sustainability

Article

Pricing Problems in Intermodal Freight Transport: Research Overview and Prospects

Christine Tawfik * and Sabine Limbourg

QuantOM, HEC Management School, University of Liege, B-4000 Liege, Belgium; sabine.limbourg@uliege.be
* Correspondence: christine.tawfik@uliege.be; Tel.: +32-(0)-4-232-7403

Received: 26 July 2018; Accepted: 4 September 2018; Published: 18 September 2018

Abstract: The aim of this paper is to consider the topic of pricing decisions in the context of intermodal transport as a subject of significant influence on intermodality's success and the move towards environment friendly modes to bring about a European sustainable transport system. We review the state of research in intermodal pricing from an Operational Research (OR) perspective as a subject with a vital link to energy consumption and sustainability assessment. In particular, we study freight transport within a revenue-maximizing perspective. Driven by the political incentives to enhance its challenged market position, we direct our discussion to the particular gap in optimization approaches that tackle service prices as explicit tactical decisions from the carriers' point of view. A suggestion to utilize the bilevel programming framework in the present context is put forward, as well as an account of its widely successful application to similar hierarchical decision schemes. Different approaches to express the shippers' behaviour—the potential intermodal transport customers—within the lower level problem are proposed, along with the modelling implications of different possible objectives as well as the multimodal network structures.

Keywords: intermodal transport; sustainable freight transport; pricing problems; bilevel programming

1. Introduction

The transport sector—currently dominated by road transport—is considered as a significant contributor to energy and climate policy as its related emissions continue not to exhibit the same decline as those in other sectors, such as industry and power generation. Even though, following a continuous increase, transport emissions have reduced as of 2007 as a result of changed policies and the universal economic situation, Greenhouse Gas (GHG) emissions from transport, excluding international maritime, represented about 23% of the total emissions in 2014, compared to 15% in 1990 and 20% in 2000 [1]. In terms of energy consumption, transport is the highest sector in this respect in the EU-28 and the second in Belgium with 31.7% and 28% of the final energy consumption in 2012, respectively [2]. Therefore, the need arises to shift towards more sustainable and energy-efficient forms of transport systems. In this context, the European Commission defined the notion of *intermodality* as *a characteristic of a transport system, which allows at least two different modes to be used in an integrated manner in a door-to-door transport chain* [3]. In the freight transport context, intermodality is commonly considered with the interpretation of a multimodal chain of transport services that links an initial shipper with the final consignee of the shipment, where the transfer between modes takes place at designated terminals/hubs without handling the goods themselves [4]. Generally, environment-friendly modes of transport, such as rail or inland waterways (IWWs), are being used for most of the travelled route, known as the main haulage, and road for the shortest possible parts, to and from the origin and destination terminals, respectively, known as the *pre- and post-haulage* or *drayage operations*.

Recently, in the interest of reducing air pollution and alleviating congestion that are approaching intolerable levels, intermodality has drawn a wide interest in the scientific and political community to achieve a better integration of the different transport modes. It is a settled debate by now that intermodal freight transport is a sustainable and ecological alternative in most cases [5,6]. Furthermore, when broadly adopted, it provides significant opportunities to generate economies of scale through freight consolidation and higher load factors [6,7]. These two previous reasons have hitherto fuelled a wide interest to enhance the position of intermodal transport in the EU market, being greatly in line with the roadmap set by the European Commission's White Paper [8] to shift 30% of road freight over 300 km to less environmentally harmful modes, such as rail or waterborne transport, by 2030, and more than 50% by 2050. However, Bouchery and Fransoo [9] showed that maximizing the modal shift does not lead to the minimum level of carbon emissions and that there is a carbon optimal level of modal shift. This result is in line with [10,11]. The authors proposed to include an environmental cost to the problem of optimally designing an intermodal network. The optimization problem is solved by bilevel programming, where the upper level searches for the optimal terminal network configurations, while the lower level performs multi-commodity flow assignment over a multimodal network. They showed in an example that the optimal layout of the network is sensitive to the carbon price. Pan et al. [12] also investigated how freight consolidation and intermodal transportation can help in curbing carbon emissions. To help close the gap between freight transport network design and its impact on the environment, especially on climate change, Mostert et al. [13] proposed a bi-objective model to evaluate the balance between economic (operational costs) and environmental (CO_2 emissions) objectives, in the framework of a network with three modes: road, intermodal rail, and intermodal inland waterway transport.

Nevertheless, the above goals remain highly ambitious as intermodal freight transport has so far failed to attract the desired flow levels on most European corridors when compared with its main competitor: all-road transport that is still in the lead with a large margin, as shown in the latest modal split figures by the European Commission [14]. This suggests, among other things, the existence of a room for improving the decision making at the intermodal carriers' side to be able to offer services with competitive qualities that could be regarded as a potential alternative to road transport at the shippers' side.

The interleaved operations involved in the intermodal transport chains, as well as the complex interactions between the different actors and stakeholders triggered several interesting research topics in OR [15,16]. Network pricing, in particular, has been considered as an especially powerful tool to divert flows between the different paths and modes. Environmentally speaking, the long-established field of *congestion pricing* has been advocated as an efficient way to improve social welfare through studying road link tolls [17] with recent applications to multi-modal networks. Environmental improvements of this nature also make sense with economical value [18]. Indeed, the competitiveness of intermodal freight transport was found to be greatly sensitive to the determination of the right service tariffs, known as the *pricing strategy* [19]. Pricing strategies are generally distinguishable in the way they handle the interplay between efficiency and competitiveness. A service price has to be high enough to cover its costs and generate a profit, and low enough to remain attractive to the target customers. Striking such a balance can be a complicated process demanding an accurate costs estimation and a clear insight of the market situation. In that respect, the context of intermodal transport imposes additional factors to account for as opposed to the single-mode transport, e.g., the modes' characteristics and their interaction along the transport chain with respect to the representation of the network and their relative costs to the overall door-to-door level, as well as the difficulty of depicting the target customers' behaviour towards the chosen pricing decisions having more than a single transport scheme to compare against. In addition to the difficulty of estimating the real incurred cost components along the transport chain (i.e., haulage, terminals and management costs), there is often a lot of interdependencies that do not make them immediately additive [20].

Despite being identified as both a significant and highly probable weakness in the face of developing intermodal transport as desirable freight transport services and, hence, promoting a shift towards more environmental and sustainable forms of freight transport schemes [21], this class of decision problems has peculiarly received little attention among researchers [19]. To the best of our knowledge, no OR framework has been introduced addressing intermodal freight service pricing, from a medium-term perspective, without making restrictive assumptions, as we explain below (e.g., simplifying shippers' reaction, small theoretical cases, simplification assumption on paths' structure, etc.). This paves the way for new modelling issues that are relevant for the intermodal context, yet have not been thoughtfully discussed.

Furthermore, in the rise of deregulation, the burden of answering pricing questions directly falls upon carriers and transport service providers. Nowadays, beside the extreme variability in pricing practices across corridors and market segments, intermodal operators essentially make their service pricing decisions based on cost assessment, bearing in mind a certain profit margin to attain. Beside the already challenged market position as exhibited by the recent modal split, this suggests a considerable room for improvement in terms of reaching high load factors of the transport services. Generally speaking, energy consumption—a vital criteriion for assessing the performance of a system in terms of sustainability—is highly dependent on the load factor [2]. The lack of transparency often hindered previous studies to provide meaningful insights on the actual pricing mechanisms in intermodal transport. For instance, the RECORDIT project (Real Cost Reduction of Door-to-door Intermodal Transport) relied on gathered empirical evidence on some parts of the European transportation network to improve the competitiveness of intermodal transport through the reduction of cost and price barriers, while respecting the principle of sustainable mobility [20].

We aim through this paper to address this gap in the literature by providing a theoretical study justifying the utilization of a fairly suitable mathematical framework with applicable characteristics to the intermodal context, namely: *bilevel programming*. Theoretically speaking, bilevel programming provides a complementary approach to the classic estimation of demand functions, thus eliminating the need to make simplification assumptions on the shipment sizes and the vehicle capacities. Moreover, in the context of a pricing problem, the tariff function in this methodology is not bound to a specific analytical form. Indeed, this represents a mathematical advantage and flexibility of the methodology. The scope of this work is two fold. First, the current state of research in pricing problems is reviewed for freight intermodal transport, in terms of the notable studies and how they differ with respect to certain decision and methodological elements. Second, we provide modelling insights on how to depict the different components of a typical intermodal carrier's pricing problem within a bilevel program: a framework though proven adequate for similar hierarchical and non-cooperative schemes, is still scarcely used in intermodal transport decision support systems.

The paper is organized as follows: we start by examining previous intermodal pricing-related approaches for the freight sector in Section 2. Section 3 covers the main applications of bilevel optimization in both the general transport and the pricing context, including the previous bilevel attempts applied to intermodal networks. In Section 4, we span the different aspects of applying bilevel optimization to intermodal freight pricing, mainly in what concerns the lower-level problem potentially expressing the service purchasers' behaviour, as well as the specific questions that arise when modelling networks incorporating modality change. Our discussion is finally concluded in Section 5.

