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Network Design Formulations, Modeling, and Solution Algorithms for Goods Movement Strategic Planning

Pruttipong Apivatanagul
University of California, Irvine
2008

UNIVERSITY OF CALIFORNIA
IRVINE

Network Design Formulations, Modeling, and Solution Algorithms for Goods Movement Strategic Planning

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Transportation Science

by

Pruttipong Apivatanagul

Dissertation Committee:
Professor Amelia C. Regan Chair
Professor Wilfred W. Recker
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2008

The dissertation of Pruttipong Apivatanagul
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2008

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2. Apivatanagul, P., and A.C. Regan, *"A Solution Algorithm for Long Haul Freight Network Design Using Shipper-Carrier Freight Flow Prediction with*

explicit capacity constraint", Journal of the Transportation Research Board, 2008 (in press).

3. Apivatanagul, P., and A.C. Regan, "*A Modeling Framework for the Design of a Multimodal Long Haul Freight Network*", proceedings of the 2007 meeting of the Transportation Research Board.
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ABSTRACT OF THE DISSERTATION

Network Design Formulations, Modeling, and Solution Algorithms for Goods Movement Strategic Planning

By

Pruttipong Apivatanagul

Doctor of Philosophy in Transportation Science
University of California, Irvine, 2008
Professor Amelia C. Regan Chair

Efficient fright transportation is essential for a strong economic system. Increases in demands for freight transportation, however, lessens the efficiency of existing infrastructure. In order to alleviate this problem effectively, evaluation studies must be performed in order to invest limited resources for maximum social benefits. In addition to many difficulties related to evaluating individual projects, complimentary and substitution effects that occur when considering transportation projects together must be properly accounted for. Current practices, however, limit the number of projects that can feasibly be considered at one time.

This dissertation proposes network design models which can automatically create project combinations and search for the best of these. Network design models have been studied for the passenger movements and focus on highway expansions. In this dissertation, the focus is shifted to freight movements which involve multimodal transportation improvements. A freight network design model is developed based on a bi-level optimization model. The development then involves two components. The first task is to set the freight investment problems within the bi-level format. This includes finding a suitable freight flow prediction model which can work well with the bi-level model. The second task is to provide a solution algorithm to solve the problem.

The dissertation sets the framework of the freight flow network design model, identifies expected model issues, and provides alternatives that alleviate them. Through a series of developments, the final model uses a shipper-carrier freight equilibrium model to represent freight behaviors. Capacity constraints are used as a means to control service limitations since reliability issues, an important factor for freight movements, cannot be captured by steady state traffic assignment. A case study is implemented to allocate a budget for improvements on the California highway network. The transportation modes are selected by the shipper model which can include truck, rail, or multimodal transportation. The results shown that the proposed network design model provides better solutions compared with traditional ranking methods. The solution algorithm can manage the problem with a reasonable number of project alternatives.

CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

The freight transportation industry forms the backbone of the US economy. Transportation activities account for approximately 11 percent of the national GDP (USDOT and BTS, 2002).It has long been recognized as an important foundation of economic strength. The demand for freight transportation movements in the US and internationally is well known to be increasing. Analysis provided by the Bureau of Transportation Statistics shows that if this trend continues that freight volume will double in the next twenty years. One of the reasons for this growth is the connection between freight transportation and increases in Gross Domestic Product (GDP) and population growth (Smith, 2002 and Kale, 2003). Two other important factors contributing this increase are the growth of international trade and of information technologies. It is obvious that the shift of manufacturing to overseas countries requires new and increased transportation activities. The growth of information technologies changes the nature of logistics operations from stationary warehouse inventories to inventories in transit as is the case in many Just in Time (JIT) delivery systems. Enhanced information technologies can be used to coordinate the use and arrival of products and materials and thus reduce onsite stocks. However, JIT systems require more individual freight shipments and more reliable transportation systems(Ferrell, et al., 2001). In the United States, the third party logistics (3PL) industry, which often manages or performs the role of freight carriers to satisfy shipment demands, grew from $10 billion in 1992 to $40 billion in 1998 (Regan, et al., 2001).

Highway expansion has been a focus of efforts to accommodate increasing freight demand since trucking is the dominant transportation mode. Limited highway capacities which must simultaneously serve the needs of goods movement and passenger transportation cause significant congestion problems in many urban regions. From the trucking industry perspective, congestion problems have five primary aspects. These are slow average speeds, unreliable travel times, increased driver frustration and accompanying lower morale, higher fuel and maintenance costs, and higher costs due to accidents and insurance. The most problematic aspect among these five is the reliability of travel times followed by driver frustration and morale, then by slow average speeds (Golob and Regan, 2001). Additionally, congestion causes increases in accidents and externalities such as air and noise pollution and, in today's climate, one of the most important externalities -- fuel consumption.

Constructing new roads to alleviate congestion or expanding existing infrastructure provides limited opportunities to solve the congestion problem due to the high cost of land use, environmental concerns, and physical barriers restricting the expansion of the existing network, especially in urban areas. Road construction is clearly a short term solution at best. Time and time again, increases in highway capacity have shown to lead to increases in both passenger and freight demand – leaving the original congestion problems unsolved.

The utilization of multimodal freight transportation systems is needed in order to use the reserve capacity and shift demand from other modes (Park and Regan, 2005). This increase drives the need for major infrastructure improvements at the local, state and federal level. Many states have undertaken recent freight planning studies, (see for example NJDOT and PBQD, 2004, MnDOT, 2005, and USDOT and FHWA, 2005). Improvements in the freight rail system may provide a long term solution for long distance goods movement, however, currently, rail and intermodal transportation do not offer the flexibility and reliability available on the highway system. Rail and intermodal facilities have to be considered for possible expansion in order to have better service quality in the future.

If incentives are provided and improvements are made, relevant companies will gain experience with and increase their intermodal freight movements over time. The immediate shift from the highway mode to intermodal modes is highly unlikely but if current capacity is not expanded it may be too late to encourage a shift in the future. The significance of intermodal transportation has been recognized as one of the requirements stated in the Federal Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 and in the Transportation Equity Act for the 21st Century (TEA 21) in 1998.

The growth of international trade further increases the importance of a multimodal freight transportation networks because of significant increases in longer haul movements (Ferrell, et al., 2001). These longer hauls lead to a transfer of goods to water, rail or air transport. Therefore congestion will occur at ports, hubs, or rail transits which are gateways between each regions or countries. These congestion problems should be identified and the opportunities for improvement should be considered together with the ground transportation network.

Although long haul freight mostly moves on the high mobility network of the interstate highway system, local road networks play an important role in providing efficient access to that network. The aforementioned recent freight studies agree that developing freight networks which are well integrated and which mitigate or eliminate system bottlenecks are the key to efficient transportation of passengers and freight. Thus, in order to design a good freight network, both local networks and high mobility networks should be considered simultaneously.

The differences in the nature of local and high mobility networks make such consideration challenging. Local networks, which consist of local roads, streets, and intersections have different problems and solutions from high mobility networks which consist of freeway, highway, and long haul railroad. Therefore, different models should be used to solve each problem separately.

Under limited budgets, the continuing growth of freight demand and the increasing importance of multimodal transportation, a multimodal freight network design model is needed in order to efficiently allocate limited resources. Instead of considering investments in each transportation mode individually, network investments should be considered in an integrated multimodal framework. This concept has been investigated by various researchers and a recent implementation and review of the relevant literature can be seen in Park and Regan (2005). The integrated network can incorporate terminal characteristics. This ability distinguishes such networks from unimodal networks. The interaction of projects in transportation networks requires the optimization model to identify attractive combinations of project alternatives. Solution algorithms for such complicated integrated models must be developed.

The freight multimodal network design model is a transportation planning support tool which includes forecasting demand by mode, and developing the next steps, action plans, and recommendations for implementation (Kale, 2003). The network design problem can be used directly to recommend the action plan for improving the existing network. Additionally, the solution can be used interactively to forecast volume by modes and identify the bottlenecks and reserve capacity in the future network. In order to forecast the volume by modes, the potential for modal shift from road to intermodal transport has to be studied. Information related to intermodal infrastructure planning is needed (Ruesch, 2001). The solution to the network design model can help to identify and recommend the future issues related to bottlenecks and reserve capacity for the multimodal freight capacity assessment.

1.2 GOALS AND TASKS

The freight network has the important task of accommodating the needs of industry thus directly impacting economic growth. The freight transportation network has to be designed appropriately in order to achieve maximum utility and utilization. The improvement of a link in the network should be considered on a system side basis rather than individually in order to fully make the best use of resources. Additionally, under budget constraints, network improvements must be carefully selected using sophisticated approaches in order to fully leverage limited resources.

Previous studies use traditional methods such as cost-benefit analysis to examine a set of scenarios. However, the complexity of transportation project selection is exacerbated by the substitution and complementary effects in a network which means that some projects compete with or support others. The number of promising scenarios may be more than can be examined on a case by case basis. A model which can deal with the combinatorial problem and consider traffic flow behaviors which change corresponding to the projects selected should be developed. Such a model is referred to as a network design model. In such an optimization problem, the existing network is provided along with a set of proposed improvement projects as well as relevant budget limitations. An objective function is used to evaluate the efficiency of alternative networks. The output of the model is the set of projects that perform best under the budget constraints.

The goal of this dissertation is to develop network design models which focus on freight network improvements. In recent years, network design models for real applications have been developed. For example, Ben-Ayed, et al. (1992) applies network design to the Tunisian highway network and Kuby, et al. (2001) applies their model to the Chinese railway network. However, there are many questions that have to be considered in order to develop a promising freight network design model.

The first task is to set the freight network design modeling framework. The framework relies on two key factors. The first is the formulation of the mathematical optimization model which is a set of rules to identify the optimal network. Another key is the approach to deal with the freight flow forecasting models. It has been mentioned previously that although freight movements generally travel on high mobility links such as the freeway system, route choice decisions can be highly related to the congestion of the local transportation links, ports, and hubs which affect network reliability. More than one model and an approach to combine them together are needed to forecast the freight flows correctly.

The second task lies on the representation of freight route choice behaviors. None of earlier research on this problem considers explicit freight behavior which involves multiple players making route choice decisions and which involve multiple modes. We believe that including the multi player aspect can give a better forecasting model when multiple modes are considered. An objective of our work is to develop a model which carefully considers multiple agents and multiple modes for the freight network design problem.

The last task is to develop a corresponding solution algorithm based on freight route choice behaviors and the mathematical optimization model. The quality of solutions from the algorithm and its computational time is evaluated.

1.3 PAPER ORGANIZATION

Chapter 1, the introduction, clarifies the need for freight network design studies, the goals of the dissertation, and the main research tasks. Chapter 2, the literature review, discusses previous studies related to freight network planning practices, freight route choice models, and network design solution algorithms. The model development begins in Chapter 3, describing the initial freight network design model. Chapter 4 goes provides details related to the modeling framework. In Chapter 5, a freight network design model is provided, along with a corresponding solution algorithm. These model concepts are developed further using a case study in Chapter 6. Chapter 7 provides relevant conclusions and a discussion of future related studies.

CHAPTER 2 LITERATURE REVIEW

This dissertation focuses on developing network design models for long haul freight movements. The review begins with an explanation of network design models and previous studies. Freight prediction models play an important role in realistic studies of freight movements. Hence, these studies are carefully examined as well.

2.1 NETWORK DESIGN MODELS

In this section, network design definitions and variations are examined. Comprehensive surveys on the network design problem were conducted by Magnanti and Wong (1984), Friesz (1985), and Yang and Bell (1998).

2.1.1 Definitions

Various network design models have been formulated for different purposes. Magnanti and Wong (1984) formulates a general model for network design as follows:

$$\text{minimize } \phi(\mathrm{f}, \mathrm{y}) \tag{2.1}$$

subject to:

$$\sum_{j \in N} f_{ij}^{k} - \sum_{i \in N} f_{ji}^{k} = \begin{cases} R_k & \text{if} \quad i = O(k) \\ -R_k & \text{if} \quad i = D(k) \quad \text{all } k \in K \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

$$f_{ij} \equiv \sum_{k \in K} f_{ij}^{k} \le K_{ij} y_{ij} \quad \text{all} \quad (i,j) \in A \tag{2.3}$$

$$(f, y) \in S \tag{2.4}$$

$$f_{ij}^k \geq 0, \quad y_{ij} = 0 \ or \ 1 \quad all \ (i,j) \in A, k \in K \tag{2.5}$$

Where k denotes a commodity in the large set, K. For each k, R_k is the required amount of flow of commodity k to be shipped from point of origin, O(k), to point of destination, D(k). f_{ij}^k is the flow of commodity k on arc (i, j). A decision variable y_{ij} is equal to 1 if the improvement project is chosen as part of the network's design, or 0 otherwise. A is a set of all arcs in a study network. $y \equiv (y_{ij})$ and $f \equiv (f_{ij})$ are vectors of design and flow variables. Q_{ij} is the capacity of arc (i,j). The set S includes any side constraints imposed upon the network design.

The model minimizes $\phi(f, y)$ subject to a bundle of flow conservative constraints (2.2). Equation (2.3) is a capacity constraint. If an arc (i,j) is not chosen as a part of the network y_{ij} = 0 hence f_{ij} = 0. Network variations change with the objective function and side constraints. When the objective function $\phi(f, y)$ is linear, the model is a linear mixed integer program. A general form of the linear function is

$$\phi(f, y) = \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k f_{ij}^k + \sum_{(i,j) \in A} F_{ij} y_{ij} \tag{2.6}$$

Where c_{ij}^k is the per unit arc routing costs for commodity k and F_{ij} is the fixed arc design costs. If congestion effects are considered, a nonlinear version of the objective function can be used. The per unit arc routing costs can be replaced by the Bureau of Public Road formula $t_{ij}\left[1+\alpha_{ij}\left(f_{ij}/Q_{ij}\right)^{\beta_{ij}}\right]$ or the queuing formula $t_{ij}/\left(Q_{ij}-f_{ij}\right)$.

Magnanti and Wong (1984) also shows that this model is a generalized model for many transportation planning problems such as a minimum spanning tree problem, a shortest path problem, a traveling salesman and vehicle routing problem, a facility location problem, and our problem, which is a network design problem with traffic equilibrium.

For this problem type, the following equations are added as side constraints.

$$c_{ij}^{k}(f,y)+w_{i}^{k}-w_{j}^{k}\geq 0 \quad for\ all\ i,j,k \tag{2.7}$$

$$\left[c_{ij}^{k}(f,y)+w_{i}^{k}-w_{j}^{k}\right]f_{ij}^{k}=0 \quad for\ all\ i,j,k \tag{2.8}$$

$$w_{o(k)}^{k}\equiv 0 \quad for\ all\ k \tag{2.9}$$

and the budget constraints - $\sum_{(i,j)\in A} e_{ij}y_{ij}\leq B$ (2.10)

where e_{ij} is the cost when arc (i, j) is chosen and B is a budget. Magnanti and Wong (1984) provides a connection between these equations and user equilibrium conditions. Consider Equation (2.7), let P_k be any path connecting the origin O(k) and destination D(k) of commodity k. If we sum Equation (2.7) for all arcs (i,j) that are part of path P_k, we get

$$\sum_{(i,j)\in P_k} c_{ij}^k(f,y) - w_{D(k)}^k \geq 0 \tag{2.11}$$

Considering Equation (2.8) and in a case in which $f_{ij}^k > 0$, we can write (2.11) as

$$\sum_{(i,j)\in P_k} c_{ij}^k(f,y) = w_{D(k)}^k \;\; if \;\; f_{ij}^k > 0 \quad for\ all\ (i,j) \in P_k \tag{2.12}$$

It can be interpreted that $w_{D(k)}^k$ is the shortest distance between O(k) and D(k) hence Equation (2.12) becomes Wardrop's user equilibrium Wardrop (1952). Consequently, adding Equations (2.7) to (2.9) as side constraints yields an equilibrium network design problem.

Although Magnanti and Wong (1984)introduces the equilibrium network design problem in a single level optimization, it can be viewed as a bi-level problem. Not only does the bi-level form of the problem clearly explain the model's behaviors, it also inspires many solution algorithms. Friesz (1985) and Yang and Bell (1998) survey the network design studies focusing on the equilibrium network design. Yang and Bell (1998)presents an interesting generic framework for network design models.

The transportation system is assumed to have a simple structure with three components which are economic activity (E), transportation systems capacity (Q), and traffic flow (F) under a management system (M). The performance function or the level of service (L) of the system then can be written as

$$L = P(Q, F, M, \alpha) \tag{2.13}$$

where α is a vector of the parameters characterizing the performance function. The capacity Q depends on the management system M and the levels of investment (I). Thus

$$Q = G(M,I) \tag{2.14}$$

Transportation demand generates traffic flows. Since the demand depends on an economic activity and the system performance. The traffic flows can be written as:

$$F = D(E,L,\beta) \tag{2.15}$$

where $\beta$is a vector of the parameters characterizing the demand function. When the level of service increases, the demand can be expected to increase. On the other hand, the level of service decreases with increasing demand. Hence the demand and the level of service will converge to a stable condition. Let the flow pattern $F*$ and the corresponding level of service $L*$ occur at this equilibrium condition. Both F* and L* satisfy both the demand and performance functions. Therefore the set of equilibrium points between supply and demand for transportation is combining (2.13) to (2.15) for a fixed activity:

$$[F*,L*] = Z(E,M,I,\alpha,\beta) \tag{2.16}$$

A network design problem is interested in finding the investment that minimizes the social costs when the economic activity E and the system management M are given. The problem can be expressed by a bi-level programming model, also known as a leader-follower game as:

$$\underset{u}{\text{minimize}}\, F(u, v(u)) \tag{2.17}$$

$$\textit{subject to } G(u, v(u)) < 0 \tag{2.18}$$

where v(u) is implicitly defined by

$$\underset{v}{\text{minimize}}\, f(u, v) \tag{2.19}$$

$$\textit{subject to } g(u, v) < 0 \tag{2.20}$$

In this model, the upper level represents transportation agencies which have an objective to minimize social costs F subject to constraints G. The upper level, however, responds to traffic conditions determined by the lower level. The lower level represents network users with an objective function f subject to constraints g. This generic model has many variations related to objective functions and constraints as discussed in Magnanti and Wong (1984). More model variations for the equilibrium network design will be presented later.

In conclusion, the Network Design Problem (NDP) addresses how to construct a network that optimizes the objective efficiency criteria while considering limitations which can come from resource constraints or specific problem requirements.

Although there are many different network design studies, they can be classified into two main groups by their different primary goals. The first goal mainly belongs to the public sector which intends to improve transportation infrastructure for social benefits. Traffic movements and traffic problems that surround the infrastructure are the main concerns. In this network design problem, the network representation shows the physical characteristics of the infrastructure including the geographic locations and the capabilities of transportation links and facilities. The solutions are directly applied to this physical network. This physical network design is the focus of this dissertation.

In the other hand, the second goal belongs to the private sector companies which intend to use the infrastructure in order to fulfill their needs. These problems are vehicle routing problems or scheduling problems which can be represented by network schemes. The standard objective of the service network design problem is to minimize the total cost for a company. The network used in this problem is the complete graph transformed from the original physical network by connecting origins, destinations, and intermediate points (i.e. transfer centers or hubs) by the shortest paths (Toth and Vigo, 2002). The traffic congestion on links usually is not considered. The travel time used to compute the shortest paths is the average travel time. The service NDP is studied extensively in the package delivery industry such as aircraft fleeting and routing, Barnhart, et al. (1998), Kim, et al. (1999), and Armacost, et al. (2004) and truck routing, Powell and Sheffi (1989) and Lin and Chen (2004).

2.1.2 Discrete and continuous network design

There is a significant difference between the two generic network design models introduced in Magnanti and Wong (1984) and Yang and Bell (1998). While the first has discrete decision variables, the other has continuous ones. Therefore, network design problems can be classified by decision variables into two different types -- discrete NDP (DNDP) and the continuous NDP (CNDP). Each has its own advantages.

Discrete models are usually used to deal with the addition of new links, while the continuous models are usually used to deal with capacity expansion or improvements (Yang and Bell, 1998). Boyce and Janson (1980) suggests that the DNDP formulations are more appropriate for transportation networks since the improvement such as lane expansions cannot be done in fractional amounts. Abdullal and LeBlanc (1979) also points to the flexibility of the discrete formulation that can easily allow the change of mean free speed for the improved links. The major drawback of their discrete models is computational time. The paper compares the solution of network design problems using continuous formulations and discrete formulations. The results show that the continuous formulations yield equal or better solutions than the discrete one. Even though their results are now more than twenty five years old, and advancements in computational power have been enormous, their findings remain relevant because the scale of problems considered have continued to grow. Additionally, the level of improvement to the existing links can be determined by the continuous model. For the discrete formulation, these levels have to be predetermined.

The characteristics of the inter-regional transportation network suggest that the long haul freight NDP should be developed using a DNDP formulation. The first characteristic is that congestion is usually given less consideration over long distance travel such as the truck movements by interstate highways (Janson, et al., 1991, and Solanki, et al., 1998). Therefore, when a transportation link receives an improvement, it is more important to update the travel speed than the link capacity. The freedom to update the travel speed and other parameters are offered by DNDP while CNDP can update only the link capacity. Additionally, besides the BPR function which represents the effect of lane expansions, various network improvements do not have corresponding representative equations. CNDP requires these equations be known and therefore cannot be applied to our study. On the other hand, DNDP can vary subjective penalties representing the current conditions and those present after improvements.

The second characteristic is that investments are complicated with some conditional requirements. The model with conditional requirements can only be implemented using discrete variables. For example, the long term investments may require both temporal and spatial implementation specifications. An example of research on the multi-stages for interstate highway NDP is found in Janson, et al. (1991). In their work, the NDP is designed using the discrete variables for the choice of improvement which are represented both as Yes-No decisions and with implementation times. In this case, the nature of the discrete model simply allows for a change in the freeflow of improved links. More complicated staged investment is considered in Kuby, et al. (2001) which considers railway network design. In their study, heuristic backwards time sequencing is used to optimize the stages of the improvements. It should be noted that if opportunity cost is considered in long range network development, then these costs must be adjusted to a single time period.

2.1.3 Variations of network design problems

Following sections show variations of the bi-level network design model which depend on changes in upper or lower level models. Similar work has been done by Yang and Bell (1998). However, many recent studies have also been added to the field. Freight network design studies are reviewed at the end of this chapter.

2.1.4 Classic bi-Level network design problem

A typical network design problem focuses on passenger car movements and has the objective to minimize the total transportation cost for all road users. The traffic conditions are assumed to be user equilibrium conditions (i.e. user optimization) and the congestion on transport links has to be considered. For network design models with discrete choice variables, Boyce, et al. (1973) and Leblanc (1975) provide classic road network design problems formulated as bi-level models. For network design models with continuous decision variables, Abdullal and LeBlanc (1979) is the earliest work. Tobin and Friesz (1988) develops sensitivity analysis for the continuous network design problem.

2.1.5 Network design problem with demand elasticity

It is well known that network improvements can have immediate and lasting impacts on the demand for transportation services. Therefore demand should not be considered fixed. Instead the elasticity of demand should be painstakingly examined whenever a potential improvement is evaluated. Boyce and Janson (1980) combines trip distribution into the lower problem. The problem is formulated as a discrete NDP with the objective of minimizing total travel cost. The NDP is then constrained by the total budget and a doubly-constrained trip distribution represented by origins and destination entropy. Therefore, both link travel costs and the trip distribution are decision variables.

