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Abstract. This paper focuses on the analysis and planning of multimodal, multiproduct transportation systems at the international, national, and regional levels, where the movements of several commodities through the transportation networks and services of several carriers are considered simultaneously. The main questions relate to the evolution of a given transportation system and its response to various modifications of its socio-economic, regulatory, and technological environment. These questions are often part of cost-benefit analyses and comparative studies of policy and investment alternatives with broad and significant impact, not only on the transportation system but also on the economy and society as a whole. Canadian researchers have contributed significantly to this field. They have not only developed models and methods to perform national planning activities, but also transferred these results to practice through decision-support software commercially distributed worldwide. This paper presents an overview of national planning issues together with the main methodological approaches proposed in the literature, reviews the contribution of Canadian researchers to the science and practice in this field, and examines current challenges and research trends.

Keywords. National and regional planning, multimodal and multiproduct transportation.

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1 Introduction

Transportation is a vital activity for the development, organization, and operations of society. One is not overstating the case by claiming that the development of transportation, in terms of geographic coverage, technology, efficiency, structure, and organizational principles, is closely related to the development of society and civilizations throughout history. There is hardly any social or economic activity that does not involve transportation and is not tributary to the efficient, smooth, and timely movement of people, goods, and information.

It is thus not surprising that significant research efforts have been and continue to be dedicated to issues related to the analysis, planning, management, and operations of transportation systems. The Canadian operations research community is at the forefront of these efforts and its contributions are many, varied, and important. Applications relate to passenger and freight transportation systems, ranging in scope from a local neighbourhood to an entire city or region, from a given pick-up and delivery zone to a specific inter-city corridor, from the transportation system of a country to that of a continent. Applications cover all modes of transportation and all planning levels, from the long term strategic view of the system, through tactical planning and allocation of resources, to short term planning of operations and their real-time dynamic management and control. Significant Canadian contributions have been made to the fundamental models and algorithms supporting all these activities and many of these contributions have been transferred to practice through decision-support systems.

This paper focuses on the analysis and planning of multimodal, multiproduct transportation systems. The focus of these models and methods is broad: they apply to strategic planning issues at the international, national, and regional levels, where the movements of several commodities through the transportation networks and services of several carriers are considered simultaneously. The main questions address the evolution of a given transportation system and its response to various modifications in its environment, e.g., transportation infrastructure, population distribution, patterns and volumes of production, consumption, and trade, policies and legislation, technology, and so on and so forth. These questions are often part of cost-benefit analyses and comparative studies of policy and investment alternatives with broad and significant impact not only on the transportation system but also on the economy and society as a whole.

Canadian researchers have contributed significantly to this field. They have not only developed models and methods to perform national planning activities, but also transferred these results to practice through decision-support software commercially distributed worldwide. The objective of the paper is therefore to present an overview of national planning issues together with the main methodological approaches proposed in the literature, to review the contribution of Canadian researchers to the science and practice in this field, and to discuss current challenges and research trends.

The remainder of this paper is organized as follows. Section 2 briefly reviews a number of fundamental concepts related to transportation systems and planning (for more detailed presentations, one may consult Crainic, 2003; Crainic and Kim, 2007; and Macharis and Bontekoning, 2004). Section 3 is dedicated to the description of national planning scope, goals, and main activities, as well as to a succinct review of the associated literature. The STAN model, planning method, and software system is described in Section 4, and we conclude in Section 5.

2 Transportation Systems

Movements of people and goods derive from, support, and impact the activities of society. The demand for freight transportation thus derives from the interplay between producers and consumers of goods and services. Producers require transportation services to move raw materials and intermediate products, and to distribute final goods in order to meet customer demands. The demand for transportation services is met by private firms, and by public and semi-public organizations that supply transportation infrastructure and services at various levels of service level and price. Governments supply a significant part of the infrastructure: roads and highways, as well as significant portions of ports, internal navigation structures, and rail facilities. Governments also regulate and tax the industry. The interactions among production and consumption activities, as well as between the corresponding transportation demand and supply, result in the traffic flows of people, goods, vehicles, and convoys one may observe in any given region.

It is noteworthy that, as illustrated in Figure 1, these processes are not straightforward and sequential. 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 in a given region may contribute to create new economic opportunities resulting in modifications in the relative importance of groups of products consumed and produced within a region and to increase volumes exchanged within the region as well as with other regions. Such modifications to the region's demand for transportation will then most probably result in new services being offered and, eventually, in new investments in infrastructure. Based on such observations, governments and international development agencies routinely use investments in transportation infrastructure as an instrument of regional development.

