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Effect of carbon emission regulations on transport mode selection in supply chains

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Abstract

Policy-makers are developing regulation mechanisms to drive down carbon emissions resulting from among others transport. We investigate what the effect of two regulation mechanisms is on the transport mode selection decision. We analyze the situation in which a single transport mode is to be selected by a decision-maker to conduct all transport (for one item). A faster transport mode typically results in lower inventory (or a higher service) at the cost of higher emissions and transport costs. We consider two possible emission regulation alternatives: an emission cost and an emission constraint. We use an accurate calculation method to determine the carbon emissions and incorporate them explicitly in our model. Our results show that the emission cost is only a small part of the total cost and we conclude that introducing an emission cost for freight transport via a direct emission tax or a market mechanism such as cap and trade are not likely to result in significant changes in transport modes and hence will not result in a large reduction of emissions. If policy-makers aim to reduce carbon emissions by a large fraction, they should implement a constraint on freight transport emissions.

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, WMO, and United Nations Environment Programme, UNEP) published an assessment which states that the increase in greenhouse gas concentrations tend to warm the surface of the earth and lead to other changes of climate (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,

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clean development mechanism and joint implementation. The European Union has already implemented the carbon emission trading scheme (EU ETS) for the energy-intensive industries, which 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. Over the last few years the carbon price has varied between €0 and €30 (European Carbon Exchange).

Currently, no regulations exist that restrict carbon emissions resulting from transport except electrically powered 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 included it already and it is likely to be included by all member states in 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 in 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 till 2030 (European Commission, 2007). Therefore the increase in emissions is due to the increase in transportation movements and an increase in energy efficiency is not enough to balance this. In this research we focus on carbon emissions because transport mainly leads to carbon emissions. It is important to reduce carbon emissions resulting from transport to meet the 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 increase the emission efficiency of transport 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 are more environmental friendly. A trade-off exists because slower transport modes generate lower transportation costs and less 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) (GHG Protocol), Artemis (Artemis), EcoTransIT (EcoTransIT), NTM (NTM) and STREAM (Den Boer, 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 was selected because it provides a high level of detail and the methodology provides estimates for parameter values which 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).

A description and the objective of NTM can be found on their Website (NTM): “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 measurement 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 is calculated firstly by Arrhenius in the 19th century (Arrhenius, 1896) and Callendar argued in 1938 that higher levels of carbon dioxide was causing an increase in the global temperature (Callendar, 1938).

Second, green supply chains and green supply chain management literature is connected to our work. Green Supply Chain Management is defined by Shrivastava (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 and Kleindorfer (2001a), (2001b), Kleindorfer et al. (2005), Srivastava (2007), Sasikumar and Kannan (2009) and Gupta and Lambert (2009). To date most research on green supply chains has focused on reverse logistics/closed-loop supply chains; see for example Blumberg (2005) and Pochampally et al. (2009). These inventory models consider systems in which products return to the manufacturer after use. The returned products can be repaired or remanufactured to be sold again. We focus on a different and important aspect of green supply chains: we focus on transport mode selection as a way to reduce emissions.

Third, our research on transport mode selection is closely related to the dual sourcing literature. In dual sourcing models a product can be purchased from two suppliers or shipped by two transport modes simultaneously, where a trade-off exists between long lead times and

lower procurement/transport costs and short lead times and higher purchase/transport costs. In our model products are ordered from one source with dual (or multiple) transport options. Minner (2003) gives an extensive overview of the literature on dual sourcing. More recent articles on dual sourcing are Veeraraghavan and Scheller-Wolf (2008) and Klosterhalfen et al. (2008).

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 and 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 and Vinod in 1970. Blauwens et al. (2006) investigate the effect of policy measures on modal shift, where the aim is to move away from road transport because of congestion. In some articles emissions are taken into account, for example Bauer et al. (2009). They develop an integer linear programming formulation to determine the service network design which minimizes the emissions. Their work differs from our work because they focus on the design of the network and this is outside the scope of our article. Meixell and Norbis (2008) present an overview of all available literature on transportation choice 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 analyze the situation of a company which can decide between several modes of transportation to transport an item from the supplier (possibly internal) to their production facility. We consider the design of the supply chain as fixed and the company decides which mode of transport to use. The transport modes differ with respect to lead time, unit transportation cost, and unit emissions; e.g. air transport has a shorter lead time and higher carbon emissions and unit transportation costs than water transport. The supply for all modes is done by an external party, e.g. a Third-Party Logistics Service Provider (3PL). We consider an infinite horizon, periodic review model with stochastic demand. Furthermore, we consider a single-location, single-product situation. We study this simplified setting so that we can focus on the analysis of the interactions and the trade-offs between carbon emissions and all relevant costs. In our model one mode is selected to transport all units. In practice some companies might prefer this for simplicity in operations planning.

We assume that companies have a cost-minimization focus. Consequently, external regulation is required to stimulate companies to reduce emissions. Governments and intergovernmental treaties can consider two types of regulations to reduce carbon emissions resulting from

freight transport. The first possible regulation is a cap-and-trade mechanism (like the ETS) which specifies a cost for carbon emissions. A tax on emissions would play a similar role, except that the price in that case is not determined by the market. The second possible regulation is a (company-wide) hard constraint on emissions. In our model we only focus on one product and assume that the company wide emission targets are translated into a product-specific target. This model also applies to a situation in which there exists a constraint on company-wide freight transport emissions in terms of company commitments, an internal target, a high emission tax or a penalty above a certain cap or stringent regulations. We develop two problem formulations for these possible regulations and investigate the effect of the regulation on the preferred transport mode and the emissions.

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 and transport costs for transport modes. Finally, we investigate the effect of the two different types of regulations with respect to emissions on the selected transport mode and the corresponding emissions. We show that including an emission cost does not lead to a large reduction of emissions for the probable range of carbon prices. Introducing a constraint on emissions is a more powerful tool for policymakers in reducing 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 for each of the regulation alternatives and (iii) a methodology to calculate the emissions. We present these ingredients in the succeeding sections of the paper with the following organization: our model and the Transport Mode Selection Problem are described in Section 2. In Section 3, we describe the emission-constrained transport mode selection problem and the emission cost-minimization transport mode selection problem which extend the transport mode selection problem. Moreover, we describe the NTM method to calculate the emission estimates. In Section 4, we solve the transport mode selection problems for the situation with an emission cost and the situation with an emission constraint. In Section 5, we determine the actual emissions for a test bed and determine the preferred transport mode for the parameter settings. In Section 6, we end with a conclusion.

2 Model without emissions

In this section we formulate our model and assumptions in Section 2.1 and the Transport Mode Selection Problem in which the costs of the transport modes are compared in Section 2.2.

2.1 Model description

We consider a single production facility of a company as part of a larger supply chain which requires an item for production. This production facility orders items from a (possibly internal) supplier for which several (two or more) different transport modes are available. The units are shipped by a third party logistics service provider (3PL).

We assume that the production facility orders items periodically from its supplier and an infinite horizon. Demand per period for the item at the production facility follows a distribution with mean μ and 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.).

Several transport modes are available to ship the product and let $I = \{1, \dots, |I|\}$ denote the set of available transport modes and $i \in I$. Let c_i ($c_i > 0$) denote the unit transportation cost for mode i and L_i ($L_i \geq 0$) the deterministic supply lead time for mode i . 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.

Several physical characteristics of the product are required for a detailed calculation of carbon emissions; the product volume v ($v > 0$) and the product density ρ ($\rho > 0$). These two characteristics are combined to obtain the weight of the product which is denoted by $w = \rho v$ in *kg*.

The unit cost of the product is denoted by k ($k > 0$). When an item is required at the facility and there are no units on stock, the demand is backordered. A penalty cost is incurred per unit on backorder at the end of a period for mode i which is a function of the unit cost k and a penalty cost rate r_p ($r_p > 0$). The average number of items backordered at the end of a period for mode i is denoted by $E[B_i]$. The average penalty cost for mode i is then $r_p k E[B_i]$. A holding cost is incurred for each unit on stock at the end of a period for mode i which is a function of the unit cost k and a holding cost rate r_h ($r_h > 0$). The average number of items on stock at the end of a period for mode i is denoted by $E[I_i]$. The average holding cost for mode i is then $r_h k E[I_i]$.

