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Advanced freight transportation systems for congested urban areas

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Abstract

Urban freight transportation constitutes both an extremely important and a rather disturbing activity. Increasingly, one observes efforts to measure and control freight movements within city centers. We introduce a possible organizational and technological framework for the integrated management of urban freight transportation and identify important associated planning and operation issues and models. We then describe a formulation for one of these problems, the design of the proposed logistical structure, and discuss algorithmic and implementation issues. Our model city and challenge is Rome.

Keywords: Urban freight transportation; Integrated planning and management; City logistics; System design; Location and allocation

1. Introduction

The transportation of goods constitutes an extremely important activity taking place in urban areas. For people, it directly ensures adequate supplies at stores as well as delivery of goods at

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home. For firms established within city limits, it forms a vital link with suppliers and customers. There are few activities going on in a city that do not require at least some commodities being moved. Moreover, the urban freight transportation industry is a major source of employment. Yet, freight transportation is also a disturbing activity in urban centers. Freight is carried by vehicles that move on the same streets and arteries used by the private and public vehicles transporting people. These vehicles make a significant contribution to congestion and environmental nuisances, such as emissions, noise, and so on, that impact adversely on the quality of life in urban centers. Freight traffic also contributes to the belief that "cities are not safe" which causes numerous citizens to move out of the city limits.

And the problem is not going to go away any time soon. In fact, the already significant volume of freight vehicles moving within city limits is growing and is expected to continue growing at a fast rate. Major contributing factors to this phenomenon are the current production and distribution practices based on low inventories and timely deliveries (the much talked about "just-in-time" paradigm), as well as the explosive growth of business-to-customer electronic business activities that generates significant volumes of personal deliveries.

Traditionally, public authorities have not addressed issues related to the transportation of goods in the city, except through the regulation on parking, street access, hours of operations, and so on. This followed from the fact that freight transportation is essentially a private industry and authorities did not feel they had anything to do with the operations of private firms. (This is true even for the transportation of dangerous goods, which is more closely monitored: special rules have been defined (e.g., particular corridors), but actual movements are rarely individually monitored or planned.) Consequently, freight transportation issues at city level are still not well understood nor quantified, and there is no methodology aimed specifically at the analysis and planning of freight movements within the city.

The situation is changing, however. Traffic conditions in cities all around the world are getting worse. The number of vehicles of all types is increasing fast and, as a consequence, congestion and pollution levels are increasing as well. Consequently, we observe increased public awareness and sometimes vociferous requests concerning these issues and, more generally speaking, the quality of life within cities. Authorities have also started to take notice and display increasing willingness to do something. We thus see the emergence of an acknowledged need to analyze and eventually control the movements of freight vehicles in cities (Dietrich, 2001; Dufour, 2001; Gerardin, 2001; Kohler, 2001; Larraneta et al., 1999; Morris et al., 1999; Patier-Marque, 2001; Ricci and Fagiani, 2001; Taniguchi et al., 2001; Thompson and Taniguchi, 2001). The concept is increasingly known as *City Logistics* (Ruske, 1994; Kohler, 1997; Taniguchi et al., 2001).

Its goals are reasonably clear:

1. Reduce congestion and increase mobility.
2. Reduce pollution and noise; Contribute reaching the Kyoto targets; Improve living conditions of city inhabitants.
3. Avoid unduly penalizing the city center commercial activities such as not to "empty" them.

Surveys and data collection activities have been undertaken in several countries and cities (e.g., Dietrich, 2001; Dufour, 2001; Gerardin, 2001; Morris et al., 1999; Patier-Marque, 2001; Ricci and Fagiani, 2001; http://www.transports-marchandises-en-ville.org; http://www.bestufs.net). These efforts are aimed at better understanding and quantifying these phenomena and, hopefully, open perspectives towards courses of action. In fact, data collection and general descriptive models are just the first step. We believe that to reach the above-mentioned goals, one needs to address the issues at a global, city-wide level. The experiments taking place in a number of European cities (e.g., Monaco, Zurich, as well as in a number of cities in Germany, the Netherlands, France, and Italy; http://www.transports-marchandises-en-ville.org) are very encouraging in this respect. These experiments are limited, however, both in the dimensions of the area covered and in the number of carriers and customers involved. New organizational models for the management of freight movements within the city limits are therefore called for, where city authorities play a more pro-active role, similar to the one they fulfill relative to public transportation. Freight transportation being performed mainly by private firms, such models cannot be achieved without public–private understanding, collaboration and innovative partnerships. *Intelligent Transportation Systems* (*ITS*) and technologies should prove a significant enabling factor towards the conception and deployment of such advanced urban freight management policies.

This constitutes an interesting challenge for Operations Research and Transportation Science. Currently, there are very few models that specifically address the issues of interest here. Most efforts reported in the literature relative to the transportation of freight in urban regions are dedicated to the activities of shippers or carriers, as illustrated by the many works dealing with the scheduling and routing of pick up and delivery vehicles and, more generally, with the planning and operation of distribution activities (Toth and Vigo, 2002; Dror, 2000; Crainic and Laporte, 1997; Crainic, 2003). A few urban passenger planning methods, such as EMME/2 (http://www.inro.ca), can integrate freight vehicles (trucks) at some aggregated level. Methods dedicated to multi-commodity, multi-modal transportation analysis and planning, such as STAN (http://www.inro.ca; Guélat et al., 1990; Crainic et al., 1990), are even fewer and more focussed on the long-haul, inter-urban aspect of the industry. Although useful in some applications, methods such as EMME/2 or STAN cannot cover the whole set of needs that come with analyzing and controlling urban freight movements and their consequences. Hence, new Operations Research models, methods, and decision support tools have to be developed.

The goals of this paper are: (1) to introduce a possible organizational and technological framework for the integrated management of urban freight transportation; (2) to identify a number of important associated planning and operation issues and the corresponding Operations Research models; (3) to describe a formulation for one of these problems, the design of the proposed logistical structure, and discuss algorithmic and implementation issues. Our model city and challenge is Rome.

The paper is organized as follows. Section 2 briefly reviews the main issues associated with urban freight transportation, as well as a number of City Logistics projects and experiments currently under way. Section 3 is dedicated to the presentation of the integrated urban freight transportation system we propose and the discussion of a number of associated deployment, management, and operation issues. A formulation for the design of the proposed logistical structure is introduced in Section 4, while computational experiments are discussed and analyzed in Section 5. We conclude in Section 6 with a number of general remarks and perspectives.

2. Freight transportation in congested cities

We address freight transportation issues in large, congested urban regions. Due to the European context where this study has been carried out, the following description makes use of vocabulary more closely related to the spatial organization of cities on this continent. With little adjustment, however, the discussion and the model proposed in this paper apply to many major North American (e.g., New York, Boston, San Francisco, ...) and Asian (e.g., Tokyo, Hong Kong, ...) cities or parts thereof. The issues related to urban freight transportation apply to the whole city territory. It is clear, however, that according to the type and density of land use in each part of the city, the organizational and technological solutions will vary. In this paper, we focus on the most dense and traffic-problematic zones where more aggressive approaches are needed.