The organizations that generate the demand for freight transportation are usually identified as *shippers*, which may be the producers of the goods or some intermediary firm, e.g., freight forwarders, third-party logistics enterprises, and brokers. Shippers have requirements in terms of cost, time, and quality of service, e.g., on-time delivery reliability. These criteria 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 in and around large urban zones. Shippers decide how much of a given product to send, when to send it, and how to ship it: what mode and carrier or combination thereof,

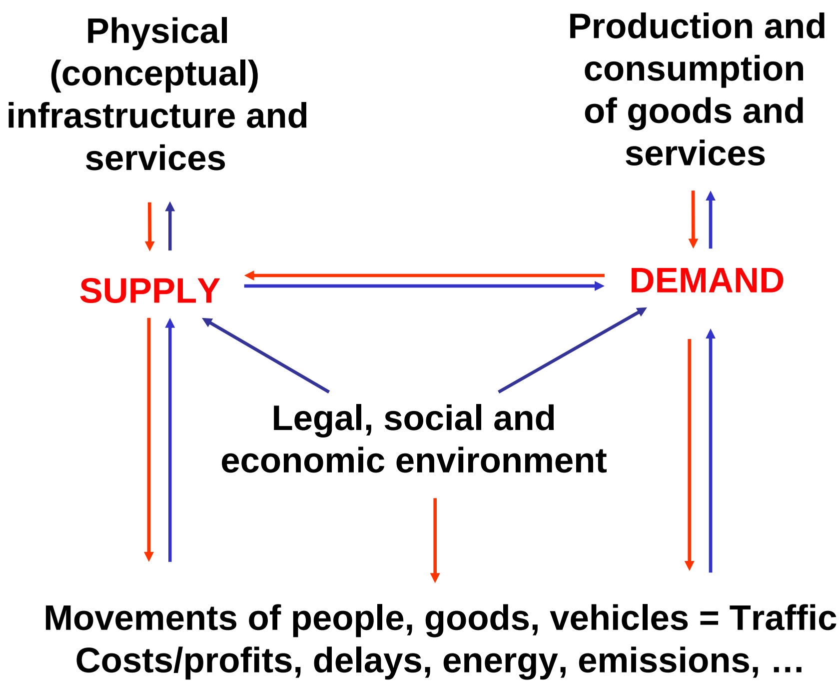

Figure 1: Transportation and society

the latter corresponding to demand for intermodal transportation. Indeed, 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 intermodal transportation systems. People use similar criteria of cost and time when selecting how to undertake their trips. Passenger transportation demand thus results from the combined personal decisions on when and how to travel to everyone's particular destination.

Carriers supply transportation services. Railroads, maritime shipping lines, motor-carrier companies, and postal services are examples of carriers. They may contribute to the infrastructure as well, as illustrated by the North-American railroad companies. Carriers are generally classified into one of two main types: *consolidation*-transportation systems, where one vehicle or convoy serves to move freight for different customers with possibly different initial origins and final destinations, and *customized*-transportation carriers that provide dedicated service to each particular customer. Within passenger transportation, the former corresponds to public transport by bus, train, or plane, while the latter encompasses transport by private means, car, bicycle, or taxi.

Truckload trucking offers a typical example of customized transportation for freight transportation (e.g., Powell, Bouzaïene-Ayari, and Simaõ, 2007). When a customer calls, the dispatcher assigns a truck and a driver (or driving team for very long movements) to the corresponding transportation task. The truck moves to the customer-designated location, is loaded, and then moves to the specified destination to be unloaded. The driver then calls the dispatcher to give its position and request a new assignment. The dispatcher may indicate a new load, ask the driver to move empty to a new location where demand should appear in the near future, or have the driver wait and call later. Maritime navigation services provided by for-hire ships belong to the same carrier type (Christiansen *et al.*, 2007).

Freight consolidation transportation is performed by Less-Than-Truckload (LTL) motor carriers, railways, ocean shipping lines, regular and express postal services, etc. Freight transportation in some countries where a central authority more or less controls a large part of the transportation system also belongs to this category. Consolidation transportation carriers and fundamentally all intermodal transportation systems are organized as so-called *hub-and-spoke* networks (Crainic and Kim, 2007). In such systems, service is offered between certain origin-destination points, the local or regional terminals. Their number is significantly larger than the number of direct, origin to destination services operated by the carrier. Consequently, and to take advantage of economies of scale, low-volume demands are moved first to an intermediate point — a consolidation terminal or a hub — such as an airport, a seaport container terminal, a rail yard, or an intermodal platform. At a hub, traffic is consolidated into larger flows that are routed to other hubs by high frequency, high capacity services; more than one service, of possibly different modes, may be operated between hubs. Lower frequency services, often operating smaller vehicles, are used between hubs and origin-destination terminals. When the level of demand justifies it, high frequency, high capacity services may be run between a hub and a regional terminal or between two regional terminals.

