PB98-128762

Intermodal Freight Planning at the Multi-state Corridor Level: State of the Practice and Future Directions

MID-ATLANTIC UNIVERSITIES TRANSPORTATION CENTER

The Pennsylvania State University
University of Pennsylvania
University of Virginia
Virginia Polytechnic Institute & State University
West Virginia University

The Pennsylvania State University • The Pennsylvania Transportation Institute • Research Office Building
University Park, PA 16802-4710
Telephone 814-865-1891 • FAX 814-865-3039

Standard Title Page – Report on Federally Funded Project

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UVA/29242/CE98/101		

4. Title and Subtitle
Intermodal Freight Planning at the Multi-state Corridor Level: State of the Practice and Future Directions

5. Report Date
November 1997

6. Performing Organization Code
III 9707

7. Author(s)
Billy M. Williams and Lester A. Hoel

8. Performing Organization Report No.
UVA/29242/CE98/101

9. Performing Organization and Name
Department of Civil Engineering
University of Virginia
Mid-Atlantic Universities Transportation Center

10. Work Unit No. (TRAIS)

11. Contract or Grand No.
USDOT-TPSU-UV-0003-1113

12. Sponsoring Agency Name and Address
Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

13. Type or Report and Period Covered
Final

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

With the completion of the Interstate highway system the transportation planning focus has changed. Fiscal constraints preclude system expansion at the pace needed to support continued robust economic growth. Therefore, attention in the public sector has shifted to getting more productivity out of the existing modal infrastructure through improvements in system operation and management. This shift from capital construction to asset management is also motivated by increased emphasis at all governmental levels on minimizing the adverse environmental and societal effects of transportation activities. In concert with these public sector forces has been the emergence of a vibrant and highly competitive global marketplace. International trade and transportation agreements have opened the door to continued explosive growth in global commerce. The successful global enterprises are characterized by efficient logistics involving just-in-time inventory systems and a strong emphasis on customer service. The transport demands of international corporations are forcing transportation service providers to be more efficient and responsive.

The combined effect of these public and private sector forces is a sea change in the way the transportation system is planned, designed, and deployed. A major element of this transportation paradigm shift involves a view of the modal systems as components of a single, integrated transportation system where each mode plays a role based on its inherent strengths. This view motivates a search for technical and institutional improvements to enhance the "seamless" flow of goods and people between the modes. In this emerging intermodal era, there will be increasing opportunities for the public and private sectors to make worthwhile investments in intermodal facilities and technology. It follows, therefore, that planning attention will be focused on improving intermodal interconnectivity. Also, the public sector will be faced with important transport policy decisions, such as carrier regulation/deregulation, truck size and weight restriction changes, and continued consolidation of the major rail carriers. Planners and decision makers will need reliable data and transportation systems analysis tools to evaluate intermodal project and policy alternatives.

Within this overall global transportation system context, this report focuses on the freight transportation planning for a major corridor. The Interstate 81 corridor is a case in point. I-81 runs from upstate New York to Tennessee through Pennsylvania, the Maryland and West Virginia panhandles and Virginia and is characterized by a high level of truck travel over much of the corridor. In spite of this corridor focus, several of the conclusions drawn in this report are relevant for freight transportation planning in general.

17. Keywords
intermodal freight, freight planning, corridor planning, network modeling, freight data

18. Distribution Statement
No restrictions. This document is available to the public through NTIS, Springfield, VA 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
unclassified	unclassified	44	

ACKNOWLEDGEMENTS

This study was conducted under the sponsorship of the United States Department of Transportation and the Virginia Department of Transportation through a grant to the Mid-Atlantic Universities Transportation Center. The authors gratefully acknowledge the sponsors' support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background

Through the last half of the 19th century and most of the 20th century, increases in transportation productivity came directly from massive capital investment in the modal systems. With the completion of the Interstate highway system the focus has changed. Fiscal constraints preclude system expansion at the pace needed to support continued robust economic growth. Therefore, attention in the public sector has shifted to getting more productivity out of the existing modal infrastructure through improvements in system operation and management. This shift from capital construction to asset management is also motivated by increased emphasis at all governmental levels on minimizing the adverse environmental and societal effects of transportation activities.

In concert with these public sector forces has been the emergence of a vibrant and highly competitive global marketplace. International trade and transportation agreements have opened the door to continued explosive growth in global commerce. The successful global enterprises are characterized by efficient logistics involving just-in-time inventory systems and a strong emphasis on customer service. The transport demands of international corporations are forcing transportation service providers to be more efficient and responsive. The combined effect of these public and private sector forces is a sea change in the way the transportation system is planned, designed, and deployed.

A major element of this transportation paradigm shift involves a view of the modal systems as components of a single, integrated transportation system where each mode plays a role based on its inherent strengths. This view motivates a search for technical and institutional improvements to enhance the "seamless" flow of goods and people between the modes. In this emerging intermodal era, there will be increasing opportunities for the public and private sectors to make worthwhile investments in intermodal facilities and technology. Anderson et. al (1995) describe the current situation in these words –

> A transportation system can only be as strong as its weakest link; today the weakest link seems to be at the intermodal points where passengers or freight need to move efficiently from truck to plane, from car to bus, from ship to train, etc.

It follows, therefore, that planning attention will be focused on improving intermodal interconnectivity. Also, the public sector will be faced with important transport policy decisions, such as carrier regulation/deregulation, truck size and weight restriction changes, and continued consolidation of the major rail carriers. Planners and decision makers will need reliable data and transportation systems analysis tools to evaluate intermodal project and policy alternatives.

These forces are altering the landscape for all facets of transportation systems planning and management. The movement of both people and goods will increasingly be planned and evaluated under the lenses of efficiency, accessibility, and sustainability. Transport systems at all levels, from neighborhoods to the global marketplace, will be transformed by the integrated system vision.

Within this overall global transportation system context, this report focuses on the freight transportation planning for a major corridor. The Interstate 81 corridor is a case in point. I-81 runs from upstate New York to Tennessee through Pennsylvania, the

Maryland and West Virginia panhandles and Virginia and is characterized by a high level of truck travel over much of the corridor. In spite of this corridor focus, several of the conclusions drawn in this report are relevant for freight transportation planning in general.

1.2 Definitions

To further clarify the corridor freight planning context, it is helpful to define a classification structure for freight flows. There are many ways to describe freight flow including commodity type, shipment distance, shipment mode, and whether the shipment is by common carrier, contract carrier, or private fleet. The following definitions provide a spatial classification in terms of shipment length and origin and destination relative to a given urban study area. Although the definitions given here closely follow those presented in the report *Analysis of Freight Movements in the Puget Sound Region* (Transmode, 1994), they are representative of widely held conventions of freight flow classification.

Long haul – Freight traffic to or from a defined study area with a shipment length of greater than 250 miles. At this shipment length, rail and intermodal service can begin to compete with motor carrier service. Growth in the intermodal sector has been especially strong during the 80s and 90s.

Short haul extraregional – Freight traffic to or from a defined study area with a shipment length of 250 miles or less. These shipments are generally made by private motor carrier with an empty return trip.

