Chapter 8

STRATEGIC NETWORK DESIGN FOR MOTOR CARRIERS

James F. Campbell

Abstract This chapter reviews Operations Research models for strategic design of motor carrier networks, including network configuration and terminal location. This includes networks for less-than-truckload (LTL), truckload (TL), and postal motor carriers that serve many origins and destinations in large geographic regions. LTL carriers, as well as postal carriers, use networks with consolidation and break-bulk terminals to combine small shipments into efficient vehicle loads. Some TL carriers use networks with relay terminals where loads can be exchanged to allow drivers to return home more frequently. The chapter reviews research in each area and proposes directions for future research.

1. Introduction

Trucking is the most important mode of land freight transportation in the world. Within the United States, motor carriers account for 81% of the freight bill ($372 billion per year in revenues), 60% of the freight volume (6.7 billion tons per year) and nearly 430 billion miles traveled per year. More broadly, within North America motor carriers account for 64% of the merchandise trade by value (versus 25% for rail) and 32% by weight (versus 17% for rail) (United States Bureau of Transportation Statistics, 2003). Truck transport is even more important within the European Union, where it accounts for 75% of inland freight ton-km (road, rail, inland waterways, and pipelines) and 44.5% of the total freight ton-km (road, rail, short sea shipping, pipelines, and inland waterways) (European Commission 2003).

Motor carrier operations provide an important and rich source of decision problems, and there has been considerable prominent Operations Research (OR) work in a variety of areas. One of the key strategic decisions for motor carriers is the physical network over which the carrier operates. This chapter reviews operations research models for strategic design of motor carrier networks. Our focus is on *strategic* network design (including network configuration and terminal location) and on newer research, rather than on tactical network design, which includes load planning and service network design. Roy (2001) describes strategic planning for motor carriers as including:

(1) "the type and mix of transportation services offered...;
(2) the territory coverage and network configuration, including terminal location; and
(3) the service policy, what service levels are offered to customers in terms of both speed and reliability."

Roy distinguishes this from tactical service network design, which includes selecting routes on which services are offered, determining the sequence of services and terminals used to transport the freight, and the movement of empty trucks and trailers to balance the network.

This chapter considers strategic network design for general freight intercity public (for-hire) motor carriers and for postal motor carriers. The primary business of these carriers is to transport freight owned by others between many origins and destinations dispersed over a large geographic region. General freight carriers are usually classified as truckload (TL) or less-then-truckload (LTL) carriers. TL carriers generally haul full truckloads, usually direct from an origin to a destination. TL carriers may also use networks with relay terminals where loads can be exchanged to allow drivers to return more frequently to their home. LTL carriers use networks with consolidation and break-bulk terminals to combine many small shipments into efficient vehicle loads. Postal (and small parcel) motor carriers are very similar to general freight LTL carriers, but the freight is more specialized, and service constraints may force tight deadlines for delivery (for example, overnight).

The remainder of this chapter is organized as follows. The following section provides some background on motor carrier operations and reviews some relevant transportation network design literature. The next three sections discuss models for strategic network design in LTL trucking, TL trucking, and postal operations. The final section is a conclusion and discussion of directions for future research.

2. Background

Motor carriers have great versatility in being able to carry virtually any type of product, and to visit nearly every address (at least in regions with a well-developed infrastructure). The motor carrier industry can be divided many different ways. Public carriers haul a wide variety of freight for many different shippers, while private carriers haul freight exclusively for their own organization. General freight carriers may haul nearly any product, while specialized carriers may focus on unique products or markets, such as household goods, automobiles and trucks, liquids, hazardous materials, temperature controlled products, express shipments, etc. Public carriers of general freight have developed networks and operations to serve many dispersed origins and destinations. (Private carriers will generally have somewhat different networks designed to serve a few-to-many traffic pattern; for example, linking a few origins, such as manufacturing locations, with many destinations, such as wholesalers, retailers or customers.)

2.1 Operations

We summarize some relevant aspects of trucking operations in this section. See Delorme et al. (1988) and Roy (2001) for more details. Stumpf (1998) provides details on LTL operations in Germany, especially for transporting partial loads, which is common there (though not so much in North America).

LTL firms are the largest part of the motor carrier industry. LTL carriers consolidate many small shipments, each generally between 100 and 10,000 pounds (50 – 4,500 kg.) from many different shippers to make efficient vehicle loads. Trailers may hold 20,000 to 50,000 pounds (9,000 – 23,000 kg.) depending on the freight. LTL carriers typically route shipments via a network consisting of end-of-line terminals and break-bulk terminals. Each end-of-line terminal collects shipments from its local service region using local pickup/delivery trucks. (Shipments may also be delivered to the terminal by the shipper.) Shipments are sorted at the terminal and loaded into line-haul trucks, which carry the shipments to break-bulk terminals for consolidation with other shipments headed in the same direction. Line-haul vehicles then carry the shipments to another break-bulk terminal, where they may be unloaded and sorted again for transport to the end-of-line terminal serving the destination. The freight is then transshipped from the line-haul truck to a local delivery truck for transport to the destination. A typical LTL carrier in the U.S. generally has "an order of magnitude fewer break-bulks than terminals" (Bartholdi et al., 2003), which may mean several hundred end-of-line terminals and a few dozen break-bulks.

In LTL operations the local collection and delivery trucks may be small straight trucks or short tractor-trailer combinations. The local collection and delivery stops may change from day to day and this portion of the operation is generally not included in strategic network design. The line-haul trucks may be long tractor-trailer combinations, with one, two, or sometimes more, trailers. National and local regulations restrict vehicle sizes and weights, though the growth of free trade regions can impose common standards in larger regions.

TL operations are simpler than LTL operations, since consolidation of many small shipments is not required. TL shipments generally fill the trailer, so that the freight may move from the origin to the destination without intermediate handling and sorting. (Some carriers will haul several large loads with a common destination in the same trailer.) In point-to-point operations, a driver hauls the load from the origin to destination. Then, after delivering a load, the driver would like to find a return load originating nearby and destined for the vicinity of his home. Such return loads are rarely available when needed, so efficient routes for drivers may require a sequence of many long-haul trips before returning home. This long-haul nature of the trips and the difficulty in finding backhauls has led to very high turnover rates for drivers (Schwarz, 1992). Annual turnover rates over 100% are common and have been reported up 150%! (Griffin et al., 2000; Hunt, 1998; Road Haulage and Distribution Training Council, 2003). Since most drivers would prefer to return to their home on a regular and frequent basis, some TL carriers have developed networks of relay terminals to allow drivers to exchange loads and operate in more regular delivery lanes or regions, and thereby return home more frequently.

Postal motor carrier operations are quite similar to LTL operations, and these carriers operate networks of consolidation and break-bulk terminals to create efficient loads. Postal carriers may also operate intermodal networks with aircraft to allow fast delivery over longer distances. Our concern is primarily on motor carrier networks, but later in this section we list some relevant research on intermodal or integrated express carriers.

2.2 Freight transportation network design

For many years when motor carrier transportation was regulated, carriers performed a limited amount of strategic planning and network design. Prior to deregulation in the U.S. (via the Motor Carrier Act of 1980) Kallman and Gupta (1979) surveyed 498 motor carriers and found that "few ... planned for longer than a year, and most did so informally." However, in a deregulated environment, the success of any transportation carrier depends on its ability to attract and retain business via competitive rates and quality service. The cost incurred for carrying freight, the rate charged to shippers, and the level of service provided are all affected by the design of the physical network over which the carrier operates.

LTL carriers and postal carriers use a network of terminals to consolidate small shipments into economic truckloads. TL carriers use networks of terminals for different reasons, primarily to allow swapping of trailers so that drivers may return home more frequently. Given that motor carriers generally operate on publicly owned infrastructure, the network to be designed includes nodes representing private or public terminal facilities (for consolidation, break-bulk, sorting, or transshipment) and links representing travel on the roadways. Generally, the demand in motor carrier network design models is for transportation of specified quantities of freight between many origins and destinations. Origins and destinations may represent actual shipment origins and destinations, or the end-of-line terminals to which shipments are collected, and from which shipments are distributed, to the ultimate customers.

