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October 2009

CIRRELT-2009-44

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Minimizing Greenhouse Gas Emissions in Intermodal Freight Transport: An Application to Rail Service Design

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Abstract. Freight transport has undesirable effects on the environment. The most prominent of these is greenhouse gas emissions. Intermodal freight transport, where freight is shipped from origin to destination by a sequence of at least two transportation modes, offers the possibility of shifting freight (either partially or in full) from one mode to another in the hope of reducing the greenhouse emissions by appropriately scheduling the services and routing the freight. Traditional planning methods for scheduling services in an intermodal transportation network usually focus on minimizing travel or time-related costs of transport. This paper breaks away from such an approach by addressing the issue of incorporating environment-related costs (greenhouse gases, to be specific) into freight transportation planning and proposes an integer program in the form of a linear cost, multicommodity, capacitated network design formulation that minimizes the amount of greenhouse gas emissions of transportation activities. Computational results based on an application of the proposed approach on a real-life rail freight transportation network are presented.

Keywords. Green logistics, greenhouse gas emissions, intermodal freight transport, scheduled service network design, space time network, multicommodity network design.

Acknowledgements. This research was financially supported by University of Southampton's 'Adventures in Research' (A2007/12) and Internationalisation Funds. Partial funding has been provided by the Natural Sciences and Engineering Research Council of Canada (NSERC), through its Industrial Research Chair and Discovery Grants programs. This support is gratefully acknowledged.

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Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2009

Introduction

Freight transport impacts the environment in various ways including the greenhouse effect (emission of gases such as CH_4, CO_2, and N_2O), toxic effects on ecosystems (e.g., acidification; by emitting CO_2, NO_x and SO_2), toxic effects on humans (by emitting non-methane hydrocarbons (NMHCs), NO_x, SO_2, and particles), land use (by infrastructure such as roads), noise, and resource consumption (Knörr, 2008). The most prominent of these impacts is the greenhouse effect, which has been acknowledged as unequivocal by the fourth Assessment Report (IPCC, 2007) of the Intergovernmental Panel on Climate Change (IPCC). The report mentions that most of the global average warming over the last 50 years is most likely attributed to the increase in anthropogenic emissions of greenhouse gases and estimates the probability that continuing greenhouse gas emissions will further warm up the climate to be at least 90%. The report further stresses the consequences of this phenomenon, e.g., reduced access to life basics such as water, food, and land. Under an international treaty, 183 states are committed to reduce their greenhouse gas emissions by ratifying the Kyoto Protocol as of 2008. Being one of the parties to the Protocol, the current goal of the UK is reducing the 1990 emission levels by 26% by 2020 (DEFRA, 2008).

To compare the environmental impact of different modes of transport, it is therefore necessary to weigh the environmental impacts of the different types of emissions. Doing so is inherently difficult, as it comes down to evaluating the uncertain effects of climate change, and putting a price tag on human health. The IPCC "does not endorse any particular range of values for the marginal damage of CO_2 emissions, but published estimates range between \$5 and \$125 (1990 US) per tonne of CO_2 emitted now. This range of estimates does not represent the full range of uncertainty" (IPCC, 1995a). In 2007, the Department for Environment, Food, and Rural Affairs of the UK estimated the cost of emitting a tonne of CO_2 at £25.50, and suggested to add 2% per year to compensate for inflation (DEFRA, 2007). An alternative way of comparing emissions is to only consider global warming, and then compare greenhouse gases by their warming potentials. However, this is difficult, as for example, CH_4 warms the atmosphere more than CO_2 does, but has a shorter life span. In this case, warming potentials have to be compared over a given time horizon relative to a benchmark value. The figures given in IPCC (1995b) for CH_4 and N_2O are 62, 23, and 7, and 275, 296, and 156 CO_2-tonnes, over 20, 100, and 500 years, respectively. This means, for instance, that over 100 years, one tonne of CH_4 released into the atmosphere has the same effect on global warming as 23 released tonnes of CO_2.

Different modes of transport emit varying amounts of greenhouse gases. Coe (2005), for example, estimates the CO_2 content of gasoline and diesel to be 2.32 kg/L[1] and

[1] In the original reference the quantities were expressed in kg/gallon which are transformed here into kg/L using the conversion formula one (US) gallon = 3.7854L.

2.67 kg/L, respectively. For electrically powered vehicles, emissions depend on how the electricity is generated, varying from burning coal to watercraft. Table 1 shows a few examples of the amount of emissions caused by generation of electricity in some European countries.

Table 1: Emissions (g/kWh) from the electricity supply for rail transport in some European countries (Sandvik, 2005)

	CO_2	NO_x	SO_2	NMHC	Particles
Belgium	0.26	0.84	0.31	0.08	0.23
France	0.11	0.33	0.30	0.02	0.03
Netherlands	0.43	1.07	0.22	0.13	0.61
Norway	0.00	0.01	0.00	0.00	0.00

Intermodal transportation is an efficient means of transporting freight by allowing the use of multiple modes of transport (such as truck, rail, air, ocean/river navigation) and is increasingly being used to ship freight (Bektaş and Crainic, 2008). We refer to Crainic and Kim (2007) for a thorough and recent review on intermodal transport and related problems. One of the advantages of intermodal freight transport is the possibility of modal shift (Rondinelli and Berry, 2000), which is defined as partially or fully transferring freight from one mode to the other in the network when it is being shipped to its final destination. Contrary to unimodal transport services, the flexibility afforded by modal shift offers ways to reduce the environmental impacts of freight transport.

In this work, we examine the impact of taking into account environmental considerations into planning decisions in freight transport where there exist multiple modes of transport. In specific, we aim to design the services in the network such that the amount of greenhouse gases emitted is minimized. We believe that this is a new approach, since a recent literature survey by Sbihi and Eglese (2007) on vehicle routing and scheduling models indicates that the existing planning approaches for transport minimize the distance or time traveled, but neglect the environmental costs.

This paper assumes that there is a unique entity centrally deciding on the routing of vehicles and loads in the network. Freight distribution decisions are currently made by independent stakeholders (e.g., carriers, shippers, third party logistic operators) and the only measures currently aimed at modal shift are indirect through improvement of intermodal facilities and other governmental policies, such as taxation. Though we cannot presume that further mechanisms will be put in place in the future to centrally regulate transportation and distribution activities, there are nevertheless emerging fields such as City Logistics (Crainic *et al.*, 2007) and National Planning (Crainic and Florian, 2008) where central mechanisms are already introduced, but emissions are rarely directly accounted for in routing decisions. Consequently, in this paper, we assume that each carrier (and shipper) optimizes its own agenda, and therefore, can dictate the routing of vehicles and flows independent of ownership or management structures, as in the two cases mentioned above. Although the central control assumption does not fully represent the reality, the solutions proposed in this paper represent “ideal” situations that reflect maximal economies from a system point of view. Hence, these solutions provide a good basis of negotiations between the players involved. As the integration of environmental issues into freight transportation planning is explored only so little, our goal is to make a first contribution toward this agenda and to offer a starting point to discuss the more complex issues in the field.