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

$$C_i = kr_p E[B_i] + kr_h E[I_i] + c_i \mu. \quad (1)$$

2.2 Transport Mode Selection Problem

The Transport Mode Selection Problem (TMSP) is aimed at selecting the transport mode which minimizes the long-run average cost per period. We first describe the Cost-minimization Problem for transport mode i and then formulate the Transport Mode Selection Problem.

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 (R,S) policy, is used and we optimize the performance for this policy. 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 has 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 for the demand during $L_i + 1$ periods 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:

$$\begin{aligned} C_i(S_i) &= E\{C_i(S_i, x)\} \\ &= kr_h \int_{-\infty}^{S_i} (S_i - x)f_i(x)dx + kr_p \int_{S_i}^{\infty} (x - S_i)f_i(x)dx + c_i\mu \\ &= kr_h(S_i - \mu'_i) + k(r_h + r_p)G_i(S_i) + c_i\mu, \end{aligned} \quad (2)$$

where $G(v) = \int_v^{\infty} (x - v)f(x)dx = f(v) - v(1 - F(v))$ and $G'(v) = F(v) - 1$.

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

$$\min_{S_i} C_i(S_i). \quad (3)$$

The optimal order-up-to level (S_i^*) satisfies the condition:

$$F_i(S_i) = \frac{r_p}{r_p + r_h}. \quad (4)$$

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

$$\bar{C} = \min_{i \in I} C_i(S_i^*). \quad (5)$$

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

3 Emissions

In this section we describe how the carbon emissions are incorporated into our model and the methodology to calculate the emissions. In Section 3.1 we define the Emission-constrained

Transport Mode Selection Problem in which we have a (hard) constraint on the carbon emissions. In Section 3.2 we define the Emission Cost-minimization Transport Mode Selection Problem in which a unit cost for emissions is charged. After that, in Section 3.3, we introduce the NTM method which enables us to calculate the emissions resulting from transportation.

3.1 Emission-constrained problem

This problem extends the TMSP by constraining the emissions per period to a maximum, which is denoted by EM_{max} (in kg). The average amount shipped per period (μ) is independent of the order-up-to level. Therefore, the emissions are independent of the order-up-to level.

For transport mode i , $C_i(S_i)$ denotes the costs for a specific order-up-to level S_i . The emissions resulting from transporting one unit with mode i is denoted by e_i (in kg). We do not consider fixed emissions per shipment because the vehicle is not dedicated. The *Emission-constrained Problem* for transport mode i is formulated as follows:

$$\begin{aligned} \bar{C}_i = \min_{S_i} \quad & C_i(S_i) \\ \text{subject to} \quad & EM_i(S_i) \leq EM_{max}, \end{aligned} \quad (6)$$

where $EM_i(S_i) = \mu e_i$ in kg . We note that the optimal order-up-to level and minimum average cost of the Emission-constrained Problem are equal to the optimal order-up-to level and the minimum cost for the Cost-minimization Problem of Section 2.2, provided it is feasible. If the Emission-constrained Problem is infeasible for mode i , we denote $\bar{C}_i = \infty$.

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

$$\bar{C}' = \min_{i \in I} \bar{C}_i. \quad (7)$$

In this problem the transport mode with the lowest minimum average cost per period which meets the emission constraint is selected.

3.2 Emission cost-minimization problem

This problem extends the TMSP by adding a cost for carbon emissions. In the Emission Trading Scheme the carbon cost is expressed in $\text{€}/(\text{metric})$ tonne emissions. We therefore specify a carbon emission cost c_e ($c_e > 0$) per tonne of CO_2 emitted. Let C_i^e denote the average cost per period including emission cost for order-up-to level S_i and is calculated as follows:

$$C_i^e(S_i) = C_i(S_i) + c_e \frac{EM_i(S_i)}{1000} = kr_h(S_i - \mu'_i) + k(r_h + r_p)G_i(S_i) + c_i\mu + \frac{c_e \cdot e_i}{1000}\mu. \quad (8)$$

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

$$\bar{C}_i^e = \min_{S_i} C_i^e(S_i). \quad (9)$$

The emission cost is a function of μ only. Hence, the optimal order-up-to level for the Emission Cost-minimization Problem (S_i^*) is equal to the optimal order-up-to level for the Cost-minimization Problem (the cost is higher however).

The *Emission Cost-minimization Transport Mode Selection Problem* (ECTMSP) is formulated as follows:

$$\bar{C}^e = \min_{i \in I} \bar{C}_i^e. \quad (10)$$

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

3.3 Emission calculations

The NTM method specifies emissions for four types of transport: air, rail, road and water. For each type we describe the calculation method for the total emissions for an average-loaded vehicle and the allocation procedure which allocates part of the emissions to one unit of our product. We describe the NTM method for air, rail, road and water transport, in Sections 3.3.1 - 3.3.4, respectively.

3.3.1 Air transport

We assume that a dedicated cargo aircraft is used. The total emissions of the vessel are determined by the emission factor (constant and variable) and the distance. Below each factor is described in more detail.

Emission factor The emission factor of an aircraft consists of two parts; a constant emission factor (CEF in kg) (for emissions during take-off and landing) and a variable emission factor (VEF in kg/km) which is linear in the flight distance. The emission factors are specific for the aircraft type, engine type and maximum load.

The load factor is defined as the actual weight of the load versus the maximum load. NTM Air (2008) provides the emission factors for load factors of 50, 75 and 100 %. The emission factors for different load factors are found by interpolating, which results in the following formula: $CEF_x = CEF_y + \frac{CEF_z - CEF_y}{z - y}(x - y)$, where $y = 50$ and $z = 75$ if $50 \leq x \leq 75$ and $y = 75$ and $z = 100$ if $75 \leq x \leq 100$.

Distance The flight distance is calculated with the method used by the International Civil Aviation Organization (ICAO). When calculating the flight distance (D_a in km) between the origin and destination location we need to take the bend of the earth into account. Using the Great-circle distance formula, the shortest distance between two locations on a sphere is calculated by following a path on the surface of the sphere. The Great-circle distance formula is:

$$D_a = \cos^{-1}(\sin(lat1) \sin(lat2) + \cos(lat1) \cos(lat2) \cos(lon1 - lon2)), \quad (11)$$

where $lat1$ is the latitude of location 1 and $lon1$ the longitude of location 1, and likewise for location 2. We note that this distance is in general not equal to the distance over road between the locations.

Total Emissions The formula for the total emissions (EM_{total} in kg) for an aircraft is then:

$$EM_{total} = CEF + VEF \cdot D_a. \quad (12)$$

Unit Emissions So far we have determined the emissions for the entire aircraft and we need to allocate part of the emissions to one unit of the product (e_a). 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). 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 167 (kg/m^3) (where 167 is a default density commonly used by transport companies, (NTM Air, 2008)). The formula to determine the dimensional weight is then $w_d = \max(w, 167v) = \max(\rho v, 167v) = v \max(\rho, 167)$. The unit emissions (e_a in kg) are calculated with the following equation:

$$e_a = EM_{total} \frac{w_d}{LO_{max} LF}, \quad (13)$$

where LO_{max} is the maximum load of an aircraft (in kg) and LF the average load factor of the aircraft, based on physical weight of the load.

3.3.2 Railway transport

Two types of railway transport are distinguished; electrical and diesel. In this section we describe the emission calculation method as described in NTM Rail (2008). The unit emissions (e_e and e_d for electrical and diesel, respectively) depend on three main factors; the emission factor, the distance and the weight of the product. The distance is divided into distances per country because the emissions to generate 1 kWh , and the fuel content, differ per country. The emissions per country are added to obtain the total emissions. Define the set of countries through which the train travels as Z and $z \in Z$.

Below we describe the formulas for the emission factor for country z (EF^z in $kg CO_2/net$ tonne km) and the distance in country z (D^z in km).