With the traffic assignment with elastic demand, the typical objective function to minimize total travel time is not suitable since a solution can achieve through minimizing travel demand and thus result in undesirable solutions involving less investment (Yang and Bell, 1998). A more appropriate upper level objective function should be maximizing consumer surplus. This measure is suggested by Kocur and Hendrickson (1982), Williams and Lam (1991), and Yang and Bell (1997) to evaluate the benefits of transport systems.

2.1.6 Maximizing reserve capacity network design

The traditional objective function of the NDP is to minimize the total travel costs or time. Other alternative system efficiency criteria can be adopted into the NDP. An original concept of reserve capacity is from timing design individual signal-controlled intersections (Allsop, 1972). Wong and Yang (1997) extends this concept to a bi-level programming that design traffic signal settings for maximization of the network reserve capacity. Yang and Bell (1998)suggests that this concept can be applied to the network design problem which allow a prediction of additional demand that can be accommodated by the road network after improvement.

Yang and Wang (2002) compares the NDP solution between travel time minimization and reserve capacity maximization. The reserve capacity indicates the maximum flow that the system can handle. In other word, reserve capacity is the system capacity. The CNDP is formulated. The reserve capacity is maximized by maximizing the multiplier that can be applied to a given O-D matrix. The multiplied volumes cannot exceed the capacity of links. The results show that there is a relationship between the solutions found based on these two competing objective functions. The solution under maximization of reserve capacity can be the same as the minimization of total travel cost when the level of congestion is low. The two objectives will conflict more as the level of congestion increases.

2.1.7 Equity network design

The equitable benefit distribution for network design provides another interesting objective. Improvement of the network can make the total system better. However travel between some O-D pairs may improve a lot while the others receive negative effects as congestion increases. Such changes, though often representing overall improvements, are very hard to sell to the public. Meng and Yang (2000) raises this issue related to the NDP. The O-D travel cost ratios before and after the network improvement are considered. For the equity of the road users, the travel cost ratios should fall between acceptable ranges. These minimum and maximum ratios of improvement are obtained by solving two bi-level programming problems.

2.1.8 Network design with multiple objective functions

Multiple objectives can also be considered in network design. The weighting method can be used to generate the Pareto optimal set. Yang and Wang (2002) uses a combined objective function that weighs both the important of reserve capacity and of total travel cost. Friesz, et al. (1993) formulates a single level mathematical program to solve the multi-objective problem under equilibrium conditions. The objectives are minimizing total user transport costs, total construction costs, and total vehicle miles traveled. However, this approach is still different from multi-objective optimization problems which explicitly consider multiple objectives.

Yang and Bell (1998)reports that the multi-objective equilibrium network design problem was first put forward by Friesz (1981) and Friesz and Harker (1983) with many other studies later including Current and Min (1986), Friesz, et al. (1993) and Tzeng and Tsaur (1997). They conclude that most network design problems have three different objective functions which are total user transport costs, total construction costs, and total vehicle miles traveled which could be considered as a surrogate for air pollution.

Recently, Chen, et al. (2003) develops a simulation-based multi-objective genetic algorithm for the Build-Operate-Transfer (BOT) case. In this case, the upper level program consists of two problems which are the profit maximization problem and the welfare maximization problem. Their work considers the uncertainty of travel demand forecasting. The travel demand is simulated based on the probability distributions. The Pareto optimal conditions of both objectives are desired at the end of the simulation.

2.1.9 Dynamic assignment and SUE assignment

A new traffic assignment approach of the lower level model can lead to more realistic route choice behaviors. Friesz (1985) suggests improvements on NDP by implementing stochastic user equilibrium assignment or dynamic assignment with the network design problems. However, Friesz comments that combining the dynamic traffic assignment with NDP is hard since this assignment problem is intractable. He suggests using dynamic adjustment mechanisms such as those used by Horowitz (1984) and Smith (1984)to study network equilibrium stability.

There are two perspectives related to the SUE assignment. The first perspective is that the perception of network costs vary from user to user -- therefore the costs are random variables distributed among user population (Daganzo and Sheffi, 1977). The other perspective is that the network itself is stochastic which means that some or all arcs are not deterministic and are random variables (Mirchandani and Soroush, 1987).

Chen and Alfa (1991) and Davis (1994) formulated their network design problem with discrete and continuous variables respectively with a logit-based SUE assignment. Yang and Bell (1998) comments that the NDPs can lead to over-investments to some routes since the logit-based SUE model will generally overestimate traffic flow on overlapping routes due to the famous property of independence of irrelevant alternatives (IIA).

2.1.10 Network design problems for other transportation modes

Kuby, et al. (2001) studies the rail NDP. Rail is one of the important modes in the intermodal system however, that study does not consider transfer points between modes. The model is a system-optimizing, capacitated, static, fixed charge mixed integer program with budget constraints. It represents economies of scale indirectly through functions and integer variables. Multi-stage developments are considered. The World Bank and the Chinese Minister of Railways funded the study to improve a spatial decision support system for railway investment planning in China.

Konings (2003) studies network design for an intermodal barge network. The study focuses on the selection of vessel size and improvement of vessel circulation time. The relationships of vessel sizes, transport volumes, transport frequencies, and cycle time are used to suggest the change of the network. There is no optimization in this study. The study also does not consider intermodal transfer points.

The concept to develop this freight network design model is introduced by Apivatanagul and Regan (2007). That paper considers issues related to the development of the freight network design model and emphasizes the importance of developing a model which can integrate multiple local networks together. An example is shown to draw the attention to designing a network for larger broader social benefits rather than focusing on local network improvements.

An early study that discusses combining a freight network equilibrium model with the network design problem is Friesz (1985). This idea is developed further by Apivatanagul and Regan (2008). That paper develops a freight network design model focusing on the modification of the lower level model which represents the freight route choice behavior. The shipper-carrier freight prediction model of Friesz, et al. (1986) is applied to the network design problem. Additionally, the model assumes that links which are overused are unreliable and will be avoided by the users. Therefore, capacity constraints are considered when the traffic volumes are assigned to the network. These constraints make the network design more sensitive to the improvement projects. A branch and bound algorithm is applied to an example which shows that the proposed network design model can identify the bottleneck problem and give a better solution compared to considering projects individually or sequentially.

2.2 SOLUTION ALGORITHMS

General network design problems are known to be NP-complete (Johnson, et al.,1978) which means there is no known algorithm to solve problems efficiently to optimality. Additionally, the objective functions of the DNDP are non-convex and usually non-linear. Optimal solution algorithms have been developed work for small networks. For large networks with complicated constraints, heuristic algorithms are used to find near optimal solutions.

2.2.1 Branch and bound algorithms

Branch and bound algorithms work by constructing a search tree and calculating lower bounds to cut (also known as pruning or fathoming) nodes that cannot contain the optimal solution. At the first node we assume that all candidate links could be included or excluded from the final network. The first node has the shallowest depth. At the deeper nodes, more candidate links are selected or rejected. The lower bound is used to fathom nodes that cannot produce a better solution compared with a current best (incumbent) solution.

Boyce, et al. (1973) and Hoang (1973) study the simplest case of network design problems. Their problem focuses on building a network which results in total shortest paths from all origins to all destinations. The problem is constrained by the total link length that can be added to the network. An implicit enumeration procedure using branch and bound is used to solve the problem. The algorithms from both papers are similar, as is that seen in Ridley (1968). Scott (1967) also solves the same problem but uses a branch and exclude method which uses a different lower bound.

At each node, Boyce’s lower bound is estimated assuming that unselected candidate links will be included in the final network before calculating the network design objective function. Tighter lower bounds are proposed by Hoang (1973) by adding the quantity that denotes the increment to the shortest route cost from node i to node j when link (i, j) is deleted from the network. However, it is reported that the bound will be weak when many links have been deleted by the algorithm. Hoang also notes that the algorithm still suffers from computational times which increase exponentially with the size of problems. Since Hoang's algorithm selects the node that has the minimum lower bound to examine first, the least lower bound of unexplored nodes will increase monotonically. Hoang uses this fact to short cut the branch and bound algorithm by comparing the lower bound with the current solution (upper bound). When the gap between these bound is small enough, the algorithm can be stopped. Dionne and Florian (1979) proposes several improvements such as a specialized algorithm to calculate shortest paths when a single arc has been deleted from the network.

The network design problem is more difficult for congested networks with nonlinear link cost functions. Several earlier researchers study highway network design for passenger movements in which the cost functions are usually assumed to be strictly increasing convex functions. Leblanc (1975) uses a branch-and-bound algorithm to solve small problems optimally. The lower bound is calculated similar to Boyce, et al. (1973). The pitfall of the algorithm is the existence of Braess' Paradox which implies that the selected network improvements do not always result in an improvement in the objective function. In order to avoid this pitfall, the traffic volumes are assigned using system optimal routing instead of user equilibrium routing. This method develops a loose lower bound.

Several papers are devoted to develop tighter lower bounds or heuristics in order to deal with larger networks. Poorzahedy and Turnquist (1982) modifies the network design problem by replacing the objective function with Beckman's Formulation. The replacement gets rid of the Braess' Paradox problem. The paper provides arguments as to why the modified problem can be used as an approximation for the original problem.

Magnanti and Wong (1984) reviews several other types of optimal procedures and heuristics developed to solve the DNDP including the branch and bound algorithm. The differences in optimal procedures related to the method used to obtain the lower bound are discussed. The heuristics commonly used to accelerate the algorithm are adding, deleting, and interchanging procedures. However at that time only medium sized problems (150 arcs, 50 nodes)can be solved optimally.

2.2.2 Bender's decomposition

Bender's decomposition is a solution algorithm for mixed integer programming (Benders, 1962). The basic idea is to partition the main problem into two subproblems which usually are a linear optimization problem and an integer one. An iterative procedure between the problems is implemented. Bender's decomposition receives computational time benefits when both subproblems are easier to solve.

Magnanti and Wong (1984) explains its application for the network design problem. It proceeds iteratively by choosing a tentative network configuration by setting values for the integer decision variables, solving for the optimal routing on this network, and using the solution to the routing problem to redefine the network configuration. The approach can apply to the scheduling problem (Florian, et al., 1976), airline network design (Magnanti, et al., 1983) and industrial system network design (Geoffrion and Graves, 1974).

Hoang (1982)studies an application of the network design problem with a user equilibrium assumption. His formulation is a mixed integer problem but only the link capacity expansion problem is considered. A generalized Bender's decomposition is applied to the problem. In order to partition the problem, its dual formulation is written. An iterative process is implemented between a master problem and the minimal convex cost multi-commodity flow problem. The master problem is a dual formulation of the network design which chooses the potential network configuration. The minimal cost flow problem uses the configuration to generate cutting planes used by the (relaxed) master problem. An algorithm by Nguyen (1974) is used to solve the minimal cost flow problem. The relaxed master problem is solved by a heuristic subgradient optimization method for the well-known knapsack problem (Shapiro ,1979).

2.2.3 The Iterative-Optimization-Assignment Algorithm

An intuitive approach to deal with a bi-level network design problem is an iterative (or feedback) process between the optimization programming model which configures tentative networks and the traffic assignment which predicts corresponding traffic movements. This heuristic approach is common for solving both the DNDP and CNDP. The sensitivity analysis approach is its variation.

For the CNDP, Yang and Bell (1998) discusses the three typical heuristic algorithm applied to most studies: the iterative-optimization-assignment algorithm; the link usage proportion-based algorithm; and the sensitivity analysis-based algorithm. The heuristic algorithm is appropriated to the CNDP which has the non-convex objective function making the problem hard to solve to optimality. These algorithms begin by configuring tentative capacity link improvements for study networks with fixed traffic volume. Then they adjust link capacities accordingly and calculate the corresponding traffic flow in each link. Influences from the capacity changes to traffic volumes are calculated. The traffic flows are adjusted by these influence factors before iterating to re-configure capacity improvements. The feedback process stops when consecutive solutions are sufficiently close.

The iterative-optimization-assignment algorithm is the simplest implementation. It was first proposed by Steenbrink (1974a,b)and is explored by Asakura and Sasaki (1990) andFriesz and Harker (1985) in solving the CNDP. The algorithm proceeds with an iterative process. Capacity configurations and their corresponding traffic volumes are provided in a feedback process to reconfigure the network without calculating influence factors. This approach does not necessarily converge. Rather, it represents a Cournot-Nash game in which each player attempts to maximize his/her objective values non-cooperatively, and assumes that his actions will have no effect on the actions of the other players (Fisk , 1984, and Friesz and Harker,1985).

2.2.4 The Link Usage Proportion-Based Algorithms

The link usage proportion-based algorithms are applied to solve bi-level transportation problems in which demands act as upper-level decision variables (Yang and Bell, 1998). In this algorithm, an influence factor for each link is a ratio between its usage and its capacity. In this case, the link that is used to its capacity or over is likely to receive an improvement. This algorithm is applied to ramp metering

(Yang, et al., 1994) and zone reserve capacity (Yang, et al., 1997), and O-D matrix estimation (Yang, et al., 1992 and Yang, 1995).

2.2.5 The Sensitivity Analysis-Based Algorithm

The sensitivity analysis-based algorithm is different by the others with its influence factor. The influence factor is the derivative of the reaction function with respect to the upper-level decision. In the case of CNDP, the upper decision is the capacity improvements and the reaction function is the relationship between the user equilibrium flow and the capacity changes. The approach is applied to the network design problem by Friesz, et al. (1990). It is a generalized approach which is further applied by many studies including optimal ramp metering in freeway networks (Yang, et al., 1994 and Yang and Yagar, 1994)), traffic signal control (Wong and Yang, 1997 and Yang and Yagar, 1995), optimal congestion pricing (Yang and Lam, 1996 and Yang and Bell, 1997).

Leblanc and Boyce (1986) formulates the DNDP with linear programming. The formulation supports piecewise linear equations which can be used to represent nonlinear equations. The user optimal behavior is assumed therefore the lower problem requiring the flows minimize the piecewise linear approximation to the integrals of the improved user-cost functions. The algorithm by Bard (1983) is proposed to solve the bi-level linear programming. In this algorithm, the objective function is defined as a convex combination of the upper and lower objective functions. The procedure then involves iteratively solving this new objective function with the same constraints (including conservation flow constraints and link capacity constraints). The paper also suggests an efficient solution procedure by solving the convex combination of non-linear increasing functions instead of linear one. The Frank-Wolfe algorithm is then applied to the approach.

Ben-Ayed, et al. (1992) implements network design problems to the Tunisian network using actual data. The case is focused on the inter-regional highway network of a developing country. Lane capacities can be increased by resurfacing road pavement which has low quality. The problem is formulated similarly to Leblanc and Boyce (1986), a piecewise linear optimization model but with continuous decision variables. Cost functions are developed by Tunisian data. The iterative-optimization-assignment algorithm is applied to solve the problem.

2.2.6 Meta-heuristic approaches

The artificial intelligent (AI) search algorithms have been implemented to solve the NDP problem. The simulated annealing approach is the first search algorithm applied to the CNDP (Friesz, et al., 1992). The algorithm has been developed to solve the NDP in case of multi-objectives by Friesz, et al. (1993) and the NDP with benefit distribution and equity by Meng and Yang (2000).

For the DNDP, genetic algorithms (GAs) have been utilized. Bielli, et al. (1998) uses the Cumulative GAs (CGAs), an improved version of general GAs, to solve the bus network design problem.

For the road network, simulation based GAs are used by Chen, et al. (2003). The simulation problem also included the stochastic of demand and multi-objective issues in the NDP. Drezner and Wesolowsky (2003) considers the NDP with facility location. The objective is to minimize total round trip cost from the origin to facility and back to origin. Four heuristics, a descent algorithm, simulated annealing, tabu search, and a GA., are used to solve the problem. The genetic algorithm performs the best in their computational experiments.

2.2.7 Heuristics for large network design problems

Janson, et al. (1991), Solanki, et al. (1998), and Kuby, et al. (2001) deal with national transportation networks which are very large systems. In order to manage such large networks, some techniques are need to simplify the problem in additional to the heuristics.

The techniques can be classified broadly into two types which are aggregation techniques and decomposition techniques. The aggregation techniques have two main approaches, network element abstraction and network element extraction. Abstraction reduces the network by appropriately aggregating an area or a corridor into a single node. The works that focus on this technique are Zipkin (1980) and Kuby, et al. (2001). However, the network topography is changed by the aggregation thus it is very hard to translate the actions from the aggregated network to the original one.

Extraction reduces the network by deleting redundant and insignificant links based on a specified criterion. Haghani and Daskin (1983) implements this approach for the

NDP which improves computational time significantly. In their algorithm, the links which have less traffic volume than a specific value will be excluded from consideration and the travel demand table is updated accordingly. Fewer links result in a faster traffic assignment algorithm. However, they report that the time needed to update the travel demand table may offset this benefit. It should be noted that the network aggregation has an important drawback related to the potential occurrence of Braess' Paradox. The deleting or grouping links in the aggregation process may increase in the network travel time. Furthermore, the optimal solution cannot be discovered for the original network (Zeng and Mouskos, 1997).

An alternative for larger networks is to use a decomposition method which moves from larger networks to smaller sub-networks. Solanki, et al. (1998) clusters the sub-networks in a hierarchical order and performs network design for each cluster separately. The smaller problems can be solved by a branch-and-bound strategy. Although the paper uses a fixed cost network, it can be adjusted to be applied to networks with nonlinear link costs.

2.3 FREIGHT FLOW PREDICTION MODELS

In most previous studies, the highway network design problem has been the focus and route choice behavior is limited to the passenger movements. In order to formulate the long haul freight network design problem, freight route choice behaviors have to be considered and the existing solution algorithms need to be adjusted accordingly. The freight flow prediction models are used to reflect the freight route choices on the transportation network. In order to select a proper model for the freight network design problem, it is crucial to understand the transportation system and economic agents who have important roles within it.

2.3.1 Economic agents in the freight transportation system

One of differences between freight and passenger movements is that the freight route choices are cooperative decisions made by multiple agents. Harker (1987) explains the relationship of these agents by Figure 2.1.

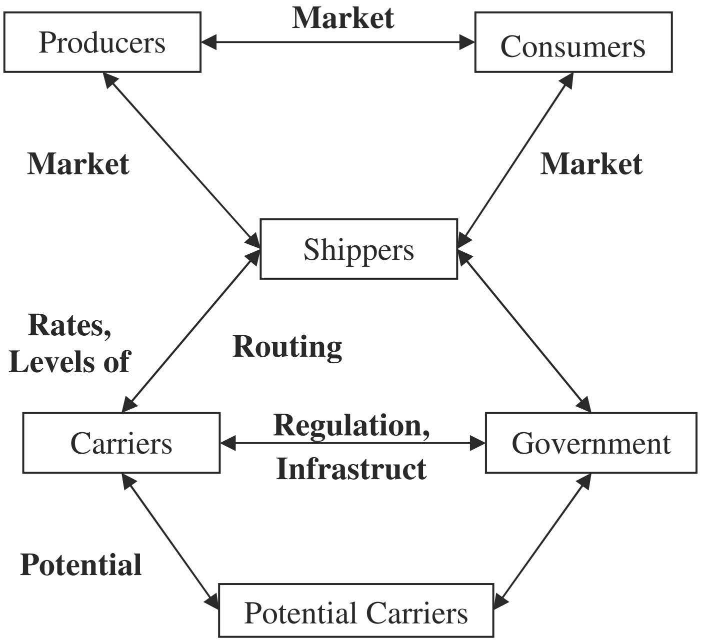


Figure 2.1 Relationship among agents Harker (1987)

The transportation demand is originated with the relationship between producers and consumers. Producers produce goods based on consumer demands which rely on the goods market price. Since these producers and consumers can locate in different regions, there are needs for transportation. The role to make the decisions on the generation of trips, the distribution of these trips, and the responsible firms which transport goods belongs to the shipper. The shippers are a conglomeration of various decision-making entities such as shipping departments of manufacturing firms, distribution departments, freight-forwarders, receiving departments of firm, etc.

The carriers transport the goods. They are selected by the shippers. The shippers decide to select which carriers based on rates, levels of service, and routing decisions. Their relationships can be viewed as one of consumers and producers of the transportation service. The government participates in the transportation systems through the provisions of infrastructure and the regulation which can effect the decisions of both the shippers and the carriers. The last economic agents are potential carriers who do not currently provide transportation services to the market but have the potential to do so when the market condition is changed.

2.3.2 Types of Freight Flow Prediction

All changes make by an economic agent in the transportation system can influence other agent's behaviors. However, these complicated behaviors cannot be captured by a single type of model. There are three general approaches used to predict freight flows (Harker, 1987).

2.3.2.1 Econometric models

The first one is the econometric model which uses time series and/or cross sectional data to estimate structural relationship between supply and demand for transportation services. The approach focuses only on the sipper-carrier-government relationship. It is very useful for studying the impact of various policies on the transportation market but it cannot detail the flows on transportation links. This model approach can be classified into supply side models and demand side models.

The supply side models focus on the issue of describing the production of freight transportation services. The intension of the model is not for prediction but to understand the production/cost characteristics of the industry such as questions of economies of scale and densities. Harker (1987) points out that the railroad industry has extensive studies on this approach (Klein, 1947, Meyer, et al., 1959, Borts, 1952 and 1960, Healy, 1961 and Healy, 1962). For a muli-product viewpoint that considers each origin-destination pair as a separate commodity, look at Jara-Diaz (1981) and Jara-Diaz (1982). In the trucking industry, early studies are pursued by Roberts (1956) and Nelson (1956). The long haul less-than-truck-load and truckload industries are studies by Friedlaender (1978) and Chow (1978).

The econometric demand side models attempt to explain the relationship of transportation demand, rate changes, and level of services. These models could be incorporated into predictive models of the freight system. The demand functions which consider economic agents as many aggregated entities are studied by Oum (1979) and Friedlaender and Spady (1981). The models assume that the producing firms are profit maximizers and that transportation is a factor in their production processes. Another demand function types consider firms' behaviors. It is early studies by Allen (1977) and leads to a logit demand formulation by Daughety (1979) and Levin (1981). The inventory-theoretic approach for the demand function is based on the perspective that the shippers make transportation decisions based on inventories. That work is studied by Chiang, et al. (1980), Roberts (1976), and Terziev (1976).Friedlaender (1969) and Friedlaender and Spady (1981) are the major works which integrate supply and demand based on an assumption of the equilibrium conditions.

2.3.2.2 The Spatial Price Equilibrium Model

The spatial price equilibrium model focuses instead on producers, consumers, and shippers. The carriers are defined within cost functions. The model uses a network model to describe relationships of producers, consumers, and the transportation systems. Each node represents a different region which can be either consumers, producers, or transshipment nodes. Demand functions are associated with each consumer node and supply functions are used with producer nodes. The concept of the equilibrium is that shippers barter between these regions until equilibrium is reached which means that there is no additional flow between each region due to commodities in the home regions are cheaper than other regions when considering transportation costs.

Harker (1987) examines major works on the spatial equilibrium model with freight studies. Early work uses a simple network which has a direct link accesses between each pair of a consumer and a producer. Takayama and Judge (1964) solves this problem by assuming linear supply and demand functions with constant transportation costs. Later this problem is formulated as a complementarity problem (Takayama and Judge, 1970 and Stoecker, 1974) with linear transportation cost functions. MacKinnon (1975) considers nonlinear functions for the problem. Florian and Los (1982) considers the problem on a network with transshipment nodes utilizing nonlinear functional forms but with path flow between the origins and destinations. A spatial equilibrium model which uses a general network, where a node can be an origin, destination and transshipment point is used, is studied by Tobin and Friesz (1983).