While general network design and tactical service network design have drawn considerable attention from operations researchers, much less work has been directed specifically at strategic network design for motor carriers. Our goal in the remainder of this section is to highlight some relevant literature for transportation network design, and to briefly mention the related work on tactical service network design for motor carriers, including load planning.

Crainic (2003) provides a comprehensive review of long-haul (intercity) transportation by both motor and rail carrier. He describes basic problems and solution approaches, and provides a broad perspective for both road and rail transport. Crainic describes strategic (long term) planning as including "design of the physical network and its evolution, the location of major facilities (e.g., terminals), the acquisition of major resources such as motive power units, and the definition of broad service and tariff policies." This is distinguished from tactical network design, which includes: "the design of the service network and may include issues related to the determination of the routes and types of services to operate, service schedules, vehicle and traffic routing, [and] repositioning of the fleet."

Section 13.4 of Crainic (2003) addresses logistics network design. This discusses location-based and network flow-based modeling approaches. Location-based models are used in transportation network design to capture decisions on the terminal locations. For a survey of this work, see Daskin et al. (2005), Daskin and Owen (2003), and Drezner and Hamacher (2002). For the network-flow based approach, Crainic (2003) provides standard arc-based and path-based fixed cost multicommodity capacitated network design formulations. In a multicommodity network flow formulation, the freight for each unique origin-destination pair is viewed as a distinct commodity. Decision variables can represent the flow on each arc or path in the network. Crainic also provides a brief discussion of solution approaches including Lagrangian relaxation, dual ascent, branch and bound, polyhedral approaches, and a variety of heuristics.

Fleischmann (1998) reviews recent literature on freight transportation network design, from the viewpoint of both a manufacturer and of a carrier. He proposes a general model for few-to-many networks and many-to-many networks and describes some solution approaches. He also briefly describes a decision support system (BOSS) for designing LTL networks, which is described in detail later in this chapter in the discussion of Wleck (1998).

2.3 Service network design

Section 13.5 of Crainic (2003) addresses service network design, which includes tactical decisions on the services to be offered (including frequencies and schedules), freight routing, terminal operational policies, and empty balancing strategies. (Kim and Barnhart, 1997, also review transportation service network design.) These problems are usually modeled via fixed cost capacitated multicommodity network design formulations. Crainic subdivides service network design into frequency service network design and dynamic service network design models. Frequency service network design models include transportation or load planning models, which can be used both to determine day-to-day operational policies and "for what-if questions raised ... in strategic planning." Dynamic service network design models are less strategic and "closer to the operational side of things."

Service network design research includes several prominent studies of LTL load planning. Crainic and Roy (1988), Roy and Delorme (1989) and Roy and Crainic (1992) discuss the NETPLAN model for service network design, freight routing and empty balancing. The model is similar to the path formulation of a capacitated multicommodity network design problem, but with a more general cost structure that includes transportation, consolidation, and penalties for capacity violations and missing service standards. The model is tested with data for two Canadian LTL companies with up to 35 terminals and almost 1000 origin-destination pairs.

Powell and Sheffi (1989) describe the APOLLO (Advanced Planner of LTL Operations) interactive DSS, which was implemented at a major LTL carrier (Ryder/PIE). This model focused on determining which direct services should be used between end-of-line terminals and break-bulk terminals, and between two break-bulk terminals. The solution approach is based on local improvement heuristics that add and drop services (links) in the network. Powell and Sheffi (1983) describe the load planning problem and a proposed network optimization model, while Powell and Sheffi (1986) highlight the benefits of having an interactive tool. Powell (1986) reports numerical experiments with 12 break-bulk terminals and over 1000 end-of-line terminals.

Braklow et al. (1992) describe SYSNET, a more comprehensive load planning system developed for one of the largest U.S. LTL carriers (Yellow Freight Systems). This was an extension and enhancement of the work for the APOLLO system. In addition to load planning, SYSNET has been used more strategically to examine questions such as break-bulk locations and capacities, whether to open end-of-lines, and deciding to which break-bulk an end-of-line terminal should be linked. All these strategic issues rely on having a good model for load planning. Bell et al. (2003) report that SYSNET has continued in use at Yellow Freight, in an evolved version, for over a decade.

Hoppe et al. (1999) address strategic load planning using a three stage solution strategy that utilizes a historic load plan to eliminate unlikely direct services, followed by a network construction phase based on the dual ascent approach of Balakrishnan et al. (1989), and then an add/drop heuristic. Numerical results are presented using real-world data sets from three different motor carriers with 48 to 92 terminals. These results demonstrate the value of having a historic load plan as a starting point — and the high quality of the historic load plans!

Dynamic service network design models include multiple time periods and use a space-time network to model schedules. Farvolden and Powell (1994) present a dynamic service network design model for general LTL transportation with 15 terminals and 18 time periods. Farvolden et al. (1993) use primal partitioning and decomposition to solve problems motivated by LTL trucking with 18 time periods and up to 30 terminals. Equi et al. (1997) provide a dynamic service network design model for transporting wood from cutting areas to ports.

In addition to the research on service network design for motor carriers, other applications of operations research to trucking include: LTL terminal layout and scheduling (Bartholdi and Gue, 2000, 2004; Gue, 1999), assigning drivers to loads for TL carriers (Powell et al., 1988), location and size of public terminals in congested areas in Japan (Taniguchi et al., 1999); fixed charge network design (Lamar and Sheffi, 1987; Lamar et al., 1990), and a large literature on freight routing (for example, see Akyilmaz, 1994; Crainic and Roy, 1992, Leung et al., 1990, and Lin, 2001).

Truck transportation is an important part of many multimodal systems. Research on air-ground multimodal network design for express package and postal delivery systems includes Barnhart and Schneur (1996), Cheung et al.!(2001), Grunert and Sebastian (2000), Grunert et al. (1999) and Kim et al. (1999). These models use trucks for collection and delivery and short-haul transportation, and aircraft for longer distance transport. For a review of intermodal rail-truck freight transport literature, see Bontekoning et al. (2004).

A final area of relevant literature is continuous approximation models for many-to-many transportation. This work reflects a somewhat higher level of planning than network design and provides analytical cost expressions to help determine the appropriate number of transshipments and terminals. Rather than treating input as discrete shipments between origins and destinations, it models demand as a continuous density function over a service region. For a review of relevant work on many-to-many transportation with transshipments, see Daganzo (1987, 1999), Hall (2003), and Langevin et al. (1996).

The following three sections of this paper review strategic network design models for LTL motor carriers, TL motor carriers and postal motor carriers.

3. Less-than-truckload network design

This section describes research on strategic network design for less-than-truckload (LTL) motor carriers. To keep a consistent set of notation and terminology we will refer to end-of-line terminals as "terminals" and break-bulk and consolidation terminals as "break-bulks." In various papers the end-of-line terminals are refereed to as depots, terminals, end-of-lines, satellite terminals, and branch offices; and the break-bulk terminals are referred to as hubs, operations centers, and sorting centers.

Haresamudra et al. (1995) describe BBNET (Breakbulk Network Software), an interactive decision support system for LTL network design. The primary focus is on finding break-bulk locations to minimize total transportation and handling costs. The software seeks to find a "near optimal design without the use of complicated mathematical programming alternatives." The package is developed in Turbo C as an extension of the HUBNET system developed for TL network design. (See the following section for details on HUBNET.)

The model includes transportation and handling costs based on input transportation and handling rates ($/lb/mile and $/lb, respectively). It assumes that adequate labor and real estate exist for the break-bulks, and that the capital requirements for different sites do not vary drastically. The required input data includes the origin, destination, and weight for each shipment, transportation and handling cost rates, handling times (min/lb), and average speed (mph). The user can specify up to 60 break-bulk locations, and the links between break-bulks, and can add or remove them interactively. Each origin and destination can either be assigned to the nearest break-bulk or the user can assign two degree × two degree latitude/longitude cells to a particular break-bulk. In addition, the user can specify the maximum number of break-bulks where a shipment is handled for each 500-mile trip increment.