Emission factor The emission factor in country z (EF_e^z and EF_d^z for an electrical and diesel train, respectively) is defined as the amount of CO_2 emitted when transporting 1 net tonne over 1 km in country z . 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). These factors are described below.

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 ($t^z \in \{flat, hilly, mountainous\}$). We define a factor T which determines the energy (cq. fuel) consumption for a flat country and the factor $\gamma(t^z)$ increases that factor for hilly and mountainous terrain (hence $\gamma(flat) = 1$ and $\gamma(mountainous) > \gamma(hilly) > 1$). Let LF 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 EF_e^z and EF_d^z (in *kg CO₂/net tonne km*):

$$EF_e^z = \frac{\gamma(t^z) \cdot T \cdot EE^z}{1000 \sqrt{W_{gr}} \cdot LF \cdot (1 - TL)}, \quad (14)$$

$$EF_d^z = \frac{\gamma(t^z) \cdot T \cdot FE^z}{10^6 \sqrt{W_{gr}} \cdot LF}. \quad (15)$$

Distance The distance traveled in country z , D^z , (in *km*) can be calculated from for example the EcoTransIT web page (EcoTransIT).

Unit emissions The unit emissions e_e and e_d (in *kg*) are a function of the weight of the product (w in tonne) and are calculated per country and then summed over the countries traversed.

$$e_e = \sum_{z \in Z} EF_e^z D^z w \quad (16)$$

$$e_d = \sum_{z \in Z} EF_d^z D^z w \quad (17)$$

3.3.3 Road transport

We have assumed that road transport takes place via integrating terminals, because it is commonly used by 3PLs (for longer distances). We assume that the items are transported from a terminal to another terminal. The total emissions of the vehicle are determined by the fuel consumption of that vehicle, the fuel emissions and the distance. Below each factor is described in more detail.

Fuel consumption The Fuel Consumption (FC in *l/km*) depends on the Load Factor (LF) and the type of vehicle and is calculated with the following formula:

$$FC = FC_{empty} + (FC_{full} - FC_{empty})LF. \quad (18)$$

Fuel emissions The fuel emissions factor (FE) is defined as gram of CO_2 emitted per liter of fuel (diesel).

Distance The distance (D in km) is the distance between the terminals. In most cases the vehicle needs to travel additional kilometers to complete the pick up and delivery of the goods, which does not directly contribute to bringing goods from location A to location B. We refer to this ‘extra distance’ as the positioning distance. To take the positioning distance into account the distance should be amplified by 20% (NTM Road, 2008). The emissions resulting from empty returns also have to be allocated to the load but only if dedicated equipment is used. Because we assume transport via integrating terminals no positioning distance or empty returns are taken into account.

Total Emissions The total emissions (EM_{total} in g) are then:

$$EM_{total} = FE \cdot FC \cdot D. \quad (19)$$

Unit Emissions We have now determined the emissions of the entire vehicle and we need to allocate part of the emissions to one unit of the product (e_r). The allocation is based on the dimensional or volumetric weight of the load, which is defined as: $w_d = v \max(\rho, 250)$, where 250 is a default density commonly used by transport companies (NTM Road, 2008). The unit emissions (e_r in g) are calculated with the following equation:

$$e_r = EM_{total} \frac{w_d}{LO_{max} LF}, \quad (20)$$

where LO_{max} is the maximum load of a vehicle (in kg) and LF the average load factor of the vehicle, based on physical weight of the load.

3.3.4 Water transport

Water transport covers short-sea transport and inland transport with diesel oil-powered vessels (NTM Water, 2008). The calculation of emissions for vessels is dependent on the type of vessel. The following procedure should be followed to obtain the emissions estimates.

Total emissions The total emissions (EM_{total} in kg) depend on three factors, the fuel consumption (FC), the distance (D_w) and the fuel emissions (FE). For a given vessel type, the fuel consumption is given in NTM Water (2008) for a given average load factor FC (in l per km). The distance D_w in km is required and can be obtained from, for example the World Port Distances website which are not always accurate (World Port Distances). The fuel emissions factor FE (kg of CO_2 emitted when 1 l of diesel is burnt) is also required. The multiplication of these three factors, yields the total emissions of the vessel (EM_{total} in kg),

$$EM_{total} = FC \cdot D_w \cdot FE. \quad (21)$$

Unit emissions Part of the total emissions need to be allocated to one unit of the product. Define the allocation fraction $\alpha \in (0, 1]$ as follows:

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

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 unit emissions (e_w in kg) are then calculated with the following formula:

$$\begin{aligned} e_w &= \alpha \cdot EM_{total} \\ &= \alpha \cdot FC \cdot D_w \cdot FE. \end{aligned} \tag{22}$$

4 Analysis

We solve the Emission-constrained Transport Mode Selection Problem (ETMSP) and Emission Cost-minimization Transport Mode Selection Problem (ECTMSP) to optimality in Section 4.1 and 4.2, respectively.

From now on, we consider the special case of normally distributed demand for exposition purposes. Similar analysis can be conducted for other distributions as well. The expected demand and standard deviation of demand during $L_i + 1$ periods is then $\mu'_i = (L_i + 1)\mu_i$ and $\sigma'_i = \sqrt{L_i + 1}\sigma_i$, respectively. Let ϕ denote the probability density function and Φ the cumulative distribution function of the standard normal distribution. The optimal order-up-to level, as specified in Equation (4), satisfies the condition:

$$\Phi\left(\frac{S_i - \mu'_i}{\sigma'_i}\right) = \frac{r_p}{r_p + r_h}. \tag{23}$$

The average cost for mode i associated with the optimal order-up-to level ($C_i(S_i^*)$) is:

$$C_i(S_i^*) = k\sqrt{L_i + 1}\sigma(r_p + r_h)\phi\left(\Phi^{-1}\left(\frac{r_p}{r_p + r_h}\right)\right) + c_i\mu. \tag{24}$$

4.1 Emission-constrained problem

When we solve the Emission-constrained problem for mode i , we notice that the average amount shipped per period is equal to μ for any order-up-to level S_i . Therefore, the emissions do not depend on the order-up-to level. For some transport modes solving the problem does not result in a feasible solution, because the emissions are larger than the maximum allowed emissions.

In the ETMSP we select the mode with the lowest cost which meets the emission constraint. We assume that the emission constraint is set in a way such that at least one mode of transport meets the constraint.

4.2 Emission Cost-minimization problem

For the Emission Cost-minimization problem the total costs depend on the emission level. We determine the optimal order up-to level (S_i^*) with Equation (23) for mode i . The cost associated with the optimal order-up-to level S_i^* (\bar{C}_i^e) is:

$$\bar{C}_i^e = k\sqrt{L_i + 1}\sigma(r_p + r_h)\phi\left(\Phi^{-1}\left(\frac{r_p}{r_p + r_h}\right)\right) + c_i\mu + c_e\mu e_i. \quad (25)$$

In the ECTMSP we select the mode with the lowest cost. The transport mode selected depends on the value of c_e .

4.2.1 Emission Cost-minimization Transport Mode Selection Problem

We denote two transport modes by i and j ($i, j, \in I$) for the purpose of comparing for which value of the emission cost both modes are equally expensive. To do so, we reformulate the ECTMSP to obtain an explicit expression for the emission cost for which the two modes are equally expensive.

We now rewrite \bar{C}_i^e and \bar{C}_j^e :

$$\begin{aligned} \bar{C}_i^e &= k\sqrt{L_i + 1}\sigma(r_p + r_h)\phi\left(\Phi^{-1}\left(\frac{r_p}{r_p + r_h}\right)\right) + c_i\mu + c_e\mu e_i, \\ \bar{C}_j^e &= k\sqrt{L_j + 1}\sigma(r_p + r_h)\phi\left(\Phi^{-1}\left(\frac{r_p}{r_p + r_h}\right)\right) + c_j\mu + c_e\mu e_j. \end{aligned} \quad (26)$$

We assume without loss of generality that $C_i(S_i^*) \geq C_j(S_j^*)$. When we combine these formulas, we find the value of the emission cost for which $\bar{C}_i^e = \bar{C}_j^e$, which is denoted by $c_e^*(i, j)$, i.e. we are indifferent between selecting mode i and j :

$$c_e^*(i, j) = \frac{(c_i - c_j)\mu - k(\sqrt{L_j + 1} - \sqrt{L_i + 1})\sigma T}{\mu(e_j - e_i)} = \frac{c_i - c_j - k\frac{\sigma}{\mu}(\sqrt{L_j + 1} - \sqrt{L_i + 1})T}{e_j - e_i}, \quad (27)$$

where $T = (r_p + r_h)\phi\left(\Phi^{-1}\left(\frac{r_p}{r_p + r_h}\right)\right)$.

