

An integrated freight transportation modelling framework

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1. Introduction

Most human activities require, either directly or indirectly, the production and consumption of certain quantities of goods and services. Moreover, in almost all cases, there is a geographical and temporal distance between the production and the consumption of these goods and services, distance that increases with the level of complexity of the human society. Hence, producers require *transportation* services to move raw materials and intermediate products, and to distribute final goods in order to meet customer demands. *Shippers*, which may be the producers of the goods or some intermediary firm (e.g., freight forwarders and brokers), thus generate the *demand* for transportation.

The demand for transportation services is met by the *supply* of transportation infrastructure and services. *Carriers* supply transportation services. Railways, ocean shipping lines, motor-carrier companies, and postal services are examples of carriers. Considering the type of services they provide, seaports, intermodal platforms, and other such facilities may be described as carriers as well. Governments contribute the infrastructure: roads and highways, as well as significant portions of ports, internal navigation, and rail facilities. Carriers may contribute to the infrastructure as well, as illustrated by most railway companies.

It is noteworthy that these are not linear, sequential processes. Rather, strong feedback loops exist among the demand, the supply, and the regulatory, economic, technological, and political environment of transportation. Thus, for example, enhancing the transportation infrastructure or services may contribute to create new economic opportunities for a given region thus modifying the demand, increasing the total volume, changing the relative importance of one product group in relation to others, etc.

In the past, most important decisions on transportation infrastructure or services did not, however, rely on a comprehensive analysis of the freight multimodal transportation system involved and of the possible impact of the contemplated action or policy on its behaviour and performance. This is in sharp contrast to the state-of-the-practice relative to person transportation, particularly within urban zones, which routinely involves the use of sophisticated analysis tools derived from research performed in university laboratories and research centres. Moreover, each of the basic transportation modes, road, rail, air, navigation and ports, was often considered separately, particularly by the organizations that supervise and regulate the transportation industry. We must also consider the fact that the availability of the data, at a given aggregation level, is far more restricted in freight transportation [3] [19] [10]. This is partly due to confidentiality reasons.

The situation has, however, significantly evolved in recent years: the *multimodal* nature of freight transportation is now generally acknowledged, as well as the fact that it forms a *system*. The former implies that one must consider in more details the variety of ways to supply transportation services. Modes, for example, may be identified not only by the infrastructure they use, but also by the service type (e.g., unit, intermodal, or general trains), the organization (e.g., Less-Than-Truckload carriers operating hub-and-spoke networks with consolidation versus Full-load motor carriers offering customized services), vehicle type or product (e.g., container ships, tankers, general cargo ships), the scope of the firm (e.g., coastal navigation versus long-haul maritime shipping), and so on.

Complex relations exist between the various transportation modes in a given region, as well as between these and their customers. Transportation services of different modes (in the broader sense of the term) and

owners share the same infrastructure and compete for its capacity. Moreover, this sharing and competing often extends to passenger transportation.

From a customer perspective, the movement of goods often requires the combined use of several modes. Road and rail, and ocean navigation combined to road and rail are two of the more frequently used transportation mode combinations. The utilization of particular loading units (the *containers*) often facilitates the operation of such *intermodal* transportation systems. Customers have also requirements in terms of cost and quality of service that directly impact the selection of a transportation mode (witness the large market share of trucking) and the behaviour of the entire system (e.g., the congestion of the road network, particularly around large urban zones). Intermodal terminals provide transfer services between two, or more, different modes.

There is thus a need to analyze and plan multimodal freight transportation as an integrated system within the region considered. An integrated, multimodal view of transportation is required to analyze the system in order to understand and predict its behaviour and that of its components, considering various social, economic, and technological trends and forecasts. An integrated view is also required to plan the sustainable development of an efficient transportation freight system by measuring the impact of contemplated investments or policies on it and its users.

Strategic national/regional planning models must provide the means to efficiently and correctly identify and represent the fundamental components of a multimodal transportation system and their interactions. A limited number of such strategic planning models (and software) have been proposed and implemented in the 1980's (e.g., *STAN* [9]). While useful, these older models and software do not fully address the range of issues and concerns (depicted in [3] [18]), that planners must now consider. Furthermore, as far as we know, no systematic procedure for assessing the performance of national/regional freight transportation models currently exists, except the one from Nijkamp et al. [19] that compares some discrete choice models and a neural network model. The objective of this paper is to make significant progress towards the development of a new generation of strategic national/regional freight transportation models by providing two stepping stones along this path: first, a comprehensive survey of the main issues and challenges to be addressed in these new models; second, a proposal for a framework to be used in the comparative analysis and assessment of such models.

This paper is organized as follows. In section 2, we briefly review existing models in the area of freight transportation. Issues and challenges to be addressed in the new generation of models are discussed in section 3. A short description of the comparative assessment framework follows in section 4.