2.3.2.3 The freight network equilibrium model.

The freight network equilibrium is similar to passenger traffic assignment except that many agents are considered. This type of model is the focus of our work on network design problems since it uses the real network to predict freight flows and thus gives specific information for each link. This information is used to select the links that should receive improvements. The next section examines this type of model in more details.

2.3.3 The Freight Network Equilibrium Model

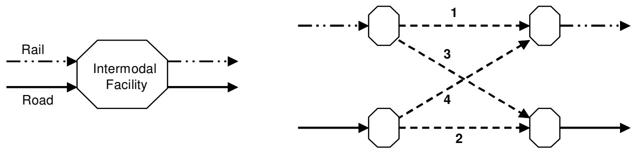
Harker (1987) summarizes three types of models that are generally used for freight studies and their weakness. Econometric models are good to study policy changes but ignore the details of the network technology. Spatial price equilibrium models focus on the consumer-producer relationship but lack the role of the transportation firm. Finally freight network equilibrium models consider transportation networks in detail but do not consider the commodity markets (consumer-producer). Nevertheless, the freight network equilibrium is suitable for further developing it to network design problems since it can specify problem locations.

With an intention to develop a multimodal network design, it is important to consider that the selected model has to be able to predict the mode changes when the study network changes. This is more important for long haul freight movements which have various transportation modes including intermodal ones. Therefore, we will classify the freight network equilibrium model based on their methods to shift flows between different modes.

Ruesch (2001) classifies the modal shift studies into two groups, macro and micro. The macro studies focus on the supply side. The macro analysis is based on aggregated freight flows on a regional, national or international level. The matrix analysis and modal split approach are used to estimate modal potentials and their flows. The micro approach study the modal shift using the decision making process on the company level. The key factors for the decision making process (cost, reliability, lead time, etc.) have to be known. The analysis of the potential modal shifts from macro and micro approaches can be used to provide to identify the development of intermodal transport services and the barriers to prevent using of intermodal transport. Freight prediction flow models can identify attractive modal shift potentials in several ways.

2.3.3.1 Modal shifting by an integrated network

The integrated networks combine transportation networks of all modes together and link them with transfer points or intermodal facilities. There are two network configurations which distinguish the integrated network from the unimodal network. The first is that parallel links are allowed in the network to represent different mode choices for two adjacent nodes. The other is the shipments can transferred between modes at transfer points. The transfer points are special combination of nodes and links. **Figure 2.2**shows the transfer points (Guelat, et al. ,1990 and Park and Regan, 2005).



(a) Physical network (b) Expanded network

Figure 2.2 Representation of intermodal transfer movements

The integrated network is beneficial to examine intermodal transportation potential. An intermodal freight model is studied by Guelat, et al. (1990). In this study, freight demand is exogenous. The inter-regional network is studied and assumed no link congestion (i.e. no capacity limit in each link). However, the average travel cost in each link is dependent on the transported volume in the link. An assumption is made that goods are shipped at minimum total generalized cost. The transported volume can change to another mode only at transfer points with some transfer costs. The assignment is obtained by a Frank-Wolf algorithm with an embedded shortest path algorithm with transfers. The algorithm is an adaptation of Dijkstra's label setting algorithm but it provides the option to change modes. The study reports the successful use of this model for application in the Brazilian transportation network modeling, the strategic analysis of a corridor development is performed for Brazil, as is an analysis of the import and national distribution system of coal in a Scandinavian country.

2.3.3.2 Modal shifting with preferences

Southworth and Peterson (2000) develops the intermodal and international freight network modeling. In this study, the transport volume and the mode sequences are provided by Commodity Flow Survey (CFS). The distinguishing point of this model is that it provides the information of routing based on a door-to-door basis. The model assigns the logical routes and completes the mode sequences if they are incomplete. The model assumes that the freight will be transported by the shortest paths. However, the carrier-shipper is allowed different preferences for the different modes. These differences are represented by relative modal impedance factors. For example, the Railroad impedance is 1:3.5 which means that one would feel indifferent between a path that travels 3.5 miles railroad and one that travels one mile on a highway. The assigned volume is represented graphically by a Geographical Information System (GIS) which provides valuable information and easy access for transportation planning.

2.3.3.3 Modal shifting with different players

As the previous discussion, the shipper is the economic agent who has the priority to decide transportation modes. Two previous approaches assume that the shipper and the carrier work together toward the same goal to reduce travel costs. However, the shipper and the carrier models can be considered separately. Two distinctive earliest models based on the freight network equilibrium referred by Harker (1987) are Roberts (1966) focuses on the shipper with constant unit costs and Peterson and Fullerton (1975) focuses on the carrier and nonlinear unit costs with a user equilibrium assumption.

The first model that considers multiple agents is Friesz (1981). That model is explained later in Friesz, et al. (1986) which applies the model to the U.S. rail network. The model considers both shippers and carriers explicitly by sequentially loading travel demand onto the transportation service network and then loading this service demand onto the physical transportation network. In order to improve the interaction between shippers and carriers, Friesz, et al. (1985) improves the model and loads both networks simultaneously. Harker and Friesz (1986b) and Harker and Friesz (1986a) introduce the consumer and the producer onto the freight network equilibrium by combining it with a spatial price equilibrium model. In his model, the freight flow is impacted by both travel costs and the commodity prices in each region. In return, the commodity prices are varied by demand and supply for the commodities. Recently, Fernandez, et al. (2003) develops a new modeling approach to a simultaneous shipper-carrier model with more advance trip distribution and mode choice formulations.

CHAPTER 3 FREIGHT NETWORK DESIGN MODELING CONCEPTS

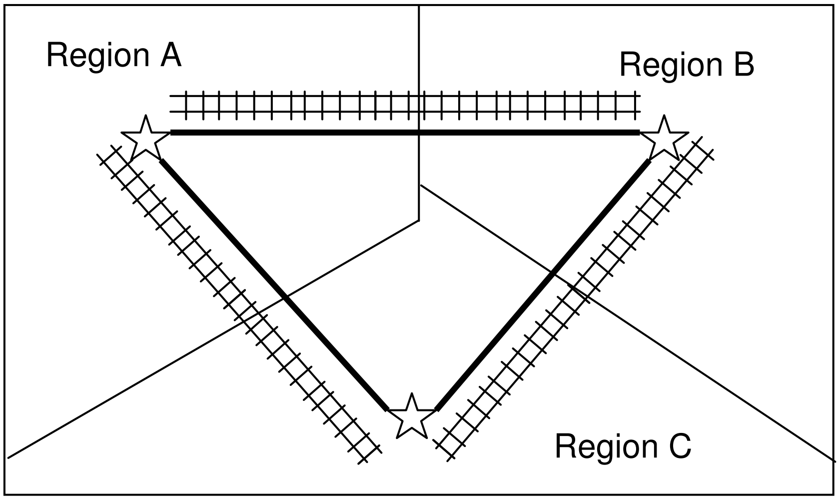
In this chapter, freight network design modeling concepts are discussed. These models pay attention to a wider and more general perspective than those discussed later which focus mainly on the network design problem for long-haul freight movements. Instead, this chapter discusses the general modeling concepts and solution algorithms for both an urban network which has high accessibility and an interstate network which in contrast has low accessibility but has high mobility.

The bi-level solution algorithm is a concentrated area of the dissertation which is explained in this chapter. Furthermore, the criteria used to measure the efficiency of the system, traditionally minimizing total travel cost, is broadened in order to embrace a wider variety of measures and points of view. For example maximal use of the reserve capacity of the network could be such a broader measure. A network design model which can account for all of these needs should be developed.

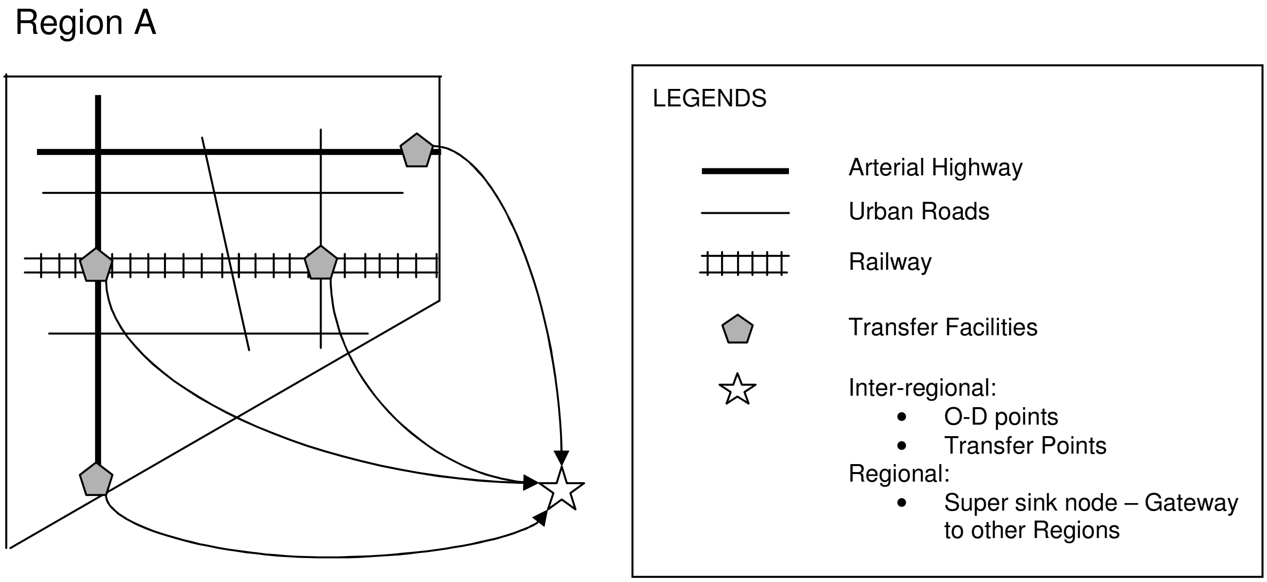
Transportation improvement alternatives must be considered simultaneously in order to develop the most efficient network. Optimization models should be developed and adopted in order to find the best solutions and in order to capture the substitution effects and complementarities of and integrated intermodal transport network. This chapter is a starting point to understand the following chapters and to expand the future work into the proper direction.

3.1 LEVELS OF TRANSPORTATION NETWORKS

An intermodal network can be classified into two levels: the urban/regional level and the inter-state or inter-regional level. The regional network design focuses on the improvement of a local network which handles short haul transportation. Short haul movements are transferred to the long haul system at transfer centers which are the gateways to other regions. The inter-regional network design focuses on the improvement of major highway and other transportation modes (e.g. rails, barges) which handle long haul transportation. The long haul demand obtained from the regional network design problem is the input to the inter-regional network design problem. The regional network has a significant role in deciding which transportation mode will be chosen because it represents an origin and destination in the aggregated inter-regional network. Consequently, the network improvement decisions at the regional level can affect the decisions at the inter-regional level. Figure 3.1 illustrates the relationship between the regional and inter-regional networks.



(a) Inter-Regional Freight Network



(b) Region/Urban Freight Network and Super Sink – Gateway to other Regions

Figure 3.1 The Relationship between Inter-Regional and Regional Freight Network

3.2 The Bi-Level Approach Concept

Bi-level programming is the traditional way to solve network design problems which deal with the two entities that have different objectives for the transportation network. The models are classified into two levels an upper level problem and a lower level problem. The upper problem, representing transport agencies, has the objective to optimize the system efficiency. The network users have the objective to optimize their own benefit therefore the network condition will converge to a user equilibrium. The lower problem manages to assign the freight flow based on the route choice behaviors such as a user equilibrium assumption. The bi-level network design model can be written in summary as follows:

Upper Level Problem (ULP)

Given: The freight flow in the network (from LLP)

Objective: Optimize the system efficiency by selecting appropriate projects

Subject to: Transportation Agency Constraints

Lower Level Problem (LLP)

Given: The network design (from ULP)

Objective: Minimize generalized costs for each individual

Subject to: Flow Conservation and Freight Route Choice Constraints

This bi-level network design framework can be adapted for different case studies. In the upper level, the transportation agency behaviors are adjusted through the system efficient criteria and additional constraints. The assumptions of freight route choice behaviors are modified though the lower level objective functions and freight route choice constraints which directly control the traffic volume in the study network. For passenger movement network design problems with dealing with urban networks, the measurement of system efficiency is minimizing the system total travel time with a total budget constraint. The lower level represents the passenger route choice behavior which is a user equilibrium assumption based on travel time. For the freight network design, the objective functions and constraints should be broadened.

3.2.1 System efficient criteria

The upper level problem objective function represents what the transportation agencies would like to achieve. The system efficient criterion is a mathematical equation to measure this achievement. For urban passenger networks, the total travel time is used as the measurement and its minimization equals to the least possible congestion based on the given project improvements. For more elaborate measurement, the total generalized costs which are the summation of all opportunity costs in monetary values can be used.

A different measurement from the generalized costs is the maximization of the network flow volume. In this case, the best project combination results in a network that maximizes reserved capacity. The reserved capacity is measured by the maximum total flows that a network can handle. Park and Regan (2005) proposes a bi-level model to measure this value and it is written as follows:

Upper Level Problem (ULP)

Given: Residual network (Capacity of a link is reserve capacity and is equal to the difference between link capacity and assign flow on the link) (from LLP)

Objective: Optimize the system for maximum network flow

Subject to: Capacity limit for each link, and optionally Resource limit, level of service requirement, etc.

Lower Level Problem (LLP)

Given: Maximum permitted O-D demand (from ULP)

Objective: Minimize individual user cost for each origin and destination (UE)

Subject to: Flow Conservation

Yang and Wang (2002) applies a similar concept by formulating a network design that maximizes the extent to which a network can be expanded. Their model will be shown in the following section. Nevertheless, it should be noted that the reserve capacity idea can be used to predetermine a set of candidate links, in addition to a set of candidate links based on levels of congestion.

In a similar manner as the urban passenger network, the efficiency criteria of a freight network design should answer the needs of the transportation agencies toward the freight network. The urban passenger network measurements can be directly applied, however, a special measurement should be provided if the agencies have specific intentions for the freight network improvements. An example of a specific intention is a smoothness of freight flows which creates reliable schedules and consequently enhances service qualities. Although the transportation networks of freight and passenger movements are indistinguishable, thus requiring simultaneous analysis, freight network design focuses on certain areas or links that significantly interrupt the movements such as ports and accessibility to warehouses and major cities. The total penalty cost from unserved demand for these critical points is a meaningful measurement for the freight network design problem.

The freedom to set the measurement is limited by the assumptions of the traffic assignment models performing in the lower level model. For example, network reliability is important. It would be nice to be able to apply a penalty cost to speed variations. However, this speed variation cannot be obtained from the static traffic assignment which is used in the lower level model.

3.2.2 Constraints

Constraints are mathematical formulations representing limitations on transportation agencies'abilities to select the improvement projects or on road users' abilities to decide their route choices. A general limitation for the transportation agency is the budget limitation and a general rule for the road users is a flow conservative rule.

The budget limitation is usually represented by a summation of total money available to spend on selected projects. This constraint is sufficient for passenger movement network design which focuses on the highway network and on a single transportation mode. The freight network has more complications resulting from its multimodal transportation perspective.

Although intermodal transportation is considered to have potential to improve the efficiency of freight movements, a network design model cannot be formulated to represent all possible benefits. A challenge is that congestion from the freight can only be realized when the model can collectively consider both the freight and passenger movements together, although the freight movements are a significant contribution to the congestion for most of the infrastructure. If the system efficient criteria is minimizing the total travel time, it is possible that improving an existing heavily congested highway will consume all resources, leaving none left to expand the intermodal system. An alternative to represent the need of the intermodal transportation improvements can be made by an assumption that the budgets will be allocated into two directions which are budget for general transport and budget for improving intermodal transport. The examples for projects which qualify as intermodal transport are mass transport improvements, expansions, and transfer facility enhancement. A concept of a budget series makes the network design model closer to the reality in which the budgets from different sources are specified for projects that fulfill certain requirements. It should be noted that the budget constraint formulation is very complicated in reality and is an interesting topic for the future research (Alan, et al. , 1981).

The transportation agencies currently pay high attention to the externalities that impact the areas surrounding transportation infrastructure. Air pollution is an urgent externality of concern to the transportation agencies. It limits the infrastructure expansion since these will attract more vehicles and thus pollution to the areas. Many emission models have been developed to forecast the amount of gas emitted from vehicles (e.g. MOBILE by the US Environmental Protection Agency; EMFAC by the California Air Resources Board). These regression models can be used to set a constraint based on the air pollution limitation based on enforced regulations.

This air pollution constraint can be set as a single equation or many equations in the same manner as the budget limit constraint. In the simplest case, a single air pollution constraint says that the sum of a particular pollutant emitted by all vehicles (in some geographic area, in some time period) must be less than an enforced limit. In the other words, the transportation agencies try to control the average pollution levels within a study area. However, a more accurate way to set the air pollution constraints is to write these for a limited sub-area or for a certain link. In this way, the constraints convey that the transportation agencies acknowledge that there are problematic transportation areas which have high externalities which can limit their ability to implement certain alternatives.

In the lower level model, constraints are used to control route choice behaviors. In the urban passenger network, the road user route choice is based on a user equilibrium assumption with mandatory flow conservation constraints. The well known Frank-Wolf algorithm can be employed in this step. In order to represent intermodal transportation which is common for freight movements, the shortest path algorithm used in the traffic assignment will have to consider the mode transfer. The shortest path algorithm with transfers developed by Guelat, et al. (1990) can perform this task.

Figure 3-2 illustrates the general framework for the bi-level network design model.

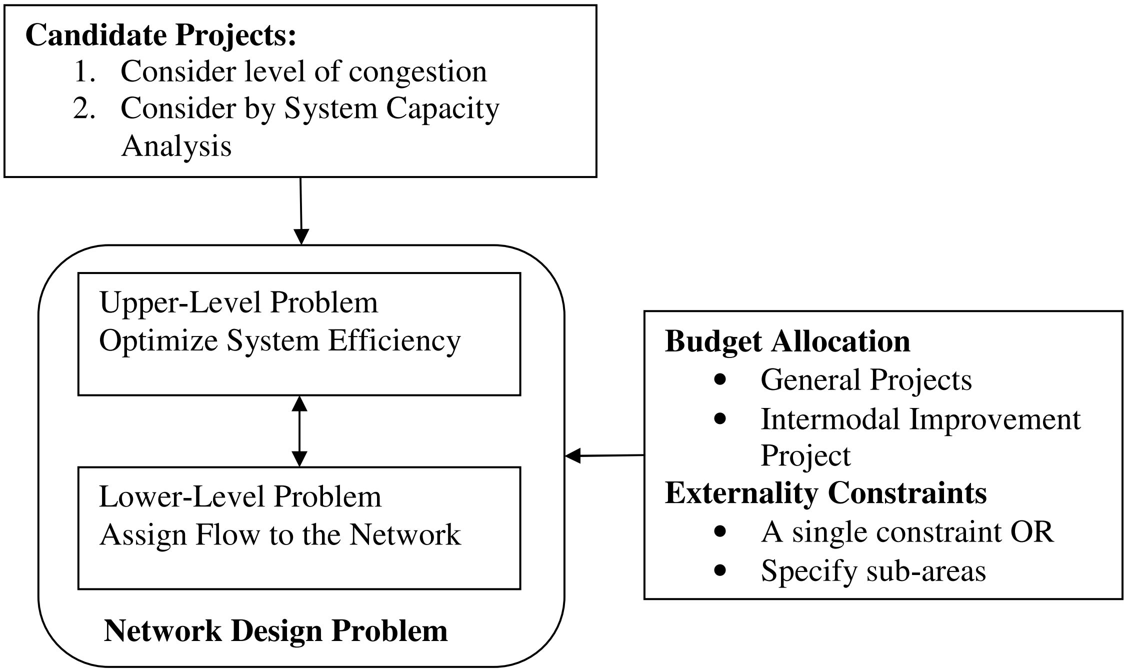


Figure 3.2 Framework of NDP models

3.3 FREIGHT NETWORK DESIGN FORMULATION

Following the bi-level approach concept, this section formulates the mathematical models for the freight network design problems for both regional and inter-regional levels. It has been previously mentioned that there is a feedback relationship between the regional and the inter-regional level. However, their different characteristics lead to different network design model formulations. This section will clarify the differences that have to be made for each level. The formulations are based on previous network design research that focuses on passenger movements. In later chapters, we focus on the long-haul freight movements only.

3.3.1 Regional network design problem

The regional level deals with urban or regional transportation networks and also local transportation networks near transfer facilities. The regional network has short freight movements, usually taken care by a single transportation mode and primarily by truck. Although this level mainly focuses on truck movements and congestion on local roads/streets and certain parts of highways, it can contribute important mode choice for long haul freight movements. For example, high congestion near the stations can dissuade shippers from using that mode.

In this dissertation, it is assumed that freight demand is exogenous and fixed. The regional level moves the freight demand out of its study region through a dummy super sink node as shown in Figure 3-1. On the other hand, the sink node gives the freight demand that originated out of the region.

In the urban area, link congestion is the main problem and the congestion is related to link capacities. A given network is represented by a graph G = (N, A) defined by a set of nodes, $n \in N$ and by a set of arcs, $a \in A$. The cost function uses the form of a BPR (Bureau of Public Roads) congestion function which is expressed in the following equation.

$$t_a(x_a) = t_a^0 \cdot \left[1 + \alpha \cdot (x_a / Q_a)^\beta\right] \tag{3.1}$$

where

$t_a(x_a)$ = travel time on link $a \in A$ as a function of link volume x_a,

t_a^0 = free-flow travel time on link a,

x_a = flow volume on link $a \in A$,

Q_a = practical capacity of existing link a,

α, β = coefficients in the polynomial delay function

Since congestion is the main problem for this network level, the transportation agencies direct the improvements to capacity expansion. Hence, the problem is formulated as continuous network design problem which can efficiently obtain the best budget allocation to spend on link capacity expansions. The BPR function can be adjusted to reflect the improvement if a link capacity is expanded. When the link is improved by u_a units, the travel time will be changed to:

$$t_a(x_a, u_a) = t_a^0 \cdot \left[1 + \alpha \cdot (x_a / (Q_a + u_a))^\beta\right] \tag{3.2}$$

If the system efficient measurement is solely based on the travel time, the traditional continuous network design which has the objective to minimize the total system delay can be written as (adapted from Yang and Bell, 1998):

Upper Level Problem (ULP)

$$\underset{\mathbf{u}}{minimize}\ Z_{ULP} = \sum_{a \in A} t_a(x_a, u_a) \cdot v_a(\mathbf{q}, \mathbf{u}) \tag{3.3}$$

subject to

$$\sum_{a \in A} g_a(u_a) \le B \tag{3.4}$$

$$0 \le \mathrm{u_a} \le u_a^{\max}, \quad a \in A \tag{3.5}$$

Lower Level Problem (LLP, Beckman's Formulation)

$$\underset{x_a}{minimize}\ Z_{LLP} = \sum_{a \in A} \int_0^{x_a} t_a(x, u_a) dx \tag{3.6}$$

subject to

$$\sum_{k \in K_{rs}} f_{p,k}^{rs} = q_p^{rs}, \quad \forall p \in P, \forall r, s \tag{3.7}$$

$$f_k^{rs} \ge 0, \qquad \forall k \in K_{rs}, \forall r, s \tag{3.8}$$

where

u_a = the continuous capacity increase of link *a*

$u_a^{\max}$ = the maximum continuous capacity that can be expanded for link *a*

$g_a(u_a)$ = the construction cost function for increasing capacity of link a by u_a unit

$v_a(\mathbf{q},\mathbf{u})$ = the flow on link *a* at UE condition given vector of demand from an origin, *r*, to a destination, *s*, $q_{rs} \in \mathbf{q}$, and vector of link improvements, $u_a \in \mathbf{u}$

$f_{p,k}^{rs}$ = path flow for O-D pair r-s for product $p \in P$ via route $k \in K$

B = budget allocation for network improvements

An Alternate upper-level system efficiency criteria, maximizing the reserve capacity, can be written as Yang and Wang (2002):

$$\underset{\mu,\mathbf{u}}{maximize}\,\mu \tag{3.9}$$

subject to

$$v_a(\mu\mathbf{d},\mathbf{u}) \le C_a(u_a), \quad a \in A \tag{3.10}$$

(3.4) and (3. 5)

An option for the formulation is a mixed integer network design problem. However, this formulation is difficult to solve and studies adopting this formulation are rare. Fortunately, the options for adding or expanding road segments in an urban area are limited. Therefore, all schemes can be enumerated by the discrete candidate projects. Each network scheme consists of the existing network and additional links. The continuous network design model can be used for each scheme to find the best solution.