If $c_e^*(i, j) \leq 0$, mode j is cheaper than mode i and is therefore always selected, in this case $e_i \geq e_j$. If $c_e^*(i, j) > 0$, mode j is selected when $0 \leq c_e < c_e^*(i, j)$, in this case $e_i \leq e_j$. The transport mode selected depends on the actual values of the parameters.

From Formula 27 it follows that $c_e^*(i, j)$ is increasing (or decreasing) in: unit cost for mode i (c_i), the lead time for mode i (L_i), and the unit emissions of mode j (e_j). $c_e^*(i, j)$ is increasing in: unit cost for mode j (c_j), coefficient of variation of demand per period ($\psi = \frac{\sigma}{\mu}$), the ratio of penalty and holding costs ($\frac{r_p}{r_h}$), the unit cost of the product (k), the lead time of mode j (L_j), and the unit emissions of mode i (e_i).

We determine which transport mode is the preferred transport mode for which values of the emission cost. Without loss of generality, we sort all modes in I in increasing order in the optimal cost for the Cost-minimization problem ($C_i(S_i^*)$): transport mode 1 having lowest cost,

transport mode 2 the lowest cost after mode 1, and so on. For each pair of transport modes we calculate $c_e^*(i, j)$ which is displayed in Table 1.

Table 1: *Indifference cost table*

	mode 1	mode 2	...	mode $ I - 1$
mode 2	$c_e^*(1, 2)$	-	...	-
mode 3	$c_e^*(1, 3)$	$c_e^*(2, 3)$...	-
\vdots	\vdots	\vdots	\ddots	\vdots
mode $ I $	$c_e^*(1, I)$	$c_e^*(2, I)$...	$c_e^*(I - 1, I)$
	$c_e^*(1)$	$c_e^*(2)$...	$c_e^*(I - 1)$

Let $c_e^*(i)$ be defined as $c_e^*(i) = \min_{j \in I, i \neq j} c_e^*(i, j)^+$ where $x^+ = \max(0, x)$ and it represents the maximum possible emission cost value for which mode i is has the lowest cost. $\min_{j \in I, i \neq j} c_e^*(i, j)^+ = 0$ implies that it is always cheaper than other and thus set $c_e^*(i) = \infty$. Let $\bar{C}_i^e(c_e)$ denote the cost for transport mode i given the optimal order-up-to level and emission cost c_e . $\bar{C}_i^e(c_e)$ is a linear increasing function of c_e . Because we have ordered the transport modes increasing in cost, mode 1 is the preferred transport mode on the domain $c_e = [0, c_e^*(1)]$. Since $c_e^*(1) = c_e^*(1, i)$, mode i is the preferred transport mode on the domain $c_e = [c_e^*(1), c_e^*(i)]$, and so on. If $c_e^*(i) < c_e^*(1)$, i is never the preferred transport mode. We combine this to construct a graph which represents the cost of the solution to the ECTMSP as a function of c_e ($\bar{C}^e(c_e)$), see Figure 8(b) in Section 5.3.

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 this study we use real-life estimates based on the NTM method. In Section 5.1 we describe the equations for four specific transport modes and we calculate the emissions for the instances of a test bed. Next we analyze the effect of parameters on the emission price for which pairs of transport modes are equally expensive in Section 5.2. Finally, in Section 5.3 we compare the solutions of the TMSP, ETMSP and the ECTMSP, in terms of costs and emissions, for a specific parameter setting. For sake of clarification we introduce Table 2 which contains all notations.

5.1 NTM emission calculations

For each of the four transport classes (air, rail, road and water) we select a representative vehicle to which we apply the NTM method. The unit emissions are a function of distance, volume and density of the product. Furthermore, we specify a test bed for which we calculate

Table 2: *Notation*

Symbol	Unit	Description
c_e	€/tonne	carbon emission price
CEF	kg	Constant emission factor
c_i	€	Transportation cost for one unit of transport mode i
C_i	€	Average cost per period of transport mode i
C_i^e	€	Average cost per period including emission cost of transport mode i
D	km	Distance
EE	g	Emissions when generating 1 kWh
EF	g/km	Emission factor
e_i	kg	carbon emissions for transporting one unit with transport mode i
EM_{total}	kg	Total emissions of shipment
FC	l/km	Fuel consumption
FE	g/l	Emissions per liter of fuel burned
γ_{tz}		Topography factor
k	€	Unit cost of a product
LF		Load factor
L_i	days	Lead time of transport mode i
LO_{max}	kg	Maximum load of a vehicle
μ		Average demand per period
r_h		Holding cost rate per day
r_p		Penalty cost per day
ρ	kg/m^3	Density of the product
S_i		Order-up-to level of transport mode i
σ		Standard deviation of demand per period
T		Energy (cq. fuel) consumption factor
TL		Transmission loss fraction
v	m^3	Volume of the product
VEF	kg/km	Variable emission factor per kilometer traveled
w	kg	Weight of the product
W_{gr}	tonne	Gross weight of a train

emissions.

Air transport The emission factors vary heavily between aircraft - engine - maximum load combinations. NTM has determined the emission factors (constant and variable) for 31 combinations (dedicated cargo aircrafts) (NTM Air, 2008). 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 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%. Hence, the emission factors are $CEF = 4139.6$ and $VEF = 15.353$.

We note that the distance over road between two locations (D) is always more than the air distance (D_a) so we have to adjust D_a to correct for this. For several routes in Europe the road distance is compared with the distance obtained with the great-circle distance formula (values obtained through a routeplanner (Google Maps©) and Distance Calculator). For the routes we investigate $D_a = 0.801D$ on average, as can be seen in Table 9 in Appendix A.

If we implement these values in the formula for the total emissions (EM_{total} in kg), Equation (12), we obtain:

$$EM_{total} = 4139.6 + 15.353 \cdot 0.801D. \quad (28)$$

For the aircraft we select the maximum load LO_{max} is 29029 kg and the average load factor (LF) is 80%. The equation for the unit emissions (e_a in kg) is then in this case:

$$e_a = EM_{total} \frac{v \max(\rho, 167)}{23223.2}. \quad (29)$$

Combining Equation (28) and (29) yields:

$$e_a \approx v \max(167, \rho)(0.1783 + 0.0005295D). \quad (30)$$

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). We use this percentage to calculate the emissions for an average trip in Europe. All constants mentioned below are taken from NTM Rail (2008).

We assume that the gross weight of the train is 1000 *tonne* ($W_{gr} = 1000$), which is the average value specified by NTM Rail (2008). We assume that a load factor of 50% is used ($LF = 0.50$).

For a diesel train we take the following parameter values. The fuel consumption factor (T) is 122.46. The fuel emissions (FE) are 3175 g/kg .

For an electrical train we assume that the energy consumption factor (T) is 540 and a 10% loss of energy due to energy transfer ($TL = 0.10$).

We do not distinguish between distances traveled in countries but rather take the average values for Europe, to be more generic and therefore suppress the subindex z . We assume that the entire track is hilly. In NTM Rail (2008) we find the following value $\gamma(hilly) = 1.25$. The average emissions to air when generating 1 kWh in Europe (EE) is 0.41 kg/kWh .