The cities of interest in this study often display an important central, core zone: the *centro*. This central zone displays a high density of construction and a mix of land utilization, administrative, commercial, residential, cultural, and possibly industrial, often including many tourist attractions. The density of the population and the levels of the commercial, administrative, and cultural activities are high. The road network is also dense and characterized by a broad variety of streets in terms of width and number of lanes. Many streets, especially in the most historic parts of the city, are very narrow and are designated as one-way only. Some are designated pedestrian zones or are dedicated to public transport only. There is usually limited parking along the streets or in organized parking facilities. Parking space is even less available for distribution (for simplicity, we group all pick up and delivery activities under the term *distribution*) vehicles that often double park. Thus, the already limited capacity of most arteries is significantly reduced by large numbers of cars (and other private transportation means, such as bicycles, motorbikes, etc.) and freight vehicles which are legally or not so legally parked. Thus, in the *centro*, traffic density is high and congestion endemic. Note that, in general, more than one such zone may be encountered in a given city. To simplify the presentation, however, and without loss of generality, we assume in the rest of the paper that only one *centro*-like zone exists.

Generally speaking, the only means of control of freight traffic within city limits are the municipal regulations on access, speed, parking, maximum vehicle dimensions and loads, and so on. There is no control or co-ordination of distribution activities. Consequently, one observes large numbers of freight vehicles of various dimensions. The average vehicle load is low and many vehicles travel empty (Morris et al., 1999; STA, 2000; http://www.bestufs.net). It is also noteworthy that in many countries there are few controls and regulations are seldom observed. The double parking of most distribution vehicles is a most telling example. It has been observed in fact, that even when reserved parking space is available, distribution vehicles are double parked to save time (Morris et al., 1999).

Many products are moved in, out, and through a city. In many cases, the in-bound and out-bound traffic is not balanced. This is the case in Rome, where the freight volume with destinations within the *centro* is larger than the one being exported out of the city (ISTAT, 1998; STA, 2000). This difference between in-bound and out-bound freight flows constitutes one of the causes of the high level of empty trips that may be observed in most major cities.

A second major cause for high empty trips and, in general, for high freight vehicle volumes is the very fine granularity of distribution decisions and shipments. Thus, with the exception of certain commodities (e.g., whole-carcass meat distribution) or large organizations (public and private post services, large supermarkets or general store chains), there is no distribution co-ordination, neither among carriers nor among the commercial enterprizes that originate or request freight movements. It is common, for example, to witness several trucks stopping one after another in front of a grocery or general store to discharge a few items. Distribution is currently managed for the best efficiency of the commercial shipper or receiver, without any consideration for the impact it may have on the transportation system and the difficulties it may induce for the city in general.

In recent years, we have witnessed the emergence and increased use of *intermodal*, *logistic platforms* (sometimes also called *city distribution centers*) that link the city to the region, country, and the world. These platforms receive large trucks and smaller vehicles dedicated to local distribution, and offer storage, sorting, and consolidation (de-consolidation) facilities, as well as a number of related services such as accounting, legal counsel, brokerage, and so on. Intermodal platforms are either stand-alone facilities situated close to the access or ring highways, or are situated within or close to air, rail or navigation terminals. Intermodal platforms are an important step towards a better city logistics organization (van Duin, 1997; Janssen and Oldenburger, 1991; Kohler, 1997, 2001; Ruske, 1994; Taniguchi et al., 2000, 2001; Thompson and Taniguchi, 2001). The organizational framework we present in the next section is an extension of this concept.

A more efficient use of vehicle capacities through the *co-ordination* and *consolidation* of freight flows may help address this issue. A few experiences in Europe tend to demonstrate the validity of this claim. Thus, in Monaco, all large trucks are banned from the city. Thus, freight destined to the city has to be first delivered to the city distribution center, a single carrier taking charge of the final distribution with special vehicles. Strict licensing practices in use in several Dutch cities impose restrictions on vehicle loads and the total number of trips, and encourage the use of electric vehicles. This has resulted in carriers initiating collaboration activities to consolidate shipments and reduce the number of trips. Similar activities may be observed in a number of German cities, where carriers have set up (with help from the municipal authorities) freight distribution services in where shipments are consolidated and distributed co-operatively. In fact, most current City Logistics proposals and projects are based on co-operation principles and the utilization of a city distribution center (e.g., van Duin, 1997; Janssen and Oldenburger, 1991; Kohler, 1997, 2001; Ruske, 1994; Taniguchi et al., 2000, 2001; Thompson and Taniguchi, 2001; http://www.transports-marchandises-en-ville.org, http://www.bestufs.net). Our proposal follows similar lines but aims to cover most (all) carriers and shippers operating over a large urban area by using a two-tiered system of distribution centers and advanced communication, computing, and decision technologies deriving from ITS.

Intelligent Transportation Systems are gradually becoming a reality in many cities and more developments are under way. Simultaneously, one witnesses an increasing number of freight vehicles being equipped with location and communication (and even computing) devices and the deployment of a number of *Commercial Vehicle Operation* (*CVO*) systems in long-haul transportation (e.g., weight-in-motion, pre-clearing, electronic identification and manifest, etc.). *Advanced Fleet Management Systems* (*AFMS*) have also been introduced to plan and operate certain fleets (e.g., express courier and major trucking companies). ITS are still far from full deployment in terms of territory or functionality. Moreover, one still has to examine the applicability of CVO/AFMS concepts and technologies within urban zones, as well as the most appropriate and efficient relations among these systems and the Advanced Traffic Management Systems (ATMS) and Advanced Traveller Information Systems (ATIS) of the city. Yet, ITS, and particularly Advanced Fleet Management Systems already permit us to envision new forms of freight distribution organization within cities, including the one presented in the next section.

3. Distribution using satellite platforms

The fundamental idea that underlies this project is that the volume of freight vehicles travelling within urban areas could be reduced through a more efficient utilization of vehicles: higher average load factors and fewer empty trips. Better fleet management practices could partially address this problem. But only partially, since it would concern individual carriers only. Significant gains can only be achieved through a *rationalization* of distribution activities involving freight *consolidation* from different shippers and carriers as well as some form of *co-ordination* of operations at the city level. Such approaches appear particularly needed in *centro*-like city zones.

Two questions are relevant to such distribution rationalization policies and the associated goal of enhancing the quality of life in cities through reduced vehicular traffic and a decrease in negative environmental impacts: (1) where and how to perform the consolidation and co-ordination activities; (2) what vehicles should perform the transportation activities.