2. Pricing Literature in Intermodal Freight Transport

Intermodal pricing questions are often considered at the tactical level of the decision horizon. Nevertheless, we notice that a relatively new line of research is currently gaining momentum while adopting a more detailed viewpoint of the pricing problem in the intermodal transport context. In most cases, it touches upon operational and Revenue (or Yield) Management (RM) aspects. A widely accepted definition of yield management is the one of Kimes [22]: *a method which can help a firm sell* *the right inventory unit to the right type of customer, at the right time, and for the right price*. For the latter, RM can be divided into four sub-problems: demand forecasting, overbooking, capacity allocation and pricing. Moreover, industries for which RM techniques are suitable share these characteristics: (1) relatively fixed capacity; (2) demand can be segmented; (3) perishable inventory; (4) product sold in advance; (5) fluctuating demand substantially; and (6) low marginal sales costs/high marginal capacity change costs. These traits are also valid for intermodal transport services. Pricing is a key component of the RM. If fixed costs are large relative to variable costs, the price of a service cannot be determined based on its cost, but it will be based on demand. Indeed, the more the demand increases, the more the fixed costs can be broken down. Market segmentation allows offering services at different prices to customers' classes. For a given price, capacity allocation includes determining the number of units of products or services offered at this price.

Traditionally, two parallel lines of research can be noted with regard to pricing road transport networks as described by the review of Tsekeris and Voß [23]: (1) pricing of congested urban networks in such a way as to reflect the societal marginal cost and the externalities created by road travellers in their private average cost; and (2) pricing highways with the objective of maximizing the profit of the private road authorities. The first principle lays down the basis of the congestion pricing field, whereas the second is closely entwined with the movements of privatization and deregulation. As far as intermodal transport is concerned, the pricing literature may be similarly divided in the above manner with congestion pricing chiefly studied in passenger transport (e.g., [24–26]), and profit maximization pricing in the freight sector. As we focus on the freight sector, the latter category provides the context of our following updated account on the state of the intermodal pricing literature. We first start by dividing our discussion according to the covered distances by the transport chains. Afterwards, we elaborate on the most common scheme in intermodal freight transport and the main scope of the remainder of this paper, i.e., corridors along medium to long distances. The approaches belonging to this latter category are further classified according to their decision level. Finally, we shed light on some cost-related decisions and the relevance of the pricing topic in general to a sustainable transport's perspective.

2.1. Short Distances

Several City Logistics measures have been implemented to alleviate the negative environmental impacts from urban freight transport. Cargo bikes, for instance, are considered as alternative forms of delivery transport as discussed in [27], together with the logistical implications resulting from the characteristics of this kind of delivering system. Parcel lockers are similarly regarded as an efficient last mile delivery system in recent years [28]. In the context of pricing as studied in this paper, Urban Consolidation Centre (UCC) is one of the initiatives to make City Logistics more economically, environmentally and socially sustainable. According to Browne et al. [29], an UCC denotes a logistics facility that is situated in relatively close proximity to a geographic area that it serves, from which goods that are dropped off by logistics companies are sorted, consolidated and finally delivered to their destinations within that area, often using environmentally friendly vehicles. In other words, UCCs can *be viewed as intermodal platforms or freight villages with enhanced functionality to provide coordinated and efficient freight movements within the urban zone* [30].

Despite their environmental advantages and their potential role in alleviating urban traffic problems, UCCs are typically associated with high set up (and sometimes operational) costs, which makes a case for the necessity of a funding scheme relying on initial subsidies from local authorities for a business continuation [31], unless in distinctive cases of private initiatives [32]. In this context, the question of pricing principally lies in the decision of the UCC operator on the fee of his/her offered services. The UCC concept is currently challenged in this respect; transport operators are hardly convinced by the additional cost of the UCC to outsource inefficient last mile deliveries [32]. A realistic service price has to recover the costs, include the traffic and societal benefits—conversely, the environmental costs—associated with UCCs at the total supply chain level [29], as well as properly reflect the financial benefits, such as the flexibility in planning and the time reduction [33]. This becomes even more complicated to quantify in the case of UCCs serving all or part of an urban area, since the parties involved tend to be unequally sharing the financial costs and benefits, as noted by Triantafyllou et al. [34] in their analysis of a case study in the UK retail sector. It has been underlined that, until recently, most of the available literature on urban freight distribution exists of companies and governmental reports [33], articulating the need for more scientific advices. Nevertheless, subsequent studies to date have been primarily occupied with evaluating existing UCCs by the means of different cost-benefit assessment methodologies. For instance, Kin et al. [32] showed that the UCC in Antwerp—one of the most congested cities in Europe—has a positive impact upon the society and the environment. It enhances city logistics in the designated area regarding pollutants emitted, congestion, noise, safety and infrastructure. Nevertheless, a thorough investigation of the pricing mechanisms merits a deeper look.

2.2. Medium to Long Distances

Bontekoning et al. [19] identified two levels at which an intermodal freight pricing strategy operates; the level of the individual actor in the intermodal chain and the door-to-door level. First, at the individual actor level, to devise his own strategy, each actor must be aware of his own market position and the cost structure of the other actors. Previous studies belonging to this class are mainly concerned with calculating opportunity costs and providing educated pricing guidelines, mostly done from the perspective of the network (mainhaul) and the drayage operators as addressed in [35,36], respectively. More recently, Wiegmans and Behdani [37] studied the cost structure of intermodal rail terminals, specifically with respect to the handling costs and the size of the terminals. Second, at the whole door-to-door level, pricing decisions are taken for the complete intermodal shipping service, while accounting for the target customers' choice and the service options they are typically presented with. Studies belonging to the latter category—the interest of the rest of this paper—should devise their methodologies in light of the actual market competition prices and with the aim of breaking even and attaining an acceptable profit margin, with respect to the incurred costs throughout the logistics chain (i.e., transport modes' operating and transshipment costs).

In the following, we intend to present an updated account of the state of literature precisely tackling the question of charging intermodal freight services, while discerning between the decision levels and key modelling components. It is worth mentioning though that several previous studies indirectly dealt with service pricing questions by addressing decision factors that influence the intermodal market position and its promotion, mostly as simulated parameters within wider decision support systems. LAMBIT [38], a Geographic Information Systems (GIS)-based location analysis model, make ex-ante and ex-post analysis of policy measures in Belgium to stimulate intermodal transport, e.g., price scenarios and subsidies. The LAMBIT is further developed in [39] to account for the question of fuel price increase and visualize their impact on the market area. Santos et al. [40] discuss the impact of three different transport policies: subsidizing intermodal transport operations, internalizing external costs and adopting a system perspective when optimizing the location of inland intermodal terminals for the Belgian case. A further elaboration on decision support studies for intermodal transport is available through [15]. More recently, Mostert et al. [41] analyzed the impact on flows of the introduction of an additional tax on the road network. Their analysis takes its sources in the recent introduction of the *Viapass* tax on highways and denser roads by the Belgian public authorities (April 2016). The Viapass tax is a kilometre-based charge for trucks only. Different kilometric tax rates are applied based on the weight and EURO norm of the vehicle. However, the studies that consider intermodal pricing as the main research question are peculiarly less in quantity and depth. Basically, pricing decisions fall into two levels: tactical and operational levels, depending on the decision's frequency and the time frame during which a decision has an impact. We, therefore, follow this same classification in our review.

2.2.1. Tactical Level

To the best of our knowledge, very few examples in the literature can be mentioned where the prices of intermodal services are tackled as decision variables through a mathematical program. Tsai et al. [42] considered the problem of finding an *optimal price* for intermodal service in competition with the all-road truck service. Two competition market models are introduced. On the supply (carriers) side, it is assumed that the market is shared between a single, profit-maximizing intermodal service provider and several highly-competitive trucking companies, all charging the same fixed prices. On the demand (shippers) side, two mode choice methods are defined for each of the presented models. For the first model, the minimum logistics costs principle is used, stating that, in a certain demand situation, all shippers will choose the mode with lower logistics costs. The second model depicts the shippers' mode choice behaviour through a logit demand function, in terms of the intermodal and truck service differences. The model is represented as a Stackelberg game, where the intermodal company is the market leader and the truck companies are the followers who respond to its pricing initiatives. The conclusions underline the importance of developing more efficient solution approaches, as well as investigating the theoretical and empirical aspects of the extended network model to consider larger and realistic cases.

Wang [43] presented a framework that is initially motivated to assist in a Port Authority's investment decisions, in the frame of an intermodal freight network. The author illustrated the interaction, as well as the mutual decision impact between three levels of players: the Port Authority, carriers (terminal operators) and shippers. In a first step, a carriers' (oligopolistic) market is considered, in terms of their pricing and routing decisions, where their equilibrium follows a *Nash equilibrium*. In a second step, the interaction between the carriers and the shippers is cast into a Stackelberg game, formulated as a bilevel programming problem. A heuristic algorithm, based on a sensitivity-analysis method, is developed for the problem. In a final step, the bilevel approach is evoked once again to evaluate the impact of several investment strategies of the Port Authority on the carriers and the shippers, through a net social benefit formulation. A small-scale case study is presented to demonstrate the efficiency and the applicability of the proposed methods.

Li and Tayur [44] jointly tackled intermodal service pricing and operations planning within a medium-term horizon, while satisfying service constraints and maximizing profit. For the pricing part, unlike the above examples, the authors chose to follow traditional marketing research approaches to model how the demands change with the prices, based on reservation prices data and probability density function regression. A mathematical program with a concave objective function is then considered, for the case of two service classes where the demand is represented in terms of the service prices. However, a stated limitation of the proposed approach is the complexity to obtain the demand (and price) function through analytical methods, when the number of customer or product classes becomes larger. The authors acknowledged the necessity to investigate numerical solution procedures in that case.

Dandotiya et al. [45] addressed the joint optimization of freight rate and rail-truck terminal location with the objective of improving the utilization of the railway infrastructure and increasing the competitiveness of Indian Railways in the logistic sectors. The outcome of the study aims to show the interrelation between terminal locations and price sensitiveness of customers while meeting the railway's profitability targets and without losing traffic to road transport. However, it is not clear how to interpret the issue of jointly attempting to answer questions that belong to different decision horizons, as terminal locations are generally regarded as infrastructure and strategic decisions. A mathematical model is developed with a non-linear shipping cost minimization function, subject to the price sensitivity of the customer and the profit margin set by the railways. The authors consider a realistic problem case based on rail-truck intermodal shipment along the Delhi–Mumbai freight corridor.