Heuristic approaches have been developed to solve this problem. The three typical heuristics approach applied are: 1) The Iterative-Optimization-Assignment Algorithm; 2) The Link Usage Proportion-based Algorithm; and, 3) The Sensitivity Analysis-based Algorithm (Yang and Bell, 1998). Meta-heuristics such as genetic algorithms, tabu search or simulated annealing are also an option.

3.3.2 Inter-regional network design problem

The inter-regional network level deals with transportation links and facilities for long haul freight operations. The network links in this level will represent the high mobility transportation links such as highway and rail links. In addition, major transfer facilities including seaports, airports, and rail stations are also included in this level. The demand is assumed to be exogenous and fixed.

In the inter-regional network, congestion occurs only at specific points in the network such as the areas near cities and ports. However we assume that the transportation links connecting these areas are not congested. Therefore, there are no capacity limits for these links though the congestion at the specific points is represented. Link costs do depend on traffic volumes however. The travel time function may have the following form as in Guelat, et al. (1990):

$$\begin{aligned} t_a(x_a) &= \sum_i \alpha_i (\beta_i + x_a)^{z(i)} \\ &\alpha_i > 0, \beta_i > 0, \quad 0 \le z(i) < \infty \end{aligned} \tag{3.10}$$

At the inter-regional level, the network design model is formulated as a discrete network design problem with zero-one decision variables. A main reason to use the discrete network design model is that it can handle the freeflow speed change for the major improvement between each region on the transport link or operation speed in case of transfer facility. The continuous network design model cannot deal with changes in free flow speed.

Transportation agencies have many alternatives to improve the inter-regional network. New technologies can be employed to improve the network in addition to capacity expansion strategies. Improvements such as double-track or electric rail can increase the capacity and speed of the rail network. Additionally, reliability and speeds at transfer facilities can be improved by adoption of improved information systems. Discrete model variables have more flexibility to improve new technology than continuous ones. Another advantage of discrete variables is these can represent logical conditions necessary for considering specific improvements. For example, improvingrail speed may not be a benefit if the technology at transfer facilities is not compatible with the new main line technology. In this case, a discrete variable can be used with logical constraints to specify that both projects or neither of them must be implemented.

Given the graph network G = (N,A), the network consists of existing links and proposed links. Let $w_a$be a 0-1 variable representing the decision on link a. If w_a is equal to one, the link must exist or must be added is to the network. Assume that the proposed links are links $w_1...w_m$ and the existing links are links $w_{m+1}\dots w_M$. The difference between a discrete network design formulation and a continuous one is the upper level problem. The upper level of the discrete formulation can be written as follow:

$$\underset{\mathbf{w}}{minimize}\, Z_{ULP} = \sum_{a \in A} t_a(x_a) \cdot v_a(\mathbf{q}, \mathbf{w}) \tag{3.11}$$

$$\sum_{a=1}^{m} c_a \cdot w_a \leq B \tag{3.12}$$

$$\sum_{a \in I_n} x_a(\mathbf{f}) = \sum_{a \in O_n} x_a(\mathbf{f}), \qquad \forall n \in N - \{r, s\} \tag{3.13}$$

$$x_a \geq 0 \qquad\qquad \forall a \in A \tag{3.14}$$

$$x_a \leq M \cdot w_a \qquad\qquad a = 1...m \tag{3.15}$$

where

w_a = 1 if link a is exist or selected to improve and 0 otherwise,

c_a = the construction cost of link a,

f = the set of path flows $\mathbf{f} = \left(\cdots, f_k^{rs}, \cdots\right)$ satisfies the route choice decision given by the lower level problem

M = very large number

$I_n, O_n \subseteq A$ = the set of links entering and leaving node n, respectively

Given the network (set of w), the lower level of the discrete and continuous network design problem share the same formulation. If travel time is the only concern for transportation agencies, the objective function of the discrete network design problem is minimizing total delay of the network by selecting set of proposed links. (3.12), (3.13), and (3.14) are the budget constraints, flow conservation constraints, and non-negativity constraints, respectively. (3.15) specifies that if a proposed link is not constructed that link cannot be used, therefore, there is no flow on the link. As in previous discussion, the system efficiency measurements and constraints can be added to the model to broaden the transportation agency needs and requirements.

For example, alternative system efficiency criteria, maximizing reserve capacity, can be adapted from Park and Regan (2005). In an inter-regional model the flow may not be limit by link capacities but it can be limited by a level of service requirement. The travel time between each origin and destination is a measurement of level of service. Therefore, the upper level problem can be written as:

$$\underset{x,u}{maximize} \quad Z_{ULP} = \sum_{r \in R} \sum_{s \in S} q_{rs} \tag{3.16}$$

subject to

$$T_k^{rs} = \sum_{a \in A} \delta_{a,k}^{rs} \cdot t_a\left(x_a(\mathbf{f})\right) \leq \phi_p \cdot T_{rs}^{\max} \tag{3.17}$$

where

T_k^{rs} = travel time on path k for O-D pair r-s,

$T_k^{\max}$ = maximum allowable travel time for O-D pair r-s

ϕ_p = a commodity-specific parameter ranging from 0 to 1.

$\delta_{a,k}^{rs}$ = indicator variable, 1 if link a is on path k between O-D pair r-s, 0 otherwise

In this formulation, the objective function is to maximize the demand travels for each O-D by selecting the appropriate projects under budget constraint. The maximum travel time constraint is used to limit flow on each path so that the level of service is satisfied.

The branch and bound strategy is expected to be the solution algorithm for these formulations. However due to the complication of the problem and network size, meta-heuristics should also be considered as alternatives.

CHAPTER 4 INTEGRATED LONG-HAUL FREIGHT AND FEEDBACK PROCESS ALGORITHMS

In this chapter, the focus is the network design model for the inter-regional freight network. The network carries mainly long haul movements which transverse states or counties and is the focus of the state level transportation agencies. An earlier version of this chapter was published in Apivatanagul and Regan (2007). This paper is our first attempt to develop the freight network design model. It discusses the framework of a good freight network design model which has to provide fairness for all transportation modes and their project improvements. The model improvements are achieved through the proper setting of the system efficiency measures, a reasonable network representation, and accurate constraints. Some interesting future studies are introduced. A naïve feedback process is used to solve the network design problem. We discovered that this feedback method can be trapped in the infinite loop and can give only the local optimal solution. Therefore, we discuss an improved solution method in chapter 5.

4.1 SELECTING TRANSPORTATION ANALYSIS TOOLS

The bi-level network design problem can be viewed as the interaction model between the transportation agencies and the transportation network users. In terms of analysis tools, it can also be viewed as the interactive procedure between the budget optimization model and the transportation analysis model. Since the transportation analysis tool is responsible to reflect the changes occurring due to transportation improvements or strategies, it determines the typeof network design models used and the types of project improvements that can be recognized by the model. A micro-simulation model can recognize a change in traffic management strategy while the static traffic assignment acknowledges a change as an average travel time. The question is, what tool is needed for long haul freight network design since the different tool will lead to the different modeling framework.

Two important functions of transportation networks are mobility and accessibility -- functions which can contradict one another. The local network, which is represented by the regional level model as described in Chapter 3, focuses on accessibility while the inter-regional network focuses on mobility between cities. Therefore the larger transportation network can be considered as many connected networks which have different functions. An inter-regional network links local networks together thus has a high level of mobility in order to provide for long distance movements. Since the local networks contain the origins or destinations of the movements, they should support the inter-regional network by providing good access for long distance movements to enter the inter-regional network. As a result, an improvement selected in a local network is related to projects selected in inter-regional network and other local networks. A transportation network should be designed using an integrated network perspective.

It is unfortunate that there is no transportation analysis tool which can work well on these two different network levels. The traditional four step model is usually used to study transportation investments due to its practical advantages. The typical traffic assignment model is based on User Equilibrium (UE) assumptions with the Bureau of Public Roads (BPR) function which is proper for project investments in a large study area involving improvements on the highway systems. However, the approach does not properly capture subtle changes such as traffic operation improvements which are usually implemented on the local networks. Oh and Cortes (1999) applies the micro-simulation model, Paramics, to transportation planning. The model can capture traffic operations changes which cannot be considered by the UE traffic assignment model.

Although a tool such as microscopic traffic simulation provides a powerful method for capturing subtle changes in transportation systems, it is limited by network size. Such detailed models are impractical for large networks and additionally, transportation planning does not require great accuracy down to the vehicle-vehicle perspective. In conclusion, the traditional four step model cannot accurately capture improvement effects in local networks while attempts to implement detailed models using microscopic simulation for large area transportation planning are impractical.

A quick solution to overcome this problem is to improve the local network information in the traditional four step model (from now on will be called the transportation planning model) through centroid connectors. In a transportation planning model, an area (or zone) is integrated to be a centroid which stores demographic, economic, and sociological information. The local network is aggregated into centroid connectors. The way in which centroid connectors are constructed as representatives for each local network is very important, however, as is typically the case, the centroid costs and distances are assumed using conservative values or calibrated values without supporting data. Additionally, the improvement effects in local networks are usually neglected. Our framework is flexible enough so that if studies are performed related to improvements in local networks, the information can be used to estimate the proper centroid connector costs under both existing conditions and improved conditions.

In the next section, the bi-level network design problem for long haul freight movements is described. This bi-level framework is flexible enough that when the information of centroid connections is improved it can combine to the model easily. A numerical example is given to show the importance of the integrated network concept in the later section.

4.2 THE LONG HAUL FREIGHT NETWORK DESIGN MODEL

Our approach centers around a bi-level network optimization model. It iterates between the traffic assignment model which predicts route choices made by network users and the budget allocation model which represents decisions made by public agencies. The model intends to join these two decisions and consequently obtain the best network. The model is generally applied to highway network design which focuses on benefits to passenger movements. Variations of objective functions and solution algorithms have been proposed (Leblanc, 1975, Abdullal and LeBlanc, 1979, Friesz, et al., 1985, and Drezner and Wesolowsky, 2003).In order to apply a similar model to design a freight network the special characteristics of freight transportation must be well understood and each component on the traditional bi-level model has to be adjusted properly.

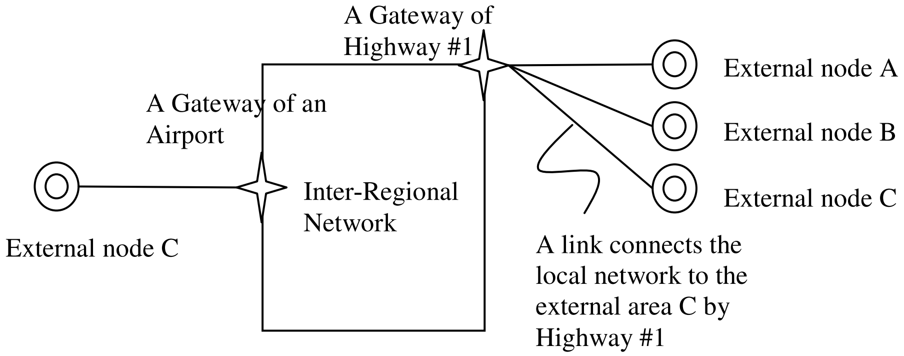
The longer trips typical of freight movements require the network design to consider both local networks and inter-regional networks simultaneously. In addition to multi-mode and multi-commodity characteristics, the nature of longer trips differentiates freight movements from passenger movements. Passenger trips are generally shorter and involve a single mode. These shorter trips simplify the bi-level model to a small simple network with few improvement alternatives. Longer trips travel on both local networks and regional networks. The multi-modal nature of freight transportation creates a situation in which the larger transportation network must be considered in order to maintain competitiveness among transport modes. The freight network representation has to be constructed properly to accommodate these characteristics.

4.2.1 The freight network representative

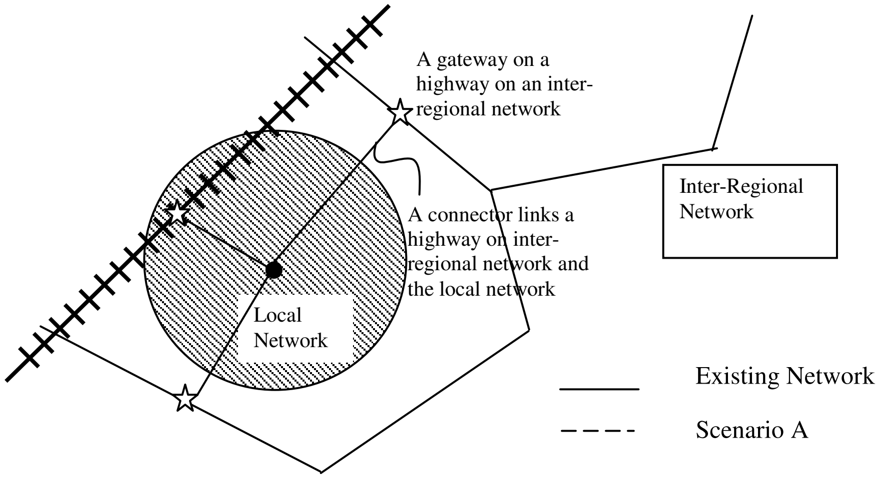
A good network representation should capture all necessary characteristics of the study while keeping the network as simple as possible. For this study, the freight network considers multiple modes. Therefore the network representation should maintain competition among transport modes.

In this study, a multi-modal inter-regional network connects the local networks. In order to simplify the problem, the inter-regional network consists of only two transportation networks, a highway network and a railroad network. The networks are connected at specific points by transfer links which allow movements between two modes. In order to complete long distance transport moves, the networks can connected to airports and seaports which are gateways to long distance trips.

In order to maintain competition between modes, movements are allowed to travel into and out of the study area. Some modes such as trains and trucks are competitive when considering longer distances in which demands can be located outside the study area. These movements are also transported through gateways. Figure 4.1(a) shows the inter-regional network, the gateways, the external nodes, and the external node connectors. The gateways can be the interception points of interstate highways and the study area boundary. They can also be intermodal transfer points such as airports, seaports, and train stations. A key issue is which external nodes should be included in the model and how to calculate the external node connector costs.



(a) External nodes for the movements out of the study Area



(b) Centroid connectors with 3 exits and 2 transportation modes

Figure 4.1 The freight network representative

External nodes are used to represent areas out of the study region which range from nearby movements to international trade transportation. Therefore, there are too many external nodes to include all of them in the regional network. In reality, the choices of external nodes are limited by the demand forecasting models which will choose the areas based on the interests of modelers. In general, the external areas usually are important business areas and some important transfer points such as airports and seaports. For less important business areas, the demand to a destination can be small and can be grouped to other nearby external areas. Greater distance separating areas usually means less travel demand and less importance between those areas. Nevertheless, the longer movements can have more competitive modes. In conclusion, the further distances should be represented by less external nodes but the longer external nodes will connect to more gateways (e.g. airports, train stations, highway etc.) because of the variety of mode choices. In Figure 4.1(a), the external node A is a nearby business area but the external node C represents a group of business areas locating far from the studying region. The long haul freight movements to C will have more alternative modes therefore the node connects to both the highway gateway and the airport gateway.

The external connector costs can be weighted average costs found using historical data for freight movements. The long haul links are uncongested so these costs can be assumed to be fixed. In the case in which there are transfer points on the paths, some penalties can be assumed. It may be important to consider cases in which the network outside the study area is changed and historical data cannot be used. In that case, it should be noted that only mega projects will have a significant impact on such a large network. Consequently, if such a project exists, it is likely to be well studied. The information from the study can be used to adjust the average costs from the historical data.

The freight network representation has to provide a way to study the integrated network consisting of local and inter-regional networks. These networks have different functions and need different analysis models. As has been discussed in the previous section, the transportation planning model is a crude method for capturing the improvement effects in the local networks since detailed traffic simulation models are impractical for large study areas. This study proposes to use data from the simulation models to estimate the centroid connector costs in order to capture the effects of local network traffic conditions.

Ademand origin or destination is represented by a centroid and a set of connectors. Connectors can connect a centroid to a regional network at various points using various modes as shown in Figure 4.1(b). Some penalty costs may apply to the connectors which link different modes. A local network that is a candidate for improvement should have additional information about the estimated connector costs before and after the improvements. The combinations of improvements are called improvement scenarios. Different scenarios result in different traffic conditions and estimated connector distances. Each scenario can be studied using a more detailed transportation model focused on the local area. The connector cost estimates are obtained using an appropriate statistical method which a subject of further research.

4.2.2 The Origin Destination Demand Matrix (OD matrix)

The travel demand usually tabulated by its origins and destinations which will be simply called Origin-Destination (OD) matrix. This OD matrix is crucial as an input to the network design model. In the freight network design, both a freight and passenger OD matrix are needed. Since truck transportation, a major mode for freight movements, shares the road network with passenger cars, a road improvement will affect route choices for both movements. In this study, the freight demand matrix is the focus.

The freight demand process is complicated and it has to pass through a disaggregation and aggregation process before the proper demand matrix for a study is ready. The general public data source is the Commodity Flow Survey Data maintained by the U.S. Department of Transportation and the U.S. Department of Commerce (USDOT and BTS ,2005). Another typical source is the commercial general commodity flow data known as the TRANSEARCH database, developed and maintained by Global Insight. The commodity flows are given on a ton basis. The flow origins and destinations are aggregated to the Bureau of Economic Analysis (BEA) level. Therefore the data requires a disaggregation process to use in study smaller areas (see for example Rowinski, et al. ,2007, Ambite, et al., 2002, and Gordon and Pan, 2001). The Benchmark Input-Output Accounts of the US is a primary source of data used for the disaggregated process and is maintained by Bureau of Economic Analysis. See for example the study of Monsere (2001). In CALTRAN and Booz Allen & Hamilton Inc. (2001), a survey with private sectors' activities is conducted to set rules to properly distribute commodities to the disaggregated areas. In order to consider the congestion trucks contribute to the road network, conversions are needed to convert commodity tons to vehicle units. Each commodity can have its conversion parameters.

The matrix dimensions for passenger and freight movements can be different. Passenger movements tend to be shorter and have different attractions than freight movements. For example, an airport can be a special attraction point that should be included in the passenger movement demand matrix. If an airport is included in the freight movement demand matrix, it means that some demand is fixed to travel to the airport therefore the mode shift possibility will be eliminated from that demand. Therefore, the airport should not be included in the freight matrix if we intend to study mode shifts.

4.2.3 Network Design Formulation

A bi-level network design approach is used as the based model for the freight network design study. A complication of transportation planning is that projects are selected by transportation agencies but the network is used by many users. Therefore, the model has to consist of two sub-models. The first model is to select the best set of project improvements and the other is the traffic assignment model used to forecast the corresponding movements on the network.

The model will focus on the improvement of the freight network at the inter-regional network level. Nevertheless, the model considers the supporting effects from the local network improvements through the selection of proposed scenarios from each zone. The freight network improvements vary widely. This is a reason to suggest using separated models or other studies to estimate how to adjust the link cost functions before and after improvements. In a transportation planning model, the BPR cost function is usually used to estimate link costs. Freeflow speeds and capacities are the main characteristics in the function which must be adjusted properly for the change from the existing conditions to the improved conditions. The Highway Capacity Manual (2000) can be a basis to adjust the capacities and freeflow speeds based on different traffic compositions and changes in highway geometries but other studies are needed to enhance the adjustment for other improvements. The following improvements are proposed for the regional network. These improvements are summarized from BTH and CalEPA (2005):

1. Construct truck lanes
2. Expand lanes in a highway
3. Construct climbing lanes
4. Construct interchanges
5. Reconstruct ramps
6. Reconstruct bridges
7. Construct grade separation
8. Intermodal facility improvements
9. Rail capacity improvements

It should be noted that there are other possible freight transportation improvement projects but these are implemented in local networks or at specific points. As mentioned earlier, these projects need different or special evaluation models. The important point is to transfer their results to the same modeling platform in order to evaluate them together thus resulting in a good integrated network and an effective budget allocation.

Using the bi-level network design concept illustrated in Figure 3.2, we will describe the upper and lower model for the long haul freight movements and its solution algorithm respectively.

4.2.3.1 Upper Level Model: The budget allocation model

The objective of budget allocation is to optimize social benefits while the traffic assignment is used to reflect the user route choices. The traffic volume obtained from the traffic assignment step can be used to adjust the penalty costs on each link before the budget allocation is implemented. For example, high truck traffic volume on a highway link can obstruct traffic flow on the link. This penalty may be calculated based on the Highway Capacity Manual (2000). Another example is that a transfer link that is over-capacity can lead to very high penalty costs. The binary integer programming will be used to model the budget allocation. Many algorithms are developed to solve integer programming problems such as branch and bound techniques, branch and cut techniques, and metaheuristics such as genetic algorithms or tabu search. An example of commercial software which provides functions to solve these problems is CPLEX. The model will select the improvement projects on the regional network and an improvement scenario for each zone. For freight network improvement, government agencies have three primary three objectives: reducing congestion, accidents, and environmental impacts. The common objective function for network improvement is minimizing congestion on the network which is closely related to pollution and accidents. An improvement that lessens congestion usually results in less accidents and pollution.