Consolidation could and does take place at intermodal logistics platforms. These are few, however, even for major cities. Moreover, intermodal platforms are usually located rather far from the *centro*. Thus, for example, consolidating into one vehicle "all" traffic originating at various locations around the city and bound for a certain street in the *centro*, would require all the traffic to be first brought to a given platform, generating significant levels of extra heavy truck traffic. Moreover, not all freight destined or originating in a city passes through an intermodal platform. Therefore, this infrastructure is not sufficient to perform the consolidation and co-ordination activities we envision.

The system we contemplate builds on and expands the intermodal platform idea. It involves mini, satellite platforms, *satellites* for short, where the freight coming from various external points could be transferred and consolidated into environment-friendly vehicles adapted for utilization in dense city zones. We call such vehicles *city-freighters*. The satellites would not perform any other activity and there would be no significant physical installations and no warehousing. This is in contrast to other proposals involving two levels of platforms. ITS technologies would be used for real-time control and co-ordination of vehicles and operations. Let us examine the system in some more detail.

3.1. Satellites

Satellites are locations where freight is transshipped from normal trucks to city-freighters for distribution within the city *centro*. The reverse operation—moving freight from the city-freighters to trucks for transportation out of the city—is also performed at satellites. As indicated previously, satellites will offer no storage facilities, trans-dock transshipment being the operational model. This emphasizes the need for real-time co-ordination, control, and dispatch of trucks and city-freighters. The objective here is to have trucks and city-freighters present at satellites on a "needs-to-be-there" basis exclusively. This implies that trucks might have to wait outside the city at platforms and similar infrastructures. Then, when space and the appropriate city-freighters are available at the designated satellite, trucks are called for loading and unloading operations. The transfer operations are to be carried out promptly so that trucks may leave as soon as possible and distribution may be performed in a timely manner.

Personnel will be required to perform the co-ordinations activities. A few people will be needed at the central location where data is processed and general decisions are taken. A co-ordinator will probability be required at each satellite as well. Transfer operations could be performed by the truck and city-freighter drivers. Note that drivers already perform loading and unloading operations at customer sites. Therefore, even if satellites might mean more work for drivers, it is still the same type of activity. When and if labor conditions require it, freight transfer personnel will have to be present at satellites.

The actual infrastructure of a satellite should be very limited. When existing installations (e.g., underground parking lots or municipal bus depots) are used, only the equipment required for communication and real-time co-ordination, dispatching, and routing has to be located. For other locations, some weather protection might be required.

Satellites differ according to the number of trucks and city-freighters that may be served simultaneously. The satellite capacity is then defined in terms of the number of trucks and city-freighters that may be served during the operating hours of the site. Physical characteristics in terms of access and available space restrict the capacity of a site. Forbidden access periods (e.g., during the day or peak traffic hours) further constrain the number of hours of operations and hence the satellite capacity. Note that the day of pick up or delivery falls within the private domain. During the day, when a particular pick up or delivery operation might take place depends on the time windows determined, on the one hand by the shipping or receiving firm and, on the other hand, by the municipality. This timing information is a major input to the dynamic management of the distribution routes.

3.2. Vehicles

Dense city zones require "small" vehicles. Research is currently underway in the area of trucks of limited capacity (e.g., 3.5 tons and less) adapted for operations within urban zones. We strongly believe these vehicles should use "clean" energy sources, such as electricity or hydrogen. Thus, two types of vehicles are to serve the city: trucks and city-freighters. Both should be equipped with ITS-type equipment including location, two-way communication and, eventually, in-vehicle computing.

Trucks are the current vehicles for distribution within the city. These vehicles belong to privately-owned fleets. They will continue to be used, but only to move freight between the satellites and the outside zones: the intermodal and logistical platforms, production and consumption centers near the city, import and export facilities, etc. Since the goal is to minimize truck movements within the *centro*, streets will be classified and not all will be open to truck traffic. Trucks need access to satellites, however. Consequently, corridors (sets of streets) will have to be defined to allow this access.

City-freighters are vehicles of relatively small capacity that can travel along the narrow and crowded streets of the *centro* to perform the required distribution activities. They should also be significantly more environment-friendly (e.g., electric or hydrogen-based traction), to contribute towards reaching the Kyoto emission targets and to reduce traffic-related noise and other perceived negative impacts. City-freighters may be of several types in terms of functionality (e.g., refrigerated or not), box design, loading/unloading technology, capacity, and so on. It is noteworthy, however, that if too many types are used, there might be difficulties in re-deploying the fleet dynamically during the day (some types might not fit all streets) and vehicle substitution issues might become a challenge. Fleets of city-freighters could be privately owned and managed, but operations have to be centrally co-ordinated. In a sense, these are "public" vehicles, the only ones authorized to circulate within the *centro*.

Many products are moved in, out, and through a city. While ITS technologies may help address some issues related to the transit of freight vehicles through urban areas, this is beyond the scope of the system presented here. From the distribution system point of view, products may be grouped into a number of somewhat homogeneous *commodities*: clothes and shoes, electronics, house appliances, dry food, liquid food, fresh and frozen food, etc. Some commodities, such as fresh and frozen food, require specially equipped vehicles. Others, such as letters and packages moved by regular post services or express courier firms, require all-day pick up and delivery operations and use, and will probably continue to use dedicated fleets of vehicles. A number of other firms, such as large retail chains, also use dedicated fleets. It is very possible that such dedicated fleets will continue to operate but under the "new" operating rules on traction type and co-ordination. Most other products and shippers will use the same city-freighter vehicles and constitute the focus of the present paper. We believe this to be the source of the most important gains in terms of vehicle utilization and impact on the quality of life in cities.

3.3. Operations

From a physical distribution point of view, the system operates according to the following sequence: demand for transportation generates truck flows towards satellites where freight is transferred and consolidated into city-freighters that perform the delivery routes and operations. From an information and decision point of view, the "demand for transportation $\Rightarrow$ truck flows" sequence yields the demand for the city-freight transportation activities that, in turn, constitutes the input to the multi-depot, multi-vehicle, multi-commodity vehicle routing problem that builds and adjusts in real-time the circuits performed by the city-freighters. Co-ordination between these two levels of demand and transportation activities includes the following activities:

- Assignment of trucks to satellites and, eventually, implementation of holding strategies for trucks at their points of origin (at the entrance of the city).
- Transfer and consolidation of freight at satellites.
- Construction of city-freight routes.
- Dynamic control and adjustment of these routes.

What are the costs associated to such a system? These are of different natures and perceived by different players. We do not intend to perform a thorough economic analysis of the proposed system. Rather, we aim to identify the main costs and performance measures, those who perceive them, who pays what, and how to evaluate the performance of the system.

The "fixed" costs of the system are composed of the acquisition cost of the fleet of city-freighters and its subsequent maintenance. This includes, when required, the construction or installation of depots and fuelling stations for the city-freighters. Some costs may also be incurred due to the installation of the satellites. The operation of the satellites will also generate costs (beyond the acquisition of ITS equipment) corresponding to the salaries of co-ordination (and, eventually, transfer) personnel. In a full economic analysis, driver costs should be included as well, because the allocation might differ between the current situation and that of the proposed system. As for transportation costs, they include those associated to the truck movements, transfers at satellites, and the city-freighter routes.