A joint pricing and design problem was studied by Ypsilantis and Zuidwijk [46] from the perspective of maritime container terminal operating companies, currently acting as network operators. The decisions are three-fold: selection of inland terminals to act as extended gates, capacities of the corridors and the prices of the transport services over the network. A bilevel programming model is developed with a profit maximization objective. The model is adapted to multimodal networks by formulating connection frequency dependent service times and accounting for economies of scale. The decision of the customers, always provided with an all-road alternative, is anticipated by minimizing their system costs at the lower level and expressing their expected service level in the constraints. A heuristic method is designed for a realistic case study and produces near-optimal solutions in a reasonable time. Some managerial conclusions were drawn by the authors from the results concerning the service dependencies in the case of the port-to-door and port-to-port services.

2.2.2. Operational Level

Although RM is essentially a legacy from passenger transportation, where it has been used to allocate capacities and manage trip prices and bookings, it has been increasingly applied in the freight context as well. At the heart of the growing discussions about the concept of *synchromodality* and using the available flexibility to create efficient transportation plans on a multimodal network, RM has been recently gaining attention and recognition as a promising instrument to help freight and intermodal carriers to better manage their revenues and price services with respect to the customers' classes [47,48].

Bilegan et al. [49], proposed a RM policy model from the point of view of a rail freight transportation company or an intermodal marketing company selling services. The model is designed to dynamically accept or reject transportation demands in favour of future forecasted demands with a higher potential profit to maximize the expected revenue of the company. The problem is tackled at the operational level and said to be inspired by bid-pricing capacity control mechanisms. The proposed approach is based on a probabilistic mixed integer programming model formulated on a space-time network representation of the transportation services. The solutions obtained from numerical simulations show that improved revenues may indeed be attained through the application of the proposed policies.

Li et al. [50] investigated a cost-plus-pricing strategy to determine the price of intermodal freight transport services as the sum of the operational cost of the transport operator and the targeted profit margins under different transport scenarios, i.e., self-transporting, subcontracting, or a combination of both. An optimal intermodal freight transport planning model is devised at a first stage to minimize the total transport costs, subject to due time requirements and modality change aspects. Customers are offered different service packages and final selections are made based on the prices and the shipment urgency. Based on a case study, simulation results show that higher service prices are observed with transport demands with larger size or shorter due time.

Liu and Yang [51], studied a joint slot allocation and dynamic pricing strategy problem for a container sea-rail transport system having demand uncertainties. A two-stage model, based on RM, is proposed to depict the real-life case of offering both contract and free sale to large and scattered shippers, respectively. In the first stage, long-term slot, as well as empty container allocation is settled for the first type of customers with negotiated prices. In the second stage, a multiproduct joint dynamic pricing and inventory control problem is solved to serve the free sale customers at each period of the free market, regarding prices as decision variables. Both stochastic models are transformed into deterministic ones using methods of chance constrained programming and robust optimization.

Van Riessen et al. [47] considered a RM based approach to increase the revenues of carriers and transportation providers in the context of synchromodal hinterland transportation of maritime containers. They attempted to overcome the inflexibility of previous transport product structures by considering each product as a fare class, differing in price and lead time. The approach is in fact crossing over two decision levels. At the tactical level, it honours long-term agreements by setting limits for each fare class, considering the available capacity at the operational level. The study aims to show that a significant revenue increase may be achieved by considering the tactical limits on all fare classes, as opposed to traditional approaches of limiting only the lower priced class. This work is further pursued in [52] by considering a framework to distinguish between different variants of the Cargo Fare Class Mix problem. The authors demonstrated, within an intermodal case study, that significant revenue potential can indeed be gained by setting limits on each fare class, thereby outperforming existing fare class mix policies.

Wang et al. [48] contributed to the field by examining the problem of dynamically allocating the network capacity of an intermodal barge transportation system. The study builds upon the work in [49] while adapting it to the studied space-time network and introducing particular accept/reject rules according to an estimation of the profitability of each new incoming demand. A negotiation process is proposed, as well as customer classification. The model takes the form of a probabilistic mixed integer program. Simulations and numerical results show that the introduced RM approach outperforms the first-come-first-serve booking strategy in terms of generated revenues and demonstrates a positive behaviour in case of scarce resources.

Wang [53] finally presented in his dissertation a RM approach to dynamically allocate the capacity of the intermodal barge transport network, where different fare classes are proposed to previously classified customers to differentiate the transport solutions offered by the carrier taking profitability into account. The approach is further developed in the context of a scheduled service network design model, leading to higher profits and better resource utilization. The novelty of this work thus lies in its application of the RM considerations at both the operational and tactical planning levels. Mixed integer linear programming (MILP) models are formulated to depict the problem at each level and approximate solution approaches are proposed.

Table 1 groups the above-mentioned research works in intermodal service pricing and discerns them in terms of the decision level, decision maker and applied methodology, principally with respect to the modelling approach.

Table 1. Comparison of intermodal freight service pricing research works.

Study	Tactical Level	Operational Level	Decision Maker	Methodology
[42]	✓		Intermodal service (rail-truck) provider	Market competition modelling
[43]	✓		Port authority, terminal operators	Nash equilibrium, bilevel programming
[44]	✓		Intermodal service company	Probability distribution, mathematical programming
[45]	✓		Rail freight policy makers	Non-linear mathematical programming
[46]	✓		Maritime container terminal operators	Bilevel programming
[49]		✓	Rail freight transportation company	Probabilistic mixed integer programming
[50]		✓	Intermodal transport operator	Cost-plus-pricing, transport planning optimization
[51]		✓	Container sea-rail transport operator	Stochastic programming, robust optimization
[47]	✓	✓	Carriers, intermodal transport providers	Markov chain, non-linear mathematical modelling
[52]	✓	✓	Carriers, intermodal transport providers	A framework based on the Cargo Fare Class Mix problem
[48]		✓	Intermodal barge transport providers	Probabilistic mixed integer programming
[53]	✓	✓	Intermodal barge transport providers	MILP models with RM considerations

Despite acknowledging being still at an early stage, operational approaches for intermodal service pricing seem to be acquiring increasing interest while relying on already solid RM frameworks from passenger transport. On the contrary, we observe that research works considering intermodal pricing adjustments on a medium-term tactical basis are scattered in methodologies and tailored to special cases, overlooking essential practical aspects especially related to the customers' reasoning depiction and demands modelling. This suggests the possibility for intermodal service providers to fall into sub-optimality, at a time of an already threatened market position for intermodal transport. We see the opportunity to define through bilevel programming a framework that is both valid to intermodal pricing as well as relevant to similar freight service pricing problems. The previous tactical approaches do not yet offer an OR framework of a generalized perspective to intermodal pricing. Even those that pointed to bilevel programming in that respect consider it with restrictive assumptions (e.g., in [42], very limited problem sizes while representing the shippers' choice by a demand function rather than a full optimization problem; in [46], limitation on the path structures as each sea container can go at most through one intermodal service). We aim to discuss potential modelling avenues that allow for the development of a services' pricing framework with a wide applicability.

In the following, before moving to elaborate more on the methodology, and its origins in game theory, within its general frame of applications on multimodal networks and pricing problems, we shed light on some pricing-related decisions that are relevant to consider as well as the existing link between optimizing the pricing decisions in the intermodal transport context and enhancing the system's performance in terms of sustainability.

2.3. Cost-Related Decisions

There are several crucial cost-related issues to consider while taking service pricing decisions for intermodal freight transport. It is important to examine the cost structure of the offered services' level/frequency and its relation to the eventual reliability and flexibility of the transport scheme according to the target shippers. Despite the increasing contributions along the related research line combining the revenue aspect of the day-to-day logistics activities with operations planning as mentioned above, the issues of service design and pricing have been mostly regarded separately in tactical optimization approaches for intermodal freight transport. In the economic literature, the cost structure of the transport carriers has been extensively studied in relation to their pricing strategies. For instance, Combes [54] analysed the complex structure of road freight tariffs within a market equilibrium model of a carrier-shipper framework. The study underlines the central role of access costs, vehicle capacity constraints and the logistic costs of shippers in the characteristics of freight tariffs.

However, to our knowledge, few works addressed the simultaneous consideration of the network design issues and the freight service tariffs to be applied, from a medium-term decision horizon from an OR perspective. The study in [44] reviewed above addresses the related topics of intermodal service pricing and operations planning. The latter issue is depicted by service constraints and defining service classes for the customers. Although it is not necessarily applied to the intermodal transport context, Brotcorne et al. [55] provided a significant contribution to the subject by presenting a generic mixed-integer bilevel formulation for the joint design and pricing problem on transport networks, with an application to the telecommunication industry. The authors considered a profit-maximization problem at the upper level by simultaneously determining the connections to be opened and the tariffs assigned to them, whereas, at the lower level, the network users select the shortest paths joining their origins and destinations. The previously joint pricing and design problem in [46] tackles the cost-related decisions within a frequency-based model by integrating service capacity constraints and setting a minimum level of service for the customers.

Nevertheless, more quantitative approaches are needed indeed along this vein of research, especially with respect to intermodal freight transport and the complex cost structure it subsumes.