The emission factor (EF_e in $kg/net\ tonne\ km$), as defined in Equation (14), for an electrical train with these parameter values is then:

$$EF_e = \frac{1.25 \cdot 540 \cdot 0.41}{1000\sqrt{1000} \cdot 0.5 \cdot 0.9} \approx 0.01945. \quad (31)$$

The emission factor (EF in $kg/net\ tonne\ km$), as defined in Equation (15), for a diesel train with these parameter values is then:

$$EF_d = \frac{1.25 \cdot 122.46 \cdot 3175}{10^6 \sqrt{1000} \cdot 0.5} \approx 0.03074. \quad (32)$$

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

$$\bar{EF} = 0.754 \cdot 0.01945 + 0.246 \cdot 0.03074 \approx 0.02223. \quad (33)$$

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 in Equations (16) and (17), we obtain the following formula for the unit emissions (e_t in kg):

$$e_t \approx 2.223 \cdot 10^{-5} \cdot D \cdot w, \quad (34)$$

where D is denoted in km and w in kg .

Road transport We assume that a Tractor + Semi-trailer is used, because it is a common type to use for longer distances. The fuel consumption for a Tractor + Semi-trailer depends on the road type and the values are given in Table 4. We assume a load factor of 70%, which is typical for transport via integrating terminals (NTM Road, 2008), the fuel consumption is then 0.3198, 0.3462 and 0.4392 l/km , for Motorway, Rural and Urban respectively.

Table 4: *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 sample cities can be found in Table 8 in Appendix A. 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:

$$\begin{aligned} FC(D) &= 17.8 \cdot 0.4392 + (D - 17.8) \cdot 0.3198 \\ &\approx 2.125 + 0.3198D. \end{aligned} \quad (35)$$

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), Equation (19), we obtain:

$$\begin{aligned} EM_{total} &= 1.05 \cdot 2621FC_{LF}(D) \\ &\approx 2752.05(2.125 + 0.3198D) \\ &\approx 5848.99 + 880.10D. \end{aligned} \quad (36)$$

For a Tractor + Semi-trailer the maximum load LO_{max} is 40 *tonne* and the average load factor (LF) is 70%. The equation to calculate the unit emissions (e_r in g) is then in this case:

$$e_r = EM_{total} \frac{v \max(\rho, 250)}{28000}. \quad (37)$$

If we combine Equation (36) and (37), we obtain the unit emissions (e_r in kg):

$$\begin{aligned} e_r &= \frac{1}{1000} v \max(250, \rho)(0.2089 + 0.03143D) \\ &= v \max(250, \rho)(0.0002089 + 0.00003143D). \end{aligned} \quad (38)$$

Water transport We assume that inland waterways are used for transport and that a general cargo vessel is used. For inland waterways NTM assumes a load factor (LF) of 50%. This factor is relatively low since in inland waterways the transport is shuttle-like (NTM Water, 2008). 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:

$$\alpha = \frac{w}{1920 \cdot 1000}, \quad (39)$$

where w is in kg .

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 larger than the distance over road. The distance (D_w) is therefore 1.20 times the road distance (D), due to a lack of empirical data this value is an educated guess. Applying these values to Equation (22), yields the following equation for the unit emissions for water transport (e_w in kg):

$$\begin{aligned} e_w &= \frac{w}{1920 \cdot 1000} 0.007 \cdot 1.20D \cdot 3178 \\ &\approx 1.3904 \cdot 10^{-5} \cdot w \cdot D, \end{aligned} \quad (40)$$

where D is in km and w in kg .

When we compare the formulas for the unit emissions for all transport modes, we can define for which range of v , ρ (or w) and D the unit emissions for one mode are lower than for another. The unit emissions are described by Equations (30), (34), (38), and (40). First, we compare air and road transport (e_a and e_r). If we fix ρ and v ($\rho, v \geq 0$) and look at the first part ($v \max(250/167, \rho)$) of both equations, it holds that the value for road is at most 1.5 times as

large as for air. The second part is for air at least 16 times as large as for road for $D \geq 0$. Hence, we conclude that $e_a > 10e_r$ for $v, \rho, D \geq 0$. Second, we compare rail and water transport (e_t and e_w). We see immediately that $e_t > 1.5e_w$ for $v, \rho, D \geq 0$. Third, we compare road and rail transport (e_t and e_r). If we take $\rho \geq 250$, the first part of both equations is equal. The second part is for road at least 1.4 times as large as for rail for $D \geq 0$. Hence, we conclude that $e_r > 1.4e_t$ for $v, \rho, D \geq 0$. We now establish the following ordering for unit emissions: $e_a > e_r > e_t > e_w$ for $v, \rho, D \geq 0$.

We have created a test bed and determine the unit emissions for the instances. We consider the distance between two locations (in km), the density (in kg/m^3) and volume (in m^3) of the product as parameters. For each parameter we have selected three different values, in total we have $3^3 = 27$ instances. The values are given in Table 5. If we apply the equations and the

Table 5: *Parameter settings*

Parameter	Number of values	Values
Distance D	3	800, 1200, 2000
Density ρ	3	100, 500, 1000
Volume v	3	0.001, 0.05, 0.50

assumptions mentioned before, we obtain the unit emissions (in kg) in Table 6.

Table 6: *Unit emissions road and air transport (in kg)*

v [l]	D ρ [kg/m^3]	800				1200				2000			
		Air	Rail	Road	Water	Air	Rail	Road	Water	Air	Rail	Road	Water
1	100	0,101	0,002	0,006	0,001	0,136	0,003	0,009	0,002	0,207	0,004	0,016	0,003
1	500	0,301	0,009	0,013	0,006	0,407	0,013	0,019	0,008	0,619	0,022	0,032	0,014
1	1000	0,602	0,018	0,025	0,011	0,814	0,027	0,038	0,017	1,237	0,044	0,063	0,028
50	100	5,026	0,089	0,317	0,056	6,795	0,133	0,474	0,083	10,332	0,222	0,788	0,139
50	500	15,048	0,445	0,634	0,278	20,343	0,667	0,948	0,417	30,934	1,111	1,577	0,695
50	1000	30,095	0,889	1,268	0,556	40,686	1,334	1,896	0,834	61,869	2,223	3,154	1,390
500	100	50,259	0,889	3,169	0,556	67,946	1,334	4,741	0,834	103,321	2,223	7,884	1,390
500	500	150,475	4,445	6,339	2,781	203,431	6,668	9,482	4,171	309,343	11,113	15,768	6,952
500	1000	300,950	8,890	12,677	5,562	406,862	13,335	18,964	8,342	618,686	22,225	31,537	13,904

From Table 6 we again notice the large difference in emissions. It also shows that the unit emissions can be as high as 619 kg (air transport, 2000 km , 500 l and $\rho = 1000$)! Since the establishment of the carbon market the price has varied between € 1 and € 30 /tonne. If the price is € 15 /tonne, the average costs per period increase with up to € $15 \cdot 0.619 =$ € 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 Cost-minimization TMSP

In this section we describe the effect of parameters on the solution of the ECTMSP and the indifference emission cost.

We assume that L_a is fixed at one day and that L_r , L_t and L_w depend on the distance; the maximum distance traveled per day is 400 km for road, 240 km for rail and 160 km for water. We select the test bed of Section 5.1 and we specify in addition the following (realistic) parameter values: $\psi = \frac{\sigma}{\mu} = 0.2$, $L_a = 1$, $L_r = \frac{D}{400}$, $L_t = \frac{D}{240}$, $L_w = \frac{D}{160}$, $c_a = 2.5$, $c_r = 1$, $c_t = 0.8$, $c_w = 0.6$ and, $r_h = \frac{0.25}{300}$ and $r_p = 10r_h$. For each pair of transport modes we calculated for which unit cost they are equally expensive (for $D = 800$ and $c_e = 0$), the values are: air-road 15734, air-rail 8492, air-water 6117, road-rail 1907, road-water 1859 and rail-water 1813. We are interested in instances for which adding an emission cost might change the preferred supply mode. We have therefore selected the following two values for the unit cost (k), 2000 and 9000.