Time measures will also be modified. New compared to current practices are the transfer times at satellites and the eventual holding time of trucks. Travel time for trucks and their impact on congestion should decrease. On the other hand, travel times associated with city-freighter routes will have to be considered. Yet, due to co-ordination and a higher loading factor, their number is expected to be less than the actual volume of trucks. And, of course, their detrimental environmental impact would be significantly less compared to the current situation.

One expects the total distribution time and cost of an individual shipment to increase due to the extra transfer operation. In our opinion, this cost increase should not be passed on to the economic agents selling or buying the products (and thus to consumers through prices). This individual increase should be more than compensated for by the gains for the collectivity in decreased congestion and pollution. It should therefore be considered as a "social" burden to be equally shared by the people and institutions of the city. How this sharing should be defined and implemented is an interesting economic topic that goes far beyond the scope of this paper. However, the current projects (e.g., Monaco, Germany, Holland) should be carefully analyzed.

A related issue is how to measure these social benefits to the collectivity and how to compare the performance of the proposed and current, or any other alternate, system. A thorough performance measurement of the system requires a detailed analysis of the congestion and environmental (emissions, noise, etc.) conditions associated to each system, as well as of the quality of distribution activities in terms of costs and time. To perform such analyses, one needs to develop new planning models and tools. These methods should combine the modelling and computing functionality of today's planning software systems (e.g., of EMME/2 and STAN) and the capability for representing and analyzing the circuit-type routes characteristic of distribution activities within the detailed representation of the city transportation network. These tools should also offer the possibility of using various pollution and dispersion models. Simulations of various scenarios could then be run and the associated performance measures could be taken and detailed by city zone, type of vehicle, time of day, etc. Taniguchi et al. (2001) (see also Taniguchi and Heijden, 2000; Thompson and Taniguchi, 2001; Taniguchi and Thompson, 2002; Taniguchi et al., 1999b) proposed an evaluation framework. It is our goal to contribute to the development of such methods. In the meantime, more aggregated measures in terms of the number of vehicles and vehicle-km (for each type of vehicle and city zone or type of street) will be used.

The planning, deployment, management, and operation of such a system require a whole new set of Operations Research models and methods. We have already mentioned the detailed planning models for the static and dynamic simulation and analysis of the city transportation system. Interesting research perspectives are also offered by issues related to dimensioning the fleet of city-freighters, locating satellites, defining access corridors, to mention but a few strategic and tactic-level issues. And, of course, there is the whole set of ITS-related models and methods to dynamically schedule and route vehicles, including truck holding strategies, the time-dependent utilization of satellites and the distribution of work among them, the dynamic control and adjustment of city-freighter routes, and so on. In the following section, we present one of these models: a satellite location formulation.

4. The satellite location problem

In this section we describe the representation of the network together with its attributes, the notation, and the capacitated multi-commodity location formulation that we propose. The focus is on the *centro*. The territory considered also includes the ring roads, the intermodal platforms, as well as the external zones and neighbourhoods in an aggregated fashion. The goal is to identify, among several candidate sites, a number of satellite locations where freight may be transshipped from normal trucks to city-freighters for distribution within the core of the city. The reverse operation—moving freight from the city-freighters to trucks for transportation out of the city—is also performed at the selected satellites.

The representation of the actual street and highway network forms the basis of the network model and is specified by a graph $\mathscr{G} = \{\mathscr{N}, \mathscr{A}\}$. The set of nodes includes the centroids representing the potential satellite locations $\mathscr{S}$, the external zones $\mathscr{E}$, and the customer zones $\mathscr{Z}$, as well as regular nodes that stand for the road intersections in the actual street network.

Several attributes are defined for each satellite location $s \in \mathscr{S}$. The fixed cost of locating the satellite, denoted by k_s, is computed as the sum of a monetary cost representing the manpower required to operate the satellite and an *undesirability factor*. The latter captures a number of non quantitative attributes associated with a site. For example, there are sites with excellent locations with respect to access from external zones and customer zones, but with less than ideal features with respect to other factors such as proximity to highly residential or historical (e.g., Piazza di Spagna) zones, or the type of street pavement (e.g., cobbled stones) that impacts on the speed and handling of vehicles. The undesirability factor of a satellite thus represents a "social" impact on the urban tissue and the quality of life of its inhabitants and visitors.

The capacity of a satellite on location $s \in \mathscr{S}$ is measured in terms of the maximum number of trucks and city-freighters, u_s^T and u_s^V, respectively, that may be served together during a given time period, multiplied by the length of the planning horizon. A lower limit, l_s^T, on the number of trucks that may be served during the operating hours of the satellite is also imposed to avoid opening low-volume satellites. Finally, an average handling (transfer) time t_s^p and cost k_p are associated to each location and product p in the set of considered products $\mathscr{P}$. The differences in handling times for different locations follow primarily from the differences in satellite layout and access. Handling costs may vary by product due to weight or special care considerations.

The *centro* is administratively divided into a number of *intra muros commercial zones*. Note that the set of commercial zones does not necessarily form a partition of the *centro*. For modelling purposes, each commercial zone is further divided into *customer zones* made up of several customers. A *customer* corresponds to a cluster of stores or locations (e.g., homes) where freight actually originates or is delivered. Each customer zone $z \in \mathscr{Z}$ is of a rather small size and is assumed to be homogeneous with respect to its population density, land use, and commercial profile: what type of stores, their number, and so on. A *centroid* is associated to each customer zone. It captures the total supply and demand of the zone for each product, defined as the aggregation of the supplies and demands of the customers in the zone. A centroid is also associated to each commercial zone.

External zones $e \in \mathscr{E}$ represent locations, far away or close by, where the traffic to and from the city originates or is directed to. The intermodal platforms and facilities (e.g., ports, rail stations, airports), as well as the production and storage facilities (or aggregation thereof), located close to the city, belong to that set. (It is noteworthy that such facilities may still be located within the city. Thus, in Rome, the flower and general markets are still located in their traditional locations close to the city center. Plans for their re-location are underway, however.) To capture traffic between the city and regions further away that does not pass through one of these intermodal transfer or storage facilities, a number of dummy nodes are added to $\mathscr{E}$ to represent the entry and exit point of the city. A centroid is associated to each external zone.

Demand is defined as the quantity of each commodity that has to be moved between customer and external zones. For analysis and modelling purposes, we assume that commodities have been grouped into a number of somewhat homogeneous *products* that are moved in standard-sized containers ("boxes"). Note that even though two or more products may use the same containers, one might still need to consider them individually, due to handling specifics (e.g., weight) and time value k_p. Let us denote by g^p_{ez} the demand for transportation from external zone $z \in \mathscr{Z}$ to customer zone $e \in \mathscr{E}$ measured as the number of standard containers of product $p \in \mathscr{P}$ to be moved during the period.