2.4. Link between Pricing and Performance in Sustainability

Although the implications of pricing decisions on a certain transport system's sustainable qualities do not seem evident, the two issues are strongly correlated with respect to the vital aspect of the *load factor*. This is shown in the context of the research project BRAIN-TRansversal Assessment of Intermodal New Strategies [56], to which this paper's work belongs. The main goal of the project is to develop a blue print establishing the detailed criteria and conditions for developing an innovative international intermodal network in Belgium, as part of the Trans-European Transport Network (TEN-T) taking rail freight transport as the main interest. It has been underlined through environmental assessment that the energy consumption is highly dependent on the load factor; an increase in load factor should be sought in order to achieve more energy-efficient, hence sustainable, transport systems. From an operational point of view, in the framework of profit maximization by optimizing on the services' prices, it has been noticed that the train load factor has been kept at high levels: 97–99%. This observation is constant throughout all the conducted experiments for three plausible future scenarios of costs' fluctuations. This exhibited property has been explained by the fact that, for a rail service to be profitable and make up for its high fixed costs, the load factor should not fall below the above mentioned levels. Therefore, freight consolidation should be sought to fill the containers, and the experiments conducted on the market formed around the European rail corridors show that this is indeed a possible endeavour, under a suitable costs and revenues optimization framework. A high load factor, in that sense, justifies the need to consider pricing decisions as it reflects an efficient strategy of providing freight carrying services, consequently, an overall enhanced performance of the transport system in terms of sustainability.

3. Bilevel Optimization

Bilevel optimization problems, introduced by Bracken and McGill [57], give the mathematical programming formulation of the (static) Stackelberg game-theoretical concept [58]. The problem involves two sequential layers of players, commonly referred to as: the leader and the follower(s). In the game, the leader, given a precedence privilege and an ability to anticipate the follower's decision logic, plays first and decides on a most advantageous strategy, taking into account the follower's optimal reaction to his/her strategy. In more mathematical terms, a subset of the variables of the leader's optimization problem is constrained to assume an optimal solution to the follower's optimization problem, which is, in turn, parameterized by the remaining variables, however not restrained to the leader's constraints. By denoting the leader and follower's decision vectors, respectively, as x and y, the objective functions as F and f, and the constraints as G and g, we get the following problem formulation [59]:

$$\min_{x \in X, y} F(x, y) \tag{1}$$

$$\text{subject to} \quad G(x, y) \leq 0 \tag{2}$$

$$\min_{y} f(x, y) \tag{3}$$

$$\text{subject to} \quad g(x, y) \leq 0 \tag{4}$$

where constraints G involve variables from both levels, in contrast to the feasible set defined by X, and must be indirectly enforced in order to bind the followers. There may be multiple optimal solutions for the lower level problem for a given set of values for the higher level decision variables. In that sense, the follower' s behaviour determines two possible approaches for the leader' s decision. The first and most commonly chosen is an optimistic approach that assumes the follower' s cooperation and subsequent choice of the most profitable solution to the leader. The second is a pessimistic approach that assumes the follower' s aggressive behaviour, leading the leader to bound the damage resulting from the follower' s most undesirable reaction.

The bilevel optimization problem was proven to be strongly Non-deterministic Polynomial (NP)-hard [60]. Later, the results were strengthened to prove that the mere check for local or strict optimality in the linear case is an NP-hard problem as well [61]. This intrinsic difficulty imposes a necessity for most classical solution methods to assume certain convenient properties for the functions, such as smoothness or convexity, to be able to efficiently handle the problem. For a comprehensive account on the bilevel optimization paradigm, including the mathematical properties, optimality conditions discussions and solution methods, we refer to [59,62]. A rigorous bibliography review, containing more than one hundred references, is available as well [63].

A particular strength of the above mathematical framework is the fact that it takes into account the strategic behaviour of the target customers through an individual optimization problem, providing the expected demands with a degree of flexibility and realism that is not affordable through classic demand functions. The special structure of the problem fits several real-world application domains having an embedded decision hierarchy within their definition. As a preface to introduce its potential application to intermodal pricing, we now emphasize on the successful application of the bilevel optimization concept in transport problems involving modality change, as well as the relevant field of (network-based) pricing.

3.1. Inter-/Multimodal Transport

In most transport-related decisions, we may observe two autonomous, and possibly conflicting, levels of decision makers: on the upper level, an authority seeks to meet certain global goals, while, on the lower level, the network users make their personal travel choices in their best interest. Based on the surveys in [59,64], the main problem classes of bilevel optimization in the domain of transport comprise: network design; signal setting; origin-destination (O-D) matrix estimation; hazardous materials management.

The literature examples in the context of inter-/multimodal transport are of a narrow perspective though and not significantly numerous. Clegg et al. [65] addressed the problem of optimizing urban multimodal transport networks in a bilevel manner. The aim is to decide on control values, in terms of signal green-times and prices, while the travellers' (rational) route and mode choices, translated into the estimated traffic flows, are at equilibrium. Yamada et al. [66] proposed a bilevel optimization model for strategic multimodal network planning. On the upper level, a discrete network design problem is considered to select a suitable subset of actions from a number of possible ones. The lower level incorporates a *multimodal multiclass UE traffic assignment* to capture the decisions' influence on the traffic and freight flows. A heuristic approach, based on genetic local search, is applied to solve the problem. Pazour et al. [67] solved a discrete network design problem. In their problem, the upper-level decision is where to add high-speed rail arcs, while the lower-level decision is the shortest path problem (for each O-D) which is affected by the placement of high-speed rail arcs in the network. The objective of the upper-level decision is to minimize costs by building the fewest high-speed rail arcs, while the lower-lever decision is to minimize travel time for each O-D by building the most high-speed arcs. The bilevel program balances the two objectives. Zhang et al. [10] presented an optimization model for terminal networks, based on bilevel programming, and taking into account environmental costs and economies of scale. The authors conduct a search among candidate policy packages of terminal configurations and CO_2 emission prices by applying a genetic algorithm, while performing a multi-commodity flow assignment over a multimodal network to derive the travellers' decisions. In the context of energy saving, Du et al. [68] exploited analytical methods, with the aim to bridge the gap between the designed policy instruments and their corresponding consumption output in the transport sector. Within a bilevel optimization framework, energy consumption is minimized on the upper level over a multimodal transport network, subject to the traffic demand distribution, resulting from a travellers' utility maximization problem on the lower level.

3.2. Pricing Problems

Bilevel pricing problems, in their economic and OR interpretation, consist of the leader's problem of setting taxes or prices for a set of offered services, while accounting for the followers' choice, having the freedom to settle for the taxed or the untaxed services, with the aim of minimizing their own costs. This approach can be regarded as a more rigorous approach in comparison to traditional demand functions, as the customers' reaction is depicted by a full optimization problem. The bilevel framework is suitable for both public and private pricing contexts. It is first introduced in [69], for a highway-taxation problem. Later, it is developed in [70] for the freight tariff-setting context, adapting the initial mathematical framework that we discuss below.

A thorough and important review of this class of bilevel problems is conducted in [71]. The authors started by presenting a general, as well as a linear version of the price-setting problem. A graphical interpretation is used to illustrate the conditions under which a bounded solution is guaranteed; namely, that the follower's feasible set is both non-empty and bounded, and that there exists at least a feasible solution for the follower using only untaxed/price-free services. The latter condition is necessary to prevent the leader of setting an infinite tax/price to their owned services. The scope of the problem analysis in the survey is further moved to its network-based framework, known as the network pricing problem (NPP). The leader is an authority owning a subset of arcs and aiming to maximize his/her revenue through a toll assignment scheme. The followers, in turn, are the users travelling the network in a cost minimization fashion, from their own perspective. The rest of the arcs, assumed to be owned by other network agents (or not), are subjected to fixed costs which are known a priori. Let K be a set of commodities, where each commodity k is associated with an origin o^k, a destination d^k and a demand η^k. Let A_1 and A_2 denote the set of toll arcs and toll free arcs, respectively, c_a a fixed travel cost on each arc $a \in A_1 \cup A_2$, and T_a a toll on each toll arc $a \in A_1$. If the flow is given by variables x_a^k on toll arcs, and y_a^k on toll free arcs, a formulation of this problem is thus given by [71]:

$$\max_{T \geq 0} \sum_{a \in A_1} T_a \sum_{k \in K} \eta^k x_a^k \tag{5}$$

$$\text{subject to} (x, y) \in \arg\min_{x,y} \sum_{k \in K} \Big(\sum_{a \in A_1} (c_a + T_a) x_a^k + \sum_{a \in A_2} c_a y_a^k \Big) \tag{6}$$

$$\text{subject to} \sum_{a \in i^+} (x_a^k + y_a^k) - \sum_{a \in i^-} (x_a^k + y_a^k) = b_i^k \qquad \forall k \in K, \forall i \in N \tag{7}$$

$$x_a^k, y_a^k \geq 0 \quad \forall k \in K, \forall a \in K, a \in A_1 \cup A_2 \tag{8}$$

where i^- and i^+ stand for the set of arc with i as head or tail, respectively, and b_i^k evaluates to -1 if i is the origin of commodity k, 1 if it is the destination, and 0 otherwise. Equation (5) gives the profit-maximization objective of the leader, whereas , Equations (6)–(8) give the followers' shortest-path problem. As the bilevel framework dictates, the optimization problem in Equations (6)–(8) appears in the constraints of the leader's problem, stating that it must be solved to optimality to obtain a feasible solution for the whole problem. The lower level has a cost minimization objective (Equation (6)) and is subject to flow conservation constraints (Equation (7)). When negative tolls are allowed, the model is said to deal with subsidies. In the same context, two main categories of the problem are introduced: *arc pricing* in contrast to *path pricing*. For the former, the previous formulation typically holds, where the leader-owned arcs are not restricted to assume similar tolls values. In the latter category, however, tolls are associated to paths that could be even priced differently for each commodity. The special case of a polynomial number of paths is also defined; namely, the highway system. Furthermore, a clear mapping scheme of the special context of product pricing is established with respect to the arc pricing context, in terms of each pair of corresponding problem elements. The particular strength of bilevel optimization is evident within this context, where the concept of reservation prices becomes embedded in the definition of the network itself in the form of the allowed toll windows. The authors refer to [69] for a two-phase procedure to convert the arc pricing problem into a single-level mixed integer problem (MIP).

