is then 0.3198, 0.3462 and 0.4392 l/km , for Motorway, Rural and Urban respectively.

Table 5: *Fuel consumption*

Road type	Motorway		Rural		Urban	
Load factor	0%	100%	0%	100%	0%	100%
Fuel consumption	0.226	0.360	0.230	0.396	0.288	0.504

A route from location A to location B mainly consists of motorway but some distance has to be traveled on urban roads. To determine an estimate for the distance traveled on urban road we calculate the average distance traversed in several cities in Europe. The values for the

Table 6: *Urban road distances*

City	Urban road distance [km]
Amsterdam	6.7
Berlin	8.5
Lisbon	10.2
Madrid	4.1
Vienna	14.9

sample cities can be found in Table 6. The average distance traveled on urban roads is 8.9 *km* (and in total 17.8 *km* for a route). The fuel consumption as a function of the distance traveled ($FC(d)$ in *l/km*) is then described with the following formula:

$$\begin{aligned} FC(d) &= 17.8 \cdot 0.4392 + (d - 17.8) \cdot 0.3198 \\ &\approx 2.125 + 0.3198d. \end{aligned}$$

The fuel emissions for diesel fuel are $FE = 2621$ *g/l*. To account for hilly terrain we add 5% (average value for Europe, NTM Road 2008) to the total emissions. If we implement these values in the formula for the total emissions (EM_{total} in *g*), we obtain:

$$\begin{aligned} EM_{total} &= 1.05 \cdot 2621 FC_{LF} d \\ &\approx 2752.05(2.125 + 0.3198d) \\ &\approx 5848.99 + 880.10d. \end{aligned}$$

For a Tractor + Semi-trailer the maximum load \hat{l}_o is 40 *tonne*. The equation to calculate the unit emissions (e_r in *g*) is then in this case:

$$\begin{aligned} e_r &= \frac{1}{1000} v \max\{250, \rho\} (0.2089 + 0.03143d) \\ &= v \max\{250, \rho\} (0.0002089 + 0.00003143d). \end{aligned}$$

Water transport All assumptions are taken from NTM Water (2008) unless indicated otherwise. The cargo capacity (maximum load) of a general cargo vessel for inland waterways is 3840 *tonne*. Hence, the average total capacity is 1920 *tonne*. Hence, we obtain the following allocation fraction:

$$\alpha = \frac{w}{1920 \cdot 1000}.$$

The fuel emissions (FE) is 3178 *kg/tonne* and the fuel consumption (FC) is 0.007 *tonne/km* (NTM Water, 2008). We assume that the distance between two locations over inland waterways is 1.2 times the distance over road. Due to a lack of empirical data this value is an educated guess. Applying these values, yields the following equation for the unit emissions for water

transport (e_w in kg):

$$\begin{aligned} e_w &= \frac{w}{1920 \cdot 1000} 0.007 \cdot 1.20d \cdot 3178 \\ &\approx 1.3904 \cdot 10^{-5} \cdot w \cdot d. \end{aligned}$$

A.2 Normal distribution

Property 1 Following the symmetry property of the normal distribution, it follows that $\Phi(x) = 1 - \Phi(-x)$. (Zipkin, 2005) If $\Phi(x) = w$, then $\Phi(-x) = 1 - w$. And correspondingly, $\Phi^{-1}(w) = x$ and $\Phi^{-1}(1 - w) = -x$. Hence, $\Phi^{-1}(w) = -\Phi^{-1}(1 - w)$.

Property 2 Let $\Phi(x) = w$ and $\Phi(x + y) = w + z$ where $y \geq 0$ (and $z \geq 0$). It holds that $x + y > x$, so $\Phi^{-1}(w + z) > \Phi^{-1}(w)$. Thus, $\Phi^{-1}(w)$ is increasing in w .

Property 3 It holds that $\phi(x + y) < \phi(x)$ for $y \geq 0$, if $x \geq 0$. So $\phi(\Phi^{-1}(w + z)) < \phi(\Phi^{-1}(w))$. Recall that $\Phi(0) = 0.5$. So for $w \geq 0.5$ ($\Phi^{-1}(w) \geq 0$), $\phi(\Phi^{-1}(w))$ is decreasing in w .

A.3 Proofs

Theorem 4.1 a $S_i^{e,*}$ is decreasing in c^e ,

b $\mathbb{E}[B_i^{e,*}]$ is increasing in c^e ,

c $\mathbb{E}[X_i^{e,*}]$ is decreasing in c^e ,

d $C_i^{e,*}$ is increasing in c^e .