The link set $\mathscr{A} = \{(i,j) \mid i,j \in \mathscr{N}\}$ represents the possible movements using the streets and arteries of the city open to commercial traffic (the others are not included in the network representation). The network is adjusted to account for the aggregation operation that yielded customers. Links are unidirectional and one-way restrictions are explicitly considered. Dummy links to connect centroids and satellite sites to the network are also included in $\mathscr{A}$. Three measures are associated to links $(i,j) \in \mathscr{A}$: an average *travel time* t_{ij} that accounts for traffic conditions and congestion at different periods of the day, and two *undesirability factors* k^V_{ij} and k^T_{ij}. Measured in money/truck-hours, the undesirability factors classify the arteries of the road network according to the maximum level of freight-vehicle traffic desired and are used as penalties to compute the travel times used in the model. By convention, a value of 0 indicates that freight vehicles cannot use the associated street, while a value of 1 indicates a link with no restrictions. Values larger than 1 indicate increasingly stronger restrictions on the flow of freight vehicles that may use the corresponding street.

City-freighter routes and truck paths may be computed on network $\mathscr{G}$. In the present model, street capacities and congestion are reflected in the average travel times and not through actual non linear functions or explicit constraints. Consequently, in any minimum cost flow-like formulation, only one path will be used for any given demand. Therefore, the location formulation is defined on an auxiliary *service network* $\widetilde{\mathscr{G}} = \{\widetilde{\mathscr{N}}, \widetilde{\mathscr{A}}\}$ built on the street network $\mathscr{G}$. The node set $\widetilde{\mathscr{N}} = \mathscr{E} \cup \mathscr{Z} \cup \mathscr{S}$ includes the centroids representing the external and commercial zones, as well as the potential satellite sites. The link set $\widetilde{\mathscr{A}} = \mathscr{R} \cup \mathscr{L}$ is made up of two sets of *service links* connecting, respectively, external zones to satellite sites and the latter to commercial zones. The service link sets $\mathscr{L} = \{(s,z) \mid s \in \mathscr{S}, z \in \mathscr{Z}\}$ and $\mathscr{R} = \{(e,s) \mid e \in \mathscr{E}, s \in \mathscr{S}\}$ represent the legal directional connections between satellites and customer zones and between external zones and satellites, respectively. Let $r_{ab} = \{(i,j) \in \mathscr{A} | \text{path from } a \text{ to } b, (a,b) \in \widetilde{\mathscr{A}}\}$. Average *travel* or *service times* $t_{sz} = \sum_{(i,j)\in r_{sz}} t_{ij} k_{ij}^V$ and $t_{es} = \sum_{(i,j)\in r_{es}} t_{ij} k_{ij}^T$ are associated to each link of $\mathscr{L}$ and $\mathscr{R}$, respectively.

Two types of vehicles serve the city. *Trucks* $\tau \in \mathscr{T}$ of capacity u_τ and *city-freighters* $v \in \mathscr{V}$ of capacity u_v. A k_v cost is associated to each unit (hour) of utilization of a city-freighter of type v, representing expenses related to crews, energy, maintenance, depreciation, and so on. A similar cost, k_τ, is assumed for each vehicle of type τ. Since the system does not have to cover carrier costs and one aims to reduce vehicle traffic in the city, k_τ may be seen as a "social" cost further penalizing the utilization of trucks in the city center.

Two sets of decision variables are required:

1. Location variables $y_s = 1$ if a satellite is located on site $s \in \mathscr{S}$, 0 otherwise.
2. Flow distribution variables $f_{esz}^{pv\tau}$ representing the quantity of product p being sent from external zone e to satellite s using a truck of type τ to be distributed to customer z using a city-freighter of type v.

The model may then be written as follows:

$$\begin{aligned}
\text{Min} \quad Z(y,f) = {} & \sum_{s\in\mathscr{S}} \left(k_s y_s + \sum_{p\in\mathscr{P}} k_p t_s^p \sum_{e\in\mathscr{E}} \sum_{z\in\mathscr{Z}} \sum_{\tau\in\mathscr{T}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} \right) \\
& + \sum_{p\in\mathscr{P}} \left(\sum_{e\in\mathscr{E}} \sum_{s\in\mathscr{S}} t_{es} \sum_{\tau\in\mathscr{T}} k_\tau \sum_{z\in\mathscr{Z}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} / u_\tau + \sum_{s\in\mathscr{S}} \sum_{z\in\mathscr{Z}} t_{sz} \sum_{v\in\mathscr{V}} k_v \sum_{e\in\mathscr{E}} \sum_{\tau\in\mathscr{T}} f_{esz}^{pv\tau} / u_v \right)
\end{aligned}$$

$$\text{s.t.} \quad \sum_{s\in\mathscr{S}} \sum_{\tau\in\mathscr{T}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} = g_{ez}^p, \quad \forall e \in \mathscr{E},\ z \in \mathscr{Z},\ p \in \mathscr{P} \tag{1}$$

$$\sum_{e\in\mathscr{E}} \sum_{z\in\mathscr{Z}} \sum_{p\in\mathscr{P}} \sum_{\tau\in\mathscr{T}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} / u_\tau \leqslant u_s^T y_s, \quad \forall s \in \mathscr{S} \tag{2}$$

$$\sum_{e\in\mathscr{E}} \sum_{z\in\mathscr{Z}} \sum_{p\in\mathscr{P}} \sum_{\tau\in\mathscr{T}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} / u_\tau \geqslant l_s^T y_s, \quad \forall s \in \mathscr{S} \tag{3}$$

$$\sum_{e\in\mathscr{E}} \sum_{z\in\mathscr{Z}} \sum_{p\in\mathscr{P}} \sum_{\tau\in\mathscr{T}} \sum_{v\in\mathscr{V}} f_{esz}^{pv\tau} / u_v \leqslant u_s^V y_s, \quad \forall s \in \mathscr{S} \tag{4}$$

$$y_s \in \{0,1\}, \quad \forall s \in \mathscr{S} \tag{5}$$

$$f_{esz}^{pv\tau} \geqslant 0, \quad \forall e \in \mathscr{E},\ z \in \mathscr{Z},\ s \in \mathscr{S},\ p \in \mathscr{P},\ v \in \mathscr{V},\ \tau \in \mathscr{T} \tag{6}$$

This formulation is a classic location–allocation model (Daskin, 1995; Drezner, 1995; Labbé et al., 1995; Labbé and Louveaux, 1997; Mirchandani and Francis, 1990) in a multi-echelon distribution setting (e.g., Aikens, 1985; Pirkul and Jayaraman, 1996; Location models for the single-echelon City Logistics distribution framework are presented in Taniguchi et al. (1999a, 2001)). The objective function accounts for the fixed cost of opening and operating the satellites as well as for the transportation costs between external zones and satellites and between satellites and commercial zones. Satisfaction of demand is enforced by the first set of constraints. Constraint set 3 corresponds to the requirement that a satellite has to handle a minimum level of truck traffic in order to be selected. Truck and city-freighter satellite capacities are enforced by constraint sets 2 and 4, respectively. Relation sets 5 and 6 are the usual requirements for the integrality of the location decisions and the non negativity of the flow variables, respectively. The next section presents a case study using this formulation based on data relative to the city of Rome.