Terminals are an essential component of transportation systems. For passenger transportation, rail stations, bus terminals, and airports provide access to mass-transportation modes. All consolidation-type freight carriers, railroads, LTL motor carriers, intermodal ocean navigation lines, etc., make an extensive use of terminals to sort and consolidate cargo into vehicles and, eventually, vehicles into convoys for increased efficiency. Rail trains, barge trains, and multi-trailer assemblies illustrate the latter case. Intermodal transportation could not exist without intermodal terminals that provide transfer services between two, or more, different modes. Terminals, on the other hand, imply additional handling of cargo and vehicles, resulting in delays, costs, and additional risk of damage. They also have limited capacity, which contributes to the delays experienced by cargo and vehicles.

Various measures are associated to the flows of vehicles and cargo and give indications on the performance level of the transportation system, e.g., the expected number of vehicles using a given road during the morning rush hour and the corresponding level of congestion, the average number of container ships waiting for access to port facilities, the total number of ton-kilometres of freight moved by a given train type, etc. Many of these system performance measures, particularly those linked to the capacity of the infrastructure or services, also translate into efficiency measures for the users of the system: average or total travel time between given origin and destination points in the network, average time required to pass through given intermodal facilities, total cost of transportation, and so on.

Each individual or organization that is part of the transportation system reacts individually to these measures and adjusts its operations accordingly (e.g., shippers may move to rail to avoid high environmental taxes on road-based transportation). These decisions and eventual modifications in shipping or operational policy will impact the entire system, by for example modifying the traffic conditions experienced by the other participants, which will then modify their behaviour resulting in further changes in transport conditions, and so on. Observed traffic and performance measures are thus the result of an *equilibrium* between the decisions of many participants reflecting their own decision criteria and general behaviour as well as the condition of the transportation system at the time the observations are made.

The transportation sector in any given region forms thus an integrated dynamic *system* and its analysis and planning should be undertaken accordingly. This is the scope of the so-called national or regional planning models and methods, which aim to represent and analyze the system in order to understand and predict its behaviour and that of its components, considering various social, economic, policy, and technological trends and forecasts.

3 National Planning

National planning methodologies — models, methods, and instruments — aim to build a comprehensive representation of a multimodal transportation system, its main components and their interactions. Their goal is to achieve a sufficiently good simulation of the global behaviour of the system to offer a correct representation of the current situation, and to serve as an adequate analysis tool for planned or forecast scenarios and policies concerning modifications in

- infrastructure through construction of new modal — roads, rail tracks, pipelines, waterways — or intermodal — maritime and river ports, land intermodal platforms and terminals, airports — facilities and expansion of existing ones. Infrastructure is also modified through the abandon of existing facilities, e.g., regional rail lines;
- technology. On the hardware side, this includes new or enhanced vehicular and infrastructure technologies such as new traction modes, improved engines, intelligent cruise control and other advanced driving assistance systems, larger ships, more efficient loading and unloading equipment, etc. Technology also includes a software component, in particular Intelligent Transportation Systems for carriers, advanced fleet management, for example, terminals, e.g., enhanced systems to manage containers in port and rail yards, and infrastructure, e.g., advanced clearing mechanisms at border control points;
- socio-economic characteristics of the region following changes in the population distribution within the region and the patterns and volumes of production, consumption,

and trade within the region as well as with external zones, due to urbanization and various other factors, such as the exhaustion of resources, industry relocation, the creation of special economic zones, the emergence of new economic players (e.g., China, India, etc.), and so on;

- policy and regulation from labour conditions to environment-motivated taxation, such as energy consumption taxes or dynamic demand management, and regulation (e.g., obligation to use rail to transit through certain region), from inter-provincial trade corridors to multi-state free trade agreements, from tariff barriers to security-related regulation, and so on.

National planning models represent flow volumes by commodity and transportation mode, as well as associated performance measures, defined on a network representation of the transportation system. The methods need to be flexible and adaptable to the scope of studies encompassing a broad range of geographical dimensions, from the level of a country or a group of countries, to that of a province, region, or corridor. They should provide the tools to analyze issues identified "now", as well as to build new evaluation procedures as the need arises. The modelling framework should be tractable and produce easily accessible results. No single formulation may address such a broad scope, and thus, a national planning methodology is typically a set of models and procedures. The three main components of such a methodology are:

1. *supply modeling* to represent the transportation modes, infrastructure, carriers, services, and lines; vehicles and convoys; terminals and intermodal facilities; capacities and congestion; economic, service, and performance measures and criteria;

2. *demand modeling* to capture the product definitions, identify producers, shippers, and intermediaries, and represent production, consumption, and zone-to-zone (region-to-region) distribution volumes, as well as *mode choices* for transportation. Relations of demand and mode choice to the performance of economic policies and transportation system performance are also addressed here;

3. *assignment* of multicommodity flows (from the demand model) to the multimode network (the supply representation). This procedure simulates the behaviour of the transportation system and its output forms the basis for the strategic analyses and planning activities. The assignment methodology must therefore be both precise in reproducing current situations and sufficiently general to produce robust analyses of future scenarios based on forecast data;

4. a number of *data-manipulation tools* for the analysis, fusion, validation, and updating of information, as well as result-analysis capabilities for, e.g., cost-benefit, environmental impact, and energy consumption policy analyses, complement the methodology.