The issues addressed in our paper fall under a general class of problems named as service network design (Crainic, 2000). Service network design appears at a tactical/operational level planning of activities and is concerned with building a cost-efficient, timely and reliable transportation plan for freight that dictates the routing of freight through the transportation network, selection, routing, and scheduling of services that will be used to carry freight, and consolidation activities in terminals. Surveys on service network design can be found in Assad (1980) and Cordeau *et al.* (1998) for rail transportation, Crainic (2000, 2003) for land-based long-haul transportation, Crainic and Kim (2007) for intermodal transportation and Christiansen *et al.* (2007) for maritime transportation. Models for service network design are usually in the form of a capacitated, fixed-charge, deterministic multicommodity network design formulation, among which we mention a path-flow-based formulation by Crainic and Rousseau (1986), an arc-flow based formulations by Powell and Sheffi (1983, 1989), and recent formulations for service network design with asset management by Andersen and Christiansen (2009), Andersen *et al.* (2009a,b) and Pedersen et al. (2009). The reader is referred to the above-mentioned survey papers for further details on the models and solution techniques available for service network design.

The fundamental contributions of this paper are: (1) to be among the first to address the issue of introducing environmental concerns into freight transportation and distribution planning models and methods, (2) to integrate environmental costs into an integer programming formulation for a scheduled service network design problem with fleet management that is able to capture and minimize a prominent aspect of environmental costs, namely greenhouse gas emissions, and (3) to present the results of computational experiments based on real data drawn from an intermodal rail freight transportation network, the results of which shed light on the extent to which it is possible to reduce greenhouse emissions through appropriately selecting the services.

The next section presents a formal description of the problem, along with the approach taken to estimate emissions and a complete description of an integer linear programming formulation for the problem. The subsequent section presents computational results obtained through the proposed formulation on a real-life data set. The last section presents conclusions and directions for further research.

Minimizing Emissions in Service Network Design

Formal definition of the problem

The problem considered in this paper is defined on a physical transportation infrastructure where the network is characterized by nodes (corresponding to, e.g., intermodal terminals, hubs) and links that are defined between pairs of nodes over which freight can be transported over a given time horizon. In this paper, we focus on container/trailer-based transport. A number of different modes of transport (e.g., truck, rail) can be run on the transportation network using different vehicle fleets. Each fleet belongs to a certain mode of transport and is characterized by the number of vehicles as well as maximal load and volume that it is able to support. A vehicle may be a truck, a train (with several cars and able to carry freight from different shippers) or a ship. A transportation cost results from a vehicle moving over a link, and we assume that the time required for this move is known and fixed. We also assume, without loss of generality, that the load and volume capacities of each fleet are fixed. In practice, one can generally change the "vehicle" but not the capacity, as the capacity depends on physical restrictions (e.g., the maximum number of cars for a train is usually dictated by physical restrictions such as the length of sidings, distance between consecutive stations, etc.). There exists a set of commodities, with each commodity corresponding to a demand defined by its weight, volume, origin (where demand becomes available at a given terminal at a given point in time over the planning horizon) and destination (where demand needs to be sent).

The problem consists of routing and scheduling the services on the transportation network such that demand requirements are met, where the service schedule has a fixed length (e.g., a week) and will repeatedly be executed over a certain period of time. The problem has two major decision components: (i) deciding how often and when each service is run over the time horizon, and (ii) determining the *flows* of the commodities. We allow the flexibility that demand can be split into a number of parts and each part can be carried with a different service. The aim is to minimize the greenhouse gas emissions of the transportation activities in the setting described above. This goal is contrary to most optimization criteria found in the literature for service network design, for which the most popular choice is to minimize the "internal" transportation cost (e.g., fuel, labor). Our approach focuses on reducing "external" costs of transport (Forkenbrock, 2001), and in particular, those related to emissions of greenhouse gases. The problem, as described, is similar to the scheduled service network design problem with fleet management concerns (see Andersen *et al.*, 2009a,b; Pedersen and Crainic, 2009), but differs with regards to its objective. In this paper, we focus on minimizing the energy consumed by all running services which directly translates into the amount of greenhouse gas (specifically, CO_2) emissions as this is the most prominent external cost of transport. The approach taken to calculate the emissions is described in the next section.

Estimating Emissions

Emissions from freight transport are related directly to the amount of energy required to perform the associated transportation operations. As for individual vehicles, Ross (1997) provides analytical approximations for calculating the energy consumption. He argues that, for a vehicle f with mass ω if the necessary total tractive power $P_f(\omega)$ (in kWh) to do so is known, then the power $P'_f(\omega)$ that has to be fed into the vehicle engine depends on the efficiency of the vehicle powertrain (vehicle components that generate power, such as the engine and transmission) as $P'_f(\omega) = P_f(\omega) \cdot \eta_t \eta_m \varepsilon$, where η_t and η_m are the engine thermodynamical and mechanical efficiencies, respectively, and ε is the powertrain transmission efficiency. Ross elaborates that these three constants can be determined by the characteristics of the powertrain. For electrically powered vehicles, $P'_f(\omega)$ can be directly converted into CO_2 emissions using conversion constants such as those presented in Table 1. For a combustion engine, the amount of fuel necessary to provide a given amount of power is given by its heat of combustion. For example, an average value for diesel is 11.83 Wh/kg (IEA, 2008). Thus, to compute the CO_2 emissions of a combustion engine, $P'_f(\omega)$ has to be multiplied by both the heat of combustion (to calculate the fuel consumption) and the CO_2 content of the fuel.

The issues related to weighing different types of emissions are clearly beyond the scope of this paper. In order to minimize emissions, we will therefore use the following simplified methods. If the carrier uses only one source for powering his fleet (e.g., diesel), we minimize the amount of energy (which can be measured in, e.g., diesel consumption) consumed. If different ways of powering the vehicles are involved (especially electrical powering), we minimize CO_2 emissions, as CO_2 is the most prominent greenhouse gas (IPCC, 2007). Below, we briefly present Ross's analytical approximations as they are central to our development of estimations.

Ross (1997) calculates $P_f(\omega)$ as the sum of work necessary to overcome rolling resistance (P_r), air drag (P_a), inertia (P_i), grade (P_g), and the power to run vehicle accessories (P_c) such as light, air conditioning, etc. Let $C_{d,f}$ be the drag coefficient (vehicle dependent dimensionless constant), α_f denote the vehicle's front surface area (in m^2), ρ represent the air density (in kg/m^3), v be the vehicle velocity (in km/h), $C_{r,f}$ denote the rolling resistance coefficient (a vehicle-dependent dimensionless constant), $\theta(t)$ denote the track gradient at time t, g represent the gravity constant (9.80665 m/s^2), m_f correspond to the (empty) vehicle mass (in kg) and ω represent the load mass (in kg). According to Ross (1997), $P_r = C_{r,f}(m_f + \omega)gv$, $P_a = 0.5C_{d,f}\alpha_f \rho v^3$, $P_i = 0.5(m_f + \omega)\mathrm{d}v^2/\mathrm{d}t$ and $P_g = (m_f + \omega)gv \sin\theta$. For estimation purposes, however, we will omit P_c from further consideration.

Based on Ross (1997), we calculate the total energy consumption $E_{ij,f}(\omega)$ of a vehicle

f traveling between terminals i and j and carrying load ω as follows:

$$E_{ij,f}(\omega) = \int_{t=t_i}^{t_j} \left(\frac{1}{2} C_{d,f} \alpha_f \rho v^3(t) + (m_f + \omega) v(t) (g C_{r,f} + \frac{\mathrm{d}v(t)}{\mathrm{d}t} + g \sin\theta(t)) \right) \mathrm{d}t, \quad (1)$$

where t_i and t_j are the start and end time of the travel from terminal i to terminal j, respectively, $v(t)$ is the speed of the vehicle at time t, and $\sin\theta(t)$ is the grade at time t. Ross does not validate his model with fuel consumptions or emissions measured in driving tests. However, the fuel consumption model in Barth *et al.* (2005) is derived from his model, and validated. Their experiments yield differences in fuel consumption and emissions between model and test data of up to 50% for high acceleration. As for speed, the experimental data collected by the Oak Ridge National Laboratory on the NO_x emissions (as mentioned in Ahn *et al.*, 2002) indicate that higher speed and acceleration do not necessarily yield higher emissions. For estimation purposes, we will therefore assume constant speed, although we discuss in more detail how speed can be included as a decision variable in a modeling context in the last section.