In order to develop a model to select proper projects for a freight network, many issues have to be considered. The first issue is that the mode shift benefit cannot be realized by the upper level model which is a supply side model. An improvement on a railroad network can redirect some commodity flows from a road network therefore it will reduce road congestion. The mode shift benefit can be captured by the lower level model after such a project is selected. Unfortunately, it is difficult to estimate this mode shift benefit and include it into the upper level model. Therefore a project that provides only mode a shift benefit will not be chosen. The second is that the traffic volume initiated by commodity flow is much less than the passenger movements. If two types of movements are considered together, a project that favors the passenger movements will always dominate freight improvement projects. It is crucial to separate the freight movements out of passenger ones in order to clearly detect the changes in freight movements. For example, consider the following upper level model:

Model 1:

$$\underset{X_i^j}{MIN} \sum_{\text{All links i}} \left[(\text{Traffic Volume})_i \times \sum_{\text{All alternatives j for link i}} \left(\text{Delay Travel Time}\right)_i^j \times X_i^j \right] \tag{4.1}$$

subject to

$$\sum_{\text{All links i}} \sum_{\text{All alternatives j for link i}} \left(\text{Capital Costs}\right)_i^j \times X_i^j \leq Budget \tag{4.2}$$

$$\sum_{\text{All alternatives j for link i}} X_i^j = 1 \qquad \textit{for } \text{All i} \tag{4.3}$$

$$X_i^j \text{ is a binary value} \qquad \textit{for } \text{All i and All j} \tag{4.4}$$

where

X_i^j is equal to 1 if the project j for link i is selected and equal to 0 otherwise

The objective function is to minimize congestion on the network. (4.2) is the budget constraint function and (4.3) specifies that only an improvement alternative is chosen for each link. The congestion is represented by delay travel time on the network links. The delay travel time is the difference between the time needed to travel the link at freeflow speed and the current speed. The objective seems to give a good freight network which has the minimum total delay (i.e. congestion). However, this model favors passenger movements and the improvements that focus on freight movements can be neglected.

In this study, the following model is suggested to reduce the bias issues between movement types. A good freight network design should reduce the freight transport costs while it is important that the design reduce the total traffic delay on the network. If both delay and freight transport costs have to be minimized, the optimization is the multi-objective function problem. In this study, the freight network is the focus, therefore the objective is set to minimize the freight generalized cost but the total traffic delay is controlled by a constraint. The upper level model in this study is set as follows:

Model 2:

$$\underset{X_i^j}{MIN} \sum_{\text{All Commodities m}} \sum_{\text{All links i}} \left[(\text{Freigh Volume})_{i,\text{m}} \times \sum_{\text{All alternatives j for link i}} (\textit{Generalized Costs})_{i,m}^{j} \times X_i^j \right]$$

(4.5)

subject to

$$\sum_{\text{All links i}} \left[(\text{Traffic Volume})_i \times \sum_{\text{All alternatives j for link i}} (\text{Delay Travel Time})_i^j \times X_i^j \right] \le MaxDelay$$

(4.6)

and (4.2), (4.3), (4.4)

In this setting, the freight improvement projects are selected to minimize the generalized costs while the projects that reduce traffic delay are selected to control the network total delay under the maximum value. All improvement projects may be selected by the model since a project will favor either freight movements or passenger movements which are provided separately by the objective function and the constraint (4.6).

The problem that the model will select only projects favor passenger movements is reduced by the separated functions as well as the fact that each function is focused on a single movement type

4.2.3.2 Lower level model: Traffic assignment

Many commodity types and passenger movements travel in the freight network. The freight network and the passenger movement network mostly overlap although the freight network includes additional facilities such as transfer facilities and intermodal facilities. An improvement for either network will affect route choice behaviors for both freight and passenger movements. Therefore, the lower level model should deal with both passenger and freight traffic assignment.

A practical method to assign commodity flows is to assign the passenger movements first to the network according to the User Equilibrium (UE) assumption. Then each commodity flow is assigned to the preloaded network by the shortest paths (Monsere , 2001 and CALTRAN and Booz Allen & Hamilton Inc., 2001). The passenger movements contribute most congestion on the network, therefore the passenger route choice should not change from the additional congestion contributed by truck traffic that will be loaded later.

The highway capacity can be obtained from the Highway Capacity Manual. The passenger car equivalent factors will be applied to the truck volumes before loading these onto the network. In order to include multi-mode alternatives, freight movements are allowed to transfer at some specific nodes. In this initial model, we assume that the congestion at transfer nodes is assigned fixed penalty costs which can vary by different commodity types.

The lower level model also has to care for the mode shifts that can happen due to future improvements. There are many approaches to split the commodity flows to different modes. An approach is to use the modal split models which assign each commodity modes using a fixed proportion. In order to study mode shift, a feed back value of travel cost is required. This approach is not efficient since an additional model is required in the iterative process (i.e. from bi to tri-level model) and the solution will likely not converge. Another approach is to assign the commodity flows using the minimum generalized cost paths given the transfer links between different networks (Monsere, 2001 and Maruyama, et al., 2001). Different commodities and different services can have a different value of time, safety, and reliability. These differences are represented by coefficients in the generalized cost functions. The generalized costs are a linear combination of those qualities and have $/ton as their units. The approach combines the modal split model and the traffic assignment together. This type of traffic assignment will be used in this study.

A suggestion to study possible mode shift is to use both approaches together. Although the combined approach between modal split – traffic assignment is convenient, it fails to reflect the existence of freight movements which remain inflexible to changing costs. In the same commodity type, there is a portion of travel demand which prefers to use the same mode. This portion has much higher penalty costs than the others which may result from inflexible schedules, freight volume, and other convenience factors for some individual shippers/carriers. A modal split model should be used to classify the fixed mode-portion before the combined traffic assignment approach is used. A feedback process for the modal split is not needed since only large changes in transportation costs can change the portion significantly. A similar concept has been implemented by CALTRAN and Booz Allen & Hamilton Inc. (2001) which uses some criteria to divide commodity flows which can be transported by an intermodal mode and those which cannot.

4.2.3.3 *Solution Algorithms*

The long haul freight network design model will be formulated using Model 2 mentioned previously as the upper level model. The lower level model is formulated by Beckman's Formulation. This means that our network design model will choose the combination of improvement projects to minimize travel costs of freight movements with a budget limit and with a traffic congestion limit for each link (4.6). Additionally, freight and passenger movements will be routed under the user equilibrium assumption. These upper and lower models will be put together as shown in Figure 4.2.

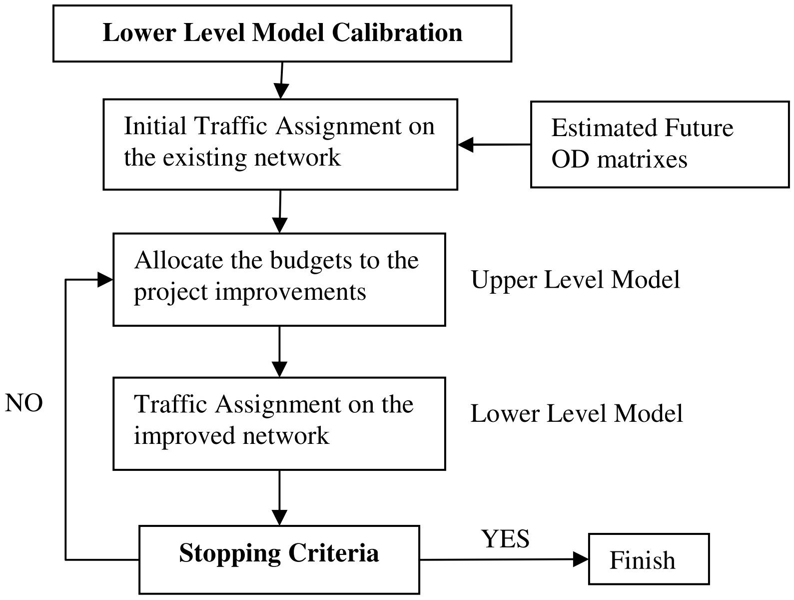


Figure 4.2 Diagram of the bi-level network design model

The solution algorithm is mainly a feedback process between the upper and lower level problem. CPLEX provides a Callable Library that allows the programmer to use CPLEX optimizers in applications written in C. This tool can be used to solve the upper level problem while the Frank-Wolfe algorithm will be used to solve the lower level model. The process will exchange information between recommended project improvements from the upper level model and the traffic condition that will really happen if the improvements are implemented by the lower level model.

Although the lower level model is opened to develop, in our model, the traffic assignment will load passenger movements and freight volumes separately as current practices. Generalized costs are used to capture transport costs which can be different for each commodity. By this practical traffic assignment, mode competitiveness is provided through the minimum generalized cost paths. The proper network modifications will allow freight volume to transfer between different modes.

A calibration for the lower level model is essential before the lower level model can be used in the feedback process. A calibration is used to reflect other factors that cannot be capture by the model. In this study, both passenger and freight movements are considered. The passenger movements can be calibrated by the existing traffic volume on important links. For the freight movements, the proportions of mode shares are used to calibrate the volume. The proportions differ by commodity types and travel distances. For example, trains are competitive to truck when the line haul is more than 500 miles for the low value commodities. There are many inputs that can be used to calibrate the model such as the link cost functions, external links connected between gateways and external nodes, and the generalized cost function for freight movements.

To initialize traffic volume on the freight network, all network link costs are set as if there is no improvement. The initial traffic volume is input into the upper level model to decide the proper projects. When the projects are selected, the network link costs are set properly and the corresponding traffic volume is obtained by the lower level model again

There are many stopping rules that can be used for this solution algorithm. Theoretically, the solution converges when two consecutive selected projects are the same. If there are many improvement projects in the network design problem, this condition may not be met. A solution is to track objective values until they have low standard deviation to a certain point and using some criteria to fix some projects that are frequently selected. If the process continues in this fashion, the model will finally give a solution.

4.3 A NUMERICAL EXAMPLE

In this section, a freight network design problem is presented. Our main purpose is to illustrate the proposed approach to study an integrated network which joins local networks together. The problem will show that the integrated network approach can provide a different perspective from which to select improvement projects on the network. A hypothetic problem with assumed values is developed for this purpose.

The problem consists of 3 local networks, cities A, B, and C which are connected by an inter-regional network shown in Figure 4.3.

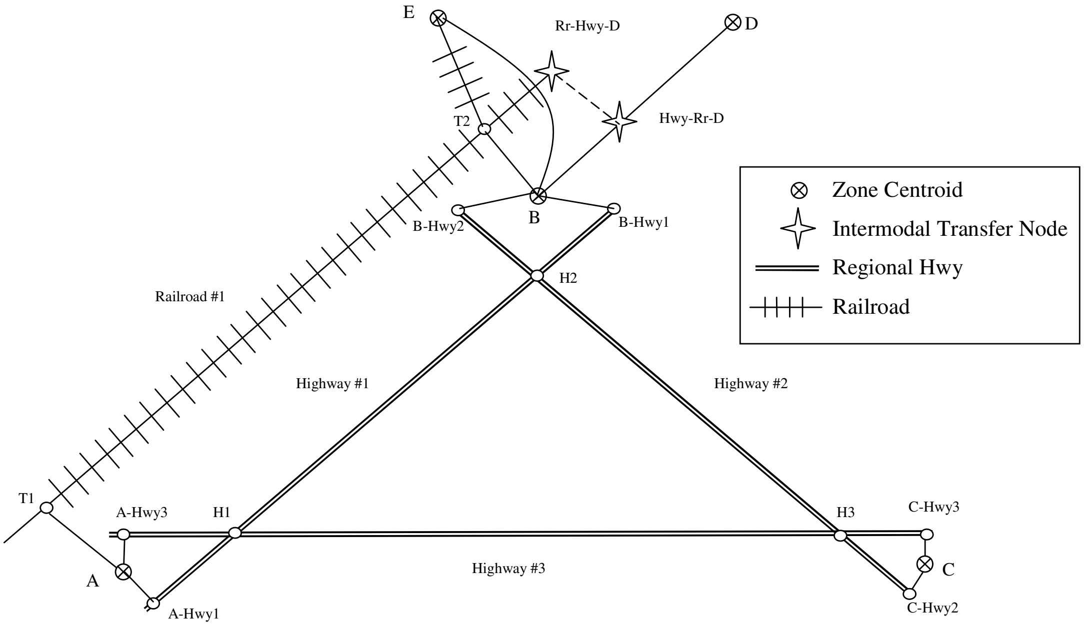


Figure 4.3 The example freight network

Three scenarios for each city are proposed. The inter-regional network has two possible improvement projects, one which improves the highway and another which improves the railway. Without loss of generality we assume that only one commodity type travels on the network. The data are summarized in Tables 4.1(a) -1(c). Although the travel time values are assumed fixed, in practice, travel times will tend to be higher nearer to origins and destinations. Carriers can make up time in the middle of their routes. The total maximum delay is assumed to be 2,400 pcu hours and the budget is assumed to be 120 monetary units. Model 2, described above, is applied to the data. The results are shown in Figure 4.4.

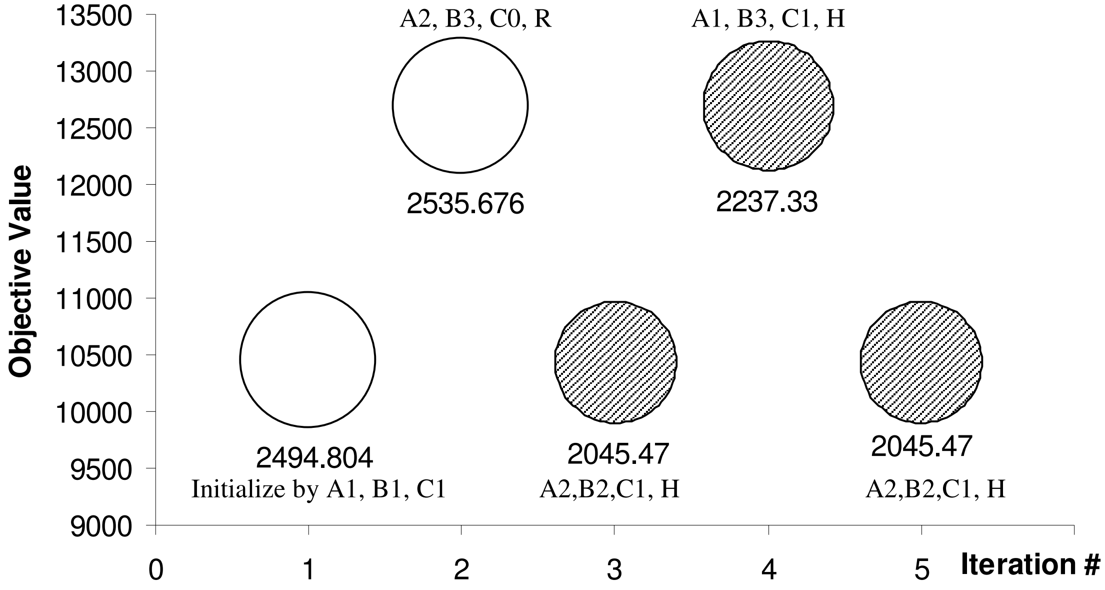


Figure 4.4Results of the example freight network

The network is initiated by selecting the basic scenario for each area which is scenario 1 focusing on maintaining the travel speed in each area. Table 4.1(c) shows the improvement project information. Each project is given a project code as its reference. In each area, there are three scenarios and an alternative to do nothing. Only one scenario will be chosen by the model but this will improve all the areas' connector speeds and distances as shown in Table 4.1(a). For example, scenario 2 of city A (referred by A2) reduces both travel distance for the connector access to Highway #1 and the connector access to Highway#3. If there is no improvement (A0, B0, and C0), each local network will suffer from significant reduction in travel speeds. The initiated traffic volume is input in the upper level model. Using these values, the upper level model suggests a new selection that is A2, B3, C0, and R. Although the selection total delay is less than the total maximum delay using the upper model calculation and the initiated traffic volume, the lower model discloses that the new selection changes the traffic volumes on the network. The result is that the real delay is more than maximum delay. This constraint violation does not hinder the algorithm. The new traffic volume from the lower model and the new selection is input to the upper level model again. In the fifth iteration, a selection is the same as the third iteration selection. This means that an endless loop is happened in the model. In this case, the selection which yields the minimum objective values in the loop is chosen to design the network. In this example, the best selection is A2, B2, C1, H with the total generalized cost of $10,429/hour.

Within the integrated network, all scenarios in all cities and the regional improvement projects work together to achieve the goal of an efficient network. If local networks and regional networks are not integrated, the network design can be different and may not achieve the global benefit such as minimizing total freight costs and restricted total delay.

4.4 INTRODUCING AN IMPROVED MODEL FUTURE STUDIES

In this chapter, a long haul freight network design framework is constructed based on a bi-level network design approach which expanded more general and practical models based on the existing road network design literature. The framework expands local road networks which are the focus of the earlier literature to multiple mode networks with multiple commodities. Network representations, the upper and lower level problems, are adjusted to be appropriate for a freight network study.

Another focus of this model is to combine various studies on effects of different network improvements into a single model through the centroid connector information. Future research that should be conducted after this model is to estimate average centroid connector costs. In this study, centroid connectors are given significant roles as connections between local network studies and inter-regional network studies. If there are project improvements for a local network, a proper model should be constructed to study improvement impacts on the local network. The data from the study can be used to estimate typical transport costs in and out the local network both before and after the improvements. Typical transport costs will be used as the centroid connector costs in order to study further impacts on the larger network (the inter-regional network that connecting other local networks together). A suitable statistic approach to identify typical transport costs that best represent the local networks is required. The task is interesting since transport models vary. Therefore techniques used to compute these average costs are different. There are at least two well known transport models related to these costs. The first one is the model which can tracks vehicle paths from their origins to destinations and the other which cannot.

In the next chapter, a second model for freight network design is represented. There are two developments which are inspired by the first model. The first improvement is based on the route choice behavior used in the lower-level model. The shipper-carrier model Friesz, et al. (1986) is used to separate the decisions made by these two agents who have different ways to define their route choices. A disadvantage of the approach is increasing computational effort but it is believed that this shipper-carrier model can understand the mode choice behavior better.

The result from the numerical example suggests the second development related to the solution algorithm. A branch and bound technique is introduced to the next model to solve two problems that can occur in the feedback process. The first problem is the infinite loop and the second is the preference to expand high traffic volume links while leaving others undeveloped. The situation develops similarly to project selections by Benefit Cost Analysis (BCA) approach when the net present value is used as a decision criterion. The high traffic link receives the improvement. Its result is additional traffic volume and the link continues to get more improvements. This high volume preference hinders the network design to produce the optimal network which can develop through the congestion reduction both by increasing the infrastructures' capacities and diverting traffic to less congested paths or less congested modes. Instead of selecting which projects should be implemented based on the traffic volume obtained by the lower level model, the branch and bound technique uses the lower level model to produce the lower bound and decides whether to keep or discard the improvement alternatives.

Table 4.1 Numerical the example inputs

Table 4.1(a): Link network data

Link Number	From	To	Condition	Transport Cost ($/ton-mile)	Travel Time ($/ton-hour)	Distance (miles)	Freeflow	Capacity	Transfer Costs	Imp Code
1	A	A-Hwy#1	No improvement	0.12	1.0	8.0	22.0	8	0	A0
			Select Scenario 1	0.12	1.0	8.0	32.0	8	0	A1
			Select Scenario 2	0.12	1.0	7.9	32.5	8	0	A2
			Select Scenario 3	0.12	1.0	8.0	30.0	8	0	A3
2	A	A-Hwy#3	No improvement	0.12	1.0	7.0	20.0	8	0	A0
			Select Scenario 1	0.12	1.0	7.0	30.0	8	0	A1
			Select Scenario 2	0.12	1.0	7.0	30.0	8	0	A2
			Select Scenario 3	0.12	1.0	7.0	30.0	8	0	A3
3	A	T1	No improvement	0.12	1.0	7.0	19.0	8	4	A0
			Select Scenario 1	0.12	1.0	7.0	30.0	8	4	A1
			Select Scenario 2	0.12	1.0	7.0	30.0	8	4	A2
			Select Scenario 3	0.12	1.0	6.8	31.0	8	3	A3
4	B	B-Hwy#1	No improvement	0.12	1.0	9.0	20.0	8	0	B0
			Select Scenario 1	0.12	1.0	9.0	30.0	8	0	B1
			Select Scenario 2	0.12	1.0	8.8	31.0	8	0	B2
			Select Scenario 3	0.12	1.0	9.0	30.0	8	0	B3
5	B	B-Hwy#2	No improvement	0.12	1.0	8.8	19.0	8	0	B0
			Select Scenario 1	0.12	1.0	8.8	29.0	8	0	B1
			Select Scenario 2	0.12	1.0	8.6	29.0	8	0	B2
			Select Scenario 3	0.12	1.0	8.8	29.0	8	0	B3
6	B	T2	No improvement	0.12	1.0	8.0	18.0	8	4	B0
			Select Scenario 1	0.12	1.0	8.0	28.0	8	4	B1
			Select Scenario 2	0.12	1.0	8.0	28.0	8	4	B2
			Select Scenario 3	0.12	1.0	7.8	29.0	8	3	B3

Table 4.1(a): Link network data (cont.)

Link Number	From	To	Condition	Transport Cost ($/ton-mile)	Travel Time ($/ton-hour)	Distance (miles)	FreeFlow	Capacity	Transfer Costs	Imp Code
7	C	C-Hwy#2	No improvement	0.12	1.0	6.0	31.0	8	0	C0
			Select Scenario 1	0.12	1.0	6.0	35.0	8	0	C1
			Select Scenario 2	0.12	1.0	5.8	36.0	8	0	C2
			Select Scenario 3	0.12	1.0	5.9	35.0	8	0	C3
8	C	C-Hwy#3	No improvement	0.12	1.0	5.8	31.0	8	0	C0
			Select Scenario 1	0.12	1.0	5.8	35.0	8	0	C1
			Select Scenario 2	0.12	1.0	5.8	35.0	8	0	C2
			Select Scenario 3	0.12	1.0	5.7	36.0	8	0	C3
9	A-Hwy#1	H1		0.12	0.5	2.0	60.0	8	0	-
10	A-Hwy#3	H1		0.12	0.5	4.0	60.0	8	0	-
11	B-Hwy#1	H2		0.12	0.5	2.0	60.0	8	0	-
12	B-Hwy#2	H2		0.12	0.5	4.0	60.0	8	0	-
13	C-Hwy#2	H3		0.12	0.5	2.0	60.0	8	0	-
14	C-Hwy#3	H3		0.12	0.5	2.0	60.0	8	0	-
15	H1	H2	No improvement	0.12	0.5	40.0	65.0	4000	0	-
			Select Scenario 1	0.12	0.5	40.0	70.0	4000	0	H
16	H1	H3		0.12	0.5	60.0	65.0	2200	0	-
17	H2	H3		0.12	0.5	40.0	70.0	2200	0	-

Table 4.1(a): Link network data (cont.)