In total, the test bed consists of 54 instances and the indifference emission cost $c_e^*(i, j)$ is calculated for each of the instances; the results are in Table 10 in Appendix B. The table shows that the indifference emission cost is very high unless the distance is large, or the product has a high volume or weight. In Section 5.1, we found that the unit emission costs can be as high as € 9.90 per product for realistic values. For this particular instance 73% of the average cost is emission cost. For road, rail and water transport the emission cost accounts for 16%, 11% and 7%, respectively of the average cost.

In this particular case the transport modes are ordered; $e_a > e_r > e_t > e_w$. Hence, the sequence in which the supply modes are preferred for increasing values of c_e is air-road-rail-water, where a few of the first modes might not be a solution because $C_i(S_i^*)$ is too high. We therefore only consider the pairs air-road, road-rail and rail-water. Equation (27) describes the effect of a specific parameter on the indifference emission cost. In Figures 1, 2 and 3 we display the effects of the unit cost of the product (k), the transportation cost ratio ($\frac{c_i}{c_j}$) and the penalty-holding cost ratio ($\frac{r_p}{r_h}$), respectively. Figure 1 is to be interpreted as follows: for a given unit cost k air is the preferred transport mode when $c_e \leq c_e^*(a, r)$, road when $c_e^*(a, r) \leq c_e \leq c_e^*(r, t)$, rail when $c_e^*(r, t) \leq c_e \leq c_e^*(t, w)$ and water when $c_e \geq c_e^*(t, w)$. From Figure 1 we see that road is the preferred transport mode for many values of the unit cost, given an emission indifference cost. Rail is the preferred supply mode for only a very small range of values. This implies that the costs of rail and water transport only differ by a small amount and are therefore almost interchangeable in the top-left corner.

For the current range of the emission cost (between 0 and 30), water transport is selected for items with a unit cost below 1000, road transport is selected for medium expensive items (unit cost between 1000 and 7000) and air transport is selected for expensive items. Figure 2

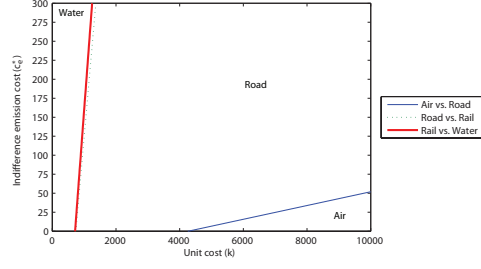


Figure 1: Indifference emission cost as a function of the unit cost $c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, v = 0.05, \rho = 1000, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$

consists of three graphs, one for each pair i and j . Let mode j be the low-emission mode, road, rail or water, and mode i the high-emission mode, air, road or rail. For each graph it holds that mode i is preferred when $c_e \leq c_e^*(i, j)$ and mode j is preferred otherwise.

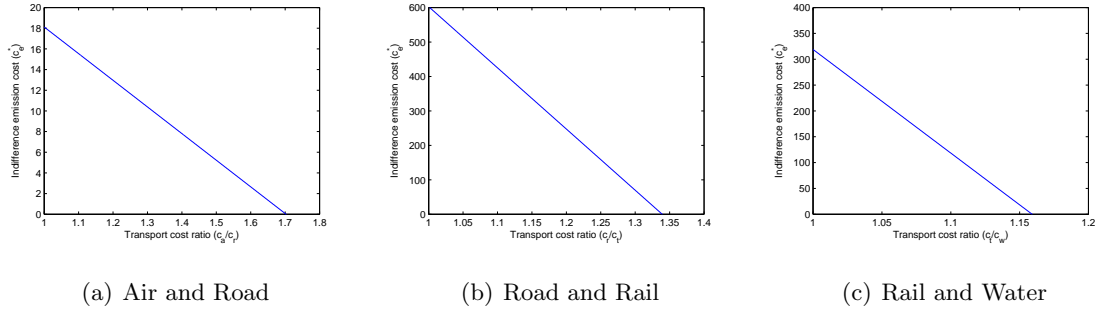


Figure 2: Indifference emission cost as a function of the transportation cost ratio ($c_a/c_r, c_r/c_t, c_t/c_w$) $c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, k = 2000, v = 0.05, \rho = 1000, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$

Figure 3 is to be interpreted as Figure 1. It shows us that the higher the penalty costs, the more a mode with a shorter lead time is favored to avoid high penalty costs.

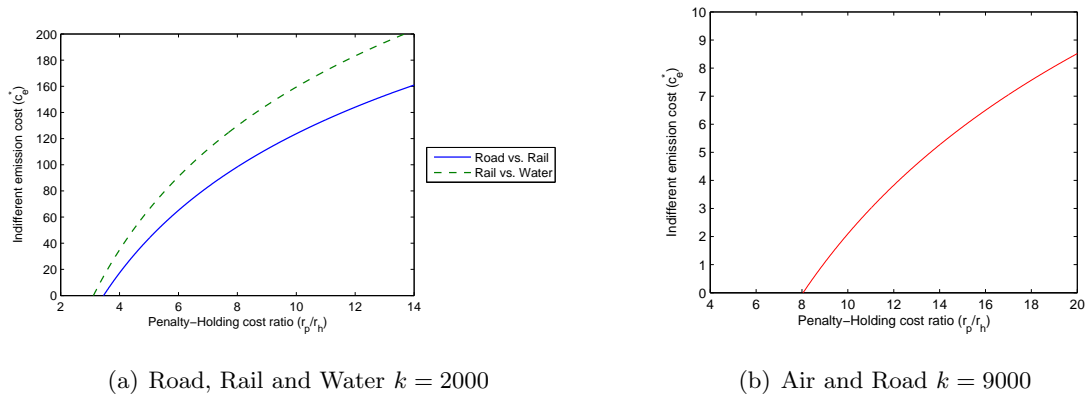


Figure 3: Indifference emission cost as a function of the penalty-holding cost ratio $c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, v = 0.05, \rho = 1000, \psi = 0.2, r_h = \frac{0.25}{300}$

Another important factor of the indifference emission cost, Equation (27), is the emissions

difference $e_j - e_i$ which is determined by distance (D), volume (v) and density (ρ). The effect of each of these parameters on the indifference emission cost is depicted in Figures 4, 5, and 6. The figures are to be interpreted similarly as Figures 1 and 3. Figure 4 shows an interesting curve, since D influences multiple factors (L_i, L_j and $e_j - e_i$). For small distances water is the preferred supply mode, rail is the preferred supply mode for a small range of distances for larger distances road is the preferred supply mode. The emissions for air transport consist of a fixed part (due to take-off and landing), it is therefore only selected for large distances. Figure 5 shows that for very small items (low volume) the indifference price grows very large, because the unit emissions are very low. The curves in Figure 6 display a peculiar shape due to the dimensional weight for air and road transport ($w_d = v \max(\rho, 250)$).

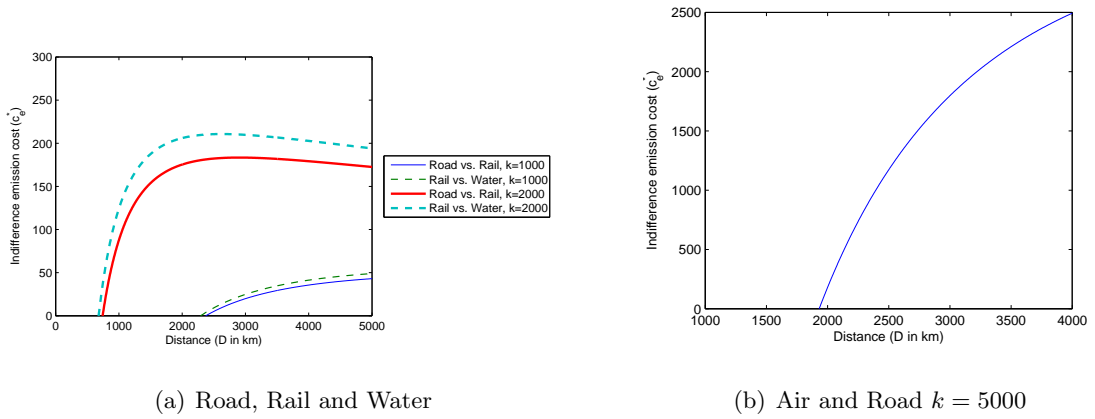


Figure 4: Indifference emission cost as a function of the distance

$$c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, L_a = 1, v = 0.05, \rho = 1000, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$$