Figure 2 presents the classical combination of these models and methods into the so-called *four-step planning* method. Such an approach starts from the economic, demographic, social,

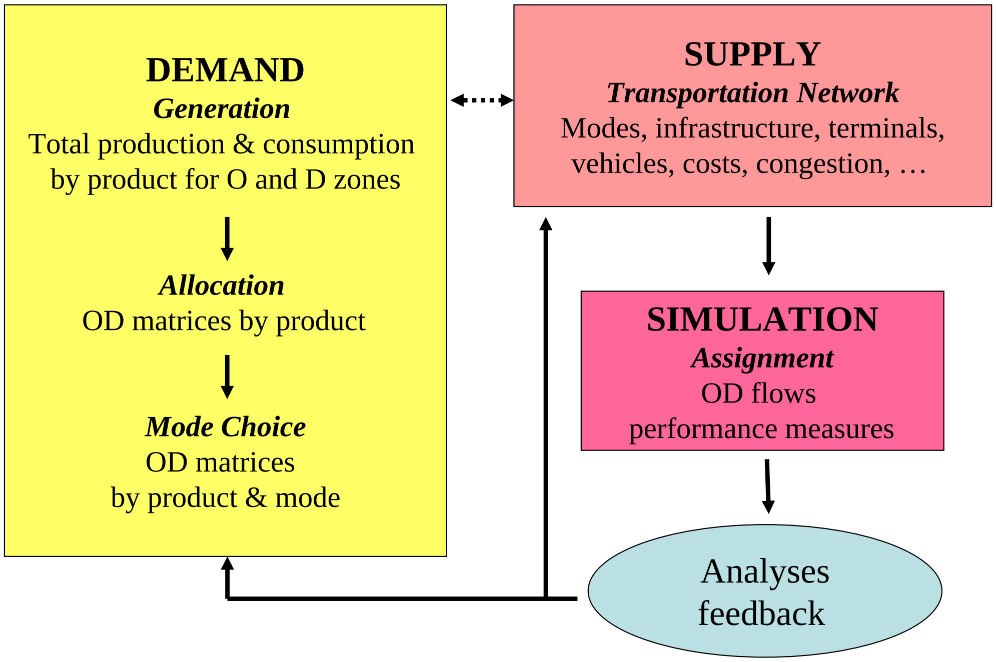

Figure 2: Four-step transportation planning methodology

and political current or forecast data in a given region. The initial step is to determine the geographical division of the region into zones and to identify the product groups to be considered. Notice that all activity — production, consumption, shipping and reception of cargo — within a zone is represented in aggregated form associated to a single point, the so-called *centroid* of the zone. This step thus reflects, and specifies for all the other steps of the planning procedure, the degree of aggregation of the data available for the region under study.

The product-specific demand is then generated in two steps: first the total production and consumption volumes (as well as imported and exported volumes, if relevant) and then, the distribution of these quantities among the origin-destination (zone-to-zone) pairs of the region. These phases are called *generation* and *allocation*, respectively. The last step of the demand-generation process corresponds to the determination of the modal choice specifying the set of modes — type of infrastructure and services — that may move the demand of each product and origin-destination pair. The *assignment* step then determines the actual itineraries used to move the demand for each product, each origin-destination pair and each mode choice, thus performing the simulation of the global behaviour of the system given the particular scenario studied.

The last two steps require the definition of the transportation supply in the region, in particular the multi-modal infrastructure and service network available to move the demand and its attributes in terms of costs, travel and terminal operation times, energy consumption or level of emissions, etc. The assignment step also requires the specification of the criteria used to select itineraries and to measure performance, as well as the rules to translate volumes of demand of given products into vehicle and convoy utilization for each transportation mode specified in the corresponding mode-choice set. The actual national planning process is rarely linear, however. Thus, for example, many analyses are usually performed on a given set of supply and demand data, both current and forecast, by varying the parameters (e.g., vehicular technology or system utilization policies) of the future scenarios contemplated. On a more general scale, feedback mechanisms are used to modify the parameters of the demand generation steps, including allocation and mode choice, for future scenarios given the simulated performance of the transportation system.

The prediction of multicommodity freight flows over a multimodal network is an important component of transportation science and has generated significant interest over the years. However, perhaps due to the inherent difficulty and complexity of such problems, the study of freight flows at the national or regional level has not yet achieved full maturity, in contrast to passenger transportation where the prediction of car and transit flows over multimodal networks has been studied extensively and several of the research results have been transferred to practice (Cascetta, 2001; Crainic and Florian, 2006; Florian and Hearn, 1995). The number of applications is increasing, however, and the methodologies used are continuously more comprehensive and sophisticated as illustrated in the survey of national planning projects undertaken in various regions of the world by Crainic, Gendreau, and Kuncyté (2006). In the following, we review the most frequently used methodologies for freight planning and point associated references.