Local traffic – Local freight pickup and delivery traffic. This category includes drayage of intermodal trailers and containers and rail car shipments and local pickup delivery of freight moving by less than truckload (LTL) motor carrier service.

Through traffic – Long haul freight traffic with neither an origin nor destination within the defined study area. Through traffic, especially waterborne imports and intermodal movements, may require storage or transshipment processing within the study area.

When the planning focus is shifted from an urban study area to a regional freight corridor, long haul traffic is of primary interest for intermodal facility and policy planning. This includes traffic with origin and/or destination in the corridor study area and through traffic. Short haul and local traffic would be of interest only if they are contributing to highway congestion at specific locations along the corridor and if there are project and/or policy alternatives to relieve the congestion.

The general definition of intermodal freight transport is "a logistically linked movement using two or more modes of transport" (Muller, 1995). Using this definition, all freight movements other than those moving from origin to destination solely by highway conveyance are intermodal movements. Rail, air, and waterway shipments all require drayage to and from terminals for all shippers and consignees except those with direct rail siding or terminal access. In the context of corridor freight planning as presented in this report, intermodal transport refers to the most common usage, i.e., truck/rail intermodal traffic. The established forms of intermodal traffic include "piggyback" or trailer on flat car (TOFC) service and container on flat car (COFC) service. Trailers and containers are onloaded and offloaded at intermodal terminals with a significance portion of the line haul being made by rail. An increasingly common extension of COFC involves stacking containers two high and is called *double stack* intermodal service. Other intermodal technologies are under development. One newer technology already seeing some use is Wabash National's RoadRailer system, which uses a special highway van/trailer that can be mounted with a rail bogie and run directly on rail. The RoadRailer system thus eliminates the need for a "piggyback" flat car. Another technology under development is CSX's Iron Highway system. The Iron Highway uses continuous articulated platforms to carry tractor trailers. The tractor trailers are driven on and off the platform, thus eliminating the need for trailer loading equipment. The prototype Iron Highway platforms are 1200 feet long. Several of these platforms can be linked together when forming trains. CSX has tested the service between Chicago and Detroit. However, CSX has suspended further research and development on the Iron Highway project until completion of the Conrail acquisition.

1.3 Problem Statement

Freight planning can be carried out at many levels. At the lowest level is site access planning for a single freight generator or transshipment facility. At the highest level would be facility or policy planning with a global freight network view. Metropolitan statistical area, state, and national freight system planning would fall between these two extremes. Corridor intermodal freight planning lies between state and national planning. Rail/truck intermodal service does not begin to compete with truck service until shipment lengths reach about 250 miles, and in the current market, rail/truck intermodal service is competing successfully with motor carrier service only when haul distances are about 700 miles or longer (Campbell, 1996). Therefore, a state level planning scope will not in general be large enough to model intermodal freight flows along a major freight corridor. Even if emerging technologies can significantly lower the rail/truck intermodal break even haul length, a multi-state study area will be needed in most cases to capture an adequate portion of a corridor's current and potential intermodal freight traffic.

In summary, the problem can be stated as a need for adequate data and analysis methods to support project and policy alternative evaluation for a multi-state region focused on a specific freight corridor.

CHAPTER 2: DATA NEEDS

This chapter focuses on the network and freight flow data requirements for corridor level planning. The first two sections address network data and flow data, respectively. In each section, we discuss ideal data requirements first, followed by a brief discussion of the data that is currently available. The final section deals with methods that planners can use to fill in some of the missing gaps by augmenting and extending the available data.

2.1 Transportation Network Data

2.1.1 Data Requirements

In short, the ideal network database for corridor intermodal freight planning will include all physical modal links and nodes with accompanying attribute data to fully define link and node capacities, constraints (other than capacity), transit and transshipment costs, and transit and transshipment times.

Constraint, cost, and capacity information will be needed at the appropriate freight disaggregation level. A fully aggregated approach would model the total of all freight movements between origin/destination pairs, while a fully disaggregated approach would attempt to model individual shipments. The fully disaggregated approach is not doable, and the fully aggregated approach will not give useful results because of the vastly different characteristics and transportation requirements for different commodity types, for example coal versus computer keyboards. Therefore, freight planning models will require data for individual commodity classes.

The classification system for U.S. freight planning is currently in transition. For commodity surveys from the 1963 Commodity Transportation Survey to the 1993

Commodity Flow Survey (CFS), the Census Bureau assembled data using the Standard Transportation Commodity Classification (STCC) system. The American Association of Railroads (AAR) developed the STCC classification codes in the early 1960s. The original purpose of the STCC was to support rate assignment for ICC-regulated rail carriers. For the 1997 Commodity Flow Survey currently underway, the Census Bureau is using the new Standard Classification of Transported Goods (SCTG) system. Like the STCC system, the SCTG system is hierarchical. The SCTG has a top level of 43 two digit codes with increasing resolution through three and four digit codes up to approximately 600 five digit codes.

The rail-only, rate making focus of the STCC system is outdated. The SCTG was designed to better support intermodal analysis. Canada helped develop and will also use the SCTG system. Specifically, the SCTG system was jointly developed by the U.S. Department of Transportation's Volpe National Transportation Systems Center and Standards and Transportation Divisions of Statistics Canada. The development team attempted to provide as much compatibility with the STCC as possible without sacrificing the SCTG development goals.

Finally, the ideal freight transportation network database will be in the form of a geographic information system. A GIS platform will allow graphical interaction with the data. Also, modeling and analysis methods can directly access the network structure and attributes. In other words, GIS technology enables the development of a fully integrated data management and analysis system.

The "multi-modal freight transportation model" presented by Jourquin and Beuthe (1996) in their paper "Transportation Policy Analysis with a Geographic Information

System: The Virtual Network of Freight Transportation in Europe" represents the kind of GIS network we envision. Beginning with a digitized physical network, Jourquin and Beuthe generated a virtual network in which the virtual links correspond to specific transport operations, i.e., physical link movements, loading and unloading, intermodal transfers, etc. The virtual network included all intermodal transfer links.

2.1.2 Current Data Availability

GIS data for the modal systems are now widely available. Many states have invested significantly in developing their own systems. At the national level, GIS data is freely available from the Bureau of Transportation Statistics (BTS) in the form of Census Bureau Tiger / Line files and in the National Transportation Atlas Databases (NTAD). The 1995 Tiger / Line files provide Traffic Analysis Zones (as defined for the Census Transportation Planning Package) and highway geodata. The NTAD97 distribution includes databases in the categories of transportation facilities, transportation networks, and background information. The following information on the NTAD97 is taken from BTS's online information.

The transportation facilities databases are –

- Public Use Airports – A point database of public use landing facilities in the 50 states and U.S. Territories.
- Runway – Runways associated with the public use airports.
- Trailer on Flatcar/Container on Flatcar – A point database of major highway-rail intermodal freight facilities in the continental U.S.
- Amtrak Station – A point database of Amtrak passenger stations in the continental U.S.