The expression (1) is apparently complex. It includes parameters that are difficult to obtain for an instantaneous calculation of energy consumption, and even more so for a moving vehicle. To overcome the apparent difficulties of correctly calculating or closely estimating fuel consumption and emissions, we propose the following approach. Based on (1), one can see that $E_{ij,f}$ is a linear function of the mass ω carried by a vehicle. Then, if $E_{ij,f}$ is known for two different load weights ω_1 and ω_2 over link (i,j) by vehicle f, (1) yields

$$E_{ij,f}(\omega) = E_{ij,f}(\omega_1) + \frac{E_{ij,f}(\omega_2) - E_{ij,f}(\omega_1)}{\omega_2 - \omega_1} \omega. \quad (2)$$

We assume that the same correlation holds for the energy $E'_{ij,f}(\omega)$ necessary to be fed into the engine of vehicle f. As both fuel consumption and CO_2 emissions depend directly on $E'_{ij,f}(\omega)$, we conclude that both fuel consumption and CO_2 emissions are linear functions of the vehicle load ω.

Fuel consumption values can easily be calculated by any carrier for their own fleet. For combustion engines, the carrier can simply measure the fuel consumption of vehicle f on trips from i to j, and, if necessary, convert it to a CO_2 emission value by multiplying it with the CO_2 content of the fuel it uses. For rail transport, "in many cases, it is known that a given amount of fuel has been consumed for a certain railway system, or that a given amount of electricity has been used to propel trains" (Jørgensen and Sorenson, 1997). Thus, our proposal is a realistic approach with the additional benefits that the carrier can independently maintain and adapt his cost database, and can additionally take into account a new construction site or new roads.

Notation

The problem is defined over a set of terminals $V' = \{v_1, \ldots, v_n\}$ and a recurring *planning horizon* divided into T time periods of equal length δ with starting times $t\delta$, $t = 0, \ldots, T-1$. The set of *vehicle fleets* is indexed by $1, \ldots, m$. For each fleet $k = 1, \ldots, m$, we define the following:

- $G_k = (V_k, A_k)$ denotes the graph representing the fleet's transportation network, where the terminal $v_{ik} \in V_k$ corresponds (but is not equal) to v_i in V', $i = 1, \ldots, n$ (it is possible that $|V_k| < n$). A_k represents the set of arcs that fleet k can travel on.
- $\phi_k \in \mathbb{N}$ denotes the number of vehicles (e.g., trains for rail) in fleet k.
- $\Omega_k \in \mathbb{R}^+$ denotes the maximal load weight that a vehicle of fleet k is able to support (i.e., weight capacity),
- $\Upsilon_k \in \mathbb{R}^+$ denotes the maximal load volume that a vehicle of fleet k is able to support (i.e., volume capacity),
- $\tau_{ijkt} \cdot \delta$, $\tau_{ijkt} \in [1, T-1]$, denotes the duration necessary for a vehicle of fleet k to travel along $(v_{ik}, v_{jk}) \in A_k$ when starting its journey at time $t\delta$,
- $\bar{c}_{ijkt} \in \mathbb{R}^+$ denotes the cost (e.g., fuel, CO_2) of an empty vehicle of fleet k traveling along $(v_{ik}, v_{jk}) \in A_k$ when starting its journey at time $t\delta$,
- $\bar{c}_{ijkt} + c_{ijkt}$, $c_{ijkt} \in \mathbb{R}^+$ denotes the cost of a vehicle of fleet k loaded with weight Ω_k traveling along $(v_{ik}, v_{jk}) \in A_k$ when starting at time $t\delta$.

For every divisible unit demand d in a given demand set D, let i_d denote the index of the origin terminal $v_{i_d} \in V'$ (the terminal where the demand originates), let j_d denote the index of the destination terminal $v_{j_d} \in V'$, let $\tau_d \in [0, T-1]$ denote the point in time when demand d becomes available, let ω_d denote its weight, and let υ_d denote its volume.

The time-space network representation

We use a time-space network to represent the terminals and links over the planning horizon. As we model a recurring planning horizon, the path of each vehicle in the time-space network has to be circular. In the time-space network, our service network design problem becomes a variant of the linear cost, multicommodity, capacitated network design problem described by Crainic (2003).

The resulting time-space network on which the problem is modeled is denoted by $G = (V, A)$. The node set V consists of T copies of $V_1 \cup \ldots \cup V_m$, such that node v_{ikt} corresponds to terminal $v_{ik} \in V_k$ at time $t\delta$. Hence,

$$V = \bigcup_{t=0}^{T-1} \bigcup_{i=1}^{n} \bigcup_{\substack{k=1 \\ v_{ik} \in V_k}}^{m} v_{ikt} \ .$$

The arc set A consists of the sets A^Y, A^W and A^I. The first can explicitly be expressed as

$$A^Y \subseteq A' = \bigcup_{t=0}^{T-1} \bigcup_{k=1}^{m} \bigcup_{i=1}^{n} \left(\left(v_{ikt}, v_{ik,\, t+1 \bmod T}\right) \cup \bigcup_{\substack{j=1 \\ (v_{ik}, v_{jk}) \in A_k}}^{n} \left(v_{ikt}, v_{jk,\, t+\tau_{ijkt} \bmod T}\right) \right),$$

where A' is the set consisting of T representations of every arc of every A_k, $k = 1, \ldots, m$ united with all arcs connecting the two representations of $v_{ik} \in V_k$ belonging to the time periods starting at times $t\delta$ and $(t + 1 \mod T)\delta$. The set A^Y is a subset of A'. Vehicles and freight assigned to arc $a_{ijkt} = \left(v_{ikt}, v_{jk,\, t+\tau_{ijkt} \bmod T}\right) \in A^Y$ for $i \neq j$ are moving along $(v_{ik}, v_{jk}) \in A_k$ starting at time $t\delta$. Vehicles and freight assigned to arc a_{iikt} are waiting at terminal v_{ik} for one time period starting at time $t\delta$. Consequently, we have $\tau_{iikt} = 1$ for all $i = 1, \ldots, n$, $k = 1, \ldots, m$, and $t = 0, \ldots, T - 1$. The reason for A^Y being a subset of A' rather than $A^Y = A'$ is that connections might not be available at all starting times, and vehicles might be prohibited from waiting at terminals during some time periods. For example, trucks are prohibited from driving at night in Austria and Switzerland. The set $A^W \subseteq \bigcup_{t=0}^{T-1} \bigcup_{k=1}^{m} \bigcup_{i=1}^{n} \left(v_{ikt}, v_{ik,\, (t+1) \mod T}\right)$ contains arcs a_{iikt} for terminals v_{ik} where freight is allowed to wait independently of vehicles. The set $A^Y \cup A^W$ therefore contains all movements and waits allowed to the vehicles and freight.

We assume that if for any $i \in \{1, \ldots, n\}$ there exist k, ℓ with $k \neq \ell$ and $v_{ik} \in V_k$ and $v_{i\ell} \in V_\ell$, then v_i is an intermodal terminal. This means that freight can be transferred between modes k and ℓ at terminal v_i. We indicate the time to transfer freight between these modes at this terminal by $\tau^I_{ik\ell}\delta$, $\tau^I_{ik\ell} \in [0, T - 1]$.