Graph processing techniques have been studied in the literature to reduce the practical size of the original network. By examining the structural properties associated to the shortest path selected by each commodity, a *shortest path graph* can be constructed, where further arcs can be eliminated using path dominance reasoning. More details on the shortest path graph construction procedure are furnished by [72,73]. There remains a considerable room for experimentation in the context of the NPP. Van Hoesel [73] proposed three possible avenues for extension: incorporating capacities on the arcs, considering other pricing mechanisms and integrating the problem of the network design. Labbé and

Violin [71], for their part, highlighted a number of open issues, such as integrating real-life features into bilevel models and tackling more variants of the product pricing problem.

It is noteworthy that bilevel programming equally has a contribution to social welfare applications; several studies have explicitly treated congestion pricing problems as Stackelberg games on traffic networks, where the users' route choice behaviour is described through a network equilibrium model. Yan and Lam (1996) [74] introduced a two-arc based pricing model that involves queuing delays. A brief account on the subject of congestion pricing within bilevel programs is given in [73]. Recently, a multi-objective bilevel pricing model is presented in [75], in the context of sustainability maximization.

4. Application to Intermodal Pricing

Returning to the context of intermodal freight service pricing, we observe that the economic interpretation of the addressed carrier-shipper problem fits both the particulars of the product pricing problem and, by consequence as already settled, the NPP. The intermodal service provider (carrier) corresponds to a revenue maximizing leader, the set of target customers (shippers) to utility maximizing or cost minimizing followers, and intermodal tariffs to price decisions, with a direct parallel of reservation prices and service assignment or arc flow variables. An alternative would always be available for the shippers, potentially represented in a competition' s all-road option. In our methodology proposal, an intermodal carrier has the precedence to make his pricing decision in the quest of revenues (more understandably profit) maximization, while being able to anticipate the rational reaction of the target shippers. These latter decision makers typically react in a cost-minimization fashion to the carrier's decision, by choosing between the intermodal carrier's and the all-road competition's services. Indeed, the sequential order of the decision-making is akin to the real-life situation, hence the relevance of the hierarchical bilevel programming structure.

The market is assumed to be composed of small shippers trying to take advantage of freight consolidation to get their shipments delivered. Furthermore, it is assumed that the intermodal carrier is not in a monopoly nor in a dominance position of the market; the competition—represented in all-road transport—is explicitly taken into account in terms of its supply and tariff. In that respect, it is presumed that the total demand is not influenced by the intermodal carrier's price and that the competition does not react in the short term to the carrier's decisions. Nevertheless, for simplification purposes, it is assumed that the carrier is in full control of the intermodal resources. To represent an oligopolistic market with reactive competition at the intermodal carrier's (upper) level is both mathematically difficult to address and beyond the scope of this paper.

We dedicate the next sub-sections to presenting some modelling insights related to expressing the particulars of intermodal service pricing within a bilevel program. We further discuss the representation of the underlying multimodal network, the possible developments of the upper-level optimization problem, and the portrayal of the shippers/followers' lower-level problem in terms of two viewpoints: freight mode choice and traffic assignment.

4.1. Network Representation

Normally, each modal network (e.g., road or rail) is represented separately. To depict multimodal networks, the idea, initially proposed in [76], is to use pseudo or virtual links to represent intermodal transfers among the modal networks. To our knowledge, one of the first software tools that allowed a graphical analysis of multimodal transport networks is STAN (Strategic Transport ANalysis) ([77]). As different transport operations can occur on the same infrastructure, a virtual link with a specific cost is created for each particular operation. A further development of this concept is implemented in an assignment model and software, NODUS [78,79]. The main contribution is the development of a structured notation and automatic generation of the virtual links created on the basis of the characteristics of the geographical nodes and links. Through the creation of virtual links, all feasible operations such as loading, unloading or transhipment are represented and their costs can be taken into account. In the same way, all kinds of vehicles using the same geographical infrastructure can be characterized and all possible combinations of modes and means can be examined. We refer to [80] for a review of the European literature on freight transport models. This approach is now commonly known as *Virtual Networks* or *Supernetworks*. The obtained network may then be used for traditional cost calculations.

4.2. Upper-Level Problem—Carrier's Decisions

At the upper level, the trivial case would be to consider a maximization problem of the intermodal carrier's (leader's) revenues, collected through the chosen service charges, and consequently achieve high load factors. An obvious upper bound to the total revenues would be given by the difference between the service prices charged by the competition and any service unit traversal costs borne by the shippers, as explained in [70] for the general context of bilevel freight tariff-setting problems.

4.2.1. Service Design

As a transport service provider seeks to attract more customers, it is reasonable to assume that he tries to enhance the offered service quality which presumably comes at an additional cost. Striking the balance between efficiency and competitiveness is the ultimate goal of pricing problems. Therefore, it is logical to consider the questions of service design and pricing in a simultaneous manner. This is particularly valid in the intermodal transport context, where devising prices largely depends on the costs of transport services in each modal sector along the door-to-door chain. In that broader sense, the leader's objective becomes the maximization of the profit, represented in the difference between the collected revenues and the service operating costs. The service design decisions are typically represented as their respective frequencies, with a crucial link of the issues of flexibility and reliability at the shippers' side. At a more operational level, the service dispatch day could equally be portrayed alongside the frequency. A usually problematic issue in this type of problems from a bilevel programming point of view is the introduction of additional design variables (e.g., service frequencies, demands routing). These (upper-level) variables normally appear combined with the (lower-level) service choice or flow variables to enforce service level-related as well as capacity constraints. The position of similar joint constraints in the bilevel program dictates the problem's feasible and optimal set of solutions. We refer to [55,81] for a thorough discussion of the conditions under which the movement of the joint constraints between the levels can be performed.

4.2.2. Asset Management

Moreover, it is valid to account for resource-balancing and asset management constraints. This is especially relevant for long-distance transport scheme as in intermodal transport and consolidation-based freight carriers. The resources requiring efficient allocation and utilization can potentially comprise vehicles, equipment, power units and staff. This aspect, of course, suggests additional burden on the incurred costs for the intermodel carriers as well as on the mathematical complexity side. The formulations must then be enlarged with further variables and constraints to represent the new design-balance requirements. A comparative analysis of different formulations addressing asset management issues in a service network design context is presented in [82].

4.2.3. Economies of Scale

The upper-level objective can be further developed by considering a marginal cost decrease induced by the potential generation of economies of scale; a strength related to intermodal transport and the integration of modes having higher payloads. With proper consolidation, transport operators can likely apply more efficient strategies to offer services, and consequently improve the overall energy consumption of their system and its performance in terms of sustainability. This concept was previously in part incorporated in a joint design and pricing framework in [46,83].

4.3. Followers' Freight Mode Choice Problem

The idea is to render the shippers' lower level problem a freight mode choice problem. The general behavioural assumption is that shippers seek to minimize their total logistics costs. There is a sufficiently wide literature that considers a corresponding functional representation that goes beyond a linear utility function of modal attributes. Several individual items interact in complex ways to determine the total logistics costs, involving commodities', shippers' and shipments' characteristics, in relation to level-of-service and mode attributes. The most notable research works related to the topic of logistics costs is found in [84,85]. The generally acknowledged structure comprise: direct shipping cost, in-transit carrying, ordering cost and inventory carrying cost. Some service-related attributes may equally be added to account for intangible elements, e.g., satisfaction with contract terms and availability of electronic data interchange services [86]. Nevertheless, an application of a normative approach provided by cost models repetitively fails to coincide with the shippers' actual choices. This is chiefly due to two reasons: the non-uniformity of the service perception among the shippers; and the lack of certain significant information for the cost calculation (e.g., discount rate, cost per order and the number of days to collect a loss and damage claim). The alternative, as explained in [86,87], is to combine discrete choice methods with the minimization of total logistics costs, in the same way that utility maximization is modelled for individuals' choice behaviour in passenger traffic in [88]. The shippers' modal selection can be specified in quantitative terms by employing a random utility model, where the choice model estimation is in fact an estimation of the missing cost variables information, together with the importance of the different cost components. The utility of a certain mode i for shipper n is expressed as: $\mu(logistics\ costs_{in}) + \varepsilon_{in}$, where μ is a negative scale parameter, $logistics\ costs_{in}$ depicts the explanatory variables of the model and ε_{in} an unobservable or random component [87]. Therefore, the event of choosing a certain alternative is considered stochastic with a choice probability depending on the distributional assumption of the disturbance term in the utility function. The Logit and the Probit models are the most commonly acknowledged. Based on a proper pool of data, a final shippers' utility can be estimated and integrated in the reaction of the followers within the bilevel intermodal pricing model.

4.4. Followers' Traffic Assignment Problem

Another alternative is to consider the shippers' problem from a route/path choice viewpoint. This case is particularly valid when the carrier do not provide the shippers with a total itinerary choice, rather with separate services' options—presumably that of the long haul—and the decision that is relative to combining those services, with possibly that of the competition, takes place on the shippers' end to satisfy the demands. Note that the network is fully connected in terms of road: the competition's continuous presence. This is a relevant case when freight forwarders act as an intermediate layer between the carriers and the shippers. An example of such a case is discussed in [70] in the context of a freight tariff setting problem, where the shippers' decision is reduced to a shortest-path assignment. As these decisions take place on the lower level, for simplification purposes, we do not differentiate between freight forwarders and shippers.