Link Number	From	To	Condition	Transport Cost ($/ton-mile)	Travel Time ($/ton-hour)	Distance (miles)	FreeFlow	Capacity	Transfer Costs	Imp Code
18	T1	T2	No improvement	0.05	0.5	50.0	45.0	8	2	-
			Select Scenario 1	0.05	0.5	50.0	50.0	8	0.5	R
19	B	Hwy-Rr-D		0.12	0.1	100.0	70.0	8	0	-
20	Hwy-Rr-D	D		0.12	0.1	50.0	70.0	8	0	-
21	B	E		0.12	0.1	350.0	70.0	8	0	-
22	T2	Rr-Hwy-D		0.05	0.1	110.0	55.0	8	2	-
23	T2	E		0.05	0.1	400.0	55.0	8	4	-
24	Rr-Hwy-D	Hwy-Rr-D		0.00	0.0	0.0	0.0	-	4	-

Table 4.1(b): OD – Travel demand matrix

From	To		
	A	B	C
A	1200	1900	500
B	1800	1500	700
C	700	800	900

Passenger movement (pcu/hour)

From	To				
	A	B	C	D	E
A	-	20	10	40	30
B	10	-	10	30	20
C	5	10	-	20	20
D	50	40	10	-	0
E	40	30	20	0	-

Freight movement (ton/hour)

Table 4.1(c): Project improvement data

Area	Scenario Description	Project Code	Investment Cost (Monetary Unit)
A	No Improvement	A0	0
	Scenario 1: Focus on Maintain Speed to Year 10th	A1	20
	Scenario 2: Scenario 1 + Improving Assessment to Hwy#1	A2	30
	Scenario 3: Scenario 1 + Improving Assessment to Railroad#1	A3	35
B	No Improvement	B0	0
	Scenario 1: Focus on Maintain Speed to Year 10th	B1	25
	Scenario 2: Scenario 1 + Improving Assessment to Hwy#1	B2	35
	Scenario 3: Scenario 1 + Improving Assessment to Railroad#1	B3	40
C	No Improvement	C0	0
	Scenario 1: Focus on Maintain Speed to Year 10th	C1	15
	Scenario 2: Scenario 1 + Improving Assessment to Hwy#2	C2	25
	Scenario 3: Scenario 1 + Improving Assessment to Hwy#3	C3	25
Hwy#1	Reduce congestion and Improve average freeflow speed	H	40
Railroad #1	Improve average speed and reduce uncomfortable factors	R	50

CHAPTER 5 THE SHIPPER-CARRIER NETWORK DESIGN MODEL

5.1 NEW CHARACTERISTICS

This chapter was first presented in Apivatanagul and Regan (2008). In the previous chapter, the first model was developed based on the bi-level network design focused on the passenger movements. The bi-level concept is still used in this second model with the following new features. We model our network design as a capacitated discrete budget allocation problem with non-linear routing costs.

5.1.1 Transportation mode choice models

The primary developments are on the lower level model. The shipper and carrier behaviors are introduced into the model through the traffic assignment process. Instead of loading the freight demand directly to the transportation network, the freight demand will be assigned into the service or shipper network first in order to select transportation modes. In the other words, the mode choice model is added into the lower model. This model is called the shipper model since the shippers decide the services that properly fit their commodities. The carrier model is the traffic assignment model because the carriers decide how to route their vehicles into the transportation network.

As the discussion in Chapter 4, there are plenty ways to add mode choice models into the network design process. Figure 5.1 shows three alternative methods and their characteristics. In the first model, the mode choice model is combined into the traffic assignment model through the uses of transfer links. The transportation mode or modes will be selected if they yield the minimum cost paths. This combined model is good in term of the computational efficiency however the route choice behaviors are aggregated through the generalized costs used in the traffic assignment process. In reality, the decision process is complicated. The most sophisticated mathematical model to simulate the decision process is the discrete choice model (see Ben-Akiva and Lerman, 1985 and Train, 2003) It can be applied to the shipper model. A survey with both qualitative and quantitative attributes can be used to study the route choices at the individual level. Nevertheless, the approach can consider a limit number of route choices. This is not suitable to study intermodal transportation since there are many possibilities that the intermodal transportation can be constructed. It is also inconvenient to transfer its mode choice decisions to the network with transshipment points. Predefined routes can be used to achieve this information transferring. The approach needs extensive survey data.

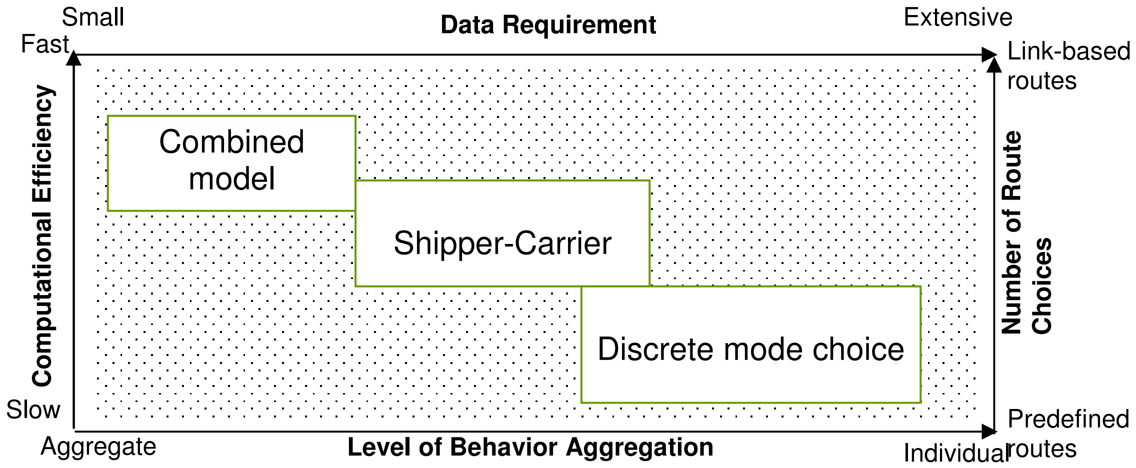


Figure 5.1Transportation modal choice model alternatives

The shipper-carrier freight network equilibrium model is selected as a suitable model which balances complexity and reality. It was first introduced by Friesz, et al. (1986). The model separates the mode choice decisions to the shipper and the route choice decisions to the carrier. This makes a big improvement from the combined model used previously. Although the mode choice decisions are partly based on the travel costs used in the route choice decisions, shipper may have additional costs such as the waiting time to receive the services. This model can also construct intermodal transportation routes when considering mode choices. In addition, the model can ultimately develop to run the shipper decisions and carrier decisions simultaneously (Friesz, et al., 1985) in order to find a converged result between these two agents' decisions. The model will be explained in the later sections.

5.1.2 Capacitated link constraints

In freight network design, relative to that of urban passenger networks, larger networks must be considered. These networks therefore require more aggregation and longer trips. Although infrastructure improvements can improve traffic conditions or other problems, the results of the improvements will be seen as average cost saving at small points on the network. In order to develop a network design model that can capture their importance, capacity constraints are introduced in the lower level problem.

The capacity constraints limit traffic volume on specific links. These capacities can represent many barriers occurring in transportation networks. In this chapter, the capacity constraints are used to capture reliability. Although the decisions to select route choices depends more heavily on network reliability than travel costs, this reliability cannot be captured by the static traffic assignment models which are typically used for the strategic planning purposes. The infrastructure improvements can increase network reliability and these results should be perceived by the network design model. In the case of highway links, the capacity can be obtained from the highway capacity manual. It can be a certain traffic volume that results in desired average speeds. For intermodal facilities, information about freight volumes can help a shipper to decide which service to use. The capacity can represent limits onnegative externalities for certain areas or limits on road usage for maintenance or other purposes.

5.1.3 The solution algorithm by branch and bound techniques

A branch and bound technique is introduced to solve two problems that occur in the feedback process used in the first model. The first problem is the possibility of facing an infinite loop in the solution process and the second is the preference to expand high traffic volume links while leaving others undeveloped. Instead of selecting which projects should be implemented based on the traffic volume obtained by the lower level model, the branch and bound technique uses the lower level model to produce the lower bound and decides whether to keep or discard the improvement alternatives. The branch and bound process and the lower bound calculation will be discussed in the later sections.

5.2 THE SHIPPER-CARRIER MODEL DESCRIPTIONS

The model is based on the bi-level concept as the previous model. Figure 5.2 illustrates the model setup. The upper level model is the budget allocation model. The proposed project improvements and the freight demand are assumed to be given. The upper model will suggest a subset of the project improvements to be examined by the lower level model. Since the branch and bound technique is used in this model, the lower level will calculate the lower bound of system efficiency that can be accomplished by the suggested projects. This information will be used by the upper model to recognize subsets that cannot achieve the best network design and suggest the next subset to the lower model. The cost function for each link is set based on the project selected for the link.

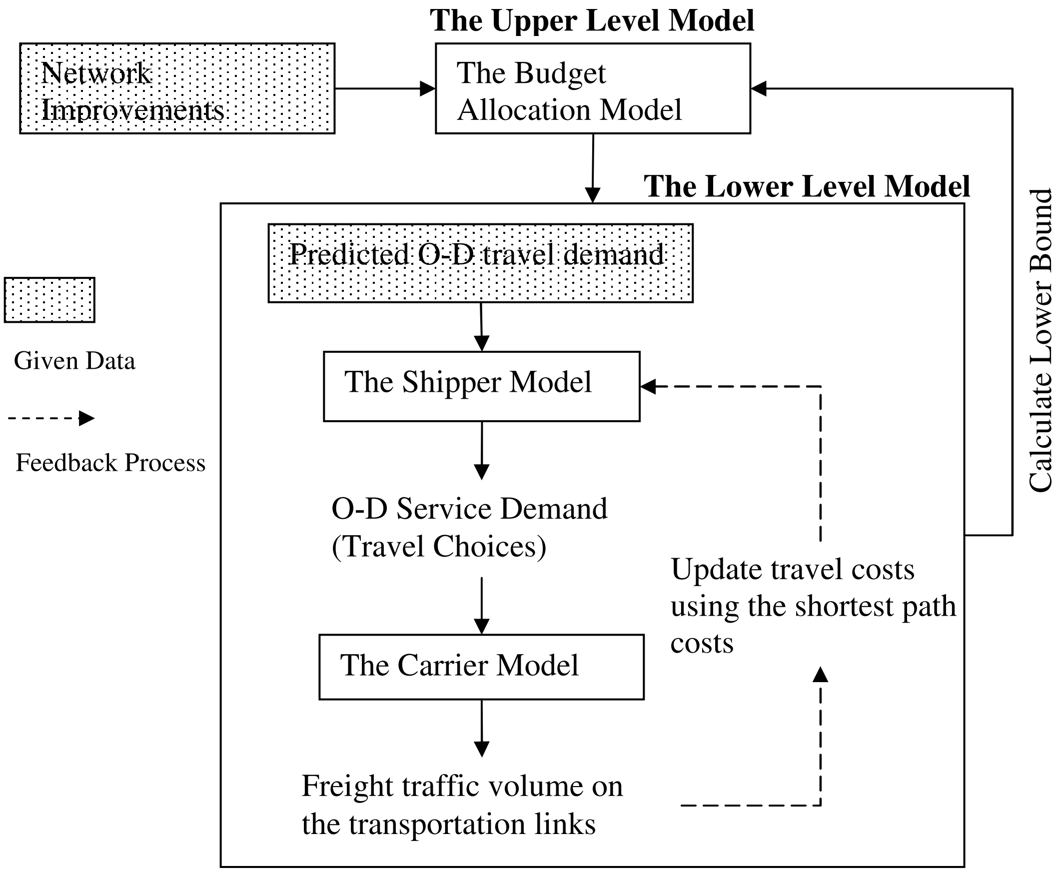


Figure 5.2 The shipper-carrier network design model

In this section, we explain the lower level model which applies the shipper-carrier freight network equilibrium model to represent the freight route choice behaviors. The branch and bound technique and its lower bound will be discussed in the solution algorithm section.

5.2.1 The shipper and carrier model

The shipper-carrier freight flow prediction model is introduced in Friesz, et al. (1986).The model develops the traffic assignments on two networks namely, the shipper network and the carrier network. The shippers decide transportation mode choices or service choices provided by the carriers. It is assumed that the shippers have limited freight routing information. Therefore, their information is represented by the service network which provides only service information between each origin and destination such as average travel costs rather than information on specific transportation infrastructure and traffic conditions. The carriers on the other hand, have this detailed network information. They use this information to route vehicles in responding to the service demand given by the shippers.

5.2.1.1 The shipper model

The shipper model selects transportation modes for freight demands from each origin to each destination. The shipper model routes freight demand from one business district to another while minimizing travel costs on the service network. The shippers are assumed to be non-cooperative users. Therefore the traffic volume will result in the user equilibrium. The output of the shipper model is the freight demands classified by different services or transportation modes. These classified freight demands will be referred to as the service demands from this point on.

The details to set up the shipper or service network are as follows. The shipper network contains transportation services on all available modes. The transport demands are assumed to originate in and are destined for central business districts (CBDs) which are represented as centroid nodes. In order to add intermodal transportation into the model, the intermodal facilities are included as intermediate nodes in the shipper network. Because of the assumption that the shipper has limited information on detailed route choices, the available transportation services are represented as directed links between the districts and intermodal facilities. The costs, capacities and other characteristics of the links are average values or shipper perceived values.

5.2.1.2 The carrier model

The carrier model receives the service demand data from the shipper model and routes these demands to the physical transportation network. This network includes intermediate nodes which represent intersections, ramp locations, and different geometric designs. In practice, the centroids are connected to the transportation network through centroid connectors.

The origin-destination travel demand matrix of the carrier model is larger than the shipper’s one. In addition to the business centers as the origins and destinations of service demands, the intermodal facilities are added as the origins and destinations on the carrier network. These service demands are created by the shippers who decide to move commodities by intermodal services. The decisions are previously made by the shipper model.

The service demands are assigned separately for each transportation mode. The carrier behaviors differ by transportation modes. On the highway, carriers who provide trucking services are non-cooperative optimizers resulting in user optimal conditions. In the rail service, it is assumed that the carrier who provides train services routes their vehicles on their own network. Therefore, the system optimal condition will result if their rail networks are used exclusively.

5.2.2 Appling the shipper-carrier model to the network design problem: A key assumption

Current freight flow prediction models assume that the transportation network is given. In the other words, it assumes short term predictions. The network design model is in the other way since it updates the network. In order to use the shipper-carrier freight network equilibrium model, an assumptions is made that service capacity will grow proportionally to the freight demand.

When there is an improvement, the update can be done easily for the physical network but it is difficult for the service network. For the carrier's network, an improvement on a transport link will change its physical characteristics directly which may result in increasing capacity or free-flow speed. On the other hand, a service link in the shipper network is a virtual link. It represents paths from an origin to a destination, therefore it consists of many physical links from the carrier network. A shortest path algorithm is performed on the carrier network in order to update the path costs.

Regarding to the capacity of the service network, the capacity of each service link is not directly controlled by the transportation infrastructure. The capacity is aggregately controlled by many carriers who provide services. Therefore, a change in the link's service capacity is hard to predict. There are two possibilities to consider the capacity of service links in the long term. First, the aggregated level of service links make an assumption that service capacity will grow proportionally to the freight demand. If the freight demands increase, it is possible that carriers will increase frequency or truck sizes to maintain the same level of service for the shipper. In a special case in which a few major projects are implemented resulting significant changes in service availability, the new service network data should be studied with a specific model and is assumed to be provided to the network design model. The other convenient assumption is to postulate that the carrier is perfectly and dynamically able to handle new demands and that therefore the level of service can be assumed to be fixed. In the other words, there is no capacity constraint on the service links. We consider the first assumption more realistic to adopt into the network design model. An exception to update the capacity on the service network is improvements on intermodal facilities, ports, or terminals. These facilities' capacities are directly influenced by the improvements therefore it is reasonable to assume that the capacities can be updated directly.

5.3 MODEL FORMULATION AND SOLUTION ALGORITHMS

Figure 5.2 illustrates how the freight network design problem is modeled by combining the budget allocation model and the shipper-carrier models. In this section, the model is formulated in mathematical forms. The following variables will be used in the model:

Subscripts

l	for the shipper network- a link in a transportation service network for the carrier network - a link in a physical transportation network
m	freight commodity
p	project that is selected to implement for the link
k	travel path

Superscripts

o	origin of the freight demand
d	destination of the freight demand

Variables

V_{mlp}	freight volume of commodity m for link l when project p is selected = service demand if l belongs to shipper model = traffic volume if l belongs to carrier model
$C_{mlp}(V)$	unit cost function for commodity m to use link l when project p is selected. The unit cost is an average unit cost when calculating the user equilibrium traffic flow and is a marginal unit cost when calculating the system optimized traffic flow.
$f_{k,m}^{od}$	freight volume of commodity m for path k from an origin o to a destination d
q_m^{od}	freight demand of commodity m from an origin o to a destination d

u_l	capacity of link *l*
$\delta_{l,k}^{od}$	link-path incidence matrix, equal to 1 if link *l* belongs to traveling path *k* from an origin *o* to a destination *d*
X_{lp}	the binary decision variable, equal to 1 if the project *p* for link *l* is implemented and equal to 0 otherwise
F_{lp}	cost to implement project *p* for link *l*
B	total available budget

5.3.1 The Upper Level Model–Budget Allocation Model

The upper level model for the freight network design is as follows:

$$\underset{X_{lp}}{MIN}\sum_{m}\sum_{\mathrm{l}}\sum_{p} C_{mlp}V_{mlp}X_{lp} \tag{5.1}$$

subject to

$$\sum_{\mathrm{l}}\sum_{\mathrm{p}} F_{lp}X_{lp} \le B \tag{5.2}$$

$$\sum_{\mathrm{p}} X_{lp} = 1 \qquad \textit{for}\ \text{all}\ \ l \tag{5.3}$$

The model is an integer optimization model with X_{lp} as a 0-1 decision variable. C_{mlp} and V_{mlp} are controlled by the lower level model. In our research, we apply a branch and bound algorithm which is convenient since it naturally consists of two major steps -- constructing a binary search tree to enumerate all possible solutions and bounding or cutting the nodes that cannot produce the optimal solution.

The nodes in a binary search tree are either partial solution nodes or complete solution nodes. Assume that there are P projects proposed to improve the network, the complete binary tree will have 2^{P+1}-1 nodes with 2^{P} complete solution nodes at the final depth. Each node contains P decision variables. Each project has a fixed position ranging from 1 to P. If a project is selected to implement, the decision variable at its corresponding position is set to one or zero for otherwise. At the root of the tree, the node is a partial solution node which has no fixed decision variables meaning that the variables are free to set to zero or one. For each depth of the tree, a decision variable will be fixed in the order from the first project to the last one. The complete solutions are at the final depth with all decision variables have fixed values. The branch and bound algorithm is used to cut out the nodes that loss potential to develop to the complete solutions that optimize the objective function instead of examining the complete tree. Figure 5.3 shows the complete tree solution when P = 3. It should be noted that the branch and bound algorithm will not examine all nodes.

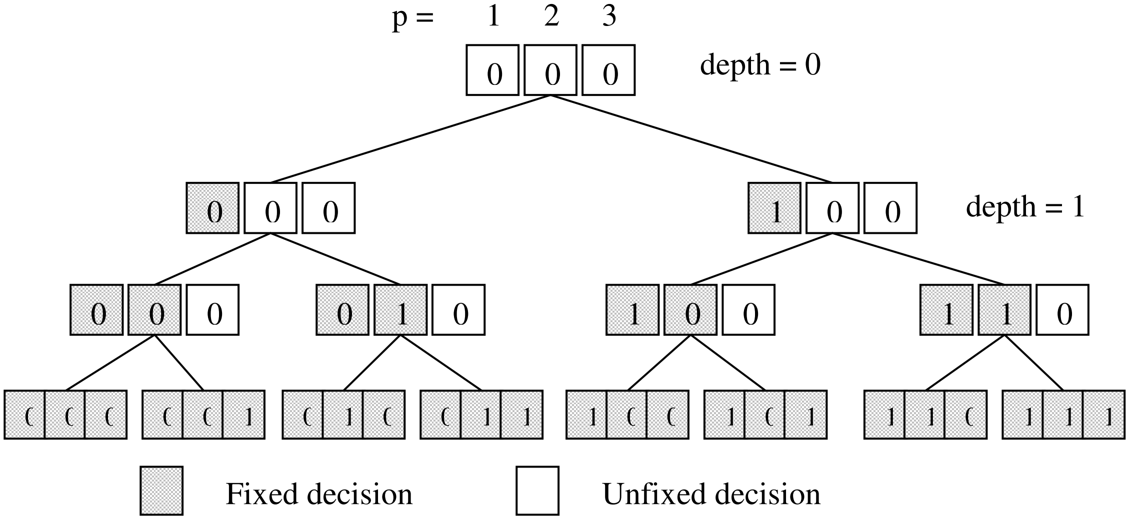


Figure 5.3 A searching binary tree (P = 3)

For the network design with the formulation as in (5.1), the branch and bound algorithm is constructed as follows:

Step 0 Initialization: All decision variables at the root node will be set to zero with no fixed variables. The node is an unvisited node. The incumbent value, which is the best objective value that the search tree has found so far, is set to infinity or a high value by default. One way to obtain the initial incumbent value is to simply select network improvement projects until the budget limit is reached. Then, continue to Step 1.

Step 1 Node Selection: Select an unvisited node. A node in the deepest level is selected, therefore the branch and bound will do a depth first search. The depth first search can be beneficial if an initial incumbent value is difficult to find. Then, continue to Step 2.

Step 2 Check Budget Constraints: For the selected node, the budget constraint is checked. The summation of the capital costs for the selected projects must be less than the budget limit. Return to Step 1 if the constraint is violated and set this node as visited (not to be explored further), otherwise continue to Step 3.

Step 3 Check for the Completed Solution: Assume that the tree depth is equal to zero at the root. Go to Step 4.1 if the node does not have the tree depth equal to P, when there are P projects proposed for the network. Otherwise, go to Step 4.2 with the node that has the complete solution.

Step 4 Call the lower level model:

Step 4.1: Calculate the lower bound using the lower level model. Go to Step 5.1.

Step 4.2: Calculate the objective value of the updated network. The update is done by replacing the cost coefficients on the links which receive the improvements. The traffic volume used to calculate the objective value is obtained by calling the lower level model. Go to Step 5.2.

Step 5 Compare the value with the incumbent value:

Step 5.1 Pruning Decision: Go to Step 6, if the lower bound of the selected node is less than the incumbent value. Otherwise, its child nodes cannot produce the optimal solution. The node will be fathomed and marked as a visited node. Go to Step 7.

Step 5.2 Setting the New Incumbent Value: If the selected node has the objective value less than the incumbent value, a new incumbent value and a new current best solution are set. Otherwise, these remain the same. Set the selected node as a visited node. Go to Step 7.

Step 6 Branching: the selected node will give two child nodes with the tree depth increasing by 1. If the selected node depth equals to *h*, the child nodes will have the tree depths equal to h+1. To enumerate the solution, the improvement project at position h+1 will be fixed to zero for the left child node and to one for another. Set the selected node as a visited node. Go to Step 1.

Step 7 Stopping Criteria: The algorithm stops when all nodes are visited. The current incumbent solution will contain the transportation network which optimizes the objective value.

5.3.1.1 Lower Bound Calculation

A lower bound is calculated for a node that has a partial solution. The process to calculate the lower bound has two steps -- updating the network and calculating the lower bound for the updated network. The original idea to apply the branch and bound approach and calculating the lower bound is from Leblanc (1975).

In order to update the network, the currently undecided projects are assumed to be implemented. For the selected node at depth *h*, the first *h* decision variables are fixed as they appear but the other decision variable from *h*+1 to the last project are set to one. For example, the root node has no fixed decisions therefore all nodes are set to one. The network is then updated by modifying the cost coefficients of the links if they receive the improvements.

In order to calculate the objective value of the upper level model, the traffic volume corresponding to the new network has to be obtained. This can be done by using the lower level model with the updated network. Substitution of the freight volume to the network design objective function yields the lower bound.

It should be noted that different route choice behaviors will result in different lower bounds. The tightest lower bound can be calculated by using the lower level model to predict flow directly. However, this method cannot identify the occurrence of Braess' Paradox since the upper level objective function and the lower objective function are different. In the passenger network, Leblanc (1975)shows that using the system optimal flow to calculate the lower bound can identify the paradox. For our model which uses the shipper-carrier model, this lower bound can be obtained by ignoring the shipper network model and calculating the route choice solely based on the carrier decisions. In the other words, the lower bound will be calculated by only the system optimal traffic assignment on the carrier network.