The third set A^I contains the additional intermodal transfers allowed to freight. Every arc $a^I_{ik\ell t} = \left(v_{ikt}, v_{i\ell,\, t+\tau^I_{ik\ell} \mod T}\right)$ connects the two representations of intermodal terminal $v_i \in V'$ for fleets k and ℓ at time $t\delta$ and $t + \tau^I_{ik\ell} \mod T$, respectively. Freight assigned to this arc is transferred from a vehicle of fleet k to a vehicle of fleet ℓ at terminal $v_i \in V'$ starting at time $t\delta$, and $\tau^I_{ik\ell}\delta$ is the time needed to do so. Therefore,

$$A^I = \bigcup_{t=0}^{T-1} \bigcup_{i=1}^{n} \bigcup_{\substack{k=1 \\ v_{ik} \in V_k}}^{m} \bigcup_{\substack{\ell=1 \\ \ell \neq k \\ v_{i\ell} \in V_\ell}}^{m} \left(v_{ikt}, v_{i\ell,\, t+\tau^I_{ik\ell} \bmod T}\right).$$

Graphs G_1 and G_2 in Figure 1 depict two sample transportation networks over a node set $V' = \{v_1, v_2, v_3, v_4\}$ using two modes of transport. Graph G shows the resulting time-space network for four time periods. Solid, dashed, and dotted arcs correspond to fleet 1, fleet 2, and intermodal transfer, respectively. Grey arcs represent waiting whereas black arcs denote moving. Vehicles of fleet 1 are not allowed to move during the time period starting at $t = 3$. The only intermodal terminal is v_3. Intermodal changes at terminals in this specific example are assumed not to require any time.

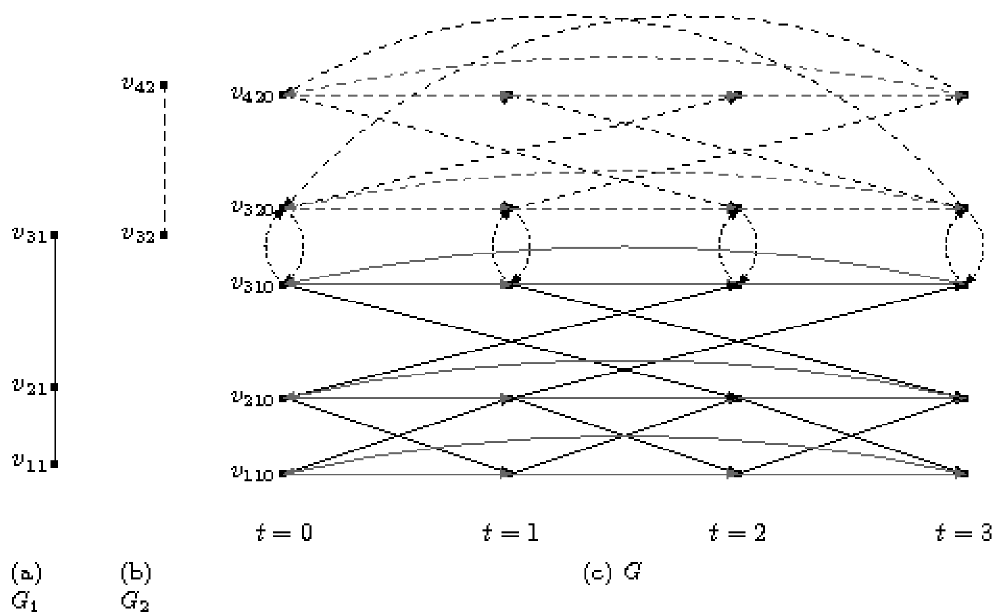

Figure 1: Two example transportation networks G_1 and G_2 and the resulting time-space network G

An integer linear programming formulation

This section presents an integer linear programming formulation for the problem considered in the paper. The formulation uses the following two sets of variables.

i. The flow of vehicles through the network are described by an integer vector $\mathbf{y}$ that contains a component y_{ijkt} for every $a_{ijkt} \in A^Y$. Variable y_{iikt} represents the number of vehicles of fleet k waiting at terminal $v_i \in V'$ for one time period starting at time $t\delta$. Variable $y_{ijkt}, i \neq j$ represents the number of vehicles of fleet k moving along $(v_{ik}, v_{jk}) \in A_k$ starting at time $t\delta$.

ii. The flow of freight through the network is described by continuous vectors $\mathbf{x^d}$ for every demand $d \in D$, which contain a component x^d_{ijkt} for every $a_{ijkt} \in A^Y \cup A^W$, and an additional component $x^{Id}_{ik\ell t}$ for every $a^I_{ik\ell t} \in A^I$, with $0 \leq x^d_{ijkt}, x^{Id}_{ik\ell t} \leq 1$. Variable x^d_{iikt} represents the fraction of w^d for demand d waiting (on a vehicle of fleet k) at terminal $v_i \in V'$ for one time period starting at time $t\delta$. Variable $x^d_{ijkt}, i \neq j$ represents the fraction of w^d for demand d moving on a vehicle of fleet k along $(v_{ik}, v_{jk}) \in A_k$ starting at time $t\delta$. Finally, varriable $x^{Id}_{ik\ell t}$ represents the fraction of w^d for demand d being transferred from fleet k to ℓ at terminal $v_i \in V'$ starting at time $t\delta$.

In the proposed formulation, no costs are associated to freight waiting or transferred at a terminal. The cost (of energy consumption) for moving freight from one terminal to another is based on (2), and composed of the cost for moving one vehicle plus the additional cost of moving the load. Thus, the objective function is structured as follows:

$$\text{Minimize} \qquad \sum_{t=0}^{T-1}\sum_{i=1}^{n}\sum_{\substack{j=1\\ j\neq i}}^{n}\sum_{\substack{k=1\\ a_{ijkt}\in A^Y}}^{m}\left(y_{ijkt}\bar{c}_{ijkt} + \sum_{d=1}^{|D|} x^d_{ijkt}\frac{\omega_d}{\Omega_k}c_{ijkt}\right). \tag{3}$$

The first term in (3) represents the cost of operating the vehicles and therefore the cost of operating the service network. The second term represents the cost of carrying freight that depends on the fraction of the carried amount over the available capacity.

The formulation consists of the following sets of constraints. The first constraint set, shown below, is related to the number of vehicles available.

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{\substack{t'=0\\ a_{ijkt'}\in A^Y\\ t-t' \bmod T\leq\tau_{ijkt'}}}^{T-1} y_{ijkt'} \leq \Phi_k \qquad t=0,\ldots,T-1;\ k=1,\ldots,m. \tag{4}$$

Constraints (4) ensure that no more than Φ_k vehicles of fleet k are used during any time interval $[t-1,t]\delta$. The flow of vehicles are modeled using the following constraints,

$$\sum_{\substack{j=1\\ a_{ijkt}\in A^Y}}^{n} y_{ijkt} - \sum_{j=1}^{n}\sum_{\substack{t'=0\\ a_{jikt'}\in A^Y\\ t-t' \bmod T=\tau_{jikt'}}}^{T-1} y_{jikt'} = 0 \qquad \forall\, v_{ikt}\in V, \tag{5}$$

which guarantee the number of vehicles of fleet k leaving (or waiting) during time interval $[t\delta,(t+1)\delta]$ equals the number of vehicles arriving (or waiting) during time interval $[t-1,t]\delta$ for every node v_{ikt} in V. The next set of constraints are used to model the flow of demand through the network.