Proof:

Proof of part a An increase in c^e , leads to a decrease in the critical fractile $\frac{p}{p+(k+c_i+c^e e_i)r_h}$. Since $F^{-1}(\alpha)$ is increasing in α , a decrease in the critical fractile, therefore leads to a decrease in $S_i^{e,*}$.

Proof of part b From part (a) it follows that an increase in c^e leads to a decrease in $S_i^{e,*}$. Since $\mathbb{E}[B_i^{e,*}] = G(F^{-1}(S_i^{e,*}))$. Combining the facts that $G(S_i^*)$ is decreasing in S_i^* . Using the fact that $F^{-1}(\alpha)$ is increasing in α , we conclude that an increase in c^e therefore leads to an increase in $\mathbb{E}[B_i^{e,*}]$.

Proof of part c From part (a) it follows that an increase in c^e leads to a decrease in S_i . Define $H(S_i) = \mathbb{E}[X_i^{e,*}] = \int_{-\infty}^{S_i} (S_i - y)f(y)dy$. Let $\epsilon > 0$, hence,

$$\begin{aligned} H(S + \epsilon) &= \int_{-\infty}^{S+\epsilon} (S + \epsilon - y)f(y)dy = \int_{-\infty}^S (S - y)f(y)dy + \int_S^{S+\epsilon} (S - y)f(y)dy + \epsilon \int_{-\infty}^{S+\epsilon} f(y)dy \\ &> \int_{-\infty}^S (S - y)f(y)dy. \end{aligned}$$

So $H(S)$ is increasing in S . Using the fact that $F^{-1}(\alpha)$ is increasing in α , we conclude that an increase in c^e therefore leads to an decrease in $\mathbb{E}[X_i^{e,*}]$.

Proof of part d Take c^e and $c'^e = c^e + \epsilon$ and $\epsilon \geq 0$.

Define $C_i^e(S_i, c^e) = r_h(k + c_i + c^e e_i)(S_i - \mu_i) + (r_h(k + c_i + c^e e_i) + p)G_i(S_i) + (c_i + c^e e_i)\mu$.

Let $S_i \geq 0$, then $C_i^e(S_i, c'^e) \geq C_i^e(S_i, c^e)$.

Let $S_i^{\epsilon,*}$ maximize $C_i^e(S_i, c'^e)$ and S_i^* maximize $C_i^e(S_i, c^e)$.

Then $C_i^e(S_i^{\epsilon,*}, c'^e) \geq C_i^e(S_i^{\epsilon,*}, c^e) \geq C_i^e(S_i^*, c^e)$ and $C_i^e(S_i^{\epsilon,*}, c'^e) \geq C_i^e(S_i^*, c'^e)$.

Hence $C_i^{\epsilon,*}$ is increasing in c^e . \square

Theorem 6.1 Consider three transport modes x, y and z such that $C_x^* < C_y^* < C_z^*$ and $e_x > e_y > e_z$. Transport mode y is not the preferred transport mode for any $c^e \geq 0$ ($C_y^{e,*} > \min\{C_x^{e,*}, C_z^{e,*}\}$) if $C_y > \bar{C}_y$, where

$$\bar{C}_y = C_x^* + (C_z^* - C_x^*) \frac{e_x - e_y}{e_x - e_z}.$$

Proof:

Proof of part a We need to proof that $C_y^{e,*} > \min\{C_x^{e,*}, C_z^{e,*}\} \forall c^e \geq 0$.

Let $c_{x,z}^e$ such that $C_x^{e,*} \leq C_z^{e,*} \forall c^e \leq c_{x,z}^e$ and $C_z^{e,*} \leq C_x^{e,*} \forall c^e \geq c_{x,z}^e$.

Assume that $C_y^* > \bar{C}_y$, then $c_{x,y}^e = \frac{C_x^* - C_y^*}{e_y - e_x} = -\frac{C_y^* - C_x^*}{e_y - e_x} > 0$

(because of assumptions on C_i^* and e_i .)

Then, $\frac{C_y^* - C_x^*}{e_y - e_x} < \frac{\bar{C}_y - C_x^*}{e_y - e_x} = \frac{C_x^* + (C_z^* - C_x^*) \frac{e_x - e_y}{e_x - e_z} - C_x^*}{e_y - e_x} = \frac{C_x^* - C_z^*}{e_x - e_z} = -\frac{C_x^* - C_z^*}{e_z - e_x} = -c_{x,z}^e$

(where the inequality follows since $C_y^* - C_x^* < 0$.)

So, $-c_{x,y}^e < -c_{x,z}^e$ and therefore $c_{x,y}^e > c_{x,z}^e$.