Traditionally, the lower level problem in the variants of the NPP problem, presented in Section 3, is handled as a shortest path problem, where the arc capacities are ignored (or assumed unconstrained) and the arc travel times, reflected in their respective costs, are regarded as constants. However, in more realistic cases, where the effects of congestion are to be taken into account, there exists a mutual dependence between the arc flows and costs. In that sense, the link flows and costs are iteratively updated, moving towards a state of equilibrium. Two main modelling branches accordingly stem from this distinction: shortest path and traffic equilibrium assignment models.

4.4.1. Shortest Path Assignment

In a shortest path assignment, more formally known as all-or-nothing (AON) assignment, all the trips from a certain origin to a destination zone are assigned to a single shortest (minimum cost) path among all feasible ones, assuming no congestion effects, hence constant link costs, and a unified costs perception for all drivers [89]. A typical formulation for such a case in a multi-commodity network is given by the problems in Equations (6)–(8). Although it seems unrealistic in terms of selecting only one path for each O-D pair and ignoring real-life aspects, it may be reasonable in sparse networks, where there are few alternative routes widely differing in cost, and in order to provide an insight on the desired path in the absence of congestion. Models, using the AON technique, mostly make similar assumptions and run necessary experiments in order to alleviate the effect of capacity shortage on their concerned decision horizon.

4.4.2. Traffic Equilibrium Assignment

The issue of congestion is explicitly considered by expressing a link cost as function of its usage level, with respect to its capacity. As the flow increases towards the capacity of a certain network link, it is conceivable that the traffic conditions deteriorate and the link speed becomes lower, which implies a higher travel time and cost, diverting in turn part of the flow to alternative, now, cheaper links. A number of such iterative procedures would take place until the fluctuation in links costs and flows would eventually converge, reaching an equilibrium configuration that can be regarded either from the user or the system perspective. Typical non-cooperative models are based on the first case, known as Wardrop's first principle of traffic equilibrium [90], stating that *the journey times on all the routes used are equal, and less than those which would be experienced by a single vehicle on any unused route*. A UE is thus attained *when no driver can unilaterally reduce his/her travel costs by shifting to another route*. We refer to [91] for a rigorous treatment of the network equilibrium problem, as well as to [92] for a thorough account on congestion issues in the frame of bilevel network design problems.

Let $G = (A, N)$ denote an underlying network, with N representing a set of nodes, A a set of links, and K a set of O-D pairs. If we define for each k^{th} pair in K a set of simple paths between its end nodes as P_k, the travel demand as η^k, the shortest route travel time as π^k, and the travel time and flow on the p^{th} route in P_k as c_{pk} and h_{pk}, respectively. Therefore, the UE principle can be mathematically expressed through the following conditions [64]:

$$h_{pk}(c_{pk} - \pi_{pk}) = 0 \quad \forall p \in P_k, \tag{9}$$

$$c_{pk} - \pi_{pk} \geq 0 \quad \forall p \in P_k, \tag{10}$$

$$\sum_{p \in P_k} h_{pk} = \eta_i^k, \tag{11}$$

$$h_{pk} \geq 0 \quad \forall p \in P_k, \tag{12}$$

for every O-D pair k.

According to Migdalas [64], there exist two main modeling approaches for the UE problem: a non-linear network model and a Variational Inequality (VI) formulation. In the first approach, for every link $a \in A$, a travel cost function $s_a(x_a)$ is defined in terms of its total flow x_a, as encountered by a user traveling on link a. A convex optimization problem can thus be formulated, for which, the conditions in Equations (9)–(12) hold as the first-order optimality conditions, assuming s_a to be positive, strictly monotone increasing and continuously differentiable. In the second approach, however, the general case where the link travel functions may also depend on the flow of neighbouring links is considered. Assuming similar properties on the link travel and the route cost function, the equilibrium problem can be formulated as VIs, in which case, the resulting bilevel program can be regarded as an equivalent to a mathematical program with equilibrium constraint (MPEC). As shown in [59], MPECs incorporate bilevel programs, whenever the lower level problem in the latter is convex and differentiable. The reverse holds as well through replacing the lower-level VI by an optimization problem. To our knowledge, the literature is nearly silent on examples incorporating a network equilibrium problem in the lower-level of a NPP, in the profit maximizing sense of the problem.

It may be argued, however, about the irrelevance of (endogenous) congestion in intermodal planning, relying on the points that pricing decisions are generally regarded for a larger interval than that of the congestion occurrence and that intermodal freight operations are typically intended to take place at low-congested times. To the first, we reply that, if the network in question experiences congestion in quite a regular manner within the decision horizon, for sufficiently long periods, taking congestion into consideration would therefore be justifiable. To the second, we point to the current state of terminal sites, or areas adjacent to the terminals, being greatly implicated by the traffic concentration that intermodal hub networks commonly generate in terms of noise, accidents and congestion. A contribution to the debate on how to render terminals more coping with the traffic growth can be found in [93].

The above equilibrium approaches have been developed to capture freight movement through the concept of spatial price equilibrium (SPE). SPE denotes that, in the case of a trade occurrence between a pair of markets, the price of a commodity at the demand market is equal to its price at the supply market plus the transport cost. The demand price is exceeded if there is no trade. The original problem dates to [94] and is proven to assume a similar structure to certain cases of the traffic network equilibrium problem in [95]. Harker [96] discussed the applicability of equilibrium models to the freight context and Lee et al. [97] give an example of a bilevel shipper-carrier model focusing on the shippers' behaviour employing SPE.

5. Conclusions

This research was motivated by the rising need to mitigate traffic flows from the road transport networks. In this context, pricing is identified as a powerful instrument to improve intermodality's share, attain more balanced modal splits and, consequently, reduce environmental impacts. We provide through this paper a comprehensive and wide-scale review of the pricing subject in the OR literature of intermodal freight transport. First, the problem is described and previous contributions are outlined, in terms of their extension of classic concepts to account for the dynamics and interaction of the different transport modes. Through our investigation, we demonstrate the scarcity, as well as the narrowness, of the previous research in its discussion of intermodal freight carriers' pricing decisions at a tactical level, overlooking important modelling issues. As a result, we conclude a significant deficiency in attaining high load factors, and, consequently, less sustainable and energy-efficient freight transport systems.

Second, an approach is proposed to express this problem as a bilevel program: a well-suited framework for similar hierarchical pricing schemes, with a potentially large room for investigation for the considered application. The compatible features of bilevel optimization are reviewed and modelling insights as to how to express the pricing problem of concern in the suggested form are provided. More precisely, a certain intermodal operator (a leader) has the precedence of setting the prices of his/her offered freight services in the quest of profit maximization, while being able to fully anticipate the shippers' (followers) rational reactions to the chosen pricing decisions when presented with a trucking alternative.

Finally, a special discussion is devoted to the multimodal network representation via the concept of virtual networks, as well as possible outlooks with respect to the shippers' behaviour depiction at the lower-level, namely: freight mode choice and traffic network assignment.

In the context of future outlooks, the intermodal transport context suggests interesting research extensions for the problem that deserve in-depth consideration, e.g., integrating service design questions to model the interaction between the different modes, as well as the potential generation of economies of scale with higher payloads reflected in a marginal cost decrease. Indeed, the latter aspect is of a high relevance to optimize the system's performance in terms of sustainability and energy consumption: a serious need for our current day's societies.

Author Contributions: Conceptualization and Methodology, the end work is the outcome of the original ideas of C.T. and the discussions and joint effort with S.L.; Writing: Original Draft Preparation, C.T.; Writing: Review and Editing, C.T. and S.L.; Supervision, S.L.; Funding Acquisition, S.L.

Funding: This research was funded by the Federal Science Policy, grant number: [BR/132/A4/BRAIN-TRAINS].