- Water Port Facilities – A point database of waterway and marine terminals in the 50 States. [Maintained by the U. S. Army Corps of Engineers.]
- Autoramp – A point database of highway/rail transfer facilities which contain autoramps in the United States.

The transportation network databases are –

- National Highway Planning Network Version 2.1 – A network database representing approximately 400,000 miles of Federal-aid roads in the 50 States and Puerto Rico. [Maintained by the Federal Highway Administration (FHWA).]
- National Railway Network – 1:100,000 – A network database of all railway mainlines, railroad yards, and major sidings in the continental U.S. compiled at a scale of 1:100,000.
- National Railway Network – 1:2,000,000 – A network database of all railway mainlines, railroad yards, and major sidings in the continental U.S. compiled at a scale of 1:2,000,000. [Maintained by the Federal Railroad Administration]
- National Waterway Network – A network database of all navigable inland and intracoastal waterways, Gulf, Great Lakes and coastal sea lanes, and major sea lanes between the continental U.S., Alaska, Hawaii and Puerto. [Maintained by the US Army Corps of Engineers.]
- National Transit Network – A network database of all fixed guideway transit networks in the continental U.S.
- Commercial Air Network – A network database of all direct air routes between commercial airports in the 50 States and U.S. Territories.

The background databases are –

- Place Names – A point database of populated places with a population greater than 2,500 located in the 50 states and U.S. Territories. Based on the 1990 Census.
- United States – An area database of the 50 states, the District of Columbia, and Puerto Rico.

- U.S. Counties – An area database of all counties in the 50 states, plus the District of Columbia and Puerto Rico.
- Urbanized Areas – An area database of urbanized areas in the 50 states and U.S. Territories. Based on the 1990 Census.
- Federally Adjusted Urbanized Areas – An area database of urbanized area boundaries jointly defined by each area and the Federal Highway Administration, and used for highway planning purposes.
- Congressional Districts – An area database showing the 104th Congress District boundaries.
- Metropolitan Statistical Areas – An area database showing primary Metropolitan Statistical Area boundaries.
- Bureau of Economic Analysis Regions – An area database showing U.S. counties aggregated into economic analysis regions as defined by the BEA.
- National Transportation Analysis Regions – An area database showing U.S. economic analysis regions aggregated into 89 transportation analysis regions defined by BTS.
- National Parks – An area database showing the boundaries of National Parks and monuments administered by the National Park Service.

As it relates to corridor intermodal planning, the NTAD network and facilities databases could be combined with the TIGER / Line files (for important nonfederal aid highways) to build the physical freight network. However, all intermodal links would have to be added. The NTAD networks are not linked nor are they linked to the facilities located by the point databases. Also, the NTAD transportation facilities databases do not include information on capacities, other constraints, and transfer times.

Depending on the nature of the corridor study area, the analysis zones could be either the Bureau of Economic Analysis (BEA) regions or National Transportation Analysis Regions (NTAR) from the NTAD or the Traffic Analysis Zones from the Tiger /

Line files. County coverages would also be readily available if counties were the appropriate analysis zones.

2.2 Freight Flow Data

2.2.1 Data Requirements

Ideally origin/destination flow data will be available for the selected analysis zones and at the desired commodity resolution. Data is also needed on how these flows traverse the network, i.e., the flows will be assigned to the network at link and transshipment node flows. Finally, the flow data needs to have sufficient detail to determine vehicle classification in important special cases. For example, it might be necessary to distinguish twin 48 truck movements from other truck movements in order to evaluate specific policy or project alternatives.

2.2.2 Current Data Availability

Flow data as described above is not currently available from a single source, and assembling a complete flow data set for any specific corridor study would be a monumental task.

BTS publishes an annual *Directory of Transportation Data Sources*. The directory is a comprehensive inventory of transportation data from both public and private sources. The 1996 directory is currently available, and the 1997 directory is under development. The *Quick Response Freight Manual* published by the Federal Highway Administration in September 1996 also includes an extensive listing of freight data sources along with an assessment of how useful each data source for state and MPO freight planning. The public data sources most important for corridor freight planning are Commodity Flow Survey (CFS) and the Carload Waybill Sample.

1993 Commodity Flow Survey

The 1993 CFS is based on questionnaire input from 200,000 domestic shippers. The sample was taken from manufacturing, mining, wholesale, auxiliary warehouses, and selected retail and service establishments. The 1993 CFS does not include inbound international shipments nor does it include domestic shipments by establishments defined as farming, forestry, fishing, oil and gas extraction, government, construction, or transportation. The CFS data is reported at the state and the National Transportation Analysis Region (NTAR) level. The NTARs are aggregates of BEA regions. There are 89 NTARs. State boundaries were ignored in the development of the NTAR boundaries.

Shippers were instructed to report the five digit STCC for the primary commodity, the city, state, and zip code of the destination, and all of the basic modes that would be used between origin and destination. The basic modes defined by the questionnaire were –

- Parcel delivery, courier, or U.S. Postal Service
- Private truck
- For-hire truck
- Railroad
- Inland water and/or Great Lakes
- Deep seas water
- Pipeline
- Air
- Other mode
- Unknown

When combination modes were indicated the shipments were summarized as either truck and rail intermodal or other intermodal (truck and pipeline, inland and Great Lakes, and inland and deep sea). Air and truck shipments were included with air shipments.

For intermodal movements, the CFS includes no data on the order of the modes nor on the absolute or relative length of the movements by the individual modes.

Carload Waybill Sample

The carload waybill sample contains confidential information on Class I railroad operations and is available only to Federal or state agencies. Rail data are aggregated at the BEA level at the five digit STCC level.

2.3 Data Extension Techniques

2.3.1 Network Data

As discussed above, publicly available GIS data provide a good starting point for an integrated freight data network. For a specific corridor study area, links would be required to represent intermodal transfer points and additional constraint and transfer time data would need to be acquired or estimated.

2.3.2 Freight Flow Data

Two basic problems exist with the available flow data. First, some needed data are missing, and second, the data are not at the desired zonal level. For example, as noted above the CFS does not include movements for several establishment groups and includes no inbound international movements. The Carload Waybill Sample can be used to address the missing imports that travel by rail or truck/rail intermodal. In some cases, internally available data may be helpful in augmenting or validating outside data. For example, the Virginia Department of Transportation is now capturing truck inspection data from its I-81 weigh stations in a digital database. The data include county of origin and destination and primary commodity. Finally, planning agencies may need to conduct special surveys or purchase data from private sources, such as Reebie and Associates' TRANSEARCH and TRANSEARCH International databases, to further augment the public data.

Data on link flows are also generally missing from the available sources. At the multi-state corridor level, however, there may be very few, if any, options for specific modal and intermodal movements between specific origin/destination pairs. To the extent this is the case, a simple rule-based method could be developed to assign the origin/destination flows to the network.

NCHRP Report 260 outlined a method for disaggregating state level data to the county level. The process uses employment data to disaggregate the origin data and input/output data to disaggregate the destination data. The Bureau of Census annual County Business Patterns data provide the employment data, and the Bureau of Economic Analysis 1987 Benchmark Input-Output Accounts of the United States provides the commodity consumption data.