BBNET determines routes based on the specified assignment of terminals to break-bulks using shortest paths through the links between break-bulks. It then calculates various performance measures. No algorithm is presented for locating break-bulks, but the authors suggest placing break-bulks in regions of high "freight density" (measured as freight flow in and out of each region) to reduce transportation cost and increase consolidation opportunities.

BBNET is validated with data from ABF Freight Systems, Inc. Numerical results are presented using disguised data for two months (average and high volume) with 10 break-bulks. The report states that the software is installed at ABF Freight Systems, Inc. where it "is being validated and verified for continued use."

Wleck (1998) describes an interactive DSS called "BOSS" used for design of LTL motor carrier networks in Europe, including location of terminals and break-bulks. Sparked by deregulation of motor carriers in Germany in the early 1990s, one strategy for small and medium size (regional) carriers was to join together to offer nationwide service in Germany and beyond. (This is very similar to the situation in the U.S. following deregulation a decade earlier.)

BOSS is used to address strategic questions, such as the number and location of terminals and break-bulks to minimize costs for facilities, transportation, and handling while meeting time standards. It uses approximations of transportation costs to allow quick evaluation of solutions. The model in BOSS assumes single assignment of customers to terminals and uses a specified maximum distance between customers and a terminal. The goal is to provide 24-hour transport between all customers. Regions served by terminals are compact and non-overlapping.

The solution method is designed to use various heuristics that can produce solutions in a "very limited computation time." It first finds an initial solution based on opening terminals that are close to the largest aggregated demands. Additional terminals may then be opened to ensure all customers are within a specified maximum distance of a terminal.

Initially a single break-bulk is opened to minimize the total distance to the initial set of terminals. Then, several stochastic and deterministic local neighborhood search heuristics are considered to find a set of improved terminals and break-bulks. Solutions near the best found are explored in more detail through a "1-opt" type exchange procedure. The solution algorithms are implemented in an interactive decision support system called BOSS.

Numerical results compare various heuristics with three sets of data for German motor carriers ranging from 35 thousand to 123 thousand customers, with up to 100 potential terminal locations and up to 50 potential break-bulk locations. Wleck also describes an application of BOSS with multiple cooperating carriers to evaluate questions concerning closure of a terminal and changing the number of terminals.

Results showed that all the heuristics performed similarly in terms of cost, but no lower bounds are available to evaluate the solution quality. Wleck states that four German carriers are using BOSS and that the algorithms "perform well in real life applications." He also argues that an interactive DSS is valuable for strategic network design to better allow many different scenarios to be examined in light of uncertain data, and to gain better insight into the sensitivity of costs and network structures to the various parameters.

Nagy and Salhi (1998) present a hub location-type model for many-to-many distribution with multistop collection and delivery tours. They include two types of vehicles: access vehicles for local delivery/collection, and linehaul vehicles for transportation between break-bulks. Each vehicle type has a volume capacity and a maximum distance/time per route. They seek to determine the number and location of break-bulks, and the local collection and delivery tours (by access vehicles) from break-bulks to origins/destinations, to minimize cost while satisfying demand and vehicle capacities. Costs include the fixed facility costs for break-bulks and transportation costs, which differ by vehicle type. The network includes direct links between all break-bulks, by assumption, so the routing of shipments between break-bulks is implicitly determined by the break-bulk locations. (The lowest cost path is a direct arc.)

Nagy and Salhi present a large integer linear programming formulation (an extension of location routing problem LR1 from Laporte, 1989), but do not solve it. Instead they present a decomposition approach where break-bulk locations are determined by an add/drop heuristic with tabu search. Routing for collection and delivery is based on the multi-depot vehicle routing heuristic in Salhi and Sari (1997). They report heuristic solutions with 249 customers and 10 break-bulks.

Other models for hub location and network design are relevant to LTL trucking, though most hub location research has been more focused on airline networks. For a recent review of hub location and network design, see Campbell et al. (2002). In a motor carrier context, hubs are break-bulks, and origins and destinations are end-of-line terminals. Early hub location models assumed two types of vehicles (often aircraft), where larger more efficient vehicles traveled between hubs and less efficient vehicles provided collection and delivery between the origins/destinations and the hubs. Hub location models have been examined for networks with single allocation (each terminals sends and receives all freight via one hub), multiple allocation (terminals may send and receive via more than one hub), arc and node capacities, and flow dependent costs. While most hub location research has focused on air networks, O'Kelly and Lao (1991) developed models for an intermodal (air-truck) two-hub express delivery network to determine where truck transportation should be used.

Tansel and Kara (2002) design a cargo delivery network that minimizes the delivery time of the latest item. This is formulated as an extension of the minimax hub location model that minimizes the arrival time of the last item (Kara and Tansel, 2001). Freight shipments follow a 3-leg route from the origin terminal (a branch office of the delivery firm) to the first break-bulk to a second break-bulk, then to destination terminal. Customers may drop-off and pick-up items at a terminal, or there may be local collection and delivery routes from the terminal. This local collection and delivery is not included in the model.

Terminals may be visited on routes with stopovers, and the model includes three types of route segments: "main lines" between terminals and break-bulks; "feeder lines" that visit several terminals and end at main lines; and "express lines" that connect two break-bulks. Main lines link one or more larger cities to a break-bulk and are served by large trucks. Feeder lines connect one or more smaller cities to the main line and are served by smaller trucks. Express lines are direct links between two break-bulks. Thus, a shipment may travel on a multistop feeder line from its origin terminal to another terminal on a main line, then on a main line to a break-bulk, then on an express line between two break-bulks, then again on a main line to the destination terminal (or to a feeder line that visits the destination terminal). Main lines and feeder lines may make multiple stops at terminals, but express lines make no intermediate stops. The problem is to determine the locations of break-bulks, the allocation of terminals to break-bulks, and the route structure between terminals and break-bulks with multiple stopovers and feeders, so as to minimize the arrival time of the latest arriving cargo at destinations. The total time includes travel times and waiting times at hubs.

To model the complex transportation with stopovers and feeder lines, there are three types of vehicles: express (type 0), main (type 1) and feeder (type 2) vehicles. A trip is defined as the path traversed from the node where an empty vehicle is initially loaded to the node where the vehicle is completely emptied. We now present the formulation.

Let $N = \{1, 2, \ldots, n\}$ be the set of nodes that serve as origins and destinations of freight. N is partitioned into two subsets where N_1 is all terminals that can be on a main line, and N_2 is all terminals that can be on feeder lines. Nodes in N_1 are handled by main line trucks; nodes in N_2 may be handled by feeder line trucks or main line trucks (if the node is on the route of a main line truck). All nodes in N_1 are potential break-bulks. Let A be the set of arcs in the transportation network that connect the nodes. Arcs for feeder lines, main lines and express lines are selected from A.

The model includes four sets of binary variables. Break-bulk location variables (y) indicate, for each potential break-bulk location, whether or not a break-bulk is established. Trip type variables (Z) indicate whether trips are with feeder line vehicles or main line vehicles. Trip arc variables (X) indicate which arcs are traversed on a trip. Service type variables (u) indicate whether each node is serviced by a main line truck or a feeder line truck. Thus:

$y_i =$ 1 if node i is a break-bulk, and 0 otherwise, where $i \in N_1$,
$Z_{ij}^1 =$ 1 if a main line trip takes place between i and j with a type 1 vehicle, and 0 otherwise, where $i, j \in N_1$,
$Z_{ij}^2 =$ 1 if a feeder line trip takes place between i and j with a type 2 vehicle, and 0 otherwise, where $i \in N_2$ and $j \in N_1$,
$X_{ij}^{kl} =$ 1 if the trip between i and j includes arc (k, l), and 0 otherwise, and
$u_{ij}^r =$ 1 if node r is served by a main line or feeder truck operating between nodes i and j, and 0 otherwise, where $r \in N$.

Define the following parameters:

$p =$ the number of break-bulks to be located,
$q_1 =$ the number of main line vehicles available,
$q_2 =$ the number of feeder line vehicles available,
$t_{kl} =$ the time to traverse arc (k,l) by a main line or feeder vehicle,
$r_i =$ the time that freight is ready at origin node i,
$\alpha =$ a scale factor to reflect reduced travel times on express lines: $\alpha \leq 1$,
$\delta =$ the time spent loading or unloading at each stop, and
$\gamma =$ the maximum allowable time for a feeder line trip.