5. Experiments and analyses

The goal of the experimental phase is to achieve a proof-of-concept of the ideas presented in the previous sections. We aim to explore the computational tractability of the location–allocation model for a problem instance of realistic dimension and perform a preliminary evaluation of the proposed satellite organization of urban freight transportation. This evaluation is to proceed by measuring the impact of the satellite-based freight distribution system on a number of measures such as the total number of truck-km within the city and the travel times.

The main challenge in designing these experiments comes from the extreme scarcity of data. Conducting a data collection, validation, and analysis exercise was totally beyond the scope and means of this study. Consequently, the case study was built based on previous studies and publicly available data sources concerning the city of Rome and its transportation system. Thus, as indicated in the conclusion of Section 3, only aggregate performance measures can be provided.

Two main issues arise when attempting to build such a case study. The first concerns the actual demand for transportation. The second, the vehicle, communication, and decision-support technologies that would be in use. Given the scope of the present study, simplifications had to be made, as explained in the following. We do not believe these simplifications to lessen the value of the experimental results and analyses. Obviously, however, much more thorough studies are required before contemplating the deployment of satellite-based systems.

The study area corresponds (in its general lines) to what is known as the *centro storico*, the historical center, of Rome (the zone within the Aurelian walls, the *Mure Aureliane*, as well as the neighbourhoods around the Vatican City). The existence of a previous study on the vehicle traffic in, out, and through the zone constitutes an important advantage for this definition of the study area.

The study zone corresponds to an extremely important and sensitive area in Rome. Beyond its obvious historical and tourist characteristics, it is also the political, administrative, economic, and cultural heart of the city. A large number of people live in this area and a significantly larger number come for work or leisure. To give a measure of the intensity of freight-related activities in the area, a recent study of the *STA* (*Società Transporti Automobilistici*), the Roman organization dedicated to planning, monitoring, and regulating urban traffic, over 35000 loading and unloading operations are performed daily in the study area. Strict regulations restrict the access of freight vehicles to this area. However, the same source indicates that less than 5% of trucks make use of the dedicated parking areas.

The zone encompasses 51 commercial zones (*ZUC—Zone Urbanistiche Commerciali*) defined by the municipality of Rome. The corresponding centroids form the demand destinations in our study. Freight is brought into the center of Rome from other points of the city, the Lazio region that surrounds Rome, the rest of Italy and the world. The data available pointed to the need to aggregate, however. Thus, the origins of the freight traffic have been aggregated into 12 *external zones* that correspond to the main 12 entry points (arteries) in the city. For convenience, the corresponding centroids have been situated "at" the intersection of the entry arteries and the ring of highways and boulevards that circles the city (the *GRA—Grande Raccordo Anulare*).

Forty-one (41) potential satellite sites have also been identified. In order not to make hypotheses on potential constructions within the city, we assumed that existing installations will be used. Twenty-nine (29) such sites have been identified corresponding to the vehicle depots of the transit company, as well as large tourist-bus parking areas built for the 2000 Jubilee. All these sites are situated within the GRA. Twelve (12) additional potential sites have been considered outside the ring road where space exists for possible construction. For convenience, these sites have been located at the external zone centroids.

Only aggregated transportation demand data was available. Two sources of data were used. The first indicates the total tonnage moved in, out, and within the Lazio province, including Rome, in 1999 (AORSM Lazio, 1999). The second gives a description of the commercial activities within Rome, aggregate statistics on the number of vehicles (of several types) entering the historical center of the city, and aggregated movement counts (a 2 by 2 matrix) between the *centro* and the outside zones (STA, 2000). Commercial activities are based on compilations of information from the Rome Chamber of Commerce and the National Institute for Statistics (ISTAT, 1998). The movement statistics were obtained by actual counts over a number of days and more in-depth interviews carried out with vehicle drivers.

While very useful, the available data sources did not allow us to define commodity-based demands, nor to identify preferred commodity—truck type pairing. Consequently, only one commodity has been considered in the study. Furthermore, given the differences between the entering and exiting freight flows in Rome (to the order of 85% and 15% of the total, respectively), only the distribution demand, from external to commercial zones, has been retained.

We focussed on the 4-hour period, from 7h00 to 11h00, which corresponds to the current legal distribution time window in Rome. This captures about half the total number of trips identified in the STA (2000) study. The same study indicates a number of socio-economic data for each commercial zone: population, number of stores (classified in 14 types), the total surface of these stores, their total number of employees, etc. Previous studies have shown that the total commercial surface is a good indicator of the intensity of freight loadings and unloadings. We therefore use this information to distribute the total demand among destination centroids (in the *centro* storico) and thus determine an approximate demand vector. Relative weights for each entry point in Rome were derived from AORSM Lazio (1999) to yield an approximate supply vector. An origin–destination demand matrix, from external to commercial zones in the city, may then be easily derived using a simple proportional (unitary cost matrix) two-dimensional balancing procedure.

The availability of data has also motivated the restriction of our study to a single truck type. Similarly, and in order not to introduce too many technological and operations hypothesis, one city-freight type has been considered only. Vehicle characteristics have been determined to reflect current wages in Italy, represent the "most" used truck type and, for the city-freighter, to respect current dimension limitations. The corresponding values are: $u_\tau = 3$ and $u_v = 1.5$ for the effective loads (in tons) of trucks and city-freighters, respectively, $k_v = 30$ (in Euros) for each hour of city-freighter utilization, $k_\tau = 100$ (Euro/hour) for truck utilization. The current wages and productivity measures in Italy were also used to determine the $k_p =$ 100 (Euro/ton) cost for the satellite handling of freight.

Table 1
Satellite characteristics

Type	k_s	t_s^p	l_s^T	u_s^T	u_s^V
PRK	2000	0.17	8	60	120
SA	2500	0.17	0	120	240
GRA	3750	0.17	8	180	480

The satellite characteristics, displayed in Table 1, have been approximated for each potential site according to its type: parking areas (PRK), vehicle depots (SA), and "new" installations outside the ring road (GRA). Capacities are in vehicle/hour, the monetary unit is the Euro, the weight unit is the ton, and the time unit is the hour. Note that capacities of GRA satellite sites have been set to accommodate the entire demand considered in the study. This data forms the *basic* scenario of our case study. To examine the impact of satellite capacity on the operations of the system, a second, *extended* scenario has been defined where the GRA satellites offer increased capacities of $u_s^T = 200$ and $u_s^V = 535$.