The steps necessary to develop a comprehensive freight flow database for a corridor planning model will be time consuming and cumbersome. Also, it is conceivable that a database adequate to support the desired analyses could not be developed within available resources.

CHAPTER 3: ANALYSIS METHODS

This chapter begins with a brief discussion of the addition of freight forecasting to the classic four-step planning model. The second section discusses two rail/truck diversion models, and the final section provides an overview of the network flow problem domain along with two examples of large-scale transportation applications.

3.1 Extension of the Four-step Planning Process

The four-step process has been firmly entrenched in U.S. transportation planning for three decades. The four steps are trip generation, trip distribution, mode split, and traffic assignment. The classic guidebook is *NCHRP Report 187 – Quick–Response Urban Travel Estimation Techniques and Transferable Parameters: User's Guide*. *NCHRP Report 187* did not address freight forecasting. Freight traffic did and still does make up a small percentage of trips in urban transportation systems. In response to the growing interest in freight planning, the *Quick Response Freight Manual* (Cambridge Systematics et. al, 1996) was intended integrate freight planning into the four-step process. Alan Horowitz, developer of the *Quick Response System II* transportation planning software system and co-author of the *Quick Response Freight Manual,* believes that the four-step process will play an important role in the future of freight planning (Horowitz, 1996).

The four-step process typically uses a gravity model for trip distribution, a logit model for mode split, and some form of interative or incremental network assignment algorithm. While the modal diversion models discussed in the next section could serve as the mode split model within a four-step freight planning process, increases in computing power and network flow problem algorithms beg the question of whether model forms that combine the trip distribution, mode split, and traffic assignment steps might work better. Also, researchers in travel demand modeling are focusing on activity-based modeling as the replacement for the four-step process, hailing activity-based modeling as the first true paradigm shift in travel demand modeling (Pas, 1996). Therefore, there seems to be no reasonable rationale for using the four-step process for freight planning unless it proves to be the best approach.

3.2 Modal Diversion Models

One method of forecasting freight system response to policy and technology changes is the use of modal diversion models. The underlying assumption of these models is that mode choice is based on perceived total logistics costs for using the feasible modal or intermodal transport options for a given set of shipments. If total logistics costs for a transport option decreases, traffic may be diverted from the competing options. Likewise, if total logistics costs for a transport option increases, traffic may be diverted to the competing options.

Mathematical models have been developed to analyze rail/truck diversion. Two transportation network based modal diversion models are discussed in *Characteristics and Changes in Freight Transportation Demand* (Cambridge Systematics, 1995). These are the American Association of Railroads' (AAR) Intermodal Competition Model (ICM) and the Truck-Rail, Rail-Truck Diversion Model (TR/RT) developed by Transmode Consultants for the Federal Railroad Administration.

The TR/RT is now being refined by the Federal Highway Administration. The information we present concerning the FHWA's use and modifications of and future plans for the TR/RT comes from a conversation with Ms. Karen White of the Transportation Studies Division of the Office of Policy Development.

The FHWA has used the TR/RT for some analyses related to truck size and weight issues and plans to release the model and a users guide within the next couple of years. The ICM and TR/RT both use the Carload Waybill Sample for rail data. For truck flows, the TR/RT, like the ICM, used the North American Trucking Survey (NATS). NATS was a survey of truck drivers conducted by Arthur D. Little, Inc. for the AAR during 1993 and 1994. Because the interviews were conducted at truck stops, it is likely that the NATS was biased toward long-haul shipments, as was its predecessor, the National Motor Truck Data Base (Cambridge Systematics, 1995). The FHWA has modified the TR/RT to use the 1993 CFS for truck movements instead of the NATS.

The *Characteristics and Changes in Freight Transportation Demand* discussion of these models highlighted some concerns relative to both the ICM and TR/RT models. Many of the TR/RT concerns will likely be addressed prior to public release of the model. We have briefly presented the models here to highlight them as candidate analysis tools for intermodal freight planning.

3.3 Network Flow Problem Models

Formal network flow problem formulations and solution methodologies have been around since the 1950s. However, except for the most simple problem form, the shortest path problem, network flow problem solution methods have not been widely used in transportation planning models. This can largely be attributed to the lack of efficient solution algorithms and the limitations of readily available computing power throughout the 1950s and 1960s when the current transportation planning paradigm was emerging and maturing. Innovations in solution algorithms and dramatic increases in computing power in the 1980s and 1990s have combined to make large-scale network flow problem formulations viable alternatives for transportation system modeling. Therefore, this chapter begins with a brief history of the network flow problem family along with definitions for each problem type. The primary reference for the material presented in this section is *Network Flows* (Ahuja et. al, 1993).

There are numerous real world systems that can be effectively modeled as networks. In many cases, the network is explicit, as with a communication network or an electrical distribution network. However, network flow problem formulations are also useful for evaluating networks that are conceptual, such as urban housing reallocation and school system racial balancing.

Three practical questions underlie network flow problem formulations:

- What is the "least cost" way to traverse the network from one point to another?
- What is the maximum flow that can traverse a network from one point to another given the network link capacities?
- What is the minimum cost strategy for sending commodity units from one or more points to one or more other points given the network link capacities?

It is easy to see why solution methods that efficiently answer these questions for large-scale networks would have broad appeal. As mentioned above, however, models based on network flow problems have not been widely applied to transportation planning.

3.3.1 Brief History of Network Flow Problem Theory

The first research efforts in network flow related to the transportation problem. Kantorovich (1939), Hitchcock (1941), and Koopmans (1947) developed the transportation problem structure and algorithmic approaches. After developing the simplex method in 1947, Dantzig published a specialization of simplex for the transportation problem in 1951.

In the 1950s attention shifted to the more general minimum cost flow problem and the other special case problems: shortest path, maximum flow, and assignment. The groundwork for the development of algorithms to solve these problems was laid by Ford and Fulkerson (1962) who developed primal–dual combinatorial algorithms and Dantzig (1962) who focused on simplex implementations.

The formal problem definitions and solution methods matured during the 1960s and 1970s. Researchers provided continuous improvements to solution methods during the 1980s. Research efforts in the 1990s have resulted in dramatic improvement to algorithm performance.

3.3.2 Minimum Cost Flow Problem

The minimum cost flow problem provides a good starting point for describing the domain of network flow problems. Although not the most general problem definition, the minimum cost flow problem is the most general network flow problem definition that 1) involves flow of one and only one "commodity" and 2) can be formulated as a linear program. The other network flow problems can be easily defined and understood in terms of their relation to the minimum cost flow problem.

The minimum cost flow problem models the movement of a single commodity over a directed graph network. The network has three types of nodes:

Supply Node – A node that has a positive net outflow (negative inflow).

Demand Node – A node that has a negative net outflow (positive inflow).

Transshipment Node – A node that has zero net outflow (and inflow).