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. European Commission. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions—A European Strategy for Low-Emission Mobility*; SWD/2016/0244 final; European Commission: Luxembourg, 2016.
2. Merchan Arribas, A.; Belboom, S.; Léonard, A. Life Cycle Assessment of freight transport in Belgium. In Proceedings of the BIVEC-GIBET Transport Research Days 2017, Liège, Belgium, 19 May 2017; pp. 179–195.
3. European Commission. *Intermodality and Intermodal Freight Transport in the European Union. A Systems Approach to Freight Transport. Strategies and Actions to Enhance Efficiency, Services and Sustainability. Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions*; COM (97) 243 final; European Commission: Luxembourg, 1997.
4. European Conference of Ministers of Transport. United Nations economic commission for Europe statistical division and European Union Eurostat. In *Glossary for Transport Statistics*; Eurostat: Luxembourg, 1997.
5. Kreutzberger, E.; Macharis, C.; Vereecken, L.; Woxenius, J. Is intermodal freight transport more environmentally friendly than all-road freight transport? A review. In Proceedings of the Nectar Conference, Umeå, Sweden, 13–15 June 2003; pp. 13–15.
6. Mostert, M.; Limbourg, S. External Costs as Competitiveness Factors for Freight Transport—A State of the Art. *Transp. Rev.* **2016**, *36*, 692–712. [CrossRef]
7. Kreutzberger, E. Impact of innovative technical concepts for load unit exchange on the design of intermodal freight networks. *Transp. Res. Rec. J. Transp. Res. Board* **2003**, *1820*, 1–10. [CrossRef]
8. European Commission. *White Paper on Transport: Roadmap to a Single European Transport Area: Towards a Competitive and Resource-Efficient Transport System*; Directorate-General for Mobility and Transport; Publications Office of the European Union: Luxembourg, 2011.
9. Bouchery, Y.; Fransoo, J. Cost, carbon emissions and modal shift in intermodal network design decisions. *Int. J. Prod. Econ.* **2015**, *164*, 388–399. [CrossRef]
10. Zhang, M.; Wiegmans, B.; Tavasszy, L. Optimization of multimodal networks including environmental costs: A model and findings for transport policy. *Comput. Ind.* **2013**, *64*, 136–145. [CrossRef]
11. Zhang, M.; Janic, M.; Tavasszy, L. A freight transport optimization model for integrated network, service, and policy design. *Transp. Res. Part E Logist. Transp. Rev.* **2015**, *77*, 61–76. [CrossRef]
12. Pan, S.; Ballot, E.; Fontane, F. The reduction of greenhouse gas emissions from freight transport by pooling supply chains. *Int. J. Prod. Econ.* **2013**, *143*, 86–94. [CrossRef]
13. Mostert, M.; Caris, A.; Limbourg, S. Intermodal network design: A three-mode bi-objective model applied to the case of Belgium. *Flex. Serv. Manuf. J.* **2017**, *3*, 397–420. [CrossRef]
14. European Commission. Energy in Figures. In *Statistical Pocketbook 2016*; European Commission: Luxembourg, 2014.
15. Caris, A.; Macharis, C.; Janssens, G.K. Decision support in intermodal transport: A new research agenda. *Comput. Ind.* **2013**, *64*, 105–112. [CrossRef]
16. SteadieSeifi, M.; Dellaert, N.P.; Nuijten, W.; Van Woensel, T.; Raoufi, R. Multimodal freight transportation planning: A literature review. *Eur. J. Oper. Res.* **2014**, *233*, 1–15. [CrossRef]
17. Lindsney, R.; Verhoef, E. Traffic congestion and congestion pricing. In *Handbook of Transport Systems and Traffic Control*; Emerald Group Publishing Limited: Bingley, UK, 2001; pp. 77–105.
18. Guide, V.D.R.; Van Wassenhove, L.N. OR FORUM-the evolution of closed-loop supply chain research. *Oper. Res.* **2009**, *57*, 10–18. [CrossRef]

19. Bontekoning, Y.M.; Macharis, C.; Trip, J.J. Is a new applied transportation research field emerging?—A review of intermodal rail–truck freight transport literature. *Transp. Res. Part A Policy Pract.* **2004**, *38*, 1–34. [CrossRef]
20. Ricci, A. Pricing of intermodal transport. Lessons learned from RECORDIT. *Eur. J. Transp. Infrastruct. Res.* **2003**, *3*, 351–370.
21. Troch, F.; Vanelslander, T.; Belboom, S.; Léonard, A.; Limbourg, S.; Merchan Arribas, A.; Mostert, M.; Pauwels, T.; Vidar, S.; Sys, C.; et al. BRAIN-TRAINS: Intermodal rail freight transport and hinterland connections a SWOT analysis to assess the Belgian rail practice. In Proceedings of the IAME Annual Conference 2015, Kuala Lumpur, Malaysia, 24–26 August 2015.
22. Kimes, S.E. Yield management: A tool for capacity-considered service firms. *J. Oper. Manag.* **1989**, *8*, 348–363. [CrossRef]
23. Tsekeris, T.; Voß, S. Design and evaluation of road pricing: State-of-the-art and methodological advances. *Netnom. Econ. Res. Electron. Netw.* **2009**, *10*, 5–52. [CrossRef]
24. Hamdouch, Y.; Florian, M.; Hearn, D.W.; Lawphongpanich, S. Congestion pricing for multi-modal transportation systems. *Transp. Res. Part B Methodol.* **2007**, *41*, 275–291. [CrossRef]
25. Wu, D.; Yin, Y.; Lawphongpanich, S. Pareto-improving congestion pricing on multimodal transportation networks. *Eur. J. Oper. Res.* **2011**, *210*, 660–669. [CrossRef]
26. Tirachini, A.; Hensher, D.A.; Rose, J.M. Multimodal pricing and optimal design of urban public transport: The interplay between traffic congestion and bus crowding. *Transp. Res. Part B Methodol.* **2014**, *61*, 33–54. [CrossRef]
27. Iwan, S.; Thompson, R.G.; Macharis, C. *Application of Genetic Algorithms in Optimizing the Logistics Network in An Urban Bicycle Delivery System*; Technical Report; Transportation Research Board: Washington, DC, USA, 2015.
28. Lemke, J.; Iwan, S.; Korczak, J. Usability of the parcel lockers from the customer perspective—The research in Polish Cities. *Transp. Res. Procedia* **2016**, *16*, 272–287. [CrossRef]
29. Browne, M.; Sweet, M.; Woodburn, A.; Allen, J. *Urban Freight Consolidation Centres*; Final Report; Transport Studies Group, University of Westminster: London, UK, 2005.
30. Crainic, T.G.; Ricciardi, N.; Storchi, G. Models for evaluating and planning city logistics systems. *Transp. Sci.* **2009**, *43*, 432–454. [CrossRef]
31. Browne, M.; Woodburn, A.; Allen, J. *Evaluating the Potential for Urban Consolidation Centres*; EUT Edizioni Università di Trieste: Trieste, Italy, 2007.
32. Kin, B.; Verlinde, S.; van Lier, T.; Macharis, C. Is there life after subsidy for an urban consolidation centre? An investigation of the total costs and benefits of a privately-initiated concept. *Transp. Res. Procedia* **2016**, *12*, 357–369. [CrossRef]
33. Van Duin, J.; Quak, H.; Muñuzuri, J. New challenges for urban consolidation centres: A case study in the Hague. *Procedia Soc. Behav. Sci.* **2010**, *2*, 6177–6188. [CrossRef]
34. Triantafyllou, M.; Cherrett, T.; Browne, M. Urban Freight Consolidation Centers: Case Study in the UK Retail Sector. *Transp. Res. Rec. J. Transp. Res. Board* **2014**, *2014*, 34–44. [CrossRef]
35. Yan, S.; Bernstein, D.; Sheffi, Y. Intermodal pricing using network flow techniques. *Transp. Res. Part B Methodol.* **1995**, *29*, 171–180. [CrossRef]
36. Spasovic, L.N.; Morlok, E.K. *Using Marginal Costs to Evaluate Drayage Rates in Rail-Truck Intermodal Service*; Transportation Research Record: Washington, DC, USA, 1993.
37. Wiegmans, B.; Behdani, B. A review and analysis of the investment in, and cost structure of, intermodal rail terminals. *Transp. Rev.* **2018**, *38*, 33–51. [CrossRef]
38. Macharis, C.; Pekin, E. Assessing policy measures for the stimulation of intermodal transport: A GIS-based policy analysis. *J. Transp. Geogr.* **2009**, *17*, 500–508. [CrossRef]
39. Macharis, C.; Van Hoeck, E.; Pekin, E.; Van Lier, T. A decision analysis framework for intermodal transport: Comparing fuel price increases and the internalisation of external costs. *Transp. Res. Part A Policy Pract.* **2010**, *44*, 550–561. [CrossRef]
40. Santos, B.F.; Limbourg, S.; Carreira, J.S. The impact of transport policies on railroad intermodal freight competitiveness—The case of Belgium. *Transp. Res. Part D Transp. Environ.* **2015**, *34*, 230–244. [CrossRef]
41. Mostert, M.; Caris, A.; Limbourg, S. Road and intermodal transport performance: The impact of operational costs and air pollution external costs. *Res. Transp. Bus. Manag.* **2017**, *23*, 75–85. [CrossRef]