Travel times are derived using a detailed street-network representation of the city of Rome available in a state-of-the-art urban planning software package (EMME/2). In this network representation, each street is characterized by its number of lanes and an average speed that accounts for congestion. Travel time on each link is then adjusted to penalize truck movements within the city center. Then, the shortest paths, using penalized travel times, are computed between external zones and satellites (t_{es}), and between satellites and commercial zones (t_{sz}). (Note that, arcs between the external zones and the GRA satellite locations with a cost of 0, as well as arcs from the satellite locations in the GRA to the commercial zone centroids with costs equal to those between the corresponding external zones and the centroids are added to the network representation.)

The location–allocation model has been solved using the branch-and-bound procedure of CPLEX, in less than 8 seconds of CPU time on one 400 MHz processor of a SUN E10000 computer. Much larger problem instances (we "solved" the 400 commercial zone problem covering the city of Rome with artificial demand data), while requiring significantly longer solution times, were still within very reasonable bounds. Thus, solving realistic problem instances is not an issue.

In the basic scenario, 38 (out of 41) satellites are open, almost all of them (34) being saturated (all capacity used). In the extended scenario, where GRA satellites offer larger capacities, 36 satellites are open, 31 at capacity. In both scenarios, all GRA satellites are open. This is not a surprise since despite longer transport distances, the cost-to-capacity ratio is interesting.

To make a preliminary evaluation of the possible impact of satellite utilization on the efficiency of the transportation system, we computed shortest path distance matrices between external and commercial zones, external zones and satellites, and satellites and commercial zones. We also computed the shortest path travel matrices, without penalties, for the same three sets of origin and destination pairs.

Several performance measures have been computed based on these distance and travel time matrices. Table 2 displays the results for each of the two scenarios. The information is displayed in three groups. In the first two, we compare the intensity of truck traffic in the city under current conditions (with no satellites) and the proposed organization. As expected, a

Table 2
Comparative performance measures

	Basic scenario	Extended scenario
No satellites		
Truck-km	4.89e+04	4.89e+04
With satellites		
Truck-km	1.53e+04	1.39e+04
City-freighter-km	7.38e+04	7.61e+04
No satellites		
Truck-hour	1849	1849
With satellites		
Truck-hour	575	514
City-freighter-hour	2808	2891
No satellites		
$\mu(T_{ez})$	0.4720	0.4720
$\sigma(T_{ez})$	0.0766	0.0766
$E(T_{ez})$	0.4623	0.4623
With satellites		
$\mu(T_{ez})$	0.4891	0.4882
$\sigma(T_{ez})$	0.0881	0.0891
$E(T_{ez})$	0.4946	0.4899

two-tiered distribution system reduces dramatically the presence of trucks in the city. The number of truck-km is reduced by 68.71% and 71.58% for the basic and extended scenario, respectively. The corresponding reductions in total truck-hours are 68.90% and 72.20%, respectively. This is a remarkable reduction and, if achieved, should prove a significant contribution to reducing the noise and pollution associated with freight traffic. Of course, city-freighters would be present. In fact, in the two scenarios, city-freighters perform 82.82% and 84.56%, respectively, of the total work measured in vehicles-km. The figures are 83.00% and 84.91%, respectively, in terms of total vehicle-hours. We expect the larger number of small vehicles to be less intrusive due to the advanced planning and operations procedures associated to an Intelligent Transportation System, as well as to the environment-friendly characteristics of the vehicles.

It is noteworthy that the benefits appear somewhat larger in the extended scenario. This follows directly from the increased capacity of the GRA satellites that allows a larger volume of cargo to be transferred to city-freighters before entering the city center. This is an important observation for the final designs of such systems. Indeed, one may envision that "satellites" be located in the intermodal platforms operating close to the city (assuming that vehicular technology, autonomy, in particular, allows it), eliminating the need for transfer activities within the city. The main concept presented in this paper for the advanced planning and operation of a dedicated, environment-friendly fleet of freight vehicles would, however, still stand.

The third group of results attempts to quantify the impact of the satellite-based operations on delivery performance. In this group $\mu(T_{ez})$ stands for the average delivery time (in hours) for the 612 origin–destination pairs with positive (i.e., larger than 1e−06) demand from an external to a commercial zone. $\sigma(T_{ez})$ stands for the corresponding standard deviation. As expected, the additional transfer operation increases the travel time. But the increase is minimal: 3.62% and 3.43% for the basic and extended scenario, respectively. To better qualify these figures, especially since a simple average does not indicate the relations between delay and volume, we computed $E(T_{ez})$, the average travel time weighted by the corresponding volume moved. In the current case, this is simply given by the product of each origin–destination demand with the travel time of the corresponding path. When satellites are used, the satellite capacity may force some demands to be split among two or more paths. In this case, the travel time of each path is multiplied by the volume it carries. The results are interesting. The increase is somewhat larger, but still minimal: 6.99% and 5.97% for the basic and extended scenario, respectively. These are very encouraging results from the point of view of the feasibility of the system. The slightly better performance of the system under the extended scenario may be explained by the possibility of better distributing flows when larger satellites are in operations.

6. Conclusions and perspectives

The transportation of goods constitutes both an extremely important and an increasingly disturbing activity taking place in urban areas. Freight movements support most city-based activities, while negatively impacting on the quality of life in cities through significant contributions to the levels of congestion, noise, and pollution. There is therefore a need for new methods and tools to study, plan, and control freight-related traffic. Integration and city-wide views are key factors of success if one desires to simultaneously reduce congestion and increase mobility, while not unduly penalizing the city center commercial activities so as not to empty them.

We have introduced a possible organizational and technological framework for the integrated management of urban freight transportation and have identified a number of important associated planning and operation issues and the corresponding Operations Research models. We have also described a formulation for one of these problems, the design of the proposed logistical structure. The proof-of-concept experimentation, based on data from the city of Rome, is very encouraging. It indicates that such a system may indeed contribute towards reaching the goals of a better city environment at a reasonable cost.

Many stages have to be accomplished, however, before such a system is fully deployed. There are methodological challenges, of course, in developing the appropriate models and tools for the analysis, planning, and operation of the system. More formidable still are, probably, the social and political challenges. We have initiated work on the former. We hope the current dialog between all stake-holders will develop and become more general. We cannot presume what form integrated freight city logistics will take. But it will include some form of consolidation and control. These are issues the models and methods we develop will help address.

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References

Aikens, C.H., 1985. Facility location models for distribution planning. European Journal of Operational Research 22, 263–279.

AORSM Lazio, 1999. Il piano regionale delle merci. Technical report, Regione Lazio, Assessorato Opere et Reti di Servizi e Mobilità, Roma, Italia.

Crainic, T.G., 2003. Long haul freight transportation. In: Hall, R.W. (Ed.), Handbook of Transportation Science, second ed. Kluwer Academic Publishers, Norwell, MA, pp. 451–516.

Crainic, T.G., Laporte, G., 1997. Planning models for freight transportation. European Journal of Operational Research 97 (3), 409–438.