Each arc in the network has an associated linear cost coefficient. The objective of the minimum cost flow problem is to minimize total arc shipping costs. The problem is subject to the following constraints:

Mass Balance – Outflows (inflows) at each node must equal the given net quantity.

Flow Balance – The flow on each arc must lie within a specified lower and upper bound. The lower bound is either zero or some positive minimum arc flow. The upper bound, when supplied, defines the arc capacity.

Examples of minimum cost flow applications are vehicle flow on an urban street network and call routing in a communications network.

3.3.3 Special Cases of the Minimum Cost Flow Problem

Shortest Path Problem

The shortest path problem is the simplest variant of the minimum cost flow problem. This problem deals only with a point-to-point flow, i.e., a single supply(origin) node and a single demand (destination) node. The objective is to find the shortest (least cost) route through the network from the supply node to the demand node. Arc capacity is not considered. The problem simply seeks to determine the least cost single route through the network between origin and destination.

Examples of shortest path applications are emergency vehicle dispatching and project scheduling.

Maximum Flow Problem

The maximum flow problem is the reverse of the shortest path problem. Like the shortest path problem, the maximum flow problem also deals with point-to-point flow. However, whereas the shortest path problem looks for the single least cost route from the origin node to the destination node given the arc costs while ignoring capacity, the maximum flow problem seeks to quantify the maximum quantity of a given commodity that could flow through the network from origin to destination given the arc capacities while ignoring cost.

Examples of maximum flow applications are point-to-point capacity in a pipeline network and troop or supply deployment through a military logistics chain.

Transportation Problem

The transportation problem is a special case of the minimum cost flow problem that includes no transshipment nodes. As mentioned earlier, the transportation problem was the first network flow problem that was formalized as an optimization problem. For this reason, the minimum cost flow problem was, and still is, often referred to as the *transshipment* problem to distinguish it from the earlier transportation problem structure (Luenberger, 1984).

Since there are no transshipment nodes in the transportation problem, the set of network nodes is partitioned into a set of supply nodes and a set of demand nodes. The cardinality of these two sets need not be equal. Other than the restriction against transshipment, the transportation problem is otherwise the same as the general minimum cost flow problem. The objective is still to find the arc flows that will transfer to given quantities of commodity from the supply nodes to the demand nodes with the least cost. In general, arc flows can be subject to flow balance.

Examples of transportation problem applications are distributions from warehouses to retail centers and factories to distribution centers.

Assignment Problem

The assignment problem is a further specialization of the transportation problem. In the assignment problem there is a one-to-one correspondence between supply and demand nodes. The problem seeks to determine the least cost one-to-one matching of supply to demand nodes.

Examples of assignment problem applications are assignment of projects to project managers and assignment of jobs to machines.

Circulation Problem

The circulation problem is the complement of the transportation problem in terms of the definition of the network nodes. Recall that the minimum cost flow problem can in general have supply, demand, and transshipment nodes. In the transportation problem, transshipment nodes are not included. In the circulation problem, on the other hand, all nodes are transshipment nodes. No external flows are introduced into the system.

Therefore, the objective is to find the least cost routing for flows circulating within the system. The traveling salesman problem is one formulation of the circulation problem.

An example of a circulation problem application is route schedule development for a commercial airline.

3.3.4 Generalizations of the Minimum Cost Flow Problem

Convex Cost Problem

As defined, the minimum cost flow problem objective function is based on arc costs that vary linearly with flow. In the convex cost problem, the objective function is generalized to allow for nonlinear arc costs. Examples where this problem structure is useful include electrical systems subject to transmission power losses and urban roadway networks where travel time increases with link volume.

Generalized Flow Problem

While the convex cost problem generalizes the arc costs, the generalized flow problem generalizes the network behavior. The minimum cost flow problem assumes the flow is conserved in the network, i.e. flows are only introduced and extracted at the nodes. In the generalized flow problem, the arcs can either consume or generate flow. This behavior is modeled by a positive multiplier that scales the entering flow up or down to calculate the exiting arc flow. Arcs that consume flow (i.e., multiplier < 1) are referred to as *lossy*, and arcs that generate flow (i.e., multiplier > 1) are referred to as *gainy*.

Multicommodity Flow Problem

The multicommodity flow problem is a generalization not of the network, but of the flows. In the normative minimum cost flow problem, only one type of commodity is being modeled by the problem formulation. In the multicommodity flow several distinct commodities or commodity classes use the same underlying network. Each commodity has its own set of mass balance constraints. However, the arc flows for the individual commodities are tied together by way of the flow balance constraints. The problem becomes one of allocating the arc capacities to the individual commodities in the least cost manner that satisfies each commodity's mass balance constraints.

3.3.5 Summary of the Network Flow Problem Domain

The network flow problems discussed above can be understood in relation to the minimum cost flow problem. Restated, the minimum cost flow problem seeks to minimize the linearly varying cost of moving a single commodity through a capacitated network with transshipment and flow conservation. The other eight network flow problems are either more general or more specific than the minimum cost flow problem on one or more of these conditions.

Figure 1 shows these relationships graphically with the problems at the top being more general and those at the bottom being more specific. The differences between the general and special case problems and the minimum cost flow problem are restated and summarized in the following tables.

Table 1 presents the network flow problems that are generalizations of the normative minimum cost flow problem, and Table 2 presents the specialized problems.

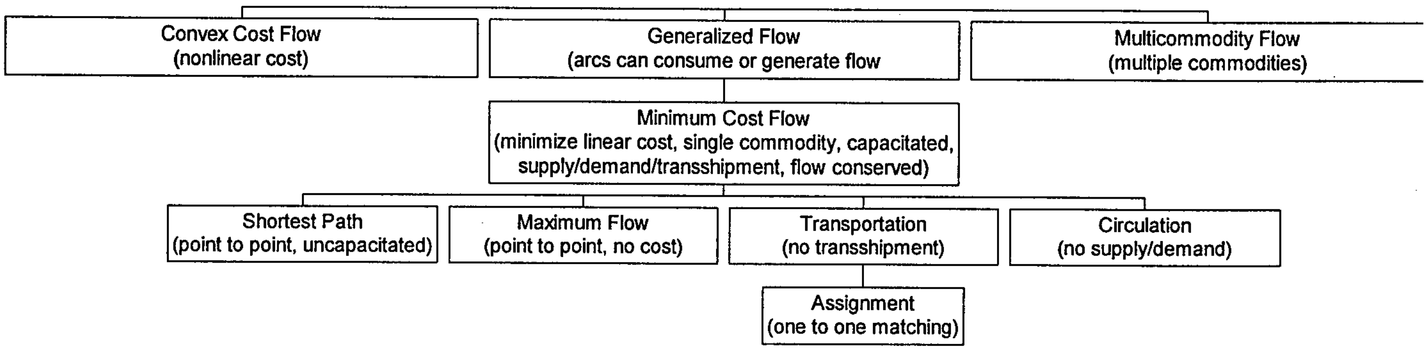
Table 1: Generalized Network Flow Problems

Problem Name	Generalizations from the Minimum Cost Flow Problem
Convex Cost Problem	Costs vary non-linearly
Generalized Flow Problem	Arcs consume or generate flow
Multicommodity Flow Problem	More than one type of commodity

Table 2: Specialized Network Flow Problems

Problem Name	Specialization from the Minimum Cost Flow Problem
Shortest Path Problem	Point-to-point flow Uncapacitated network
Maximum Flow Problem	Point-to-point flow Flow maximization objective No flow costs
Transportation Problem	No transshipment nodes
Assignment Problem	One-to-one matching
Circulation Problem	All nodes are transshipment nodes

Figure 1: Network Flow Problem Class Structure



3.3.6 The Transshipment Problems

Because of their relationship to the transportation problem that was developed earlier, the minimum cost flow problem and the multicommodity flow problem are also referred to as the transshipment problem and the multiproduct transshipment problem (Luenberger, 1984). Linear program formulation of these two classical network flow problems follow.