42. Tsai, J.; Morlock, E.; Smith, T.E. *Optimal Pricing of Rail Intermodal Freight: Models and Tests*; Technical Report; Transportation Research Board: Washington, DC, USA, 1994.
43. Wang, Y. A Bi-Level Programming Approach for the Shipper-Carrier Network Problem. Ph.D. Thesis, New Jersy Institute of Technology, Newark, NJ, USA, 2003.
44. Li, L.; Tayur, S. Medium-term pricing and operations planning in intermodal transportation. *Transp. Sci.* **2005**, *39*, 73–86. [CrossRef]
45. Dandotiya, R.; Nath Banerjee, R.; Ghodrati, B.; Parida, A. Optimal pricing and terminal location for a rail–truck intermodal service—A case study. *Int. J. Logist. Res. Appl.* **2011**, *14*, 335–349. [CrossRef]
46. Ypsilantis, P.; Zuidwijk, R. *Joint Design and Pricing of Intermodal Port-Hinterland Network Services: Considering Economies of Scale and Service Time Constraints*; Technical Report; Erasmus Research Institute of Management: Rotterdam, The Netherlands, 2013.
47. Van Riessen, B.; Negenborn, R.R.; Dekker, R. Synchromodal container transportation: An overview of current topics and research opportunities. In Proceedings of the International Conference on Computational Logistics, Delft, The Netherlands, 23–25 September 2015; pp. 386–397.
48. Wang, Y.; Bilegan, I.C.; Crainic, T.G.; Artiba, A. A Revenue Management Approach for Network Capacity Allocation of an Intermodal Barge Transportation System. In Proceedings of the International Conference on Computational Logistics, Lisbon, Portugal, 7–9 September 2016, pp. 243–257.
49. Bilegan, I.C.; Brotcorne, L.; Feillet, D.; Hayel, Y. Revenue management for rail container transportation. *EURO J. Transp. Logist.* **2015**, *4*, 261–283. [CrossRef]
50. Li, L.; Lin, X.; Negenborn, R.R.; De Schutter, B. Pricing intermodal freight transport services: A cost-plus-pricing strategy. In Proceedings of the International Conference on Computational Logistics, Delft, The Netherlands, 23–25 September 2015; pp. 541–556.
51. Liu, D.; Yang, H. Joint slot allocation and dynamic pricing of container sea–rail multimodal transportation. *J. Traffic Transp. Eng.* **2015**, *2*, 198–208. [CrossRef]
52. Van Riessen, B.; Negenborn, R.R.; Dekker, R. The Cargo Fare Class Mix problem for an intermodal corridor: Revenue management in synchromodal container transportation. *Flex. Serv. Manuf. J.* **2017**, *29*, 634–658. [CrossRef]
53. Wang, Y. A Reactive Decision Support System for Intermodal Freight Transportation. Ph.D. Thesis, CIRRELT, Montreal, QC, Canada, 2017.
54. Combes, F. On Shipment Size and Freight Tariffs Technical Constraints and Equilibrium Prices. *J. Transp. Econ. Policy* **2013**, *47*, 229–243.
55. Brotcorne, L.; Labbé, M.; Marcotte, P.; Savard, G. Joint design and pricing on a network. *Oper. Res.* **2008**, *56*, 1104–1115. [CrossRef]
56. BRAIN-TRansversal Assessment of Intermodal New Strategies. BELSPO Project. 2014. Available online: http://www.brain-trains.be/ (accessed on 6 September 2018).
57. Bracken, J.; McGill, J.T. Mathematical programs with optimization problems in the constraints. *Oper. Res.* **1973**, *21*, 37–44. [CrossRef]
58. Stackelberg, H.V. *Theory of the Market Economy*; Oxford University Press: Oxford, UK, 1952.
59. Colson, B.; Marcotte, P.; Savard, G. An overview of bilevel optimization. *Ann. Oper. Res.* **2007**, *153*, 235–256. [CrossRef]
60. Hansen, P.; Jaumard, B.; Savard, G. New branch-and-bound rules for linear bilevel programming. *SIAM J. Sci. Stat. Comput.* **1992**, *13*, 1194–1217. [CrossRef]
61. Vicente, L.; Savard, G.; Júdice, J. Descent approaches for quadratic bilevel programming. *J. Optim. Theory Appl.* **1994**, *81*, 379–399. [CrossRef]
62. Dempe, S. *Foundations of Bilevel Programming*; Springer Science & Business Media: Berlin, Germany, 2002.
63. Vicente, L.N.; Calamai, P.H. Bilevel and multilevel programming: A bibliography review. *J. Glob. Optim.* **1994**, *5*, 291–306. [CrossRef]
64. Migdalas, A. Bilevel programming in traffic planning: Models, methods and challenge. *J. Glob. Optim.* **1995**, *7*, 381–405. [CrossRef]
65. Clegg, J.; Smith, M.; Xiang, Y.; Yarrow, R. Bilevel programming applied to optimising urban transportation. *Transp. Res. Part B Methodol.* **2001**, *35*, 41–70. [CrossRef]
66. Yamada, T.; Russ, B.F.; Castro, J.; Taniguchi, E. Designing multimodal freight transport networks: A heuristic approach and applications. *Transp. Sci.* **2009**, *43*, 129–143. [CrossRef]

67. Pazour, J.A.; Meller, R.D.; Pohl, L.M. A model to design a national high-speed rail network for freight distribution. *Transp. Res. Part A Policy Pract.* **2010**, *44*, 119–135. [CrossRef]
68. Du, L.; Peeta, S.; Wei, P.; Sun, D. A quantitative and systematic methodology to investigate energy consumption in multimodal transportation systems. *Transp. Res. Board Annu. Meet.* **2014**, *4*, 229–256. [CrossRef]
69. Labbé, M.; Marcotte, P.; Savard, G. A bilevel model of taxation and its application to optimal highway pricing. *Manag. Sci.* **1998**, *44*, 1608–1622. [CrossRef]
70. Brotcorne, L.; Labbé, M.; Marcotte, P.; Savard, G. A bilevel model and solution algorithm for a freight tariff-setting problem. *Transp. Sci.* **2000**, *34*, 289–302. [CrossRef]
71. Labbé, M.; Violin, A. Bilevel programming and price setting problems. *4OR* **2013**, *11*, 1–30. [CrossRef]
72. Bouhtou, M.; Grigoriev, A.; Hoesel, S.V.; Van Der Kraaij, A.F.; Spieksma, F.C.; Uetz, M. Pricing bridges to cross a river. *Naval Res. Logis.* **2007**, *54*, 411–420. [CrossRef]
73. Van Hoesel, S. An overview of Stackelberg pricing in networks. *Eur. J. Oper. Res.* **2008**, *189*, 1393–1402. [CrossRef]
74. Yan, H.; Lam, W.H.K. Optimal road tolls under conditions of queueing and congestion. *Transp. Res. Part A Policy Pract.* **1996**, *30*, 319–332. [CrossRef]
75. Wang, J.Y.; Ehrgott, M.; Dirks, K.N.; Gupta, A. A bilevel multi-objective road pricing model for economic, environmental and health sustainability. *Transp. Res. Procedia* **2014**, *3*, 393–402. [CrossRef]
76. Sheffi, Y. Urban transportation networks: Equilibrium analysis with mathematical programming methods. In *Traffic Engineering Control*; Prentice-Hall: Upper Saddle River, NJ, USA, 1985.
77. Crainic, T.G.; Florian, M.; Guelat, J.; Spiess, H. Strategic Planning of Freight Transportation: STAN, an Interactive-Graphic System. *Transp. Res. Rec.* **1990**, *1283*, 97.
78. Jourquin, B. Un Outil D'analyse Économique des Transports de Marchandises Sur des Réseaux Multi-Modaux et Multi-Produits: Le réseau Virtuel, Concepts, Méthodes et Applications. Ph.D. Thesis, Facultés Universitaires Catholiques, Mons, Belgium, 1995.
79. Jourquin, B.; Beuthe, M. Transportation policy analysis with a geographic information system: The virtual network of freight transportation in Europe. *Transp. Res. Part C Emerg. Technol.* **1996**, *4*, 359–371. [CrossRef]
80. De Jong, G.; Vierth, I.; Tavasszy, L.; Ben-Akiva, M. Recent developments in national and international freight transport models within Europe. *Transportation* **2013**, *40*, 347–371. [CrossRef]
81. Crevier, B.; Cordeau, J.F.; Savard, G. Integrated operations planning and revenue management for rail freight transportation. *Transp. Res. Part B Methodol.* **2012**, *46*, 100–119. [CrossRef]
82. Andersen, J.; Crainic, T.G.; Christiansen, M. Service network design with asset management: Formulations and comparative analyses. *Transp. Res. Part C Emerg. Technol.* **2009**, *17*, 197–207. [CrossRef]
83. Brotcorne, L.; Marcotte, P.; Savard, G.; Wiart, M. Joint Pricing and network capacity setting problem. In *Advanced OR and AL Methods in Transportation*; Publishing House of Poznan University of Technology: Poznan, Poland, 2005.
84. Baumol, W.J.; Vinod, H.D. An inventory theoretic model of freight transport demand. *Manag. Sci.* **1970**, *16*, 413–421. [CrossRef]
85. Sheffi, Y.; Eskandari, B.; Koutsopoulos, H.N. Transportation mode choice based on total logistics costs. *J. Bus. Logist.* **1988**, *9*, 137.
86. Vieira, L.F.M. The Value of Service in Freight Transportation. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 1992.
87. Ben-Akiva, M.; Meersman, H.; Van de Voorde, E. Recent developments in freight transport modelling. In *Freight Transport Modelling*; Emerald Group Publishing Limited: Bingley, UK, 2013; pp. 1–13.
88. Ben-Akiva, M.E.; Lerman, S.R. *Discrete Choice Analysis: Theory and Application to Travel Demand*; MIT Press: Cambridge, MA, USA, 1985; Volume 9.
89. Ortúzar, J.D.D.; Willumsen, L.G. Modal split and direct demand models. In *Modelling Transport*, 4th ed.; John Wiley & Sons: New York, NY, USA, 2011; pp. 207–225.
90. Wardrop, J.G.; Whitehead, J. Some theoritical aspects of road traffic research. *Proc. Inst. Civ. Eng.* **1952**, *1*, 767–768.
91. Patriksson, M. *The Traffic Assignment Problem: Models and Methods*; Courier Dover Publications: Mileona, NJ, USA, 2015.

92. Marcotte, P. Network design problem with congestion effects: A case of bilevel programming. *Math. Programm.* **1986**, *34*, 142–162. [CrossRef]
93. Slack, B. Satellite terminals: A local solution to hub congestion? *J. Transp. Geogr.* **1999**, *7*, 241–246. [CrossRef]
94. Samuelson, P.A. Spatial price equilibrium and linear programming. *Am. Econ. Rev.* **1952**, *42*, 283–303.
95. Dafermos, S. Isomorphic multiclass spatial price and multimodal traffic network equilibrium models. *Reg. Sci. Urban Econ.* **1986**, *16*, 197–209. [CrossRef]
96. Harker, P.T. Multiple equilibrium behaviors on networks. *Transp. Sci.* **1988**, *22*, 39–46. [CrossRef]
97. Lee, H.; Song, Y.; Choo, S.; Chung, K.Y.; Lee, K.D. Bi-level optimization programming for the shipper-carrier network problem. *Clust. Comput.* **2014**, *17*, 805–816. [CrossRef]