5.3.2 Lower model formulation- network equilibrium models

The traffic assignment for shipper-carrier freight flow prediction models can be solved using sequential Friesz, et al. (1986) or simultaneous (Friesz, et al., 1985 and Fernandez, et al., 2003) models. In this research, a sequential model is used. It is assumed that there are no link interactions -- meaning that the traffic volume in a link will not have an effect on other links. The passenger movements can be preloaded to the highway network in order to represent the real congestion which is a combination of both passenger and truck traffic volumes. In the case of multiple commodities, each commodity will be assigned sequentially according to its priority.

Therefore, the generalized mathematical model for each network and each commodity can be written by applying the Beckman's Formulation.

$$MIN \quad \sum_{l} \int_{0}^{V_{mlp}} C_{mlp}(w)\, dw \quad (5.4)$$

subject to

$$\sum_{k} f_{k,m}^{od} = q_{m}^{od} \qquad \forall\, o,d \qquad (5.5)$$

$$f_{k,m}^{od} \geq 0 \qquad \forall \quad k,o,d \qquad (5.6)$$

$$V_{mlp} \leq u_{l} \, \forall\, l \qquad (5.7)$$

$$V_{mlp} = \sum_{o}\sum_{d}\sum_{k} f_{k,m}^{od} \delta_{lk}^{od} \, \forall\, l \qquad (5.8)$$

In this study, the explicit link capacity constraint, (5.7), is added to the traditional formulation. A major problem of static traffic assignment is that it cannot detect dynamic congestion or queues on the links. The congestion on the links is average congestion and therefore the assignment cannot indicate links' reliability. Since reliability is important for freight route choice decisions, it is assumed that the over capacitated links are unreliable and will be avoided by the shipper and carrier. The capacity can be used to limit the traffic volume to result in a certain service level.

The modified shipper-carrier freight flow prediction model cannot be solved with the traditional Frank-Wolfe algorithm. In this paper, the barrier optimization method (Yang and Yagar, 1994) is applied to the developed problem. The algorithm is based on the logarithmic barrier method.

Given the barrier augmented function:

$$F(V,\ \gamma^n) = \sum_l \int_0^{V_{mlp}} C_{mlp}(w)\, dw \qquad (5.9)$$

when the link has no limited capacity

$$= \sum_l \int_0^{V_{mlp}} \left(C_{mlp}(w) + \gamma^n \frac{1}{u_l - w}\right) dw \qquad (5.10)$$

when the link has limited capacity

The algorithm steps are as follows:

```
Step 0 Choose a feasible solution, the vector of traffic volume $\mathbf{V}^{\mathbf{0}}$. Set n = 1 (outer loop counter)
While ( $\mathbf{V}^{\mathbf{0}}$ is not converged) do
    While ($\mathbf{z}$ is not converged) do
    Step 1 Let $\mathbf{z}^{\mathbf{0}} = \mathbf{V}^{\mathbf{n-1}}$. Set g = 1 (inner loop counter)
    Step 2 Perform all-or-nothing assignment based on $C_{mlp}\left(z_l^g\right)$ for links that have no capacity constraint and $C_{mlp}\left(z_l^g\right) + \gamma^n / \left(u_l - z_l^g\right)$ for links with the capacity constraints. Let the link flow from this assignment is $y_l$ .
    Step 3 Find $\alpha^*$ to minimize F($\mathbf{z}^{\mathbf{g}} + \alpha\,(\mathbf{y}-\mathbf{z}^{\mathbf{g}}), \gamma^n$) in the range
        $0 \le \alpha \le \min\left(1, \min_{z<y} \frac{u_l - z_l^g}{y_l - z_l^g}\right)$
    Step 4 Move the volume $z_l^{g+1} = z_l^g + \alpha^*\left(y_l - z_l^g\right)$ for all link, l. g = g+1
    End while
Step 5 $\gamma^{n+1} = \sigma.\gamma^n \left(0 < \sigma < 1\right)$ and n =n+1
End while
```

The barrier method always maintains a feasible solution. It is started with a feasible solution with a high value of γ. The high gamma value prevents the solution from violating the capacity constraints. For each γ, the Frank-Wolfe algorithm (Step 1 to 4) is performed. In Step 3, α^* is limited to a certain range to guarantee that the next solution is still a feasible solution. The γ value is lessened in the next iteration to allow a solution which is closer to the capacity limit. In this study, $C_{mlp}(V)$ is assumed to be a strictly increasing convex function. Therefore, the algorithm will converge when $\gamma \rightarrow 0$ with a unique solution.

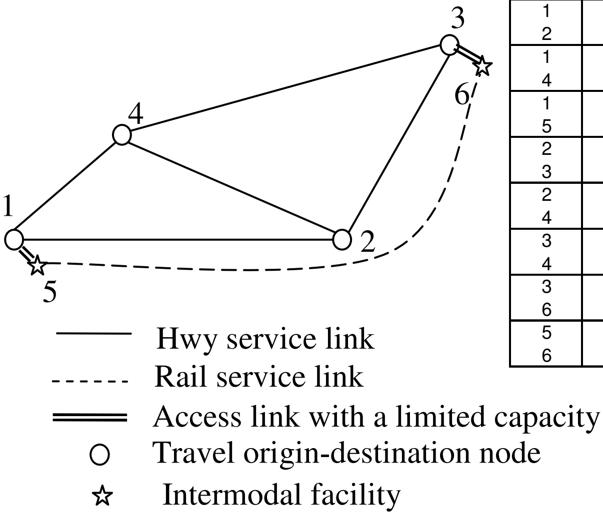
5.4 A NUMERICAL EXAMPLE

The numerical example in this paper consists of two networks, two modes, and a single commodity. The first network is the shipper network consists of 4 origin-destination (o-d) nodes, 2 intermodal transfer nodes and 16 transportation service links. The intermodal facilities are represented by virtual links which have limited capacities. Other service links can be used beyond their capacities but will cause more congestion. The shipper considers costs from service waiting time and delivery price which can be written as:

$$\text{Shipper cost} = \text{VOT}(\text{WT}^0)(1+0.15\left(\frac{V_{mlp}}{Capacity}\right)^4)+\beta\,(\text{DP})^{od} \tag{5.11}$$

Where VOT	Value of Time for waiting for the services
WT^0	Free flow waiting time
β	Service preference factor
DP^{od}	Delivery price for a service connect an origin, o, and a destination, d.

The delays increase when shippers use the services more. The delivery price for each service is obtained by the minimum cost to travel from an origin to a destination in the real transportation network (i.e. the carrier network). If the shipper prefers one type of service more than another, it can adjust the delivery price using the service preference factor (β). For example, a certain commodity type may typically ship in a large volume therefore it may get a cheaper rate for using the rail mode. In this example, the factor is set as one. The shipper network is shown in Figure 5.3 with its associated parameters.



I	J	VOT ($/hour.unit weight)	WT^0 (hr)	Capacity (unit weight/hr)
1	2	0.88	1.0	Unlimited
2	1	0.88	1.0	Unlimited
1	4	0.88	1.0	Unlimited
4	1	0.88	1.0	Unlimited
1	5	0.88	1.0	5
5	1	0.88	1.0	5
2	3	0.88	1.0	Unlimited
3	2	0.88	1.0	Unlimited
2	4	0.88	1.0	Unlimited
4	2	0.88	1.0	Unlimited
3	4	0.88	1.0	Unlimited
4	3	0.88	1.0	Unlimited
3	6	0.88	1.0	5
6	3	0.88	1.0	5
5	6	0.88	1.0	Unlimited
6	5	0.88	1.0	Unlimited

Figure 5.4 The example shipper network configurations

The travel demand for each origin and destination is shown in Table 5.1. This demand will be assigned to the shipper network. The assigned demand will be converted to the service demand and is assigned to the carrier network to obtain the traffic volume in each transportation link.

Table 5.1 The travel demand for the shipper network example

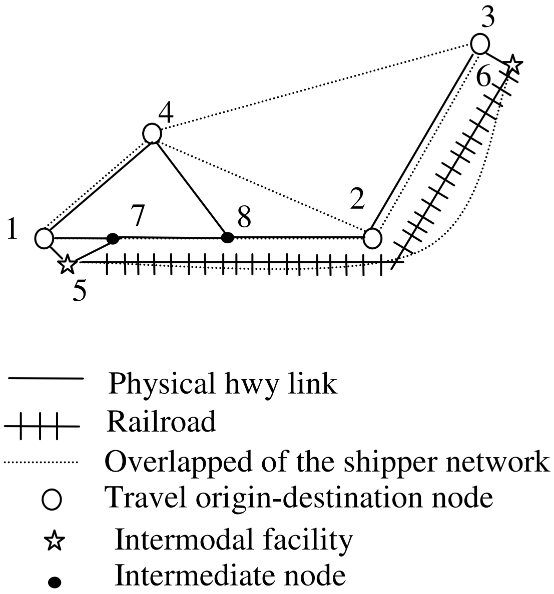
I	J	Travel Demand (unit weight)
1	1	0
	2	8
	3	10
	4	4
2	1	8
	2	0
	3	8
	4	4
3	1	12
	2	8
	3	0
	4	8
4	1	4
	2	4
	3	4
	4	0

The second network is the carrier network which represents the physical transportation network. This network has 6 o-d nodes which are 4 original o-d nodes from the shipper network and 2 o-d nodes are the transfer nodes. There are 16 highway links and 2 rail links connecting with 18 nodes. The carrier considers the costs by their fixed delivery price which will be increased with the congestion. For each link, the carrier cost can be written as:

$$\text{Carrier cost} = DP_l \left(1+0.15\left(\frac{V_{mlp}}{Capacity}\right)^4\right) \qquad (5.12)$$

Where DP_l is the fixed delivery price for link, l.

The carrier network has overlapping nodes from the shipper network. The network is shown in Figure 5.4.



I	J	DP^l (\$/unit weight)	Capacity (unit weight/hr)
1	4	1.5	10
4	1	1.5	10
1	7	0.5	10
7	1	1	20
2	3	2.5	10
3	2	2.5	20
2	8	2.5	20
8	2	2.5	15
3	6	0.5	5
6	3	0.5	5
4	8	1.5	10
8	4	1.5	15
5	7	0.5	5
7	5	0.5	5
5	6	3	Unlimited
6	5	3	Unlimited
7	8	1	10
8	7	1	10

Figure 5.5 The example carrier network configurations

The objective function of the network design is to minimize the total travel cost on the carrier network. The details of five projects proposed to improve the network are shown in Table 5.2. Instead of setting the budget limit in monetary units, the budget is set to a number of projects to implement. When a project is implemented, it is counted as a unit. The lower model will be used to calculate the lower bound at each search tree node. The results from the network design will be compared to the traditional method which prioritizes each project separately by its benefit (the difference between the total carrier cost prior to and after the project implementation). An initial network will be set as the original network without any project improvement. The depth first search method will be used in order to set a better incumbent value as soon as possible.

Table 5.2 Details of the improvement projects

Project	Related Network	Related Link		Capacity		Cost*	Benefit **	Improvement Note
		From	To	Existing	Improved			
1	Carrier-Hwy	2	3	10	15	532	79	Expansion of service capacity by 5
2	Carrier-Hwy	8	2	15	20	564	46	Expansion of service capacity by 5
3	Shipper	1	5	5	10	592	19	Expansion of the explicit capacity by 5
	Shipper	5	1	5	10			Expansion of the explicit capacity by 5
	Carrier-Hwy	5	7	5	10			Expansion of service capacity by 5
	Carrier-Hwy	7	5	5	10			Expansion of service capacity by 5
4	Shipper	3	6	5	10	595	16	Expansion of the explicit capacity by 5
	Shipper	6	3	5	10			Expansion of the explicit capacity by 5
	Carrier-Hwy	3	6	5	10			Expansion of service capacity by 5
	Carrier-Hwy	6	3	5	10			Expansion of service capacity by 5
5	Carrier-Rail	6	5	Unlimited	Unlimited	600	11	Reduce the travel costfrom 3.0 to 2.8

* Cost when only a project is implemented. For example, implementing only project one give the total carrier cost = 532 unit money

** The difference betwwen the existing condition and Cost

5.4.1 Parameters of the Barrier-Traffic Assignment

The barrier optimization method has been applied to the Frank – Wolfe algorithm in order to impose the capacity constraints to transportation links. There are two additional parameters for this traffic assignment. The initial penalty, γ, and the step size to reduce this penalty for each iteration, σ .

The parameter values affect the algorithm running time. If the initial penalty is too high, the early iterations are pointless since the traffic volume will remain the same until the penalties are reduced to a certain value. On the other hand, too low a penalty will lead to the traffic volume that violates the capacity constraints. The initial penalty for this network problem is equal to 3.0 by applying the empirical results.

The step size, σ, controls both running time and quality of the results. If the step size is large, the running time will be fast but can lead to poor results. Figure 5.6 shows the difference between the traffic volumes in a capacitated link with various step sizes and the converged traffic volumes.

The traffic volumes traveling from node 3 to node 6 are considered. If the results have converged, the link capacity will be used up and the difference will be equal to zero percent. The results show that the barrier optimization method requires very fine step sizes in order to converge to the correct values. The barrier optimization method has a known problem that it will converge slowly at later iterations.

In order to solve this problem, a varied step size can be developed with larger steps to begin with and then reduced step sizes at later iterations. For this example, the finest step size, 0.001, is used.

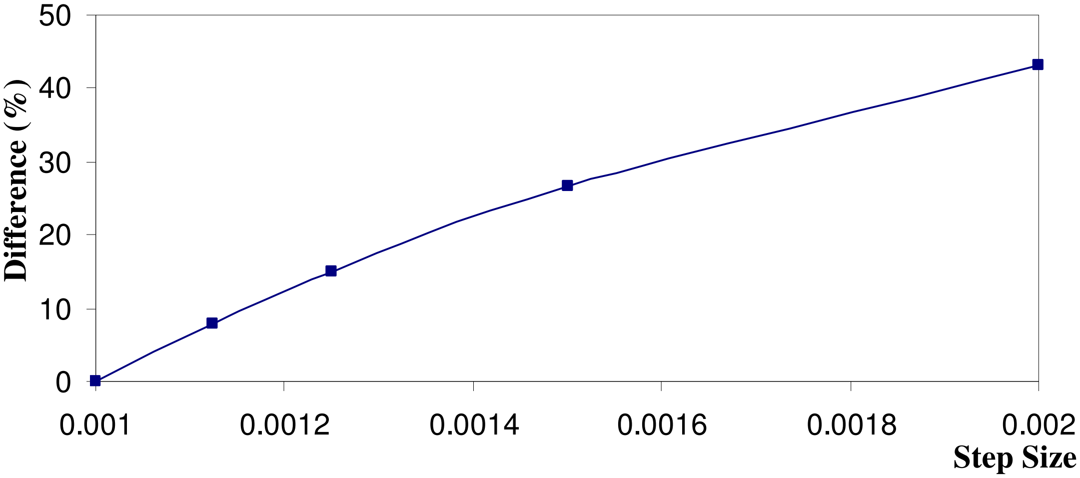


Figure 5.6 Relationship between step sizes and the flow difference (%)

5.4.2 Network Design Results and Branch and Bound Efficiency

Table 5.3 and 5.4 shows the comparison between the projects selected by the network design and the projects selected by a ranking process. A ranking process calculates the total travel cost (the upper level objective function) for each project when it is implemented individually. Traffic volumes are predicted by the lower level model for total cost calculations. The projects will be ranked in ascending order by their total costs. The first project has the highest priority to be chosen since it lowers the objective value the most. The number of projects that will be selected depends on the budget constraint.

Table 5.3 Project selections by ranking processes

# of Projects Allowed	Projects selected by Ranking Process					Obj fn Value
	1	2	3	4	5	
1	X					534
2	X	X				500
3	**X**	**X**	**X**			497
4	X	X	X	X		446
5	X	X	X	X	X	443

Table 5.4 Project selections by the network design model

# of Projects Allowed	Projects selected by Network Design					Obj fn Value
	1	2	3	4	5	
1	X					534
2	X	X				500
3	**X**		**X**	**X**		470
4	X	X	X	X		446
5	X	X	X	X	X	443

The comparison result turns out that the project selections are mostly the same except when the budget constraint is set to implement three projects. In this case, the ranking method yields the sub-optimal solution for the network design. By considering projects in a case-by-case basis, the ranking method fails to capture the benefit of combining projects 3 and 4 which will solve a bottleneck problem to access the rail mode. It proposes to implement projects 1, 2, and 3 which give the total carrier cost of 497.0 monetary units. In this small network, this problem can be anticipated by a human. For larger networks however, with more explicit capacity constraints on the links, the bottleneck problems can occur with more complicated situations, especially when the intermodal transportation is considered. Our network design model can detect these problems and gives the best solution for the network. It proposes to implement projects 1, 3, and 4 which give the total carrier cost of 469.9 unit costs. Table 5.5(a) and (b) show the link flows on the shipper and carrier networks for the existing condition, the condition when implementing the projects proposed by the ordering method, and the optimal condition given by the network design model.

Table 5.5The link flows for the existing networks and the improved networks

I	J	Existing Network		Improvement 1*		Improvement 2**	
		Cost	Volume	Cost	Volume	Cost	Volume
1	2	12.4	15.4	11.2	15.1	11.3	14.4
2	1	12.0	15.7	12.0	15.7	10.7	12.9
1	4	3.9	4.7	3.9	4.7	3.9	6.9
4	1	3.9	4.3	3.9	4.2	3.9	4.8
1	5	3.4	2.9	3.3	3.1	3.5	4.4
5	1	2.6	5.0	2.5	5.0	2.7	10.0
2	3	9.8	15.4	6.7	15.1	6.1	14.4
3	2	6.5	15.7	6.5	15.7	6.1	12.9
2	4	10.2	4.0	10.2	4.0	9.5	4.0
4	2	10.8	4.0	9.7	4.0	9.8	4.0
3	4	15.8	7.3	15.8	7.3	14.8	5.1
4	3	19.3	3.7	14.9	3.8	14.6	3.2
3	6	1.5	5.0	1.6	5.0	1.6	10.0
6	3	1.4	2.9	1.4	3.1	1.4	4.4
5	6	3.9	2.9	3.9	3.1	3.9	4.4
6	5	3.9	5.0	3.9	5.0	3.9	10.0
		Total Cost	1004.4	Total Cost	913.8	Total Cost	834.0

(a): The shipper network flows

I	J	Existing Network		Improvement 1*		Improvement 2**	
		Cost	Volume	Cost	Volume	Cost	Volume
1	4	1.6	7.4	1.6	7.2	1.7	9.4
4	1	1.5	4.6	1.5	4.4	1.5	4.8
1	7	1.9	15.7	1.9	15.8	2.1	16.3
7	1	1.2	20.5	1.2	20.5	1.2	22.9
2	3	7.5	19.1	3.4	18.9	3.2	17.6
3	2	3.1	23.0	3.1	23.0	2.7	18.0
2	8	3.7	27.0	3.7	27.0	3.0	22.0
8	2	4.6	23.1	3.1	22.9	4.1	21.6
3	6	0.6	5.0	0.6	5.0	0.6	10.0
6	3	0.5	2.9	0.5	3.1	0.5	4.4
4	8	1.8	10.3	1.7	10.2	1.7	9.7
8	4	1.6	11.5	1.6	11.5	1.5	9.1
5	7	0.6	5.0	0.5	5.0	0.6	10.0
7	5	0.5	2.9	0.5	3.1	0.5	4.4
5	6	3.0	2.9	3.0	3.1	3.0	4.4
6	5	3.0	5.0	3.0	5.0	3.0	10.0
7	8	1.4	12.8	1.4	12.7	1.3	11.9
8	7	1.9	15.5	1.9	15.5	1.4	12.9
		Total	610.6	Total	497.0	Total	469.9

(b): The carrier network flows

* The improvement proposed by the traditional case by case analysis

** The improvement proposed by the network design model

The branch and bound algorithm accelerates the optimization by cutting the time to call the lower bound for the nodes that cannot develop to the optimal solution. The number is of interest since the lower bound is a single process that requires significant computational time. Table 5.6 shows the number and the feasible solution for each budget level. It can be seen that the efficiency of the branch and bound depends on the budget level (and also investment costs). From Table 5.6, the branch and bound requires certain amount to call the lower bound before it begins to cut the unnecessary nodes efficiently. Therefore, the branch and bound will perform better in cases in which there are more feasible solutions. In case of three projects, the algorithm explores only 12 nodes while there are 26 feasible solutions.

Table 5.6 The branch and bound computational effort for each budget level

# of Projects Allowed	# of Feasible Projects	# of Lower Bound Calculations
1	6	10
2	16	11
3	26	11
4	31	5
5	32	8

The efficiency of the proposed algorithm depends on two considerations. The first one is the size of the transportation network of interest which relates to the efficiency of the lower level problem. The lower level model is solved using the logarithmic barrier method which is an efficient algorithm. Therefore the application of lower level problem to the real network should not require significant computational effort. The second problem is the number of improvement projects.

The branch and bound method will work much slower as project numbers increase. However, the number of projects that have direct impacts on the long haul freight network will typically be fairly small. If it is needed to consider large number of projects, the branch and backtracking proposed by Poorzahedy and Turnquist (1982) can be an alternative. It has a similar structure to our branch and bound algorithm but it improves the efficiency by only considering non-dominated scenarios.

The observation for this example suggests using a heuristic which examines only project sets that allocate all resources. Since the objective of our network design is to minimize travel costs, spending the budget to add more projects should result in a better network. This anticipation will reduce the number of project sets to be examined dramatically. However, this heuristic has an assumption that there is no Braess' Paradox and all projects contribute positive effects to the objective value.

5.5 CONCLUSION AND FORWARD TO CHAPTER 6

In this chapter, a network design model for long haul freight movements is proposed. A sequential shipper-carrier freight flow prediction model is used to represent the freight movement behaviors. Additionally, an explicit link capacity constraint is added to the traffic assignment in order to represent physical or psychological barriers to using some transportation links. In this study, the capacity represents reliability. It is assumed that the over capacitated links are unreliable and will be avoided by the shipper and carrier. A branch and bound algorithm is used to search for the optimal solution. In the next chapter, a case study for a larger network is implemented based on the same concept.

CHAPTER 6 CASE STUDIES

6.1 INTRODUCTION

This paper expands the long haul freight network design model developed by Apivatanagul and Regan (2008) (explained in Chapter 5) by conducting a case study on the California transportation network. The primary objective is to apply our network design model to a real transportation network and actual freight demand. The case study is a validation step that can demonstrate that useful problems can be solved with reasonable computational time.

Although the model concepts and the solution algorithm introduced are quite general, some details are modified to fit the case study. The freight model developed by Apivatanagul and Regan (2008) is explained first. The problem setting and the data base development is then described, followed by the solution algorithm. The result is the comparison of project selections made using the network design model and using case by case evaluation. The final section presents our conclusions and future research.