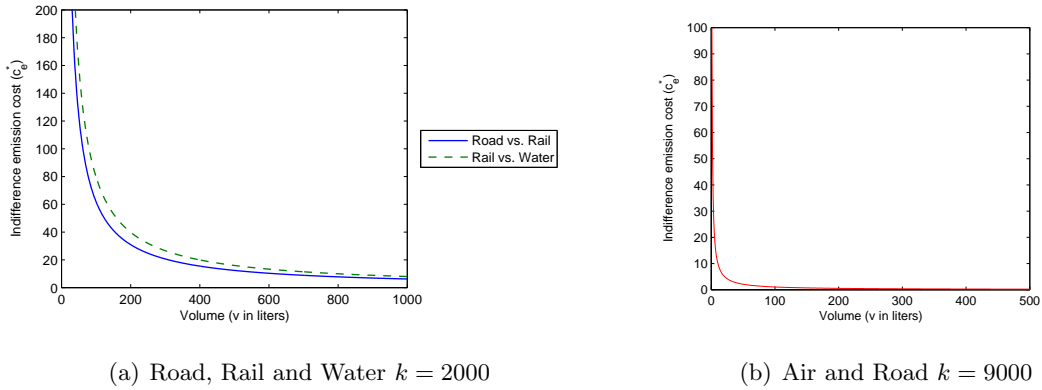


Figure 5: Indifference price as a function of product volume

$$c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, \rho = 1000, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$$

Lastly, we determined for which combinations of the unit cost and density of the product, which mode is preferred. We have selected four specific products to include in the graph. We selected two products with a low volume ($v = 6.4 \cdot 10^{-3}$), sugar ($k = 1$ and $\rho = 1586.2$) and

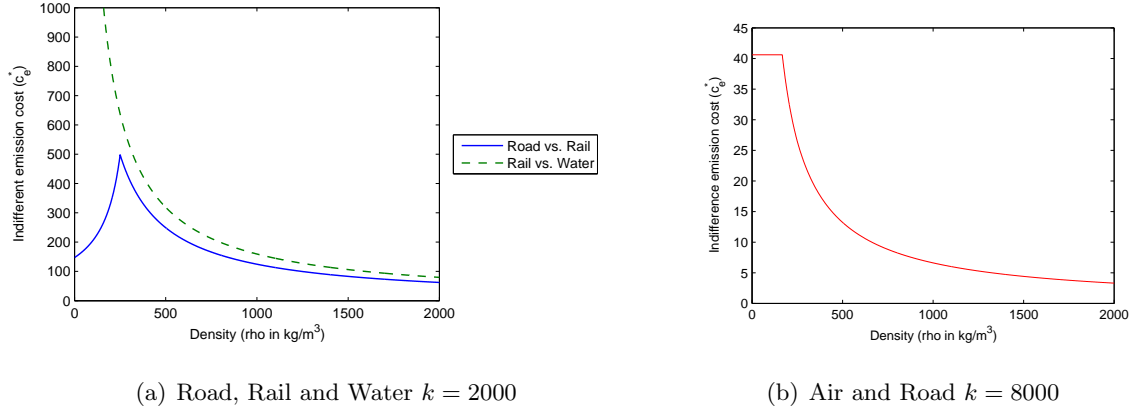


Figure 6: Indifference price as a function of product density

$$c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, v = 0.05, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$$

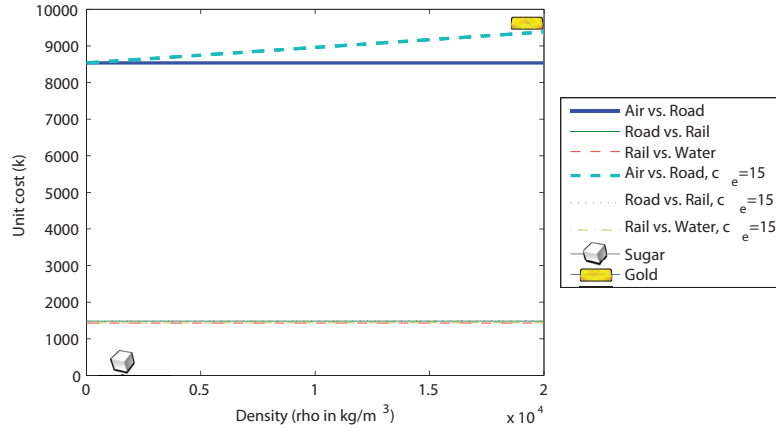
gold ($k = 9635$ and $\rho = 19320$), and two products with a high volume ($v = 0.3375$), rockwool insulation ($k = 12.50$ and $\rho = 141.3$) and a television ($k = 4000$ and $\rho = 145.8$). We, therefore, created two graphs; one for a low-volume product (Figure 7(a)) and one for a high-volume product (Figure 7(b)). For two values of the emission cost, 0 and 15, we determined the unit cost for which we are indifferent between choosing mode i and j as a function of the density.

For the low-volume case (Figure 7(a)) we define which transport mode is preferred for which range of the unit cost; water transport is preferred on the range 0-1430, rail transport on the range 1430-1480, road transport on the range 1480-8550 and air transport from 8500 on. When an emission cost is included the range for which a transport mode is preferred increases as a function of density (except for air transport). It is hard to see from the figures that the curves change, except for air-road, which indicates just how small the influence of the emission cost is on the total cost. For the low volume case and $\rho = 20000$, the indifference unit cost for rail-water is 1430.9 when $c_e = 0$ and 1444.6 when $c_e = 15$. For air-road this effect is larger, this is due to the fact that the emissions for air transport are very high. In Figure 7(b) we see a similar effect, the influence of the emission cost is bigger, because the unit emissions are higher.

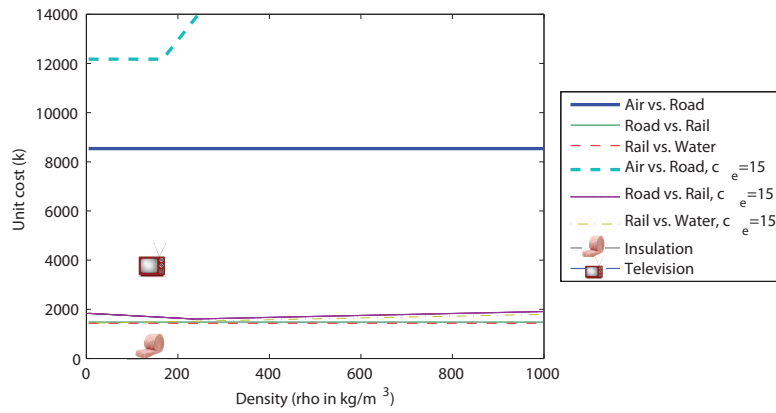
5.3 Comparison of emission regulations

So far we have only investigated the effect of parameters on the preferred supply mode and the solution to the ECTMSP. In this section we compare the solutions of the TMSP, ETMSP and the ECTMSP, in terms of cost and emissions.

Let us first construct the average cost curves (using S_i^*) as a function of the emission cost (in € /tonne) for all transport modes. We have used the following parameter setting: $c_a = 2.5$, $c_r = 1$, $c_t = 0.8$, $c_w = 0.6$, $D = 800$, $L_a = 1$, $L_r = 2$, $L_t = \frac{10}{3}$, $L_w = 5$, $k = 2000$, $v = 0.05$, $\rho = 1000$, $\psi = 0.2$, $r_h = \frac{0.25}{300}$, $r_p = 10r_h$. These parameter values correspond with the following



(a) Low volume ($v = 6.40 * 10^{-4}$)



(b) High volume ($v = 0.3375$)

Figure 7: Unit cost as a function of product density

$$c_a = 2.5, c_r = 1, c_t = 0.8, c_w = 0.6, D = 1200, L_a = 1, L_r = 3, L_t = 5, L_w = 7.5, v = 0.05, \psi = 0.2, r_h = \frac{0.25}{300}, r_p = 10r_h$$

average cost (for $c_e = 0$); $\bar{C}_a^e = 33.48$, $\bar{C}_w^e = 20.69$, $\bar{C}_t^e = 20.49$ and $\bar{C}_r^e = 20.39$ and the following emissions $e_a = 30.095$, $e_r = 1.268$, $e_t = 0.889$ and $e_w = 0.556$.