3.1 Demand

The modeling of demand attempts to describe the economic activities of a region, its production, consumption, import and export of goods. For planning purposes, the output of demand models is a series of product-specific demand matrices indicating the volumes to be moved from one zone to another. The process is often completed by the modeling of mode choice, which specifies for each product and origin-destination combination on what set of transportation infrastructure or services the demand may be moved.

A number of countries have developed *input-output* models of their economy which serve to determine the basic production and attraction of goods (Isard 1951; Casceta 2001 and references therein). In order to use an input/output model as a demand model, it is necessary to disaggregate the inputs and outputs by region and zone. This process is complex, and is usually not integrated with a supply representation and assignment procedure. When an input/output model is not available, the initial determination of origin-destination matrices is carried out by using national statistics on production, consumption, imports and exports combined with surveys of particular industrial sectors to complete missing or unreliable information. This process may be tedious since one has to reconcile data from several sources which may be collected by using different geographical subdivisions or inconsistent product definitions. The results of the disaggregated input/output model or the ad hoc estimation procedures serve for the initial computation of origin-destination matrices for each product but without a subdivision by mode.

A second class of models that is well studied for the prediction of interregional commodity flows is the *spatial price equilibrium model* and its variants (Friesz, Tobin, and Harker, 1983; Harker and Friesz 1986a,b; and Harker 1987; see also Florian and Hearn, 1995 and Nagurney, 1999). This class of models determines simultaneously the flows between producing and consuming regions, as well as the selling and buying prices that satisfy the spatial equilibrium conditions. A spatial equilibrium is reached when for all pairs of supply and demand regions with a positive commodity flow, the unit supply price plus the unit transportation cost is equal to the unit demand price; the sum is larger than this price for all pairs of regions with no exchanges. A simple network (bipartite graph) is generally used to represent the transportation system. These models rely to a large extent on the supply and demand functions of producers and consumers, respectively, which are rarely available and quite difficult to calibrate. There are thus relatively few applications of this class of models for the determination of demand by products.

3.2 Mode choice

Mode-choice models aim to describe the set of transportation modes or services that may be used to carry specific products or groups of products. The mode choice definition may be rather general, e.g., petroleum moves by ship and pipeline, extremely specific indicating a particular set of single or multimodal paths for a given product, shipper, and origin-destination pair, or anywhere in between. The level of detail of modal specification need not be the same for all products or inter-zone trade flows. The specification of mode choice may be inferred from historical data and shipper surveys or it may result from a formal description and modeling effort (Winston 1983). The output of this process are either coefficients that indicate how to split the demand of a given origin-destination pair between the paths of a given set, or origin-destination demand matrices with particular sets of allowed modes.

Random utility models, developed and largely used for the analysis and planning of person transportation systems, have been proposed for freight transportation as well, but their use in actual applications is scarce (Cascetta 2001). The huge number of paths that have to be explicitly generated and stored, coupled to the challenge of performing this task for forecast data, may explain this phenomenon. At aggregated levels, mode choices have been specified for particularly important product flows by explicitly surveying the major logistic chains used between pairs of macro-regions.

3.3 Supply representation and assignment

Once modal origin-destination matrices have been developed, the next step is to assign them to the supply network model by using some route choice mechanism. The results of such an assignment model — product flows and performance measures — form part of the input to demand and cost-benefit modeling and analysis.

One class of assignment mechanisms is based again on the application of *random utility models* to the choice of paths defined previously by the mode choice phase. It is noteworthy that the attributes of predefined paths are determined by the state of the network at generation time and are not responsive to assignment results. Thus, for example, congestion conditions are very difficult to represent. Moreover, the utility and choice models have to be calibrated, and all paths have to be generated, for each scenario, which is quite difficult to perform when forecast data is used.

Another class, *network optimization models*, enable the prediction of multicommodity flows over a multimodal network that represents the transportation facilities at a level of detail appropriate for a nation or region. The demand and mode choice are exogenous and intermodal shipments are permitted. Within the specified mode choice, the optimization (assignment) engine determines the best (with respect to the specified network performance measures) multimodal paths for each product and origin-destination pair. The emphasis is on a proper representation of the network and its different transportation modes, the corresponding intermodal transfer operations, the various criteria used to determine the movement of freight, the interactions and competition for limited resources captured through the representation of congestion effects, and the associated estimation of the traffic distribution over the transportation system considered to be used for comparative studies or for discrete time multi-period analyses.