$$\sum_{\substack{j=1 \\ a_{ijkt}\in A^Y\cup A^W}}^{n} x^d_{ijkt} + \sum_{\substack{\ell=1 \\ \ell\neq k \\ v_{i\ell}\in V_\ell}}^{m} x^{Id}_{ik\ell t} - \sum_{j=1}^{n} \sum_{\substack{t'=0 \\ a_{jikt'}\in A^Y\cup A^W \\ t'+\tau_{jikt'} \bmod T=t}}^{T-1} x^d_{jikt'} - \sum_{\substack{\ell=1 \\ \ell\neq k \\ v_{i\ell}\in V_\ell}}^{m} \sum_{\substack{t'=0 \\ t'+\tau^I_{i\ell k} \bmod T=t}}^{T-1} x^{Id}_{i\ell kt'} = 0,$$

$$\forall v_{ikt} \in V \setminus \left(\left(\bigcup_{\substack{k=1 \\ v_{i_d k}\in V_k}}^{m} v_{i_d k\tau_d} \right) \cup \left(\bigcup_{t=0}^{T-1} \bigcup_{\substack{k=1 \\ v_{j_d k}\in V_k}}^{m} v_{j_d kt} \right) \right),\ d = 1, \ldots, |D|. \quad (6)$$

Equalities (6) ensure that the amount of d leaving during time interval $[t, t+1]\delta$ equals the amount of d arriving during time interval $[t-1, t]\delta$, for every transhipment node in V (except those representing the origin and destination terminals) for each $d = 1, \ldots, |D|$).

The shipment of demand from their origin nodes are modeled using the following set of constraints,

$$\sum_{\substack{k=1 \\ v_{i_d k}\in V_k}}^{m} \left(\sum_{\substack{j=1 \\ a_{i_d jk\tau_d}\in A^Y\cup A^W}}^{n} x^d_{i_d jk\tau_d} + \sum_{\substack{\ell=1 \\ \ell\neq k \\ v_{i_d \ell}\in V_\ell}}^{m} x^{Id}_{i_d k\ell\tau_d} \right) = 1 \qquad d = 1, \ldots, |D|, \quad (7)$$

which ensures that, for each demand $d \in D$ and for each node $v_{i_d} \in V'$, the amount of d waiting, leaving or being transferred at this node during time interval $[\tau_d, \tau_d + 1]\delta$ equals 1. Similarly, arrivals of demand to their destination node are modeled by the following set of constraints,

$$\sum_{t=0}^{T-1} \sum_{\substack{k=1 \\ v_{j_d k}\in V_k}}^{m} \sum_{\substack{i=1 \\ a_{ij_d kt}\in A^Y\cup A^W}}^{n} x^d_{ij_d kt} = 1 \qquad d = 1, \ldots, |D|, \quad (8)$$

which guarantees that, for all $d \in D$, the amount of d arriving at all nodes in V representing v_{j_d} over the planning horizon equals 1. Load and volume capacity limitations of a service are imposed by the following two sets of constraints.

$$\sum_{d=1}^{|D|} x^d_{ijkt}\omega_d \leq y_{ijkt}\Omega_k \qquad \forall\, a_{ijkt} \in A^Y, \quad (9)$$

$$\sum_{d=1}^{|D|} x^d_{ijkt}\upsilon_d \leq y_{ijkt}\Upsilon_k \qquad \forall\, a_{ijkt} \in A^Y. \quad (10)$$

Constraints (9) and (10) restrict the amount of freight to be shipped on a service by its load and volume capacities, which increase linearly with the frequency of the corresponding service.

The following set of constraints are used when storage of freight at an intermodal terminal is not allowed, and are used to prohibit the formulation from virtually storing freight at a terminal by transferring it back and forth between transportation modes.

$$x^{Id}_{ik\ell t} \leq z^{Id}_{ik\ell t} \qquad \forall a^I_{ik\ell t} \in A^I : a_{iikt} \notin A^W,\ d = 1, \dots, |D|, \qquad (11)$$

$$z^{Id}_{ik'\ell t} + \sum_{\substack{k=1 \\ k \neq \ell \\ v_{ik} \in V_k}}^{m} x^{Id}_{i\ell k, t+\tau^I_{ik'\ell} \bmod T} \leq 1 \qquad \forall a^I_{ik'\ell t} \in A^I : a_{iik't} \notin A^W,\ d = 1, \dots, |D|. \qquad (12)$$

The two sets of constraints (11) and (12) use a binary variable $z^d_{ik\ell t}$ indicating whether (part of) demand d has been transferred from fleet k to fleet ℓ at terminal v_i during time interval $[t, t+1 \mod T]\delta$. If there has been such a transfer during time interval $[t, t+1 \mod T]\delta$, then no transfer is allowed at terminal v_i from fleet ℓ to any other fleet during time period $[t + \tau^I_{ik\ell} \mod T, t + \tau^I_{ik\ell} + 1 \mod T]\delta$.

The final set of constraints of the formulation, shown below through (13)–(16), are the nonnegativity and integrality restrictions imposed upon the decision variables.

$$y_{ijkt} \in \{0, 1, \dots, \Phi_k\} \qquad \forall a_{ijkt} \in A^Y, \qquad (13)$$

$$x^d_{ijkt} \in [0, 1] \qquad \forall a_{ijkt} \in A^Y \cup A^W, d = 1, \dots, |D|, \qquad (14)$$

$$x^{Id}_{ik\ell t} \in [0, 1] \qquad \forall a^I_{ik\ell t} \in A^I, d = 1, \dots, |D|, \qquad (15)$$

$$z^{Id}_{ik\ell t} \in \{0, 1\} \qquad \forall a^I_{ik\ell t} \in A^I : a_{iikt} \notin A^W, d = 1, \dots, |D|. \qquad (16)$$

The model shown above with the objective function (3) and constraints (4)–(16) is a scheduled service network design model with fleet management in the form of a mixed integer, linear cost, multicommodity, capacitated network design formulation, and henceforth referred to as $\mathcal{F}$.

We assume that a carrier aiming to minimize the environmental impact of their transportation activities is willing to revise its service schedule in order to do so, and therefore do not require, in the formulation $\mathcal{F}$, that services are predefined in the network. This is in contrast to the service network design definition by Crainic and Laporte (1997). In other words, unlike the approach taken in approach taken in Andersen and Christiansen (2009) and Andersen *et al.* (2009a), services need not be defined *a priori* in formulation $\mathcal{F}$. However, if such services exist, they can easily be integrated by enforcing special constraints that model the predefined services, as we do in our computational experiments presented in the next section. Our formulation is general, developed with no specific problem or data set in mind and thus offers a high degree of flexibility to accommodate a variety of practical problems. The formulation may be used to select the most appropriate vehicles or services from an environmental point of view for freight transportation.

Implementation on a Real-Life Network

This section presents results of computational experiments with the proposed formulation on a data set drawn from a real-life intermodal rail network operating over Austria, the Czech Republic, and Poland, described by Andersen *et al.* (2009a). The network consists of 12 nodes, of which five are intermodal terminals. The graph representation of the transportation network of this instance is shown in Figure 2.