Crainic, T.G., Florian, M., Guélat, J., Spiess, H., 1990. Strategic planning of freight transportation: STAN, An Interactive-Graphic System. Transportation Research Record 1283, 97–124.

Daskin, M.S., 1995. Network and Discrete, Location, Models, Algorithms, and Applications. John Wiley & Sons, New York, NY.

Dietrich, W.J., 2001. Approches et pistes suivies en Suisse. In: Patier-Marque, D. (Ed.), L'intégration des marchandises dans le système des déplacements urbains—Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000. Études et recherches, vol. 15. Laboratoire d'Économie des Transports, Lyon, France, pp. 191–198.

Drezner, Z. (Ed.), 1995. Facility Location. A Survey of Applications and Methods. Springer-Verlag, New York NY.

Dror, M. (Ed.), 2000. Arc Routing: Theory, Solutions and Applications. Kluwer Academic Publishers, Norwell, MA.

Dufour, J.-G. 2001. L'émergence du problème des marchandises en villes en France et en Europe de l'Ouest. In: Patier-Marque, D. (Ed.), L'intégration des marchandises dans le système des déplacements urbains—Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000. Études et recherches, vol. 15. Laboratoire d'Économie des Transports, Lyon, France, pp. 19–29.

Gerardin, B., 2001. Premier bilan des expériences pilotes françaises en matiére de TMV. In: Patier-Marque, D. (Ed.), L'intégration des marchandises dans le système des déplacements urbains—Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000. Études et recherches, vol. 15. Laboratoire d'Économie des Transports, Lyon, France, pp. 183–189.

Guélat, J., Florian, M., Crainic, T.G., 1990. A multimode multiproduct network assignment model for strategic planning of freight flows. Transportation Science 24 (1), 25–39.

ISTAT, 1998. Il transporto di merci su strada nel 1998. Technical report, ISTAT, Roma, Italia.

Janssen, B.J.P., Oldenburger, A.H., 1991. Product channel logistics and city distribution centers; The case of the Netherlands. In: OECD Seminar on Future Road Transport Systems and Infrastructures in Urban Areas, Chiba, pp. 289–302.

Kohler, U., 1997. An innovating concept for city-logistics. In: Proceedings 4th World Congress on Intelligent Transportat Systems, Berlin (CD ROM).

Kohler, U., 2001. How to change urban traffic with city logistics. In: Schnieder, E., Becker, U. (Eds.), Control in Transportation Systems 2000—Proceedings 9th IFAC Symposium, Braunschweig, Germany, vol. 1. Pergamon, Oxford, pp. 199–201.

Labbé, M., Louveaux, F.V., 1997. Location Problems. In: Dell'Amico, M., Maffioli, F., Martello, S. (Eds.), Annotated Bibliographies in Combinatorial Optimization. John Wiley & Sons, New York, NY, pp. 261–281.

Labbé, M., Peeters, D., Thisse, J.-F., 1995. Location on networks. In: Ball, M., Magnanti, T.L., Monma, C.L., Nemhauser, G.L. (Eds.), Network Routing, Handbooks in Operations Research and Management Science, vol. 8. North-Holland, Amsterdam, pp. 551–624.

Larraneta, J., Munuzuri, J., Montero, G., 1999. Analysis of urban freight requirements and alternative solutions—an application in Sevilla. In: Taniguchi, E., Thompson, R.G., (Eds.), City Logistics I, 1st International Conference on City Logistics. Institute of Systems Science Research, Kyoto, pp. 245–259.

Mirchandani, P.S., Francis, R.L. (Eds.), 1990. Discrete Location Theory. John Wiley & Sons, New York, NY.

Morris, A.G., Kornhouser, A.K., Kay, M.J., 1999. Getting the goods delivered in dense urban areas: a snapshot of the last link of the supply chain. Transportation Research Record 1653, 34–41.

Patier-Marque, D., 2001. Diagnostique sur les enquêtes françaises: tentative de globalisation. In: Patier-Marque, D. (Ed.), L'intégration des marchandises dans le système des déplacements urbains—Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000. Études et recherches, vol. 15. Laboratoire d'Économie des Transports, Lyon, France, pp. 125–144.

Pirkul, H., Jayaraman, V., 1996. Production, transportation, and distribution planning in a multi-commodity tri-echelon system. Transportation Science 30 (4), 291–302.

Ricci, A., Fagiani, P., 2001. Régulation du Transport de Marchandises en Ville: concertation ou répression? L'expérience italienne. In: Patier-Marque, D. (Ed.), L'intégration des marchandises dans le système des déplacements urbains—Actes des Treizièmes Entretiens Jacques Cartier, Montréal, octobre 2000. Études et recherches, vol. 15. Laboratoire d'Économie des Transports, Lyon, France, pp. 199–208.

Ruske, W., 1994. City logistics-solutions for urban commercial transport by cooperative operations management. In: OECD Seminar on Advanced Road Transport Technologies, Omiya, Japan.

STA, 2000. Studio per la mobilità delle merci nell'area centrale di Roma. Technical report, STA—Società Trasporti Automobilistici, Roma, Italia.

Taniguchi, E., van der Heijden, R.E.C.M., 2000. An evaluation methodology for city logistics. Transport Reviews 20 (1), 65–90.

Taniguchi, E., Thompson, R.G., 2002. Modeling City Logistics. Transportation Research Record 1790, 45–51.

Taniguchi, E., Noritake, T., Yamada, T., Izumitani, T., 1999a. Optimal size and location planning of public logistics terminals. Transportation Research E 35 (3), 207–222.

Taniguchi, E., Thompson, R.G., Yamada, T., 1999b. Modelling city logistics. In: Taniguchi, E. Thompson, R.G., (Eds.), City Logistics I, 1st International Conference on City Logistics. Institute of Systems Science Research, Kyoto, pp. 3–37.

Taniguchi, E., Kawakatsu, S., Tsuji, H., 2000. New co-operative system using electric vans for urban freight transport. In: Sucharov, L.J., Brebbia, C.A. (Eds.), Urban Transport and the Environment for the 21st Century VI. WIT Press, Southampton, pp. 201–210.

Taniguchi, E., Thompson, R.G., Yamada, T., Duin van, J.H.R., 2001. City Logistics: Network Modelling and Intelligent Transport Systems. Pergamon, Amsterdam.

Thompson, R.G., Taniguchi, E., 2001. City logistics and transportation. In: Handbook of Logistics and Supply-Chain Management. Elsevier, Amsterdam, pp. 393–405.

Toth, P., Vigo, D. (Eds.), 2002. The Vehicle Routing Problem. SIAM Monographs on Discrete Mathematics and Applications, vol. 9. SIAM.

van Duin, J.H.R., 1997. Evaluation and evolution of the city distribution concept. In: Urban Transport and the Environment for the 21st Century III. IT Press, Southampton, pp. 327–337.