Intermediate parameters calculated in the formulation are:

$A_j =$ the arrival time of a vehicle at node j,
$T_{hj} =$ the total trip time from h to j,
$D_h =$ the departure time of a main line vehicle from break-bulk h,
$\hat{D}_h =$ the latest time at which all incoming freight by main line trucks is available at node h.

The latest arrival time at a destination is denoted by Ω, which is given by the maximum of the A_j values. The formulation is:

Minimize Ω

Subject to

$$Z^1_{ij} \leq y_j \qquad \text{for all } i, j \in N_1 \tag{8.1}$$

$$Z^2_{ij} \leq 1 - y_j \qquad \text{for all } i \in N_2,\ j \in N_1 \tag{8.2}$$

$$\sum_{i,j \in N_1} Z^1_{ij} \leq q_1 \tag{8.3}$$

$$\sum_{\substack{i \in N_2 \\ j \in N_1}} Z^2_{ij} \leq q_2 \tag{8.4}$$

$$\sum_{j \in N_1} y_j = p \tag{8.5}$$

$$\sum_{\substack{i \in N, j \in N_1 \\ i \neq j, j \neq r}} u^r_{ij} = \begin{cases} 1 & \text{if } r \in N_2 \\ -1 & \text{if } r \in N_1 \end{cases} \tag{8.6}$$

$$u^r_{ij} \leq Z^1_{ij} \qquad \text{for all } i, j, r \in N_1 \tag{8.7}$$

$$u^r_{ij} \leq Z^t_{ij} \qquad \text{for all } i \in N_t,\ j \in N_1,\ r \in N_2,\ t = 1, 2 \tag{8.8}$$

$$\sum_{k:(k,l) \in A} X^{kl}_{ij} - \sum_{k:(l,k) \in A} X^{lk}_{ij} = \begin{cases} Z^t_{ij} & \text{if } l = j \\ 0 & \text{if } l \neq i, j \\ -Z^t_{ij} & \text{if } l = i \end{cases}$$
$$\text{for all } i \in N_t,\ j \in N_1,\ t = 1, 2 \tag{8.9}$$

$$X^{kl}_{ij} \leq Z^t_{ij} \qquad \text{for all } (k, l) \in A,\ i \in N_t,\ j \in N_1,\ t = 1, 2 \tag{8.10}$$

$$\sum_{a:(a,r) \in A} X^{ar}_{ij} - \sum_{b:(r,b) \in A} X^{rb}_{ij} \geq u^r_{ij}$$
$$\text{for all } i \in N,\ j \in N_1,\ r \in N \tag{8.11}$$

$$A_j = (D_h + T_{hj}) Z^1_{jh} \qquad \text{for all } j, h \in N_1 \tag{8.12}$$

$$\sum_{(k,l) \in A} t_{kl} X^{kl}_{jh} + \delta \sum_{r \neq h,j} u^r_{hj} = T_{hj}$$

$$\text{for all } j \in N_1,\ h \in N_1 \tag{8.13}$$

$$\hat{D}_h \geq (r_i + T_{ih}) Z^1_{ih} \qquad \text{for all } i \in N_1,\ h \in N_1 \tag{8.14}$$

$$D_h \geq (\hat{D}_l + \alpha t_{lh}) y_h \qquad \text{for all } h, l \in N_1 \tag{8.15}$$

$$2\left[\sum_{(k,l)\in A} t_{kl} X^{kl}_{ij} + \delta \sum_{r \neq i} u^r_{ij}\right] \leq \gamma Z^2_{ij}$$

$$\text{for all } i \in N_2,\ j \in N_1 \tag{8.16}$$

$$\Omega \geq A_j \qquad \text{for all } j \in N_1 \tag{8.17}$$

$$X^{kl}_{ij} \in \{0,1\} \qquad \text{for all } i \in N,\ j \in N_1,\ (k,l) \in A \tag{8.18}$$

$$u^r_{ij} \in \{0,1\} \qquad \text{for all } i, r \in N,\ j \in N_1 \tag{8.19}$$

$$Z^t_{ij} \in \{0,1\} \qquad \text{for all } i \in N_t,\ t = 1,2,\ j \in N_1 \tag{8.20}$$

$$\hat{D}_h, D_h \geq 0 \qquad \text{for all } h \in N_1 \tag{8.21}$$

$$A_j, T_{jh} \geq 0 \qquad \text{for all } j, h \in N_1 \tag{8.22}$$

Constraint (8.1) forces main line trips to end at break-bulks, and constraint (8.2) forces feeder line trips to end at non-break-bulk nodes. Constraints (8.3) and (8.4) enforce the limits on the availability of vehicles. Also, it is assumed that the number of express vehicles available allows for a direct trip between each pair of break-bulks, so the number of express vehicles is at least $p(p-1)/2$. Constraint (8.5) requires that p break-bulks be established. Constraint (8.6) ensures that all non-break-bulk nodes r are assigned to a truck, and that no break-bulk nodes are assigned to main line or feeder trucks. Constraints (8.7) and (8.8) ensure that a trip is established between nodes i and j, whenever any node r is assigned to it. Constraint (8.9) is the flow conservation equation and constraint (8.10) assures that if arcs are assigned to a trip, then the trip must exist. Constraint (8.11) assures that for every node visited by a trip, there is some arc in or out of the node. Constraints (8.12) and (8.13) establish the arrival times of vehicles, based on departure times, travel times, and loading/unloading times. Constraints (8.14) and (8.15) are nonlinear constraints that establish the departure times for trucks at each node. Constraint (8.16) enforces the maximum time limit for feeder lines and constraint (8.17) sets the latest arrival time at the end of a main line trip. Constraints (8.18) – (8.22) limit the values of decision variables and intermediate parameters appropriately.

This model includes two different service types (main line and feeder), three different vehicle and trip types (main line, feeder and express), as well as time limits for feeder line trips. It assumes trucks capacities are not an issue, though main line and feeder line capacities are discussed and constraints are provided. The formulation includes several nonlinear constraints (8.12), (8.14) and (8.15) for which the authors provide linear forms.

This formulation is not solved in Tansel and Kara (2002). However, when the feeder component is removed and the number of main line vehicles is unrestricted (remove constraint 3), then this reduces to the latest arrival hub location problem (Kara and Tansel, 2001). In this case, the set N_2 is null and there are two types of vehicles: express vehicles operating directly between two break-bulks, and main line vehicles operating directly between a break-bulk and a terminal. Kara and Tan (2003) present some solutions for ground transportation of parcels in Turkey. (Note that air transportation is not needed in Turkey to provide a high level of service due to the small size of the country, and the good infrastructure for ground transport.) Results show that four well-located break-bulks (instead of the 25 currently used) can reduce the latest delivery time by almost two hours, as well as the number of vehicles required and the fuel consumed.

Bartholdi and Dave (2002) and Bartholdi et al. (2003) report on the development of a network design tool for LTL carriers. Bartholdi and Dave (2002) describe a "visual, user friendly tool, NetworkDesigner®, that generates the hub-and-spoke distribution system." No details on the model or solution algorithm are provided, but the report mentions the use of "custom heuristics based on problem structure ... implemented within the commercial MIP solver." This was developed to redesign the network at RPS (now FedEx Ground) and the report states that it generates "robust solutions that compare favorably with solutions generated by a commercial model being used by FedEx Ground." Though no details are provided, some of the questions that can be addressed with the tool "include break-bulk location."

Bartholdi et al. (2003) provide details on a model to assign terminals to break-bulks and route LTL freight through the network. This model explicitly includes the use of a truck (tractor) pulling two 28 foot "pups" between break-bulks. It assumes these pups can be used for local collection and delivery, though it does not model local collection and delivery. Because the total daily volume between each pair of terminals is less than a full truckload (2 pups), break-bulks are used to consolidate shipments. Each terminal is assigned to one hub and the basic decision is: To which break-bulk should each terminal be assigned? These assignments need to be determined before, or concurrently with, the break-bulk locations. This paper focuses on the assignment question; break-bulk location is not explicitly discussed.