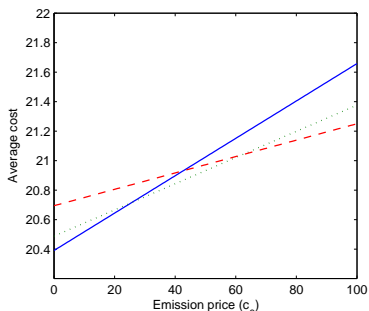
For the ECTMSP we determine per pair of transport modes the emission cost for which we are indifferent between choosing a mode. The modes are reordered in increasing cost; road, rail, water and air and the results are displayed in Table 7. From this table we read that road transport is preferred on the interval $c_e \in [0, 25.69]$, rail transport is preferred on the interval $c_e \in [25.69, 62.05]$ and water transport is preferred on the interval $c_e \in [62.05, \infty]$.

The average cost curves as a function of the emission cost are displayed in Figure 8(a), (air transport is not included in the graph because it is always most expensive). The cost of the solution of the ECTMSP, as a function of c_e ($\bar{C}^e(c_e)$), is given in Figure 8(b).

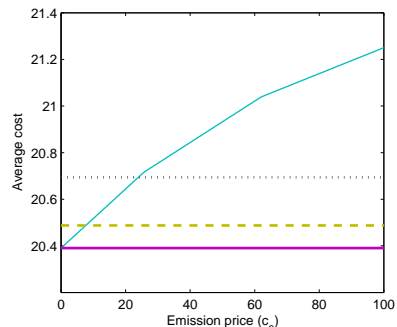
In Figure 8(b) we also display the cost of the solution for the other two problems; TMSP (\bar{C}) and ETMSP (\bar{C}'). Road transport is cheapest and therefore selected in the TMSP. In the

Table 7: Indifference cost table

	Road	Rail	Water
Rail	$c_e^*(r, t) = 25.69$	-	-
Water	$c_e^*(r, w) = 42.70$	$c_e^*(t, w) = 62.05$	-
Air	$c_e^*(r, a) = -45.42$	$c_e^*(t, a) = -44.50$	$c_e^*(w, a) = -43.30$
$c_e^*(i)$	25.69	62.05	∞



(a) Average cost



(b) Solutions to TMSP, ETMSP and ECTMSP

Figure 8: Unit as a function of product density

EU ETS the emission cost has not been higher than 30 which implies that under the ECTMSP road transport would be selected, which yields the same solution (and emissions) as the TMSP. In this case introducing an emission cost has no impact on the emissions (it only increases cost).

Road is selected in the ETMSP if $EM_{\max} \geq 1.267$, rail if $0.889 \leq EM_{\max} < 1.267$ and water if $0.556 \leq EM_{\max} < 0.889$. This implies that the emissions of the solution to the ETMSP are at most equal to the emissions of the solution to the TMSP and the ECTMSP. If a more stringent emission constraint would be applied such that rail or water transport has to be selected, the emissions are reduced.

6 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 which 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 analyze the effect of emission regulations on the transport mode selection problem

in terms of cost and emissions of the solution. Our focus is on a decision maker which has to select one out of several available modes of transportation. 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 and yields the optimal average cost. The TMSP has been extended in two directions to include carbon emissions: including an emission constraint, which resulted in the Emission-constrained TMSP and including an emission cost, which resulted in the Emission Cost-minimization 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 consider 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 has the lowest emissions.

For the Emission Cost-minimization TMSP we are 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 results clearly show that the impact of emission related charges is small: the emission related charges need to be extremely high in order for a decision maker to select a different transportation mode. Our results provide a clear insight, based on a variety of parameters, which transportation mode to choose. Only in the cases of road vs rail and rail vs water in continental transport, emission charges do appear to make a difference for high volume products. In other cases, emission charges will only lead to increased costs for the operators while not affecting the transportation mode selection.

We also compare the solutions to the TMSP, Emission-constrained and Emission Cost-minimization TMSP, in terms of cost and emissions. For the example we consider, it appears that the solution of the TMSP is equal to Emission-Cost minimization TMSP for realistic values of the emission cost (between 0 and 30 euro/tonne): road transport. Including an emission constraint enables policy makers to decrease the emission by one-third (if rail transport is chosen) or even by a half (if water transport is chosen). We therefore conclude that an emission constraint on an individual selection decision is a much more powerful tool for policymakers to reduce emissions. Therefore, commitments by CEO's to reduce their carbon emissions by a fixed percentage, which effectively function as carbon emission caps on individual companies, appear to be much more effective than carbon markets or carbon pricing mechanisms.

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A Emission parameters

Table 8: *Urban road distances*

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

Table 9: *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

B Indifference emission costs

We have used the following abbreviations for the transport modes Air (a), Road (r), Rail (t) and Water (w). When $k = 2000$ all $c_e^*(a, j)$ for $j \in \{r, t, w\}$ are negative, we have removed these columns from the table. The indifference emission cost are rounded to the nearest integer.

Table 10: *Indifference emission costs*

D [km]	v [m ³]	ρ [kg/m ³]	k								
			2000			9000					
			$c_e^*(r, t)$	$c_e^*(r, w)$	$c_e^*(t, w)$	$c_e^*(a, r)$	$c_e^*(a, t)$	$c_e^*(a, w)$	$c_e^*(r, t)$	$c_e^*(r, w)$	$c_e^*(t, w)$
800	0.001	100	2,134	5,814	31,027	-	1,081	9,001	163,087	294,034	1,191,146
800	0.001	500	2,569	4,270	6,205	-	353	3,029	196,387	215,959	238,229
800	0.001	1000	1,285	2,135	3,103	-	177	1,515	98,193	107,979	119,115
800	0.05	100	43	116	621	-	22	180	3,262	5,881	23,823
800	0.05	500	51	85	124	-	7	61	3,928	4,319	4,765
800	0.05	1000	26	43	62	-	4	30	1,964	2,160	2,382
800	0.5	100	4	12	62	-	2	18	326	588	2,382
800	0.5	500	5	9	12	-	1	6	393	432	476
800	0.5	1000	3	4	6	-	0	3	196	216	238
1200	0.001	100	10,220	19,094	79,657	611	8,660	16,038	148,704	265,099	1,059,473
1200	0.001	500	12,373	14,046	15,931	207	2,822	5,402	180,037	195,012	211,895
1200	0.001	1000	6,186	7,023	7,966	103	1,411	2,701	90,019	97,506	105,947
1200	0.05	100	204	382	1,593	12	173	321	2,974	5,302	21,189
1200	0.05	500	247	281	319	4	56	108	3,601	3,900	4,238
1200	0.05	1000	124	140	159	2	28	54	1,800	1,950	2,119
1200	0.5	100	20	38	159	1	17	32	297	530	2,119
1200	0.5	500	25	28	32	0	6	11	360	390	424
1200	0.5	1000	12	14	16	0	3	5	180	195	212
2000	0.001	100	14,419	25,772	103,016	6,403	14,300	20,607	126,704	223,768	884,180
2000	0.001	500	17,534	18,982	20,603	2,171	4,649	6,946	154,076	164,817	176,836
2000	0.001	1000	8,767	9,491	10,302	1,085	2,324	3,473	77,038	82,408	88,418
2000	0.05	100	288	515	2,060	128	286	412	2,534	4,475	17,684
2000	0.05	500	351	380	412	43	93	139	3,082	3,296	3,537
2000	0.05	1000	175	190	206	22	46	69	1,541	1,648	1,768
2000	0.5	100	29	52	206	13	29	41	253	448	1,768
2000	0.5	500	35	38	41	4	9	14	308	330	354
2000	0.5	1000	18	19	21	2	5	7	154	165	177