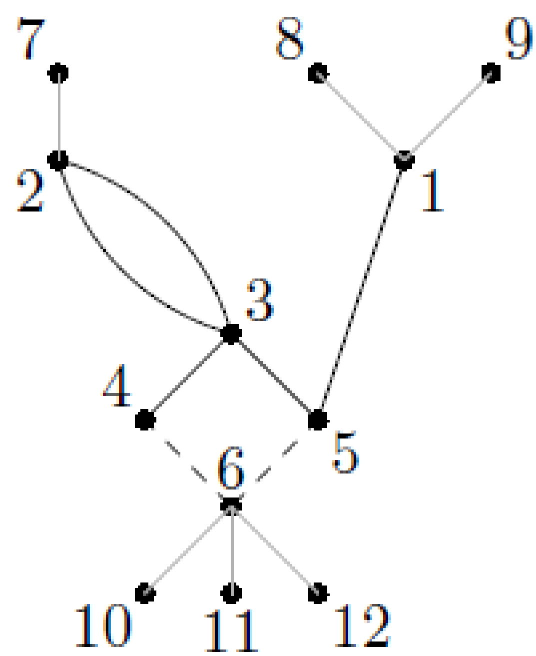

Figure 2: Graph representation of the network described in Andersen *et al.* (2009)

The scheduled service network design problem comprises 22 possible services of two fleets operating between nodes labeled ‘1’ (Gdynia), ‘2’ (Swinoujscie), ‘3’ (Wroclaw), ‘4’ (Miedzylesie / Lichkov), ‘5’ (Chalupki / Bohumin) in Poland (shown via solid lines) and ‘4’ (Miedzylesie / Lichkov), ‘5’ (Chalupki / Bohumin), ‘6’ (Wien) in Austria and the Czech Republic (shown via dashed lines). Connections to nodes $\{7, \ldots, 12\}$ (shown via grey lines) are external, some of which consist of shipping lines and ferries, and are not a part of the overall design problem. The problem instance has three modes: two modes represented by Polish and Austrian/Czech railways, respectively, and the external services. Though the former two are rail, they represent two different modes from the view of the freight, which has to be shifted from one mode to the other at the border nodes labeled '4' and '5'. The planning horizon is one week, divided into 84 time slots, of two hours each. There are 40 commodities, each with a corresponding origin-destination pair. Further details of this data set can be found in Andersen *et al.* (2009a).

As mentioned above, the formulation $\mathcal{F}$ used in the computational experiments is generic and does not require any services to be predefined, although it can accommodate specific features of a given instance. The instance considered here has predefined services that consist of only one link except for those passing through node three, which consist of two links. Therefore, in testing specific instance, we added to $\mathcal{F}$ a set of instance-specific constraints enforcing that a train arriving at node three from node two immediately continues to either node four or five, and the other way around. We also added to $\mathcal{F}$ a set of constraints enforcing minimum and maximum frequencies for the different services imposed by the original data set, and a set of additional constraints enforcing that the minimum frequencies on the links between nodes two and three and between nodes six and four and five are sufficient to accommodate the freight volume passing through these links.

The computational testing was performed using AMPL/CPLEX 11.0 as an optimizer on a computer server with 2GHz processor with 1Gb memory. During preliminary computational testing, formulation $\mathcal{F}$ in its initial form exhibited excessive computational times. To speed up computation, we supplemented the formulation with the following strong forcing constraints (17) described by Andersen *et al.* (2009a),

$$x^d_{ijkt} \leq y_{ijkt}, \qquad \forall a_{ijkt} \in A^Y,\ d = 1, \ldots, |D|, \tag{17}$$

as well as with a set of valid inequalities suggested by Holmberg and Yuan (2000) and adapted to our formulation:

$$x^d_{ijkt} = 0, \qquad \forall a_{ijkt} \in A^Y : i = j_d \text{ or } j = i_d, \tag{18}$$

both of which are generic valid inequalities for formulation $\mathcal{F}$.

The data set given in Andersen *et al.* (2009) does not contain any data related to energy consumption (i.e., c_{ijkt} and $\bar{c}_{ijkt}$). Therefore, we approximate the energy required to traverse link (i, j) carrying a load of ω, based on (1) as follows:

$$\tilde{E}_{ijkt} = C_{r,f}(m_k + \omega)gd_{ij}, \tag{19}$$

where the mass m_k of an empty freight train is estimated at 400 tonnes; a train consists of 25 wagons, each of which typically weighs 12.5 tonnes (Deutsche Bahn, 2008) and a typical locomotive weighs 87 tonnes (Siemens, 2008). The weight of a container is estimated at 10 tonnes, as the load factor (net tonnes/gross tonnes) of light cargo is 0.44 (Knörr, 2008) and a container wagon has 23.5 gross tonnes (Deutsche Bahn, 2008). The distance d_{ij} between terminals i and j are obtained from Rail Cargo Austria (2006), Rozklad-PKP (2009) and Wikipedia (2009). The rolling resistance coefficient $C_{r,f}$ is set to 0.001. The resulting value for $\tilde{E}_{ijkt}$ is converted into CO_2 emissions by 0.986 CO_2kg/kWh (Knörr, 2008) for connections in Poland, and by (78/290.5)·0.067 (km/h)+(212.5/290.5)· 0.565 (km/h) (Knörr, 2008) for connections through Austria and the Czech Republic, as 78 km of the 270 km between nodes five and six are in Austria, and 192 km in the Czech Republic.

The experiments are conducted to shed light on the CO_2 savings that can be obtained through the proposed formulation and to compare the resulting values with the more traditional objectives considered in the literature. To this end, we ran the CO_2-minimizing formulation $\mathcal{F}$ against the version where the time-value minimizing objective function of Andersen *et al.* (2009) is used instead (which is henceforth referred to as $\mathcal{F}_t$). The goal is to capture the trade-off between value of time and amount of emissions. The formulations were run on three sets of smaller scale instances were produced from the original instance with varying number of commodities. Sets I, II, and III each contain five instances with five, 10 and 15 commodities, respectively. Instance names are designated X_Y where X denotes is the number of commodities in the instance and Y represents to the instance number within the corresponding set. All other parameters in the instances remain the same as in the original instance. A three-hour time limit was imposed on the solution time of all the instances.

Table 2 shows the results of comparing the two formulations, $\mathcal{F}$ and $\mathcal{F}_t$, on the 15 instances. The first column shows the name of the instances. Columns two to seven present, the standardized values of time and amount of CO_2 emissions obtained through the two formulations, under columns titled 'Time value' and 'CO_2 (tonnes)', respectively. The column labeled 'CPU' denotes either the time required to solve the formulation for the corresponding instance (in seconds) or the optimality gap in parentheses if the formulation could not be solved within the time limit of three hours. The column titled 'Time' presents the percentage increase in the value of time from that produced by formulation $\mathcal{F}_t$ to that output by formulation $\mathcal{F}$. The last column titled 'CO_2' reports the percentage reduction in the amount of CO_2 emissions from that produced by formulation $\mathcal{F}_t$ to that output by formulation $\mathcal{F}$.