Minimum Cost Flow Problem–Linear Formulation

Consider a directed network, $\mathbf{G} = (\mathbf{N}, \mathbf{A})$, where $\mathbf{N}$ is a set of *n nodes* and $\mathbf{A}$ is a set of *m arcs*. Each arc $(i, j) \in \mathbf{A}$ has a specific *cost,* c_{ij}. Each arc $(i, j) \in \mathbf{A}$ can also have a *capacity,* u_{ij} and a *lower bound,* l_{ij}. For each node $i \in \mathbf{N}$ there is a number b_i representing the available supply at node i. Nodes with $b_i > 0$ are *supply nodes*; those with $b_i < 0$ are *demand nodes*; and those with $b_i = 0$ are *transshipment nodes.* Let the decision variables be the arc flows, x_{ij}, for each arc $(i, j) \in \mathbf{A}$. The optimization problem can be formulated in algebraic terms as:

Minimize

$$\sum_{(i,j)\in \mathbf{A}} c_{ij}x_{ij} \tag{1}$$

subject to

$$\sum_{\{j:(i,j)\in \mathbf{A}\}} x_{ij} - \sum_{\{j:(j,i)\in \mathbf{A}\}} x_{ji} \quad \forall\, i \in \mathbf{N}, \tag{2}$$

$$l_{ij} \le x_{ij} \le u_{ij} \qquad \forall\,(i,j)\in \mathbf{A}, \tag{3}$$

where $\sum_{i=1}^{n} b_i = 0$.

In matrix form, the minimum cost flow problem is represented as:

Minimize

$$\mathbf{cx} \tag{4}$$

subject to

$$\mathbf{Nx} = \mathbf{b} \tag{5}$$

$$\mathbf{l} \le \mathbf{x} \le \mathbf{u} \tag{6}$$

This formulation is the same as is presented in reference (Ahuja et. al, 1993). Luenberger presents the minimum cost flow with only non-negativity constraint on the arc flows, i.e., with no lower bound or capacity restrictions (Luenberger. 1984).

Multicommodity Flow Problem–Linear Formulation

The multicommodity flow problem is simply the minimum cost flow problem with multiple product flows. The problem formulation is similar except that arc costs and arc flows are summed over the commodities and the arcs, and there is a mass balance constraint at each node for each commodity. The multicommodity flow problem can be formulated as:

Minimize

$$\sum_{1 \le k \le K} c^k x^k \tag{7}$$

subject to

$$\sum_{1 \le k \le K} x_{ij}^k \le u_{ij} \qquad \forall\, (i,j) \in \mathbf{A}, \tag{8}$$

$$\mathbf{N}\mathbf{x}^k = \mathbf{b}^k \quad \text{for } k = 1,2,\cdots,K, \tag{9}$$

$$0 \le x_{ij}^k \le u_{ij}^k \ \ \forall\, (i,j) \in \mathbf{A} \text{ and } k = 1,2,\cdots,K, \tag{10}$$

where there are K total commodities.

The individual commodity capacities in equation (10) are optional. In the absence of individual commodity capacities, flow is balanced in aggregate only by equation (8). The individual equation (9) for each commodity is analogous to equation (5) in the minimum cost flow problem.

3.3.7 Two Recent Multicommodity Flow Problem Algorithms

Brief summaries of two recent algorithmic approaches to the multicommodity flow problem follow. The discussions are intended to describe the basic approach, not to present the problem formulations in detail. The approaches are presented to illustrate large-scale freight planning applications of the multicommodity flow problem. Some additional applications are noted in Chapter 5.

<u>Use of Equivalent Linear Subproblem</u>

Gédéon, Florian, and Crainic (1993) present a solution approach to a "normative transshipment problem" over a multimodal network. The problem they develop is a convex cost generalization of the multicommodity flow problem.

The steps in the linear approximation algorithm (LAA) are applied iteratively given an initial feasible solution. The steps are:

LAA Step 1 (Linear Subproblem): Formulate and solve a linear approximation of the top level problem.

LAA Step 2 (Descent Direction): Use the linear subproblem solution to calculate a descent direction.

LAA Step 3 (Stopping Criterion): Test for optimality.

LAA Step 4 (Line Search): Perform a line search to determine the best solution along the descent direction.

LAA Step 5 (Variable Update): The new feasible solution is processed.

Although developed as a multiproduct solution method, the linear approximation method was tested on a single commodity problem involving the shipment of coal in Finland (Gédéon et. al, 1993). The paper's conclusions include a statement that the linear approximation method should be compared to a network-based method for determining the minimization descent direction.

A Primal-Dual Heuristic

Barnhart and Sheffi (1993) seek to develop a solution method that will overcome the limitations in problem size imposed by linear programming-based methods. The large-scale problem they address is shipment routing for a freight carrier (test data provided by North American Van Lines). This problem is truly large-scale because each shipment is considered as a separate commodity. An LP corresponding to the test data would contain "more than 2.5 million rows and more that 6 million columns." The authors maintain that LP-based methods cannot even find an initial solution to this problem. They compare the performance of their method to two LP-based methods: Dantzig-Wolfe decomposition and Primal-Dual decomposition.

In brief, the primal-dual heuristic method (PDN) uses shortest paths to construct admissible sets to restricted primal and dual problems which are solved with a network-based algorithm. The PDN steps are:

PDN Step 1(Initialization): Generate initial dual solution.

PDN Step 2 (Decomposition): Construct the admissible sets.

PDN Step 3 (Heuristic Solution): Solve the restricted primal-dual problem.

PDN Step 4 (Termination Test): Test for optimality or unsolvability of the reduced problem.

PDN Step 5 (Iterate): Generate new dual feasible solution.

CHAPTER 4: POLICY AND INSTITUTIONAL ISSUES

In addition to the technical issues related to freight modeling and planning, important policy and institutional issues must be addressed. We briefly discuss a few such issues in this chapter under the headings of data, public/private participation, and goal setting.

4.1 Data Issues

The pressing need to develop accurate planning models comes at a time of austerity in public finance. The mantra "do more with less" is resounding through all areas of public service. Open data access and data sharing will be key elements of any strategy that has a chance of successfully developing the needed data. Cooperation among users with similar needs and economies of scale will be essential.