Studies in the 1970s used rather simple network representations (e.g., Jones and Sharp, 1977; Sharp, 1979). Several studies also attempted to extend spatial equilibrium models to include more refined network representations and to consider congestion effects and shipper-carrier interactions. Friesz, Gottfried, and Morlok (1986) present a sequential model which uses two network representations: detailed separate networks for each carrier, and an aggregate, shipper-perceived network. On each carrier network commodities are transported at the least total cost. On the shipper-perceived network, traffic equilibrium principles are used to determine the carriers that shippers choose to move their traffic. This approach was quite successful in the study of logistics of products where a very limited number of shippers and carriers interact and strongly determine the behaviour of the system. A typical example is the coal market between electric utilities in the United States and their suppliers in exporting countries. Friesz and Harker (1985), Harker and Friesz (1986a,b), Harker (1987, 1988), and Hurley and Petersen (1994) present more elaborate formulations. This line of research has not, however, yielded practical planning models and tools yet, mainly because the formulations become too large and complex when applied to realistic situations. For a more detailed review of these efforts see Guélat, Florian, and Crainic (1990) and Crainic, Florian, and Léal (1990).

Models based on more sophisticated representations of the supply network were introduced by a group of Canadian researchers from the Centre for Research on Transportation (CRT) in Montreal in the second half of the 1980s (Florian and Crainic 1989; Crainic, Florian, and Leál 1990; Guélat, Florian, and Crainic, 1990). They proposed a modelling framework of a multimodal network, made up of modes, nodes, links, and intermodal transfers, on which multiple products are to be moved by specific vehicles and convoys between given origin and destination points according to a generalized cost combining several criteria, most notably, cost and time. Later, Jourquin and Beuthe (1996) proposed a methodology based on the same general ideas and used it to perform several research projects in Europe (e.g., Jourquin and Beuthe, 2003, 2006, and Geerts and Jourquin, 2001). We present this Canadian contribution to national planning and the developments that followed in the next sections.

4 The STAN Model and Method

Our contribution to the field takes the form of scientific results, instrumental developments, and a worldwide commercial distribution of the resulting decision-support system called *STAN* (*Strategic Transportation ANalysis*). We briefly review these contributions in this section.

The primary goal when developing *STAN* was a methodology independent of particular applications. The aim was and continues to be to offer a modelling framework sufficiently general and flexible to provide the means to address a wide variety of cases in terms of geographical dimensions and richness of details in the supply, demand, and decision criteria representation. A second and closely related objective was to provide a method and software robust with respect to their utilisation by planners without a deep knowledge of optimisation. These objectives explain a number of design choices which have been *a posteriori* justified by the industrial utilisation of the methodology.

4.1 The STAN methodology

The STAN modelling framework of the supply side of a national transportation system is that of a multimodal network, made up of modes, nodes, links, and intermodal transfers. Here, a mode is a means of transportation having its own characteristics, such as vehicle type and capacity, as well as specific cost measures. Depending on the scope and level of detail of the strategic study, a mode may represent a carrier or part of its network representing a particular transportation service, an aggregation of several carrier networks, or specific transportation infrastructures such as ports.

The network consists of nodes $\mathcal{N}$, links $\mathcal{A}$, modes $\mathcal{M}$, and transfers $\mathcal{T}$ that represent all possible physical movements on the available infrastructure. To capture the modal characteristics of transportation, a link $a \in \mathcal{A}$ is defined as a triplet (i, m, j), where $i \in \mathcal{N}$ is the origin node, $j \in \mathcal{N}$ is the destination node, and $m \in \mathcal{M}$ is the mode. Parallel links are used to represent situations where more than one mode is available for transporting goods between two adjacent nodes. This network representation enables easy identification of the flow of goods by mode, as well as various cost functions (e.g. operating cost, time delay, energy consumption, emissions, noise, risk, etc.) by product and mode.

To model intermodal shipments, one must allow for mode transfers at certain nodes of the network and compute the associated costs and delays. Intermodal transfers $t \in \mathcal{T}$ at a node of the network are modeled as link to link, hence mode to mode, allowed movements. A path in this network then consists of a sequence of directed links of a mode, a possible transfer to another mode, a sequence of directed links of the second mode, and so on.

On the demand side, a product is any commodity (or collection of similar commodities) — goods or passengers — that generates a link flow. Each product $p \in \mathcal{P}$ transported over the multimodal network is shipped from certain origins $o \in \mathcal{N}$ to certain destinations $d \in \mathcal{N}$ within the network. The demand for each product is exogenous and is specified by a set of O-D matrices. The mode choice for each product is also exogenous and is indicated by defining for each O-D matrix a subset of modes allowed for transporting the corresponding demand. Shipper behaviour is assumed to be reflected in these O-D matrices and associated mode choice. Let $g^{m(p)}$ be a demand matrix associated with product $p \in \mathcal{P}$, where $m(p) \subseteq \mathcal{M}$ is the subset of modes that may be used to move this particular part of product p.