Let us now compare two expressions for $C_x^* - C_z^*$:

$$C_x^* - C_z^* = (e_y - e_x) \frac{C_x^* - \bar{C}_y}{e_y - e_x} + (e_z - e_y) \frac{\bar{C}_y - C_z^*}{e_z - e_y}$$

$$C_x^* - C_z^* = (e_y - e_x) \frac{C_x^* - C_y^*}{e_y - e_x} + (e_z - e_y) \frac{C_y^* - C_z^*}{e_z - e_y}$$

We have shown before that $c_{y,z}^e = \frac{C_x^* - C_y^*}{e_y - e_x} > \frac{C_x^* - \bar{C}_y}{e_x - e_x}$, hence $c_{y,z}^e = \frac{C_y^* - C_z^*}{e_z - e_y} < \frac{\bar{C}_y - C_z^*}{e_z - e_y} = c_{x,z}^e$

Where the last equality is derived below:

$$\frac{\bar{C}_y - C_z^*}{e_z - e_y} = \frac{C_x^* + (C_z^* - C_x^*) \frac{e_x - e_y}{e_x - e_z} - C_z^*}{e_z - e_y} = \frac{C_z^* - C_x^*}{e_x - e_z} = \frac{C_x^* - C_z^*}{e_z - e_x} = c_{x,z}^e.$$

So we find the following ordering $c_{y,z}^e < c_{x,z}^e < c_{x,y}^e$, which determines the ordering of the profits for any value of c^e :

$$C_x^{e,*} < C_y^{e,*} < C_z^{e,*} \quad \text{for } 0 \leq c^e \leq c_{y,z}^e$$

$$C_x^{e,*} < C_z^{e,*} < C_y^{e,*} \quad \text{for } c_{y,z}^e \leq c^e \leq c_{x,z}^e$$

$$C_z^{e,*} < C_x^{e,*} < C_y^{e,*} \quad \text{for } c_{x,z}^e \leq c^e \leq c_{x,y}^e$$

$$C_z^{e,*} < C_y^{e,*} < C_x^{e,*} \quad \text{for } c^e \geq c_{x,y}^e$$

From this we can conclude that $C_y^{e,*} > \min\{C_x^{e,*}, C_z^{e,*}\} \forall c^e \geq 0$.

Proof of part b Proof is analogous to proof of part a. If $C_y^* \leq \bar{C}_y$, $c_{x,y}^e \leq c_{x,z}^e$ and $c_{y,z}^e \geq c_{x,z}^e$, hence $c_{x,y}^e \leq c_{x,z}^e \leq c_{y,z}^e$.

The ordering of the profits for any value of c^e is:

$$\begin{aligned} C_x^{e,*} < C_y^{e,*} < C_z^{e,*} & \text{ for } 0 \leq c^e \leq c_{x,y}^e \\ C_y^{e,*} < C_x^{e,*} < C_z^{e,*} & \text{ for } c_{x,y}^e \leq c^e \leq c_{x,z}^e \\ C_y^{e,*} < C_z^{e,*} < C_x^{e,*} & \text{ for } c_{x,z}^e \leq c^e \leq c_{y,z}^e \\ C_z^{e,*} < C_y^{e,*} < C_x^{e,*} & \text{ for } c^e \geq c_{y,z}^e \end{aligned}$$

From this we can conclude that $C_y^{e,*} = \min\{C_x^{e,*}, C_y^{e,*}, C_z^{e,*}\} \forall c^e \in [c_{x,y}^e, c_{y,z}^e]$. □

A.4 Indifference emission costs

We have used the following abbreviations for the transport modes Air (a), Road (r), Rail (t) and Water (w). In scenario 6 there is a cell with 335.6*, this number represents the indifference emission cost between air and rail transport, because road transport is not efficient in that scenario.

Table 7: *Indifference emission costs*

D [km]	v [m^3]	k	2000			9000		
			ρ [kg/m^3]	$c_{a,r}^e$	$c_{r,t}^e$	$c_{t,w}^e$	$c_{a,r}^e$	$c_{r,t}^e$
800	0.01	100	184.7	4225.1	32816	893.0	20320	148720
800	0.5	100	-	-	362.1	0.5	41.0	2680.3
800	0.01	1000	7.1	2506.2	3011.4	122.8	12203	14602
800	0.5	1000	-	-	-	-	-	-
2000	0.01	100	303.4	2831.8	21996	1441.9	14057	100030
2000	0.5	100	-	-	145.8	335.6*	-	1706.5
2000	0.01	1000	21.0	1683.1	1929.4	206.1	8514.0	9733.0
2000	0.5	1000	-	-	-	-	-	-

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