There are still many questions to be answered concerning data confidentiality. Shippers and carriers are rightfully protective of their trade secrets. Open dialog and formal working groups are needed to facilitate workable solutions (Pisarski, 1997).

Data are available in scattered sources. BTS has made strides in cataloging data sources and improving the quality of data products such as the CFS. Much more work lies ahead.

4.2 Joint Public/Private Participation

Innovative approaches to bring the public and private sectors into close partnership are needed at each stage of the transportation system planning and management process. Private sector cooperation and expertise are needed for data development, project and policy analysis, and even project finance.

4.3 Goal Setting Issues

At the core of the four-step process was a very simple goal – provide system capacity to meet forecast system demand. The requirements of the National Environmental Protection Act were shoe horned in. Prior to the ISTEA, the push was still to build. The job of managing for optimal efficiency will be a messier prospect and a job that will involve a much broader set of players. Consensus building and goal setting must not be short changed as we move forward into the new planning paradigm.

Ken Ogden suggests an overall goal of minimizing the *total social cost* of moving goods while meeting the freight needs of the community (Ogden, 1996). He goes on the suggest six specific policy goals in support of the overall goal –

- Public sector macroeconomic performance – to contribute towards local, regional, state, and national economic performance.
- Cost and quality of freight services – to improve freight efficiency and productivity by reducing transport operation costs, especially those associated with traffic congestion.
- Environmental – to minimize the adverse environmental effects of freight activities.
- Infrastructure and management – to provide and manage an adequate public infrastructure.
- Road safety – to minimize the number and severity of truck crashes.
- Urban structure – to contribute towards "desired" urban structure.

He is quick to point out that these goals will sometimes be in conflict or even mutually exclusive. The urban structure goal is subjective, and the economic performance goal can have winners and losers. Therefore, it is evident that goal setting will involve delicate balance and compromise. For a multi-state freight corridor, it is likely that intermodal project alternatives will favor economic development in some locations over, and possibly even at the expense of, other locations.

CHAPTER 5: CURRENT INITIATIVES

In this chapter, we will highlight a few examples of efforts aimed at addressing the needs and issues identified in the preceding chapters.

5.1 Data Needs

In March of this year, the Transportation Research Board held an invitation-only conference titled *Information Needs to Support State and Local Transportation Decision Making into the 21st Century*. This scope of the conference was broad, yielding findings in three major categories: content, methods, and institutions. The conference provided a good starting point for continued work in defining the data needs for 21st century planning. The conference was co-sponsored by BTS, FHWA, the Federal Transit Administration, the American Association of State Highway and Transportation Officials, and the Association of Metropolitan Planning Organizations.

The 1997 CFS is underway. Although the sample size was reduced from 200,000 establishments to 100,000, BTS and the Census Bureau report that the sample was more carefully chosen and that improvements in the questionnaire process will yield an improved product over the 1993 CFS.

5.2 Analysis Tools

As mentioned in Chapter 3, the FHWA is in the process of making improvements to the Truck-Rail, Rail-Truck Diversion Model. The usefulness of this model can be tested when the FHWA distributes the model and user's guide.

If network flow problem models prove themselves useful for freight planning, the significant amount of ongoing research in the network flow problem area should make worthwhile contributions to freight modeling applications. A sampling of the current research follows –

- *Dual-Ascent Procedures for Multicommodity Location-Allocation Problems with Balancing Requirements* (Crainic and Delorme, 1993) – a fleet management application
- *An Analytical Framework for Routing Multiattribute Multicommodity Freight* (Popken, 1996) – an shipment routing application for less-than-truckload operation
- *Production, Transportation, and Distribution Planning in a Multicommodity Tri-Echelon System* (Pirkul and Jayaraman, 1996) – a plant and warehouse location application
- *Formulation and Solution of a Multicommodity, Multimodal Network Flow Model for Disaster Relief Operations* (Haghani and Oh, 1996) – a multicommodity flow problem application to disaster relief
- *A Model for Medium-Term Operations Planning in an Intermodal Rail-Truck Service* (Nozick and Morlock, 1997) – an operations planning application for intermodal rail-truck service

5.3 Statewide Planning

Many states have initiated freight planning activities. These include New Jersey, New Mexico, Kansas, Wisconsin, and Washington State. In Virginia, preliminary work has been done to establish a freight planning GIS database (Goodloe et. al, 1996), and a follow on project is underway to develop a statewide freight planning framework.

5.4 Urban Planning

Two conferences were held in 1996 with a focus on MPO level freight planning. The conferences were sponsored by the U.S. Department of Transportation and were called the *National Freight Planning Applications Conference* (October) and the *Urban Goods Movement and Freight Forecasting Conference* (September).

Several MPOs are making great strides in freight planning. Two notable examples are the San Francisco Bay area's Metropolitan Planning Commission and the Puget Sound Regional Council.

5.5 Freight Stakeholders National Network

In the area of public private partnership, it is important to mention the Freight Stakeholders National Network (FSNN). The FSNN is a cooperative effort among eight national associations –

Air Freight Association
American Association of Port Authorities
American Trucking Association
Association of American Railroads
Intermodal Association of America
National Association of Manufacturers
National Industrial Transportation League
National Private Truck Council

The FSNN supports local Freight Stakeholders Coalitions in their efforts to –

- Organize the freight community to maximize its influence
- Participate actively in the freight transportation planning process
- Provide education and information on freight sector needs
- Heighten the awareness of freight and its importance to the local economy
- Identify freight transportation system bottlenecks
- Recommend specific projects to support a more efficient flow of freight

(Meyer, 1996)

Page intentionally left blank

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Our conclusions and recommendations fall into two categories, institutional responsibilities and research directions.

6.1 Institutional Responsibilities

6.1.1 Federal Role

The federal government will have an important role in the future of transportation planning. Responsibility for the following recommendations will fall to several entities, such as the FHWA, BTS, the Census Bureau, and the TRB.

- Establish an overall framework for freight planning that includes definition of planning at the various levels and the lead agencies for planning at these levels
- Continue to sponsor conferences to establish planning goals and data needs
- Coordinate, facilitate, and disseminate research
- Continue to tailor data products to the needs of planning agencies and continue to improve data accessibility
- Take lead in multi-state planning efforts

Also, it appears that the current federal freight planning efforts are not well coordinated with multiple agencies holding conferences and preparing documents. It would be useful to designate one agency, office, or department as the lead agency for transportation planning initiatives.

6.1.2 Professional Association Role

The Freight Stakeholder National Network is a good example of what the professional associations should be doing. Professional associations have important roles to play in public relations, education, lobbying, and agenda setting.

6.1.3 State Role

The states will need to augment federal data, set statewide planning goals, act as arbiter for conflicts between MPOs, and participate in multi-state planning efforts.

6.1.4 MPO Role

MPOs will have a primary focus on operational issues such as congestion mitigation and site access. MPOs will also be responsible for project prioritization for freight projects within their purview. Therefore, MPOs must increase their expertise in freight planning and their understanding of its importance.