The flows of product $p \in \mathcal{P}$ on the multimodal network are the decision variables of the model. Flows on links $a \in \mathcal{A}$ are denoted by v_a^p and flows on transfers $t \in \mathcal{T}$ are denoted by v_t^p; v stands for the vector of all product flows. Vehicle and convoy (e.g., train) movements are deduced from these flows. Cost functions are associated with the links and transfers of the network. For product p, the respective average cost functions $s_a^p(v)$ and $s_t^p(v)$ depend on the transported volume of goods. Then, the total cost of product p on arc a is $s_a^p(v)v_a^p$, and it is $s_t^p(v)v_t^p$ on transfer t. The total cost over the multimodal network is the function F, which is to be minimized over the set of flow volumes that satisfy the flow conservation and non negativity constraints:

$$F = \sum_{p \in P} \left(\sum_{a \in \mathcal{A}} s_a^p(v)v_a^p + \sum_{t \in \mathcal{T}} s_t^p(v)v_t^p \right). \tag{1}$$

Let $\mathcal{L}_{od}^{m(p)}$ denote the set of paths that for product p lead from origin o to destination d using only modes in $m(p)$. The path formulation of the flow conservation equations are then:

$$\sum_{l \in \mathcal{L}_{od}^{m(p)}} h_l = g_{od}^{m(p)} \qquad o,\ d \in \mathcal{N},\ p \in \mathcal{P},\ m(p) \subseteq \mathcal{M}, \tag{2}$$

where h_l is the flow on path $l \in \mathcal{L}_{od}^{m(p)}$. These constraints specify that the total flow moved over all the paths that may be used to transport product p must be equal to the demand for that product. The non-negativity constraints are:

$$h_l \geq 0, \qquad l \in \mathcal{L}_{od}^{m(p)},\ o,\ d \in \mathcal{N},\ p \in \mathcal{P},\ m(p) \subseteq \mathcal{M}. \tag{3}$$

The relation between arc flows and path flows is $v_a^p = \sum_{l \in \mathcal{L}^p} \delta_{al} h_l,\ a \in \mathcal{A},\ p \in \mathcal{P}$, where $\mathcal{L}^p$ is the set of all paths that may be used by product p, and $\delta_{al} = 1$ if $a \in l$ (and 0, otherwise) is the indicator function which identifies the arcs of a particular path. Similarly, the flows on transfers are $v_t^p = \sum_{l \in \mathcal{L}^p} \delta_{tl} h_l,\ t \in \mathcal{T},\ p \in \mathcal{P}$, where $\delta_{tl} = 1$ if $t \in l$ (and 0, otherwise). Then, the system optimal multiproduct, multimodal assignment model consists of minimizing (1), subject to constraints (2) and (3). The optimality principle ensures that in the final flow distribution, for each product, demand matrix, and origin-destination pair, all paths with positive flows will have the same marginal cost (lower than on the other paths). When required, a decision criterion equilibrating the average generalized cost on the paths of certain products may be also used.

The algorithm developed for this problem exploits the natural decomposition by product and results in a Gauss-Seidel-like procedure (Figure 3 gives a schematic description of the algorithm), which allows the solution of large size problems in reasonable computational times, even though functions and functional derivatives must be computed numerically to account for user-defined functions (Guélat, Florian, and Crainic, 1990).

Initialization. $k = 0$, v^0 is the initial solution.

Major cycle. $k = k + 1$; For each product $p \in \mathcal{P}$ do

Descent Direction. Compute the *descent direction* $d^k = y^k - v^k$, where y^k is the "all-or-nothing" solution to the linearized problem

$$\text{Min } F(v^k) + \bigtriangledown F(v^k)(v - v^k) \text{ subject to } v \in \Omega^p, \tag{4}$$

and Ω^p stands for constraint set (2) - (3) for product p ; This involves solving a shortest marginal cost path problem for each OD pair.

Line Search. Find the *step length* λ_k^p solution of $\text{Min}_{0 \leq \lambda \leq 1} F(v^k + \lambda d^k)$.

Flow Update. $v^{k+1} = v^k + \lambda_k^p d^k$.

Stopping Criteria. The algorithm stops either when the relative gap is below a given threshold or when a predefined number of major cycles have been performed.

Figure 3: The STAN assignment algorithm

4.2 The STAN software

The initial STAN development took place at the Centre for Research on Transportation (CRT), a multi-disciplinary and multi-university institution initiated by and located on the campus of the Université de Montréal. (The CRT has recently evolved into the Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation - CIRRELT.) The interest of the CRT researchers, professors and students in the area of national freight planning was motivated by a project in Brazil that lasted from 1983 to 1989. The aim of the project, which was funded by the International Development Research Centre (IDRC), Canada, was to develop a strategic planning tool for the development of the main export corridors of goods from Brazil. Other than the group of professors and graduate students from the CRT, the team of the project consisted of personnel from GEIPOT, the transportation planning organization of the Ministry of Transportation of Brazil, and professors from the Catholic University of Rio de Janeiro (PUC-RJ).