The solution approach used a greedy heuristic for initial assignment of terminals to break-bulks, then an improvement heuristic to consider skipping an intermediate break-bulk — or skipping sorting at a break-bulk. The greedy heuristic seeks to minimize the approximate transportation and sorting costs, by assigning terminals in decreasing order of "freight intensity" (the sum of the freight in and freight out), where each assignment must satisfy certain business rules (e.g., driving hours, sorting time and capacity).

Because of consolidation at break-bulks, most trailers between break-bulks are fully loaded. This results in all paths visiting either one or two break-bulks for sorting. The improvement heuristic considers direct paths, as well as paths via break-bulks, but without the sorting at a break-bulk. Trailers sent on direct paths (not sorted at a break-bulk) must utilize at least a minimum percentage of capacity (75% for FedEx Ground). For example, if one trailer (one "pup") at an origin terminal can be filled for a specific destination terminal, then that trailer need not be opened and sorted at any intermediate break-bulks. It might travel direct from the origin terminal to the destination terminal, or via one or two break-bulks with another pup, that is opened and sorted.

The model does not allow multiple stops at terminals on route to/from a break-bulk, but it does permit shipments between an origin and destination (o-d) to be split over multiple routes. (There is not a unique path for an o-d pair.) Origins and destinations are terminals, and the model defines a freight flow variable for each possible path type for each origin-destination pair. It also includes variables for the flow of trailers and trucks, where a tractor can pull two trailers. A lengthy Integer Linear Programming (ILP) formulation is provided that minimizes transportation costs plus sorting costs at break-bulks. Small instances were solved using CPLEX 7.5, but it was "difficult to solve even small problems with 3 break-bulks and 30 terminals." (The FedEx Ground network had 388 terminals and 24 break-bulks!)

To find solutions for problems of realistic size in reasonable time, they partitioned the problem based on break-bulk pairs and associated terminals (termed a "dyad"), and then solved the routing problem for each dyad. Each dyad consisted of two break-bulks and a number of terminals (usually 20 – 40). Thus, any freight between two terminals assigned to the two different break-bulks shows up in exactly one such dyad. (This was about 89% of the freight in the data set used.) However, any freight between terminals assigned to the same break-bulk shows up in many such dyads — and might be routed differently in different dyads! In the computational experiments, these different routings occurred rarely.

For each dyad they determined the freight routing using parallel computing on a cluster of commodity computers (up to 128 Pentium processors). With 24 break-bulks, there are 276 dyads ($276 = 24 \times 23/2$). They report that a "typical run" took 6 hours and used a total processing time of 457 hours. However, 17% of the dyads (46/276) were not solved within 10% of optimality, and no integer solution at all was found for 10 dyads ($10/276 = 3.6\%$).

Typical results showed that about 34% of packages are double sorted at two break-bulks (vs. 89% in the initial solution), 34% are routed via two break-bulks, but sorted only at one break-bulk (usually the 2nd one visited), 22% of packages are routed via a single break-bulk where they are also sorted, and about 9% of packages are not sorted at any break-bulk (though they may be routed via two, one or zero break-bulks). One interesting finding was that more trailers were routed direct from the origin terminal to the break-bulk of the destination (bypassing the break-bulk of the origin terminal), than the other way around.

4. Truckload network design

This section describes research on strategic network design for truckload (TL) motor carriers. TL carriers may operate without a network by dispatching a driver sequentially on a long tour of point-to-point trips. For efficiency, the carrier would like to find a sequence of trips that minimizes the empty miles traveled from the destination of one trip to the origin of the subsequent trip. Such tours may take a driver away from home for 14–21 days (Taylor et al., 1999), and lengthy tours have led to high turnover rates among TL drivers. Hunt (1998) reports driver turnover rates for TL carriers as high as 200%, in contrast to rates often less than 10% for LTL carriers. High rates of driver turnover both increase training costs (estimated at $3000 to $5000 per driver in the U.S.) and accident rates (Hunt, 1998).

Some TL carriers have developed relay networks, where terminals serve as relay point at which drivers can exchange loads (trailers). A relay network can produce much shorter driver tour lengths, and can help increase efficiency by allowing the load to continue moving with another driver while the first driver rests. Disadvantages of relay networks include the extra distance that might be traveled via the terminals, and the added time for swapping loads.

To keep a consistent set of notation and terminology we will refer to relay terminals as "terminals". In various papers these are refereed to as relay points, hubs, and transshipment points. Note that terminals for TL networks do not involve the loading, unloading and sorting functions of break-bulks in LTL networks. Terminals serve primarily as places for drivers to swap trailers. Thus, it is possible for these terminals to be simple facilities such as public rest areas or private truck stops.

Only a few authors have addressed TL network design. Meinert and Taylor (1999) summarize a number of studies that have been carried out over the past decade using data for the largest U.S. TL carrier. In general, this work uses simulation models to explore different strategic and operational concerns. The earliest work on relay networks for TL carriers involves the HUBNET interactive simulation tool developed for J.B. Hunt, Inc. Taha and Taylor (1994) provide an overview of this work, including results of preliminary testing. This paper also highlights the differing motivations for hub-and-spoke-like networks in LTL and TL trucking. They identify a key tradeoff for TL networks as whether or not the added circuity to travel via hubs is offset by the decrease in costs associated with reduced driver turnover.

HUBNET is a simulation system to evaluate relay terminal networks for TL trucking. It provides interactive tools to help the user construct a network, and then it simulates TL operations. HUBNET assume three types of drivers: local drivers for collection and delivery between the terminals and the shipment origins/destinations, lane drivers between terminals, and non-network drivers for loads that would exceed the maximum circuity if sent via the network. (Note that not all loads are sent via the network.) Local drivers are based at a terminal, and lane drivers travel along the network to one terminal before returning to their home terminal. Rather than treat each demand point individually, HUBNET divides the U.S. into sixty-five two degree × two degree latitude and longitude geographic regions. It calculates freight density and load imbalances for each region to assist in the network design.

HUBNET is designed to address three problems: location of terminals, determination of which terminals to connect with direct routes, and determination of the geographic service area for each terminal. Explicit solution algorithms for these problems are not provided but it states that the solutions "use load volume and geographical distance considerations to suggest initial hub (terminal), spoke, and area layouts, but allow for significant user interaction ... "

Three important factors for finding terminal locations are identified: (1) locate in or near "high volume geographical regions"; (2) place hubs at "almost equal distances across the service area," so that drivers can be "assigned to runs equal to some fractional or complete multiple of a shift duration" to "maximize driving time while returning home much more often"; and (3) the location of existing terminals. The final suggestion is that "perhaps a hybrid of each of the three above considerations should drive hub (terminal) location."

Direct links between hubs are selected based on distance and load volume. For the most part, nodes that are less than a one shift drive apart are connected via direct routes, but there are exceptions if intermediate nodes are on the direct path, and for very high volume nodes. The size and shape of service regions are based on load volume, proximity to other hubs, roadways and geography.

HUBNET provides an initial solution superimposed on a map of the U.S. The user can then add or remove terminals and direct links, and re-allocate service regions to terminals based on the two degree × two degree latitude/longitude cells. Then primary function of HUBNET is to simulate TL operations with the interactively designed network, and to generate performance measures to compare the relay network and point-to-point operations. Thus, the input to the simulation phase is an order history (demand), a relay network with up to 60 nodes, the service area of each terminal (specified by two degree × two degree regions), the number of drivers available, the percentages for each of three types of drivers, and the maximum allowable circuity (as an excess mileage percentage). HUBNET assigns drivers to terminals based on local demand and uses shortest paths for travel between terminals. For more details on the software, see Taha et al. (1996), which describes the local module for intra-hub area driver assignments and load assignment; and the freight lane module for inter-hub transportation.

Results are reported for two networks to serve the U.S.: one with 24 terminals and one with 32 terminals. Results show the average tour length can be "drastically reduced" from about 18 days with the current point-to-point operations to 2 days or less with a relay network. However, the circuity increases from 3.5% to 15% with a network, and the "first dispatch empty miles" also increase from 5.6% to about 15% with the network.