2. Freight transportation models

As mentioned above, national/regional freight transportation planning models must provide the means to efficiently and correctly represent all the fundamental components of a multimodal transportation system, namely, demand, supply, performance measures and decision criteria, and their interactions.

The modelling of demand takes into account the economic activities of a region: production, consumption, imports, exports. In most cases the output of such a model is a series of *O-D demand matrices*, one per product, specifying the volumes to be moved from one zone to another. These matrices have often to be built from an *input/output* model of the corresponding country, or from national statistics and survey of particular industrial sectors, and in this case data have to be reconciled as precisely as possible but this work can be very tedious. The *spatial price equilibrium* model of Friesz et al. [7] and its *generalized* variant [11] belong to this category of models, but they provide a complete prediction of interregional flows. Economic concepts provide relationships between flows, prices of products and transportation costs, but the results are excessively aggregate and flows are "polarized" towards few O-D pairs and zero towards other, contrary to all empirical evidence.

Classical supply modelling involves network representations. Guélat et al. [9], Crainic and Kim [2], Jourquin

and Beuthe [14], and Jourquin and Limbourg [15] use a sophisticated one, in which there are as many links as possible transportation modes between each pair of nodes of the network, and the intermodal transfers are also taken into account as links between fictitious *exploded* nodes. Flow variables and various cost functions are associated to the links.

Friesz et al. have presented in [8] a two-tier model, which consists in using two network representations sequentially. Shippers work on the first one which is aggregated with respect to them and deals with their *perception* of the system. Carriers only work on their physical subnetwork and minimize their total costs. Hurley and Petersen [12] reused this approach to deal with varying tariffs of the carriers. In practice this approach is limited to a small number of shippers and carriers [6], and this is the same thing for more complete formulations such as the one of Fernandez et al. [4]. This is to be contrasted with the system-wide model of [9], in which shippers' behaviour is assumed to be reflected in the origin/destination matrices used and the specification of the mode choice.

The next step is to assign the O-D matrices to the supply network model by using route choice mechanisms and network optimization techniques. The results of such an assignment model, product flows and performance measures, reflect the simulated behaviour of the transportation system and form part of the input to a wide array of analyses, including cost-benefit, as well as demand modelling and analyses. Authors have proposed several classes of assignment models, based on the well-known Wardrop's principles [21], which rely on different assumptions regarding user behaviour. Wardrop's first principle, so-called *user optimization*, consists in assuming that each unit of demand corresponds to exactly one decision maker who makes decision for his/her sole benefit. The opposite approach, called *system optimization* and embodied in Wardrop's second principle, consists in assuming that all units of demand are assigned on the network in order to optimize a single, global objective function.

The user optimization approach, particularly adapted for passenger transportation systems, provides the so-called Network Equilibrium Model (NEM) at the global level. This model can be formulated as several well known mathematical problems, such as *variational inequality*, *non-linear complementarity*, and *fixed point* problems, see [20], [13], [5], [1]. Concerning the system optimization approach, an intuitive decomposition algorithm was implemented by Guélat et al. [9] in the *STAN* system and provided rather good solutions in practical experiments. The algorithm developed for this problem exploits the natural decomposition by product and results in a Gauss-Seidel-like procedure. Note that this system optimal assumption can be adapted at an individual level, considering average or marginal cost functions on the arcs. This system is now used in many organizations over several countries in the world.

With regards to the precedent models, the resolution is often sequential, that is to say that demand and supply models are established, and then the assignment procedure is performed. In the *random utility* models, such as presented by Cascetta [1] or Nielsen [17], some feedback is proposed, particularly for the demand model. The distribution of this latter model is given by the classical *Logit* model. Unfortunately, the variables of the random utility model correspond to the paths of the transportation network, and their huge number in freight transportation may prevent from efficient applications on real-life data. Jourquin and Limbourg [15] have recently shown that the solutions of equilibrium assignment techniques do not differ very significantly from the one obtained by a simple all-or-nothing assignment. Finally, we just mention here a specific equilibration procedure [16], an alternative procedure [10], and the *econometric* models; the interested reader should refer to the survey of Harker in [11], and to the aggregate and disaggregate models of Winston [22].

3. Issues and challenges

As far as we know, the scientific and practical knowledge of demand modelling is very high. With regards to supply modelling and assignment/simulation, the knowledge gap is large. In the definition of the O-D matrices, a certain aggregation of the decision makers, with their own specific characteristics, in each O-D point is unavoidable. The level of this aggregation is rarely well defined and taken into account. It turns out that in actual freight transportation systems, a lot of decision makers are hidden in this latter aggregation.