A number of important issues became apparent early into the project: a great variety of national planning projects may arise, even when a single country or region is considered, requiring significant flexibility in the representation of the transportation system; a hard-coded model could not address this challenge; planners require many tools to handle data and results, perform studies, and produce the associated analyzes; planners are not, and do not need to be, operations researchers or computer science specialists. This motivated the development of a flexible methodology to address the various issues identified in the project. This methodology then served as the basis for the STAN software package, which shared many of its components with the EMME/2 software dedicated to the planning of multimodal urban passenger transportation systems (Spiess 1984; Babin *et al.*, 1982; the current version of the software is called Emme 3).

A set of technical reports (Florian and Crainic, 1989) documents the project and its results, including the first applications to various Brazilian cases. Guélat, Florian, and Crainic (1990) then present the general model and assignment methodology, Crainic, Florian, and Leál (1990) focus on the analysis of national, multimodal rail transportation systems, while Crainic et al. (1990) describe the STAN decision-support system. INRO (http://www.inro.ca) was assigned the commercialization rights to the STAN software and continued its development since 1986. A number of these developments were performed in collaboration with CRT researchers (Crainic, Florian, and Larin, 1994; Crainic *et al.*, 1999, 2002).

STAN, the interactive-graphic software system, is made up of a large number of tools to define and compare scenarios, input, display, analyze, modify, and output data, as well as define the supply network (according to the indicated modelling framework), generate demand, specify the assignment model parameters, and perform the corresponding simulation. Matrix-based computing tools may be used to implement a whole gamut of mode choice and demand generation and allocation models. Similarly, a network calculator can be used to combine network data to implement various performance and analysis models, including connectivity studies, incident impact analyzes for hazardous goods, and environment impact studies (emissions, noise, etc.) for given network regions and vehicle fleets. Moreover, the path-analysis capability offers the possibility to interactively select and examine paths according to generalized, user-defined criteria, to perform *select element* (link or intermodal transfer) studies, and to compute demand or performance matrices for selected products and OD pairs (Crainic *et al.*, 1999, 2002). A macro language can be used to program complex operations and procedures. See Larin *et al.* (2000) for a detailed description of the current version (6.2) of the STAN system, components, interfaces, and tools.

The STAN software was adopted for strategic freight planning in several countries, including Finland, Sweden, Norway, Italy, Spain, Germany, the United Kingdom, China, and Mexico, and has been applied successfully for scenario analysis and planning. Currently, 52 institutions in 18 countries use STAN. A few of the numerous studies undertook with the help of STAN are mentioned in the references indicated above. Most applications, however, have been carried out by public agencies and private organizations around the world. While the results of these analyses are not available for public scrutiny, they witness the success of Canadian operations research applied to transportation.

5 Perspectives

We have presented an important contribution of the Canadian operations research community to transportation science, the STAN methodology and decision-support system for the analysis and planning of multimode, multiproduct national transportation systems.

The challenge in the building of a national strategic planning tool is the provision of the large amounts of data required. One needs to have information about the input-output structure of the economy and reliable data on shipments of all products in order to build demand models that would produce the product based origin-destination matrices that are required for the freight network assignment model. One also needs information on the economic profiles of shippers and carriers, as well as accurate description of the infrastructure and services provided, or planned, for the region. The strategic level of planning described in this paper does not take into account the logistic aspect of freight transportation at the company level nor does it consider the multiple levels of such logistic systems. Nevertheless, the countries that used STAN found it very useful, in particular for the planning of strategic freight corridors as well as various policy and investment analyses at the system level. It is worth noting that, compared to applications of urban planning models, strategic national freight methods, decision support systems and models do not abound.

Work is still continuing in this area. A first group of projects targets new models and procedures to enhance the performance of the system simulation (assignment) step in terms of problem dimensions and computational efficiency (e.g., Crainic, Damay, and Gendreau, 2008), as well as to provide the means for increased accuracy and refinement in the representation of the behaviour of transportation systems under various system configurations and data availability (e.g., Crainic, Damay, and Gendreau, 2008). A second group of projects aims to provide answers to emerging needs in terms of particular studies and elements to include in the representation of the transportation systems, such as the integration of logistics chains in the system modelling and simulation (e.g., Crainic, Florian, and Noriega, 2007) and the representation of the impact of Intelligent Transportation System technologies on the behaviour of the transportation system. Contemplated issues of interest concern the links between transportation policies, system performance, and the environment, as well as the relationships between transportation policies and the performance of logistics chains. We expect to report on some of these developments in the near future.

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