The figures in Table 2, especially those presented in the last two columns, show that to minimize the amount of emissions, one has to bear a quite significant change in the value of time, at times up to a 350% increase over the time-optimized result. The savings in CO_2, however, are noteworthy. The proposed formulation is able to attain up to 30% reduction in the amount of emissions. We note that the reason that the emitted amounts are so high is due to the (empty) trains being heavy (estimated at 400 tonnes), combined with the fact that the conversion rate from kWh to CO_2kg for Poland is particularly high

Table 2: Comparison of the results of the time-value and CO_2 minimizing formulations

	$\mathcal{F}_t$			$\mathcal{F}$			% Change	
Instance	Time value	CO_2	CPU	Time value	CO_2	CPU	Time	CO_2
5_1	1.00	1.11	275.91	3.38	1.00	7.98	238.25	9.85
5_2	1.00	1.11	(9.72%)	3.47	1.00	25.08	247.32	10.25
5_3	1.00	1.08	586.48	3.91	1.00	268.70	291.31	7.08
5_4	1.00	1.14	(8.72%)	3.12	1.00	55.69	211.84	12.54
5_5	1.00	1.04	77.01	3.40	1.00	23.91	240.10	3.55
10_1	1.00	1.36	782.28	3.21	1.00	(8.31%)	220.81	26.21
10_2	1.00	1.43	424.62	3.82	1.00	(8.62%)	281.77	30.21
10_3	1.00	1.30	(11.19%)	3.73	1.00	(5.23%)	273.34	23.01
10_4	1.00	1.25	(3.74%)	4.40	1.00	(5.99%)	339.67	20.30
10_5	1.00	1.35	460.61	4.50	1.00	(9.05%)	350.19	26.18
15_1	1.00	1.33	409.03	4.19	1.00	(6.86%)	319.34	24.83
15_2	1.00	1.38	(5.99%)	3.57	1.00	(1.12%)	257.02	27.73
15_3	1.00	1.23	3355.33	4.52	1.00	(5.33%)	351.64	18.81
15_4	1.00	1.26	8011.52	4.07	1.00	(9.18%)	307.15	20.91
15_5	1.00	1.23	(3.23%)	4.16	1.00	(6.82%)	316.29	18.95

as compared to other countries (Knörr, 2008). From a problem solution perspective, Table 2 shows that most of the Set I instances were solved to optimality within the time limit. This was, however, not the case for the instances in Sets II and III. The average gaps, however, are typically less than 9% for these instances. These results also show that it becomes more difficult to solve formulation $\mathcal{F}$ as the size of the problem increases.

The results presented in Table 2 show rather extreme cases where there are no time restrictions are imposed on formulation $\mathcal{F}$, and none so on the emissions in $\mathcal{F}_t$. To look further into the trade-offs between value of time and the amount of CO_2 emissions, we conducted further experiments where formulation $\mathcal{F}$ was run with additional constraints gradually limiting the total value of time to either 45%, 65% or 85% of the time value initially output by the same formulation. These experiments were only run on the Set I and II instances as Set III instances proved to be difficult to solve with the constrained formulation within the given time limit. The results are presented in Table 3.

The first column in Table 3 shows the tested instances. The second column shows, for each instance, the amount of emissions obtained (in tonnes) with the time-value minimizing formulation $\mathcal{F}_t$. The next three columns titled $\mathcal{F} - 45\%$, $\mathcal{F} - 65\%$ and $\mathcal{F} - 85\%$ show the amount of emissions produced by formulation $\mathcal{F}$ when the total time is constrained by 45%, 65% and 85%, respectively. Finally, the last column shows the emissions produced by formulation $\mathcal{F}$ when there are no time restrictions. The figures given in parentheses represent the percentage reductions in the amount of emissions produced by the constrained formulations relative to the values displayed in the second column. These results indicate that it is possible to further reduce the (value of) time associated with shipping the commodities to their destinations, down to 45%, while compromising the CO_2 emissions only by 0.5%. The reduction in time corresponds to,

Table 3: CO_2 outputs (in tonnes) with constrained delivery times

Instance	$\mathcal{F}_t$	$\mathcal{F}-45\%$		$\mathcal{F}-65\%$		$\mathcal{F}-85\%$		$\mathcal{F}$	
5_1	1.00	0.90	(9.85%)	0.90	(9.85%)	0.90	(9.85%)	0.90	(9.85%)
5_2	1.00	0.90	(10.25%)	0.90	(10.25%)	0.90	(10.25%)	0.90	(10.25%)
5_3	1.00	0.93	(7.08%)	0.93	(7.08%)	0.93	(7.08%)	0.93	(7.08%)
5_4	1.00	0.87	(12.54%)	0.87	(12.54%)	0.87	(12.54%)	0.87	(12.54%)
5_5	1.00	0.96	(3.55%)	0.96	(3.55%)	0.96	(3.55%)	0.96	(3.55%)
10_1	1.00	0.75	(25.21%)	0.75	(25.21%)	0.75	(25.21%)	0.74	(26.21%)
10_2	1.00	0.70	(30.21%)	0.70	(30.21%)	0.70	(30.21%)	0.70	(30.21%)
10_3	1.00	0.78	(21.91%)	0.78	(21.91%)	0.78	(21.91%)	0.77	(23.01%)
10_4	1.00	0.81	(18.93%)	0.81	(18.93%)	0.81	(18.93%)	0.80	(20.30%)
10_5	1.00	N/A	(N/A%)	N/A	(N/A%)	0.74	(26.18%)	0.74	(26.18%)

* No feasible solution produced within the specified time limit.

on average, only a 58% increase in time over those produced by the time-value minimizing formulation $\mathcal{F}_t$. In other words, these results suggest that roughly the same amount of emissions produced by formulation $\mathcal{F}$ can be realized in much less shipment time (and value thereof) than the same formulation calls for.

To further look into the service frequencies and volumes of demand carried on each link, we present parts of the solutions of instances 10_1 and 10_4 in Tables 4 and 5, respectively. The first column of these tables, titled *Service*, shows the available services by their departure and arrival points. Columns titled *Freq* show the frequency of the corresponding service within the time horizon, while columns titled *Volume* present the amount of goods carried on each service, in load-carrying units per week (transformed from cargo volume in tons per month in Andersen *et al.*, 2009). These results are presented separately for formulations $\mathcal{F}_t$, $\mathcal{F}$ and $\mathcal{F}_t$ with the additional time limitations using the convention as above.

Table 4: Comparison of service frequencies and volumes carried for instance 10_1

	$\mathcal{F}_t$		$\mathcal{F}-45\%$		$\mathcal{F}-65\%$		$\mathcal{F}-85\%$		$\mathcal{F}$	
Service	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*
`Swinoujscie−Miedzylesie`	1	24	1	48	1	48	1	48	1	48
`Swinoujscie−Chalupki`	3	10	0	0	0	0	0	0	0	0
`Gdynia−Chalupki`	4	80	4	80	4	80	4	80	4	80
`Chalupki−Gdynia`	4	24	4	24	4	24	4	24	4	24
`Swinoujscie−Wroclaw`	1	14	1	0	1	0	1	0	1	0
`Miedzylesie−Wroclaw`	0	0	1	26	1	26	1	26	1	26
`Chalupki−Wroclaw`	2	26	0	0	0	0	0	0	0	0
`Wroclaw−Miedzylesie`	0	0	1	12	1	12	1	12	0	0
`Wroclaw−Chalupki`	1	26	0	0	0	0	0	0	1	12
`Lichkov−Wien`	1	24	2	60	2	60	2	60	1	48
`Bohumin−Wien`	3	116	2	80	2	80	2	80	2	92
`Wien−Lichkov`	0	0	1	26	1	26	1	26	1	26
`Wien−Bohumin`	1	50	1	24	1	24	2	24	2	24

Table 5: Comparison of service frequencies and volumes carried for instance 10_4

	$\mathcal{F}_t$		$\mathcal{F}-45\%$		$\mathcal{F}-65\%$		$\mathcal{F}-85\%$		$\mathcal{F}$	
Service	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*	*Freq*	*Volume*
`Swinoujscie−Miedzylesie`	1	24	0	0	0	0	0	0	1	50
`Swinoujscie−Chalupki`	1	44	1	50	1	50	1	50	0	0
`Gdynia−Chalupki`	4	28	4	28	4	28	4	28	4	28
`Miedzylesie−Swinoujscie`	1	8	1	24	1	24	1	24	1	24
`Chalupki−Swinoujscie`	1	16	0	0	0	0	0	0	0	0
`Chalupki−Gdynia`	4	18	4	18	4	18	4	18	4	18
`Swinoujscie−Wroclaw`	1	0	1	18	1	18	1	18	1	18
`Miedzylesie−Wroclaw`	1	14	0	0	0	0	0	0	1	14
`Chalupki−Wroclaw`	0	0	1	14	1	14	1	14	0	0
`Wroclaw−Miedzylesie`	0	0	1	30	1	30	1	30	1	30
`Wroclaw−Chalupki`	1	12	0	0	0	0	0	0	0	0
`Lichkov−Wien`	1	24	1	30	1	30	1	30	2	80
`Bohumin−Wien`	2	84	2	78	2	78	2	78	1	28
`Wien−Lichkov`	2	22	1	24	1	24	1	24	2	38
`Wien−Bohumin`	2	34	2	32	2	32	2	32	1	18