In fact, it is often difficult to ascertain which actors (shippers, carriers, brokers) are actually making the ultimate decisions with respect to mode choice and routing. Furthermore, the situation is usually far more complicated, since some shippers own and operate their transportation fleet, other are particularly linked with specific carriers, or other involve systematically brokers to convey their products. Once again, it is particularly difficult to identify the decision makers in such cases. This lack of clear definition of the key stakeholders in a given setting has important, and unsettling, consequences on the choice of the proper “cost” elements one should consider in a model: should one base transportation decisions on tariffs proposed by carriers to shippers or rather on the actual costs incurred by carriers?

Another major concern is the fact that in strategic models, the planning horizon is normally quite long. This implies an aggregation of flows and capacities with respect to the time dimension. This aggregation hides variations in flows and capacities, thus making it difficult to identify situations of congestion and, as a consequence, to account for the resulting delays.

The advent of new technologies and business practices, such as Intelligent Transportation Systems, e-logistics and integrated logistical chain management, cannot be ignored: future models for strategic freight transportation will have to carefully and comprehensively address these new realities and measure their impact. They should also integrate capabilities to represent and assess tradeoffs between “costs” and other performance measures (e.g., travel or delivery time, environmental impacts, energy consumption, etc.), relative impacts of integrated logistics chains, technology changes for transportation and intermodal transfer facilities, environmental impacts, etc.

The implementation of a comparison framework, described in the next section, aims to contribute towards filling this knowledge gap and answering some of these relevant issues.

4. Framework for a comparison study

The objective of this comparative framework is to assess systematically alternative modelling decisions by observing the results produced by various models for sets of “representative” planning *scenarios*. These scenarios are defined around *case studies* that define in as much detail as possible (i.e., if possible in a fully disaggregate fashion) settings for freight transportation. More precisely, each case study is defined by a *territory* on which a number of freight consumers, producers and carriers are observed. The latter provide the transportation network and the different modes, facilities, and the eventual capacities of each of them. The two others indicate what sort of products are moved and define the volumes and the timing of shipments. External zones are also considered for imports and exports.

With regards to these elements, atomic data defined for individual shippers and carriers are first processed to build the demand and supply models, with respect to four dimensions of aggregation:

- The first step in demand modelling revolves around the division of the territory under study into a number of *zones* to which demand will be associated (in fact, each demand will be defined as going from some origin zone to some destination zone). The number of these zones is of course inversely proportional to the demand density and to the aggregation level.
- The second step in demand modelling deals with the specification of the number of products to be considered. It is indeed impossible to deal with a complete and detailed description of all the products that exist in reality and must one resort to some grouping (aggregation) of commodities to define the products considered in a model or study. This step yields one O-D demand matrix for each product defined.
- The supply model defines the transportation network with regards to the various identified modes. Once again, the number of modes that one decides to consider implies an aggregation of the individual carriers in a few groups. For instance, one could decide to consider all truck transportation as a single

mode or, conversely, to distinguish between truckload trucking and less-than-truckload trucking, or between private truck fleets and common carriers, etc.

- The fourth dimension of aggregation is temporal, as mentioned in the previous section. One must set the number and especially the length of the observation periods considered, in which flow variations may impact on observed delays because of congestion.

In our framework, each scenario will be defined by specifying a level for each of the four dimensions of aggregation. Therefore, for each case study, there will be several scenarios that will be considered in the framework. Each scenario will be studied under the assumptions described earlier for user behaviour (user-optimized, system-optimized, etc.) through their associated assignment procedures. Various performance measures (in particular with respect to flows, costs and delays) will be recorded in each case and compared with the original data of the case study. This approach will allow us to assess both the impact of the aggregation levels (by comparing the results obtained by any given assignment procedure for different scenarios) and the impact of the assignment procedures (by comparing the various results obtained for a given scenario), as well as any cross-effects (for instance, it may turn out that a given assignment procedure performs better at higher levels of aggregation, while others are more adequate when dealing with rather disaggregate data).

These comparisons will also point out to any refinement that would be required in the overall modelling. For instance, the user's behaviour concerning one product could be made user-optimized whereas the rest would remain system-optimized; or the most important shippers, as they have a lot of influence on the assignment, could have specific products defined for them to allow a better accounting of their shipments in the assignment. This should help us to define models that simulate much more precisely the global behaviour of the transportation system.

The case studies used as inputs to the framework have to be relevant benchmark instances. They are indeed a key element of the framework with respect to the comparisons and analyses to be performed. They may also be instrumental in highlighting the exact data requirements for the analysis tool when used for specific purposes, e.g., the difficulty to collect some data at a given aggregation level.

As for the output, the performance measures to be collected and analyzed must be carefully defined. Apart from the obvious measures related to volumes, costs and delays, we aim to assess for each scenario environmental impacts and relationships between the performance of the transportation system and that of specific supply chains. We also want to observe how much the growth in the deployment of Intelligent Transportation Systems and the electronic society will impact the planning and operations of freight transportation, e.g., the control and coordination of operations in real-time.

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