6.2 Research Directions

We recommend the following general directions for freight planning research –

- The multicommodity network flow problem should be investigated as an alternative freight flow model. Since shippers and carriers are using network flow problem applications for shipment routing and even facility location, it is a reasonable hypothesis that planning models based on the network flow problem structure should provide good results.
- Methods are needed to integrate freight planning models with general equilibrium models of regional and national economies (Ogden, 1996). It is clear that freight policy and project decisions can have significant economic impact.

- Methods for determining the appropriate aggregation levels for analysis zones and commodity types are needed for each freight planning level.
- Research is needed on how to model total logistics costs. For example, can total logistics costs be effectively modeled as transport costs plus some function of commodity value per unit weight or unit volume? Should total logistics cost be modeled as a random variable?
- Much could be learned from comparative modeling of corridors with and without intermodal service.
- Research is needed on how to efficiently and effectively model network constraints.
- Developed models should be tested based on there predictive ability, not just how well they can be calibrated to a base year. For example, models calibrated on previous years could be tested on their ability to predict historical effects of changes such as motor carrier and rail deregulation, NAFTA, introduction of intermodal service in a corridor, etc.

In summary, the prospects for freight planning at the multi-state corridor level and for freight and transportation planning in general are promising. However, there is much work to be done before transportation planners and officials have the data and analysis tools they need to answer the right questions and support good project and policy decisions.

REFERENCES

Ahuja, R.K., Magnanti, T.L., and Orlin, J.B. (1993), *Network Flows: Theory, Algorithms, and Applications,* Prentice Hall, Englewood Cliffs, New Jersey.

Anderson, S.E. et. al (1995), *Toward the Future: The Promise of Intermodal and Multimodal Transportation Systems*, Southwest Region University Transportation Research Center, Center for Transportation Research, University of Texas, Austin.

Barnhart C. and Sheffi, Y. (1993), A network-based Primal-dual heuristic for the solution of multicommodity network flow problems, *Transportation Science,* **27**, No. 2, 102-117.

Barton – Aschman Associates, Inc. (1991), *A Research Process for Developing a Statewide Multimodal Transport Forecasting Model – Final Report* (Report No. FHWA-HPR-NM-91-07), New Mexico State Highway and Transportation Department.

Campbell, K. (1996), Commercial freight and intermodal transportation, *Advanced Technology and Applications for the I-81 Corridor*, Proceedings of the Mid-Atlantic Universities Transportation Center, March 24-26, 61-62.

Clark, D.B. (1996), Intermodal transportation, yesterday, today, and tomorrow, *Advanced Technology and Applications for the I-81 Corridor*, Proceedings of the Mid-Atlantic Universities Transportation Center, March 24-26, 63-65.

Crainic, T.G. and Delorme, L. (1993) Dual-ascent procedures for multicommodity location-allocation problems with balancing requirements, *Transportation Science*, **27**, No. 2, 90-101.

Dantzig, G.B. (1951) Application of the simplex method to a transportation problem, In *Activity Analysis and Production and Allocation,* edited by T. C. Koopmans, Wiley, New York, 359-373.

Dantzig, G.B. (1962) *Linear Programming and Extensions,* Princeton University Press, Princeton, New Jersey.

Ford, L.R. and Fulkerson, D.R. (1962), *Flows in Networks*, Princeton University Press, Princeton, New Jersey.

Galligan, W. (1996), Problems and potential with intermodal service, *Advanced Technology and Applications for the I-81 Corridor*, Proceedings of the Mid-Atlantic Universities Transportation Center, March 24-26, 65-67.

Gédéon, C., Florian, M., and Crainic, T.G. (1993), Determining origin-destination matrices and optimal multiproduct flows for freight transportation over multimodal networks, *Transportation Research – Part B*, **27B**, No. 5, 351-368.

Goodloe, J.C., Brich, S.C., and Demetsky, M.J. (1996) *Development of a GIS Freight Planning Database*, Report No. UVA/29242/CE97/102, Mid-Atlantic Universities Transportation Center, University of Virginia.

Haghani, A. and Oh, S. (1996), Formulation and solution of a multi-commodity, multi-modal network flow model for disaster relief operations, *Transportation Research – Part A*, **30**, No. 3, 231-250.

Hitchcock, F.L. (1941), The distribution of a product from several sources to numerous facilities, *Journal of Mathematical Physics*, **20**, 224-230.

Horowitz, A.J. (1996), Freight forecasting: The context, *Urban Goods Movement and Freight Forecasting Conference*, Proceedings of the U.S. Department of Transportation, September, 2-1 – 2-14.

Jourquin, B. and Beuthe M. (1996), Transportation Policy analysis with a geographic information system: The virtual network of freight transportation in Europe, *Transportation Research – Part C*, **4**, No. 6, 359-371.

Kantorovich, L.V. (1939), Mathematical methods in the organization and planning of production, Publication house of the Leningrad University, Translated in *Management Science*, **6** (1960), 366-422.

Koopmans, T.C. (1947), Optimum utilization of the transportation system, *Proceedings of the International Statistical Conference*, Washington, D.C.

Meyer, R. (1996) Freight stakeholders national network, *National Freight Planning Applications Conference*, Proceedings of the U.S. Department of Transportation, October 14-16, 2-27 – 2-38.

Nozick, L.K. and Morlok, E.K. (1997) A model for medium-term operations planning in an intermodal rail-truck service, *Transportation Research – Part A,* **31**, No. 2, 91-107.

Ogden, K.W. (1996), Urban goods movement and its relation to planning, *Urban Goods Movement and Freight Forecasting Conference*, Proceedings of the U.S. Department of Transportation, September, 2-1 – 2-14.

Pas, E.I. (1996), Recent advances in activity-based travel demand modeling, *Travel Model Improvement Program – Activity-Based Travel Forecasting Conference: Summary, Recommendations, and Compendium of Papers*, Edited by L.J. Engelke, Texas Transportation Institute, June 2-5, 79-102.

Pirkul, H. and Jayaraman, V. (1996) Production, transportation, and distribution planning in a multicommodity tri-echelon system, *Transportation Science*, **30**, No. 4, 291-302.

Pisarski, A.E. (1997), Overview and executive summary, *Conference Proceedings 14: Information Needs to Support State and Local Transportation Decision Making into the 21st Century* (Prepublication copy available at http://www.bts.gov/NTL/data/irvine.pdf) , Proceedings of the Transportation Research Board, March 2-5, 9-23.

Popken, D.A. (1996) An analytical framework for routing multiattribute multicommodity freight, *Transportation Research –Part B*, **30**, No. 2, 133-145.

Roger Creighton Associates, Inc. (1983), *National Cooperative Highway Research Program Report 260: Application of Statewide Freight Demand Forecasting Techniques*, Transportation Research Board, National Research Council, Washington, D.C.

Roger Creighton Associates, Inc. and R.L. Banks & Associates, Inc. (1977), *National Cooperative Highway Research Program Report 177: Freight Data Requirements for Statewide Transportation Systems Planning – Research Report*, Transportation Research Board, National Research Council, Washington, D.C.