Taylor et al. (1995) describes the use of HUBNET to evaluate terminal location methodologies, the number of terminals, and a policy that restricts drivers to a particular traffic lane. They compare three terminal location methodologies: "distance-based," "flow-based," and "hybrid-based." For distance-based location, terminals are located one day apart — but no method is provided. For flow-based location, terminals are placed in regions "characterized by low imbalance between originating and destinating loads". (As earlier, this is based on a partition of the U.S. into 65 grid cells based on latitude and longitude.) To do this, the authors provide the following small IP that "minimizes the total freight imbalance of a user-specified number of selected regions".

Let $X_j = 1$ if a terminal is assigned to grid j; and 0 otherwise. Let C_j be the load imbalance for grid j (equal to total loads in − total loads out) and A_{ij} is 1 if grid i is contiguous to grid j; and 0 otherwise. Let p be the desired number of terminals.

$$\text{Minimize } Z = \sum_{j=1}^{65} |C_j| X_j$$

Subject to:

$$\sum_{j=1}^{65} A_{ij} X_j \geq 1 \qquad \text{for all } i \tag{8.23}$$

$$\sum_{j=1}^{65} X_j = p \tag{8.24}$$

$$X_j = \{0, 1\} \qquad \text{for all } j$$

The objective minimizes the sum of absolute values of freight imbalances. Constraint (8.23) ensures that each grid cell either contains a terminal or is adjacent to a cell with a terminal. Constraint (8.24) forces the number of hubs to be the desired value (24 or 32 were used in the computational results).

The third terminal location methodology, hybrid-based, is a combination of "heuristics, expert judgment, and the location of existing terminal locations for J.B. Hunt Transport, Inc."

HUBNET is used to simulate operations with either 24 or 32 terminals, whose locations are derived from the three location methodologies, and with policies that allow drivers to travel to one or two terminals from home, before transferring loads. Five primary performance measures are calculated including lane and local driver tour length, average miles per driver per day, first dispatch empty miles, and average circuity as a function of trip miles.

The best results were with 32 terminals, hybrid-based locations, and a policy that restricts drivers to travel between two adjacent terminals. In comparison to the current point-to-point method of operations, this reduces average tour length by 90% (to about 2 days), and total miles per driver by 14.6%. However, circuity and first dispatch empty miles increase. Further testing showed that the best scenario is when 53% of the loads are moved via the network (vs. point-to-point). This suggests that limited implementation of a relay terminal network could be worthwhile, to allow some shipments to travel direct while others use the network. As for the best method for network design, in this paper expert judgment was preferred. The authors state that J.B. Hunt is experimenting with a zone delivery system where drivers return home at least one day each week. They also say that

> "real-time optimization technology is used to identify ... beneficial load switches, along with recommended switch points and times, based on current positions and final destinations. In a sense, this allows a ... network to be implemented with a nearly infinite number of hubs since truck stops, rest areas, and existing terminal yards are used as switch points."

Because the research with HUBNET indicated that a partial relay network was most promising, Taylor and co-authors followed up with a series of papers addressing different alternatives for implementing a limited network. One key theme in these works is the desire to restrict drivers to lanes between terminals or to geographic zones. These approaches will reduce tour length for the driver (and hence turnover), but will generally increase the total distance traveled, as routes are longer than point-to-point.

Taylor et al. (1999) examines a region in the southeastern U.S. and compares seven alternatives:

(1) point-to-point routes.
(2) a southeast zone with 6 zone perimeter terminals "in locations that provide access to major highways and existing freight corridors."
(3) one "key lane" in and out of the southeast region.
(4) another "key lane" in and out of the southeast region.
(5) two "key lanes" in and out of the southeast region.
(6) one "key terminal" in the center of the southeast region.
(7) a "hybrid model" with 1 central terminal and 6 perimeter terminals.

The point-to-point scenario is the default condition where drivers haul a sequence of TL moves from origin to destination. This produces long tours where drivers are on the road for 2 – 3 weeks at a time. The zone scenario allows drivers to stay within the southeast region by exchanging loads at the perimeter terminals. In the three "key lane" scenarios a percentage of loads are sent via drivers shuttling back and forth along a high traffic corridor between Atlanta, Georgia (near the center of the southeast region), and another city providing good access to points outside the southeast. The "key terminal" scenario uses a single terminal in Atlanta, rather than the 6 perimeter terminals to exchange loads. The "hybrid model" combines the "key terminal" and zone model.

For each scenario, the authors simulate one week of operations and collect performance measures for drivers, carriers and customers with four key metrics and eleven secondary metrics. The key carrier performance metrics are percentage circuity (actual miles compared to point-to-point miles) and first dispatch empty miles (average number of empty miles from dispatch to load pickup). The key driver performance metric is the average number of miles per driver per day. (This affects driver pay and turnover.) The key customer performance metric is the percentage of loads that are delivered late.

Results showed that different scenarios were preferred by the different stakeholders (drivers, carrier and customers), but the zone model appeared to provide the best overall solution in this region when considering the driver, carrier and customer objectives together. The authors also considered having more or fewer terminals and concluded that 4-6 terminals in the southeast region seem to "offer the best compromise solutions relative to all four of the key metrics." They then considered the northeastern region of the U.S. and found similar results; and even stronger evidence for a zone scenario in some cases, due to the more isolated nature of the northeast relative to the rest of the U.S.

Finally, they reported that J.B. Hunt is using a key lane approach in the eastern U.S. and a zone system in the northeast U.S., and that these have reduced turnover rates from 53% for the general point-to-point drivers to 22% for those with regular routes or zones. Meinert and Taylor (1999) mention consideration of a national network of zones, though they provide no details.

Taylor and Meinert (2000) further examine a zone strategy from the perspective of the customer, the carrier, and the driver. They seek strategies that can improve quality for driver (job quality), customer (on time pickup and delivery) and carrier (lower turnover). They provide an experimental design to evaluate how the number of terminals, the length of haul from zone centroid to the terminal and back, and the distribution of freight within the zone affect a zone-based network. They develop a simulation model (in SIMNET II) for an idealized rectangular two-zone system. They consider $1-4$ terminals evenly spaced along a 500-mile boundary, average hauls of 400, 600 or 800 miles, and a uniform and concentrated demand distribution.

The model generates demand patterns, simulates operations (using the U.S. Department of Transportation driver work rules), and calculates performance measures for the driver, customer and carrier. It includes rules to determine whether the load is sent direct or via a terminal. (Generally, longer trips and those with less circuity are sent via a terminal.) Results shows that the zone model reduces flow times and can improve on-time service. Taylor et al. (2001) also consider zone dispatching. Simulation results indicate that multi-zone dispatching works best when zone boundaries are configured to minimize, to the extent possible, the freight imbalance between zones

Hunt (1998) provided a different model for designing a relay network for TL motor carriers. The general approach involves first routing freight flows over a roadway network and then locating relay terminals at intervals along the network. Drivers relay loads between adjacent terminals. (Hunt also provides some interesting historical background on ancient relay networks of the Persians, Romans, and Chinese, as well as the Pony Express system in the U.S. from the mid-1800s.)

The solution approach is a four step process, using the underlying U.S. interstate highway system as the physical road network. The first step routes freight flows across the physical network. The second step is to create the relay network by locating relay points on the physical network. The third step is to route the commodities across the relay network, and the final step is to assign drivers to relay points. We will focus on the first three steps below.

The input includes the demand (origin, destination, and time window), the physical network (e.g., U.S. interstate highway system) and the desired, minimum and maximum distances between relay points. Hunt considered several methods of routing freight across the network, each of which may produce a different relay network. The simplest method is an independent shortest path algorithm that ignores interactions and backhaul opportunities. Several other methods presented try to create improved (lower cost) routings by accommodating backhauls. These include solving IP formulations, using a dependent shortest path algorithm that routes and re-routes commodities to try to improve backhauls, a shortest path tree algorithm, and a linear programming relaxation.