The main implications of the results shown in Tables 4 and 5 are as follows: (i) Minimizing time implies running more (and frequent) services on the network as compared to minimizing emissions, (ii) There is slightly a better utilization of service capacity in the case of minimizing CO_2 emissions, thus resulting in a plan that generally dictates carrying more load on links than the time-value minimizing plan. Notice that in some cases there are services being run even though no goods are carried on such service (e.g., service `Swinoujscie−Wroclaw` in Table 5), which is due to the additional inequalities imposing minimum frequency requirements on some services as specified by the original instance.

We now look at the actual time that individual commodities spend in being transported and Table 6 reports some statistics in this respect. This table reports, for all the 15 instances tested, the average amount time (in two-hourly time units) required to ship commodities to their destinations from the time they become available, under both time and CO_2 minimizing scenarios reported under columns $\mathcal{F}_t$ and $\mathcal{F}$, respectively. The final column of this table shows the percentage increase in time.

The increase in time in going from a time-value minimizing to a CO_2 minimizing scenario, as reported in Table 6, is seen to be rather significant. The reason for this is, under a CO_2 minimizing plan, the commodities spend long times at intermodal yards, waiting for a (less-frequent) service to carry them to their subsequent destination. The time-value minimizing plan, on the other hand, provides more frequent services and thus prevents long waiting times at yards. To give the reader a better picture of this phenomenon, we present Table 7 detailing two itineraries for a given commodity in instance 5_1, originating from Wien at time 81 and destined to Gdynia. The table shows the type of operations the commodity goes through (under column titled 'Operation') and

Table 6: Differences in freight travel time (in two-hourly units) between formulations $\mathcal{F}_t$ and $\mathcal{F}$

	Average time		
Instance	$\mathcal{F}_t$	$\mathcal{F}$	% Change
5_1	46.20	141.20	205.63
5_2	50.20	215.00	328.29
5_3	46.60	232.20	398.28
5_4	53.60	175.00	226.49
5_5	37.80	151.40	300.53
10_1	32.80	169.20	415.85
10_2	33.40	197.50	491.32
10_3	34.60	204.70	491.62
10_4	33.60	246.30	633.04
10_5	31.10	241.00	674.92
15_1	38.80	224.13	477.66
15_2	35.93	179.80	400.37
15_3	37.60	229.87	511.35
15_4	35.87	197.47	450.56
15_5	38.00	216.07	468.60

the points in time that these operations take place (under columns 'Time start' and 'Time end'). The designation '(+1)' (respectively, '(+2)') indicates that the total time of shipment extends into one (respectively, two) additional planning horizon(s). The last column of this table shows the available number of services running between the corresponding locations shown under the 'From/To' columns.

Table 7: Sample itineraries of one commodity in instance 5_1 produced by formulations $\mathcal{F}_t$ and $\mathcal{F}$

From	To	Operation	Time start	Time end	Available no. of services
Time-value minimizing plan:					
Wien	Wien	Wait	81	7 (+1)	
Wien	Wien	Intermodal transfer (from external)	7 (+1)	9 (+1)	
Wien	Bohumin	Transport	9 (+1)	19 (+1)	3
Bohumin	Chapulki	Intermodal (cross-border) transfer	19 (+1)	20 (+1)	
Chapulki	Gdynia	Transport	20 (+1)	28 (+1)	4
Gdynia	Gdynia	Intermodal transfer (to external)	28 (+1)	30 (+1)	
CO_2 *minimizing plan*:					
Wien	Wien	Wait	81	24 (+1)	
Wien	Wien	Intermodal transfer (from external)	24 (+1)	26 (+1)	
Wien	Bohumin	Transport	26 (+1)	36 (+1)	1
Bohumin	Chapulki	Intermodal (cross-border) transfer	36 (+1)	37 (+1)	
Chapulki	Chapulki	Wait	37 (+1)	2 (+2)	
Chapulki	Gdynia	Transport	2 (+2)	10 (+2)	4
Gdynia	Gdynia	Intermodal transfer (to external)	10 (+2)	12 (+2)	

It is seen from the two different itineraries in Table 7 that the total time (in two-hourly units) required to ship this commodity to its destination is 33 under the time-value minimizing plan and 99 for the CO_2-minimizing plan. The difference between the two is caused by the significant amount of waiting that occurs in the latter. This can be further explained by the fact that the CO_2-minimizing plan offers fewer services in the network than the time-value minimizing plan, which forces the commodities to spend long and idle times in yards waiting for the available service to take them to their destination.

Conclusions

In this paper, we have identified and addressed some environmental considerations in the context of intermodal freight transportation and proposed ways to introduce environmental costs (greenhouse gas emissions, to be specific) into planning models for transportation. We have proposed a formulation for scheduled service network design problem with fleet management, which, to our knowledge, is a first to explicitly consider greenhouse gas emissions as a primary objective. The formulation has been implemented on a real-life intermodal rail network data. Computational experiments have been carried out to compare the solutions under time and emission minimizing scenarios. Our results capture and present the trade-offs between conflicting objectives of minimizing time-related and environmental costs, and also provide empirical figures on the order of magnitude that the two objectives might differ from one to the other.

There are extensions of this work that deserve further attention. We have already mentioned that our formulation assumes a "system optimum" for a world where each carrier (and shipper) is assumed to have ownership of the transportation infrastructure (as in the case of National Planning or City Logistics). A further extension of the problem could thus consider the case where the "central control" assumption does not hold, and where there are entities, either in coalition or competition, to serve the customer demand and carry out the freight transportation operations.

In terms of solution methodology, our computational experience with the proposed formulation has proved the difficulty of obtaining optimal solutions even with state-of-the-art optimization software. Effective solution methodologies are thus needed for solving the formulation. In terms of the design aspect of the problem, the approach presented here assumed vehicle velocities to be fixed inputs (parameters) to the formulation, whereas their treatment as decision variables would allow for a more flexible service design and is likely to result in more savings in terms of emissions.

The above-mentioned extensions are only some of the aspects of the field of "Green Logistics," a little-explored but nevertheless growing area of research where efforts are directed towards reducing the hazardous environmental effects of transport. We believe that the approach taken in this paper constitutes an important step towards these goals.

Acknowledgements

This research was financially supported by University of Southampton's 'Adventures in Research' (A2007/12) and Internationalisation Funds. Partial funding has been provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada, through its Research Chairs and Discovery grant programs. This support is gratefully acknowledged. At the time of writing the paper, the first author was a postdoctoral research fellow at the School of Management, University of Southampton, while the first author was the NSERC Industrial Research Chair on Logistics Management, ESG UQAM, and Adjunct Professor with the Department of Computer Science and Operations Research, Université de Montréal, and the Department of Economics and Business Administration, Molde University College, Norway. We thank Dr. Jardar Andersen for kindly providing the data set used to perform the experiments. We also thank three anonymous referees for their valuable comments which helped to improve the paper.

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