The second step of locating relay points uses the freight routes from the first step as input. The problem is then to determine the smallest set of relay points (i.e., fewest) along routes, such that the travel distance between adjacent relay points is between the specified minimum and maximum distances and the travel distance between the end points (origins and destinations) and the closest relay point is less than half the specified maximum distance. (Hunt suggests that for full-day driving the minimum distance be 300 miles and the maximum distance be 500 miles.)

Hunt describes two algorithms for locating relay points: the "Spring Algorithm," that tries to iteratively improve a feasible solution; and a greedy algorithm that iteratively adds relay points one at a time. We present the Spring Algorithm first.

The idea behind the Spring algorithm is inspired by the forces of attraction from a stretched spring and repulsion from a compressed spring. For example, two terminals that are closer together than the minimum distance would experience a repulsive force, while two terminals farther apart than the maximum distance would experience an attractive force. The algorithm begins by creating a feasible solution that places terminals along each route the desired distance apart. It then calculates "spring forces" between all adjacent terminals and between terminals and adjacent origins/destinations. These may be attractive or repulsive depending on the spacing between terminals. It then calculates "gravitational forces" between pairs of terminals on different routes but nearby (e.g., within 200 miles). Finally it combines spring forces and gravitational forces for all terminals and calculates new positions for terminals as the projection of the sum of forces along the route. Then any terminals in close proximity (within a specified distance of each other) are combined into a single terminal.

Hunt also considered a greedy algorithm based on identifying feasible terminal "windows" along the roadways for each route, that take into account the minimum and maximum distances between terminals. Because routes may overlap, several windows may overlap. The greedy approach selects terminal locations that "cover" the most uncovered sets of windows one at a time until all are covered.

The Spring algorithm and the greedy algorithm were implemented using an object oriented design in Java and C++. The methods were tested on small problems using data for the southeast U.S., where the interstate system included 251 nodes and 329 edges. Demand was based on test data from the U.S. Postal Service that contained up to 50 origin-destination pairs. Any origin-destination pairs less than 250 miles apart were treated separately outside the relay terminal network. Results showed that the Spring algorithm consistently produced fewer relay points that the greedy algorithm (ranging from 17 to 63 for various problems), but did take more cpu time. However, this may not be an important factor for strategic network design.

Once the relay network is established, then the freight must be routed via the relay terminals. This is similar to the first step and the same solution approaches as in step one are used, but now all freight must be routed via at least one relay terminal. From the resulting freight flows, the traffic on individual "legs" between adjacent relay points and between origins/destinations and relay points can be calculated. This is then used to determine the number of drivers to assign to each terminal, where each driver travels no farther than the adjacent relay terminal.

Results showed that different initial freight routings did produce different relay networks, but the "majority of loads required less than 25 extra miles for travel via the relay networks (vs. direct point-to-point routes), and the majority of loads had equal or improved service times. However, in some cases the maximum excess miles was very large (over

20%). Thus, some loads should probably not be sent through relay network.

Hunt suggests (as did the earlier work with HUBNET) that TL carriers might operate partial relay networks, where some loads are sent through relay terminals and others are sent point-to-point. Hunt also mentions some problems and areas for future research in implementing the Spring Algorithm, including some caused by network structures that prevent the algorithm from escaping local optima.

5. Postal network design

This section describes research on strategic network design for postal motor carriers. While there is much research on integrated or intermodal parcel and express carriers that combine air and truck, it is beyond the scope of this chapter.

Donaldson et al. (1999) provide a model to design the network for first class mail transport in the U.S. The origins and destinations of shipments are 148 area distribution centers (ADCs) that serve local post offices. Any origin-destination pairs over 1800 miles apart must be served by air and are not considered. Also, local mail within the metropolitan area of an ADC is not considered. Mail may be sent direct from an origin to destination if demand is sufficient, or via one crossdocking center (i.e., transshipment terminal). Service levels are specified so that mail for origins and destinations less than 600 miles apart should be delivered in two days; and mail for origins and destinations less than 1800 miles apart should be delivered in three days.

The fundamental problem is to locate crossdocking centers to minimize the total transportation cost. The authors formulated an IP to calculate transportation costs for a given set of origins, destinations and crossdocks. They solved the IP for various specified sets of crossdocks to find the "best" set. The formulation is presented below using the following variables and parameters:

$I = \{i\}$ is the set of origin nodes,
$J = \{j\}$ is the set of destination nodes,
$K = \{k\}$ is the set of crossdock nodes,
$x_{ij}^{k} =$ flow on the path from origin i to destination j through crossdock k,
$x_{ij} =$ direct flow from origin i to destination j,
$R_{ij} =$ number of trucks on link (i,j) from origin i to destination j,
$O_{ik} =$ number of trucks on link (i,k) from origin i to crossdock k,
$D_{kj} =$ number of trucks on link (k,j) from crossdock k to destination j,
$c_{ij} =$ cost of sending a truck from i to j,

$C =$ truck capacity,
$S_{ij} =$ flow (demand) from origin i to destination j.

Any full truckloads from origin i to destination j will be shipped direct and are not included in the formulation. Thus, S_{ij} includes only partial truck loads. The formulation is:

$$\text{Minimize } \sum_{i,j} R_{ij}c_{ij} + \sum_{i,k} O_{ik}c_{ik} + \sum_{k,j} D_{kj}c_{kj}$$

Subject to:

$$\sum_{k} x_{ij}^{k} + x_{ij} = S_{ij} \qquad \text{for all } i \in I,\ j \in J \qquad (8.25)$$

$$\sum_{j} x_{ij}^{k} \leq CO_{ik} \qquad \text{for all } i \in I,\ k \in K \qquad (8.26)$$

$$\sum_{i} x_{ij}^{k} \leq CD_{kj} \qquad \text{for all } k \in K,\ j \in J \qquad (8.27)$$

$$x_{ij} \leq R_{ij}S_{ij} \qquad \text{for all } i \in I,\ j \in J \qquad (8.28)$$

$$x_{ij} \geq 0 \qquad \text{for all } i \in I,\ j \in J \qquad (8.29)$$

$$x_{ij}^{k} \geq 0 \qquad \text{for all } i \in I,\ j \in J,\ k \in K \qquad (8.30)$$

$$R_{ij} = \{0,1\} \qquad \text{for all } i \in I,\ j \in J \qquad (8.31)$$

$$D_{jk}, O_{ik} \text{ nonnegative integers} \qquad \text{for all } i \in I,\ j \in J,\ k \in K \qquad (8.32)$$

The objective minimizes total transportation cost. Constraint (8.25) ensures that all destinations are satisfied either via a direct link or a crossdock. Constraints (8.26) and (8.27) establish the number of trucks to carry the flows through crossdocks. Constraint (8.28) establishes the number of direct trucks. Constraints (8.29) – (8.32) restrict the variables to be nonnegative and integer, as appropriate.

Before solving this IP, there is preprocessing to generate only the feasible direct links and paths through crossdocks, based on travel times, handling times at crossdocks, and specified service levels. Several solution approaches were tried, including branch and bound, Bender's cuts, and a relaxation heuristic. Only this last approach was efficient enough for the real-world problems considered.

The relaxation heuristic relaxes the integrality constraints on the links from origins to crossdocks or from crossdocks to destinations This allows the problem to be decomposed by either origin or destination, and though it does not guarantee optimality, it did produce small gaps on the problems considered. The solution procedure is to iteratively solve single commodity problems from one origin to all destinations, where the truck variables are integer on direct links, and on links from origins to crossdocks, but not on links from crossdocks to destinations. These single origin solutions are then combined by adding the flows on common links. This may produce fractional truck variables on links from crossdocks to destinations, and this provides a lower bound. Fractional values are rounded up to provide an integer solution and an upper bound. Any crossdock-to-destination links whose flow is below a specified threshold are then eliminated. The procedure stops when the gap between the upper and lower bounds is small enough. The authors considered relaxing the integrality constraints between either the origin and crossdock or between the crossdock and destination, but the results were similar.

Results were provided for two situations. The first considered where to locate a single crossdock center to serve the southeast and mid-Atlantic U.S. There were 36 origins/destinations (ADCs) in eleven states, and three possible crossdock locations were considered. The problem was solved for each crossdock location using the relaxation heuristic and all three gaps were about 4%. The best heuristic solution was within 0.1% of the optimal solution (found by branch and bound).

The second analysis considered where to locate crossdocks for the entire U.S. For this analysis there were 148 origins/destinations (ADCs). Nineteen different sets of crossdocks were considered, ranging from a single crossdock in one of five different cities to a set of 22 crossdocks. The relaxation heuristic solved all problems in reasonable time. The gaps depended on the candidate crossdocks sets and ranged from 1% for one crossdock to almost 20% for the twenty-two crossdock problem. Though transportation costs decreased with larger numbers of crossdock centers, the results showed little improvement with more than 4 or 5 crossdocks. Note that while realistic problems of continental scale could be solved, the crossdock locations were inputs to the model, and the best set of crossdocks examined is not necessarily the best set that exists.

Ernst and Krishnamoorthy (1996, 1999) developed hub location models for the design of motor carrier postal networks that focus specifically on the locations of mail consolidation and sorting centers. Ernst and Krishnamoorthy (1996) introduce the use of hub location models in postal network design for Australia Post. The model includes the collection of mail from postcode districts (origins) to a mail sorting center (hub), the transfer of mail between sorting centers (hubs), and then distribution from a sorting center (hub) to the destination postal district (destination). Because each of these three components may involve a different type of transportation (e.g., size of motor vehicle), there are separate cost coefficients for each type of transport.

Ernst and Krishnamoorthy (1996) provides an efficient formulation for the single allocation p-hub median problem (Campbell, 1996), which restricts each origin and destination to a single sorting center. The problem is formulated on a complete graph $G = \{V, E\}$ with node set $V = \{v_1, v_2, \ldots, v_M\}$, where nodes correspond to origins and destinations (i.e., postal districts) and potential hub locations. Let d_{ij} be the distance from node i to node j and let W_{ij} be the volume of mail to be transported from i to j. Distances are assumed to satisfy the triangle inequality. Let p be the number of hubs to locate. Mail travels from the origin to a hub, possibly to a second hub, and then to the destination. Three cost parameters χ, α, and δ are the unit cost for transportation from an origin to a hub (collection), between two hubs (transfer), and from a hub to a destination (distribution), respectively. Generally, shipments are consolidated at the hubs to exploit the economies of scale, so $\alpha < \chi$ and $\alpha < \delta$. For the Australia Post application, the respective values are: $\chi = 3$, $\alpha = 0.75$, and $\delta = 2$.

The decision variables are:

$Z_{ik} = 1$ if node i is allocated to a hub at node k, and 0 otherwise, and
$Y^i_{kl} =$ flow from hub k to hub l that originates at node i.

Thus, a hub is located at node k if $Z_{kk} = 1$. The total flow originating at origin i is:

$$O_i = \sum_{j \in V} W_{ij} \quad \text{for all } i \in V,$$

and the total flow destined for destination i is:

$$D_i = \sum_{j \in V} W_{ji} \quad \text{for all } i \in V.$$

The formulation to minimize total transportation costs is:

$$\text{Minimize} \sum_{i \in V} \sum_{k \in V} d_{ik} Z_{ik} (\chi O_i + \delta D_i) + \sum_{i \in V} \sum_{k \in V} \sum_{l \in V} \alpha d_{kl} Y^i_{kl}$$

Subject to:

$$\sum_{k \in V} Z_{kk} = p \qquad (8.33)$$

$$\sum_{k \in V} Z_{ik} = 1 \quad \text{for all } i \in V, \qquad (8.34)$$

$$\sum_{j \in V} W_{ij} Z_{jk} + \sum_{l \in V} Y^i_{kl} = \sum_{l \in V} Y^i_{lk} + O_i Z_{ik} \quad \text{for all } i, k \in V, \qquad (8.35)$$

$$Z_{ik} \le Z_{kk} \quad \text{for all } i, k \in V, \qquad (8.36)$$

$$Y^i_{kl} \ge 0 \quad \text{for all } i, k, l \in V, \qquad (8.37)$$

$$Z_{ik} \in \{0, 1\} \quad \text{for all } i, k \in V, \qquad (8.38)$$

The objective is to minimize the total cost for collection, distribution and transfer. Constraint (8.33) ensures that exactly p hubs are selected, and constraints (8.34) ensure that each origin/destination is allocated to a single hub. Constraints (8.35) enforce flow conservation at the hubs. Constraints (8.36) ensure that every allocation establishes a hub. Constraints (8.37) and (8.38) restrict the variables appropriately.

The authors solve this formulation using branch and bound with an upper bound based on simulated annealing for the Australia Post data set, based on postal operations around Sydney, Australia. They find optimal solutions for problems with up to 50 origins/destinations and five hubs. For larger problems with up to 200 origins and destinations and 20 hubs, they find near-optimal solutions (within 1%) using a simulated annealing-based heuristic.

Ernst and Krishnamoorthy (1999) extended the single allocation hub location problem to include capacities on the flow being sorted at the hubs (not the total flow through the hub). They also replaced the specification of exactly p hubs, by a fixed cost for hubs in the objective, so that the model would determine both the number and locations of hubs. Capacities are specified by a parameter Γ_k and the following constraints are added to the formulation:

$$\sum_{i \in V} O_i Z_{ik} \leq \Gamma_k Z_{kk} \quad \text{for all } k \in V.$$

Although the capacitated hub location problems are more difficult to solve than the corresponding uncapacitated hub median problems, the authors provide optimal solutions for problems with up to 50 origins and destinations, using two levels of fixed costs for hubs and two levels of capacity. Generally, tightening the capacities increases the cpu times, as well as the optimal number of hubs.

There has been considerable subsequent research on a wide range of hub location problems, including those with single and multiple allocation, node and arc capacities, flow thresholds, flow-based cost functions, and more general network structures. In general, hub location problems explicitly model different vehicle types (and costs) to reflect consolidation activities, and address strategic network design including location of consolidation or sorting centers and selection of network links. These types of networks are common for a variety of transportation systems, including LTL motor carriers and postal system. Although much of the hub location research is relevant to the design of LTL and postal networks, and much of it uses the Australia Post data set for testing, this literature is generally more algorithmic and theoretical, rather than being applied explicitly to design motor carriers networks. (The recent work by Kara and Tansel discussed in the section on LTL network design is an exception.) See Campbell et al. (2002) for a recent review of hub location research.

6. Conclusion

Motor carriers provide a vital function in modern societies, and their importance is likely to grow with the increasing customer requirements for better service and reduced cycle times. There is a vast amount of operations research work on tactical planning (e.g., load planning) and operational planning (e.g., vehicle routing) for motor carriers, but somewhat less attention on strategic planning, including strategic network design. This chapter provides a survey of relevant published work on strategic network design for less-than-truckload, truckload and postal motor carriers. The focus has been on research with a strong link to *motor carrier* network design, not on general network design or on primarily algorithmic advancements. While the published research conveys a range of models and solution techniques to address different problems, many for major motor carrier firms, there may well be other significant models and results currently in use by carriers, but not described in the literature.

Motor carriers are large complex organizations that must serve a varying demand over a large geographic area in a very competitive and dynamic environment, often with tight service constraints. These environmental pressures generate a need for future research in a variety of areas. One area for future work is to better address the merger of motor carrier networks. This may result from standardization of local and national transportation regulations as international trade rules are liberalized — and from the increasing concentration in the industry through mergers and acquisitions. A second area for future work is strategic network design for time definite trucking, in which motor carriers provide "guaranteed" service of one, two, three, ... days between specified origins and destinations. This market allows motor carriers to exploit their cost advantage over air carriers for deferred airfreight. A third area is in application of hub location research to less-than-truckload network design. There is a great deal of research on optimal hub location and network design that is more theoretically oriented, than practically oriented, and more tuned to air transportation, than ground transportation. Extending this work with applications for LTL carriers could be quite beneficial. Finally, given the current size of large motor carriers, and trends for them to become even larger, research is needed to help solve larger problems of practical size.

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