6.2 THE LONG HAUL FREIGHT NETWORK DESIGN MODEL

The main contribution of Apivatanagul and Regan (2008) is the application of the shipper-carrier freight flow prediction model to reflect freight route choice behavior and ultimately to design the optimal integrated network which combines multiple dense local network areas together. The binding of the multiple network areas takes place in the shipper or service network. The links in the shipper network are available transportation services linking strategic transportation points including large cities, rail stations, and ports together. Intermodal transportation is achieved through the transfer links created to connect different modes. The input to the shipper network is the freight demand between large cities. The output is the freight demand classified by modes between cities and intermodal facilities. Each carrier network represents a dense network area. It receives the shipper output, converts it into vehicle units and routes it to the highway or railway networks. The network improvements on the shipper network will result in mode shifts which are decided based on the origins and destination demands over long distances. The network improvements on the carrier network will aim to reduce travel delay and costs within narrower areas with predetermined transportation modes.

A branch and bound algorithm is applied to our freight network design model. The algorithm represents the upper level model by searching the best alternative within budget constraints. It will occasionally call the freight flow prediction model (the lower level model) to generate a lower bound to accelerate the search process. The application of the branch and bound algorithm is described in the solution algorithm section. The freight flow prediction model is more than an algorithm – it is also a traffic assignment process. That process is described subsequently. Figure 6.1 shows the process of interaction between the upper and lower levels.

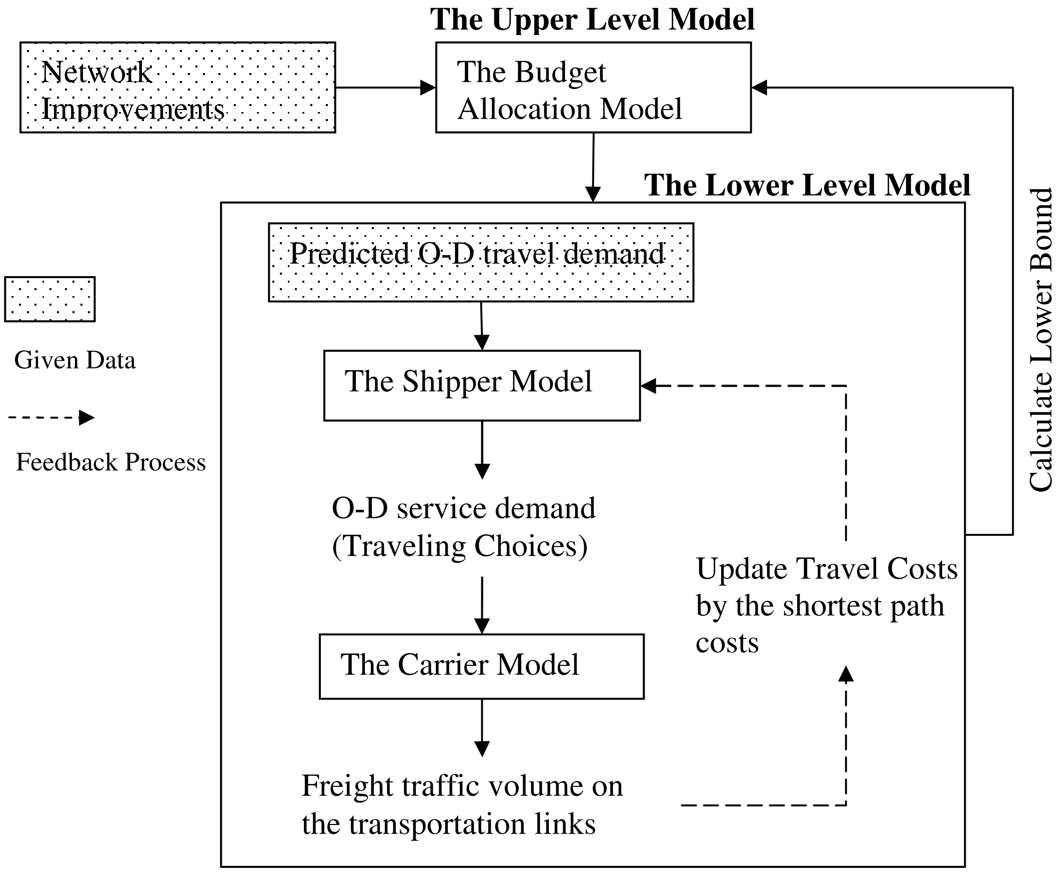


Figure 6.1 The Shipper-Carrier Network Design Model

The process is the same as that described in Chapter 5. The upper level model is a budget allocation model which is solved by the branch and bound algorithm. The proposed project improvements and the freight demand are assumed to be given. The upper model will suggest a subset of the project improvements to be examined by the lower level model. Since the branch and bound technique is used in this model, the lower level will calculate the lower bound associated the suggested projects. This information will be used by the upper model to recognize subsets that cannot achieve the best network design and suggest the next subset to the lower model. The cost function for each link is set based on the project selected for the link.

The lower level consists of the shipper model and the carrier model. The shipper model receives the freight demand and predicts its mode choices. The shipper model assigns the freight demand into the network of available services that minimize total costs. The service demand is used by the carrier model. The carrier model assigns the service demand to the highway or railway network to obtain traffic volumes. The lower bound is calculated by these traffic volumes and fed back to the upper level for further searching. In the next section, we describe the freight model developed for the California transportation network in more detail.

6.3 A CASE STUDY OF THE CALIFORNIA TRANSPORTATION NETWORK DESIGN

6.3.1 Upper Level Model

A freight network design model is developed for the California transportation network. The model uses the shipper-carrier network design concept. It can be used to design a robust integrated network for the whole US. However, this case study will only focus on the freight movements moving in and out of the state of California. The transportation network is developed based on the National Transportation Atlas 2007 Database USDOT and BTS (2007). The freight demand data is based on the 2002 commodity flow survey (CFS) data USDOT and BTS (2005). We assume that the base year is 2002 and the freight network will be designed for year 2022 with an annual growth rate of 3.4% per year USDOT and BTS (2003).

We assume that the transportation agency seeks to reduce the highway congestion. Therefore, highway travel time is the measure of social cost considered in the model. The upper level can be formulated as in Equations (6.1) to (6.3)

$$\underset{X_{lp}}{MIN} \sum_{l} \sum_{p} C_{lp} V_{lp} X_{lp} \quad (6.1)$$

subject to

$$\sum_{\mathrm{l}} \sum_{\mathrm{p}} F_{lp} X_{lp} \leq B \quad (6.2)$$

$$\sum_{\mathrm{p}} X_{lp} = 1 \qquad \textit{for } \text{all } l \qquad (6.3)$$

where

V_{lp} the truck volumes on the highway carrier link l when implement project p

$C_{lp}(V)$ time to transverse link l when implement project p with the truck volumes V_{lp}

X_{lp} the binary decision variable, equal to 1 if the project p for link l is implemented and equal to 0 otherwise

F_{lp} cost to implement project p for link l

B total available budget

The objective function minimizes the total cost to use the network. In this case study, this cost is total time for all trucks. The upper level varies project decisions to obtain the minimum value. The truck traffic will change according to the improvement project selected and is predicted by the lower level model. The projects must be within the budget. Equation (6.3) indicates that if there are multiple project levels for a link, only one level will be selected.

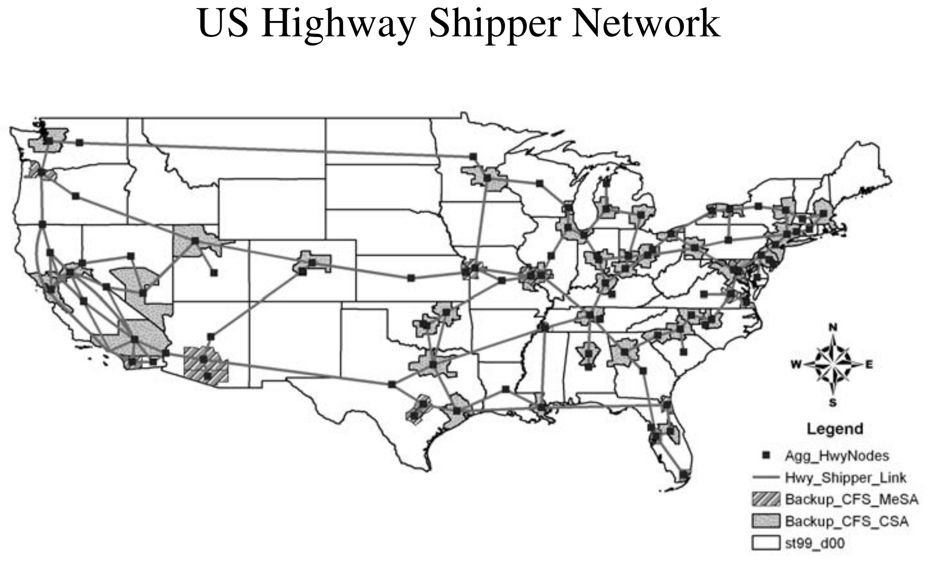
6.3.2 Lower Level Model: the Shipper Model

The lower level consists of the shipper and carrier networks. The shipper network has the railway and highway networks. The shipper network is developed to connect 43 Combined Statistical Areas (CSAs), 18 Metropolitan Statistical Areas (MSAs), 33 remainder areas of the states (excluding areas that are CSAs or MSAs), and 4 maritime ports within California (Ports of San Francisco, Sacramento, Los Angles and Long Beach). The freight demands (in tons) between the areas are obtained from the CFS data except for those related to ports. In order to examine the finer freight movements within California, the data is disaggregated to the ports and to three other areas of California. Employment data is used to roughly disaggregate the data. Note that this is a common approximation made in the absence of better demand estimation information.

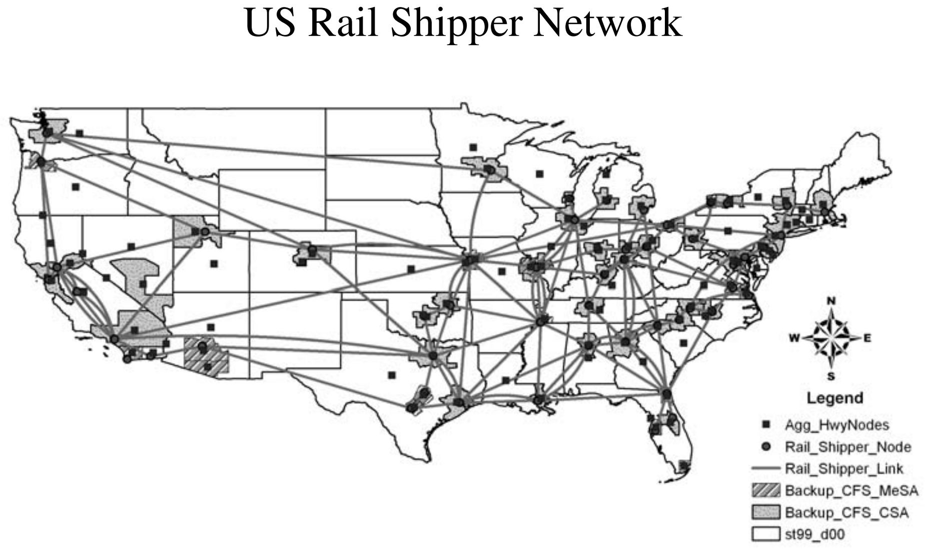
The data for this case study data was developed for the purpose of providing a “proof of concept” test for our model. If the model results were intended for implementation, much more effort and expense should be expended to develop the best possible inputs (both the network and the demand data) for the model.

The links in the shipper network are service links which are the shortest paths that connect all areas together. The highway network has the truck service links connecting all area centroids together. The railway network has the rail service links connecting all rail stations together. For each CSA or MSA, a virtual rail station is located at the centroid of the actual rail stations within the area. A transfer link is constructed between each area and its virtual rail station to allow for intermodal transportation. Additionally, the rail service links have parallel links offered by different companies. The transfer links between the rail services of different companies are provided to account the transfer costs. Figure 6.2 (a) and (b) shows the highway and railway shipper networks.

It is assumed that there is no congestion on the shipper network. Shippers also move a single commodity type with a truck service or a rail service and pay an average cost for each service. The average costs are estimated by the total revenue and total ton-miles from USDOT, et al. (2008) and ATA (1995). The average costs in 2002 constant dollars are 8.54 cents/ton-mile and 2.26 cents/ton-mile for truck and rail services, respectively. The transfer links between truck and rail services include penalty costs to represent the extra costs and time need to transfer containers. The links also have capacities in order to control excessive use of rail stations and local access links.



(a) The Shipper Network of Truck Services



(b) The Shipper Network of Rail Services

Figure 6.2 Developed US Shipper Network

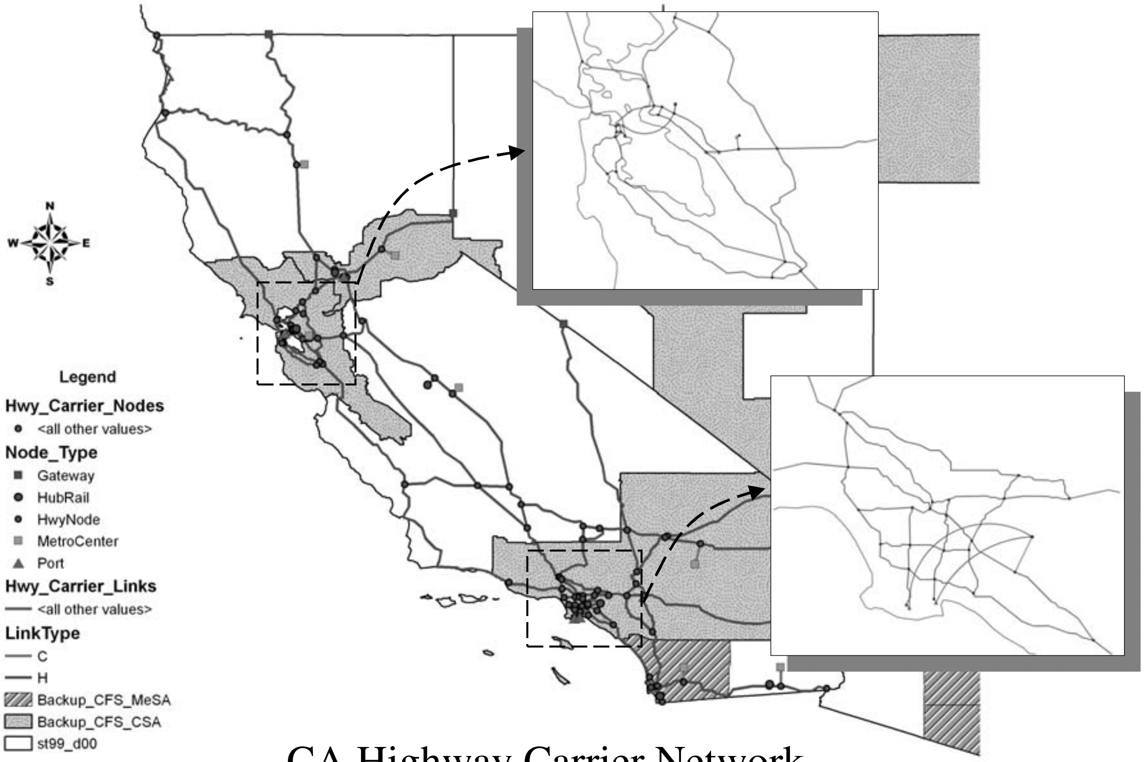
As the discussion in Chapter 5, the link capacity is used to represent the infrastructure limit due to many aspects that the static traffic assignment cannot capture. In the shipper model, the cheapest transportation modes are logically selected mode. However, many decision components that are combined to the total costs cannot explicitly considered such as reliability and other preferences. These barriers from unsatisfactory are set as capacity at the transport facilities including rail stations and intermodal facilities. In this study, it is assumed that the major disadvantage of rail mode and intermodal transportation happen at the provision activities when the vehicles leaving and arriving stations which include many inconvenience such as schedule, unreliability, and the poor assessment.

All or Nothing assignment with capacity control is used for the shipper model. The algorithm will be explained later in the solution algorithm section. In order to set the capacity, the freight demand is assigned to the shipper network with no usage limit at the transfer links. The value at the 95 percentile for all link usage is set to be the capacity. For this study, this it is estimated at 3540 tons/hour for rail stations in the state. A single penalty value is set to 19.12 cents/ton which will yield the market share in ton-miles between the two modes to 0.502:0.498 (rail:truck) in the whole US corresponding to the ton-mile market share ratio estimated by the CFS data.

6.3.3 The Lower Level Model: the Carrier Model

The carrier receives the service demand from the shipper and routes their vehicles corresponding to the demands while minimizing travel time. The service demand is converted from ton units to truck units and then to passenger car units. The ton-truck conversion factor estimated by USDOT, et al. (2008) data for the whole US is 5.03 tons/vehicle. However, this number is too small compared with the known market price about of $1.78/mile for truckload transportation USDOT and FHWA (2000). If the truck unit cost in ton-miles is assumed to be accurate, the carrier must load an average of 21 tons/vehicle to sufficiently substitute for the market price per vehicle. 21 tons/vehicle is used for the ton-truck conversion. The pcu-truck factor is 1.5 based on the latest Highway Capacity Manual (in flat terrain).

The transportation network for the carrier model represents the physical transportation network within the state of California. NTAD assigns the highway links that are used to do strategic planning. As shown in Figure 3, our case study adopted the NTAD strategic network within California as the carrier network. The centroids of CSAs, MSAs, ports, and the remainder areas connect to the highway network thru the centroid connectors. The rail service links connect the rail stations and the ports to represent the direct access. The service links have limit capacity but do not contribute to congestion on the highway network. It is assumed that the highway has congestion represented by the BPR functional forms. The capacity is estimated from the average number of lanes. A lane is assumed to carry 2200 passenger car units/hour. In order to reach the destination on time or leaving the congestion areas, the carriers minimize their travel times, resulting in a user equilibrium condition in the study area.



CA Highway Carrier Network

Figure 6.3 Developed California Carrier Network

6.3.4 Improvement Projects and Locations

A set of improvement projects is a required input for the network design model. The model will select the best subset of these according to the stated objective function. Relationships between the proposed improvement actions and link performance are very important. Until now, the primary measure of link performance was the BPR function –the relationship between road expansion and traffic speed. Clearly there is a need to study other measures related to transportation improvements.

In this case study, a set of improvement projects is designed to test whether our model can capture various pitfalls undetected when each project is considered separately. The network design model is expected to perform better budget allocation than heuristically picking the projects at the top of ranking. Various improvements can be tested on the network if they are related to travel costs in the shipper network or travel time in the carrier network. Sixteen projects are predetermined by carefully examining each link improvement and its benefit through the lower level model. All highway links in the carrier network are tested. The best four projects measured by the benefit cost ratio are selected for inclusion in our improvement proposal. The benefit is measured by comparing the total travel time under existing conditions and when a selected link receives an improvement. The improvement is a highway lane expansion resulting in an additional capacity of 2,200 pcu per hour. The cost is assumed to be a unit of monetary value. Four other projects are proposed for the same selected links but with two lane expansion (4,400 pcu per hour improvements). There are a total of eight highway improvement projects on the carrier network. Table 6.1 shows the information related to these projects.

The other eight projects are related to rail transportation. Four projects are related to rail capacity expansions accessing ports. The rail capacity is estimated by railway density between rail stations and ports. This information is obtained from the NTAD database. The density is represented by annual million gross ton miles per mile (MGTM/M) which is the standard measure provided by the Federal Railroad Administration (FRA). The railway links accessing the ports of San Francisco and

Sacramento have densities of around 0.1 – 4.9 MGTM per mile or roughly a one way traffic of six to 280 tons per hour.

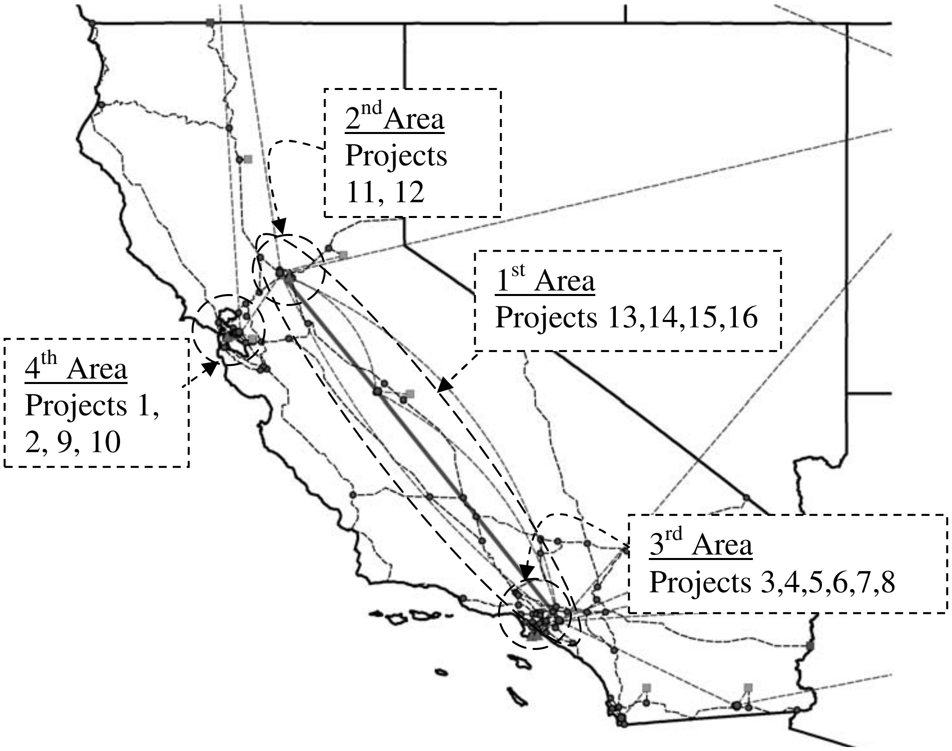
Table 6.1Project Improvement Information

Project	Cost	Benefit	B/C Ratio	Truck Benefit	Network Changes
1	1.40	11.08	7.91	7.39	Expand Highway Capacity from 8480 to 10680 pcu/hour
2	2.80	14.96	5.34	9.97	Expand Highway Capacity from 8480 to 12881 pcu/hour
3	15.12	83.05	5.49	55.37	Expand Highway Capacity from 8800 to 11000 pcu/hour
4	30.24	123.98	4.10	82.65	Expand Highway Capacity from 8800 to 13200 pcu/hour
5	10.85	47.23	4.35	31.49	Expand Highway Capacity from 8800 to 11000 pcu/hour
6	21.70	74.14	3.42	49.42	Expand Highway Capacity from 8800 to 13200 pcu/hour
7	5.25	22.71	4.33	15.14	Expand Highway Capacity from 11000 to 11000 pcu/hour
8	10.50	32.56	3.10	21.71	Expand Highway Capacity from 8800 to 13200 pcu/hour
9	5.56	25.04	4.50	16.69	Increase Port Access Capacity from 150 to 200 ton/hour
10	11.07	49.81	4.50	33.21	Increase Port Access Capacity from 200 to 250 ton/hour
11	0.70	3.85	5.50	2.57	Increase Port Access Capacity from 30 to 40 ton/hour
12	1.24	6.82	5.50	4.54	Increase Port Access Capacity from 30 to 50 ton/hour
13	3.29	-	-	-	15% rail price reduction (2.26 to 1.92 cent/ton-miles)
14	1.94	-	-	-	15% rail price reduction (2.26 to 1.92 cent/ton-miles)
15	1.94	-	-	-	15% rail price reduction (2.26 to 1.92 cent/ton-miles)
16	3.29	-	-	-	15% rail price reduction (2.26 to 1.92 cent/ton-miles)

* Existing Highway Capacity is the average capacity for the entire link length

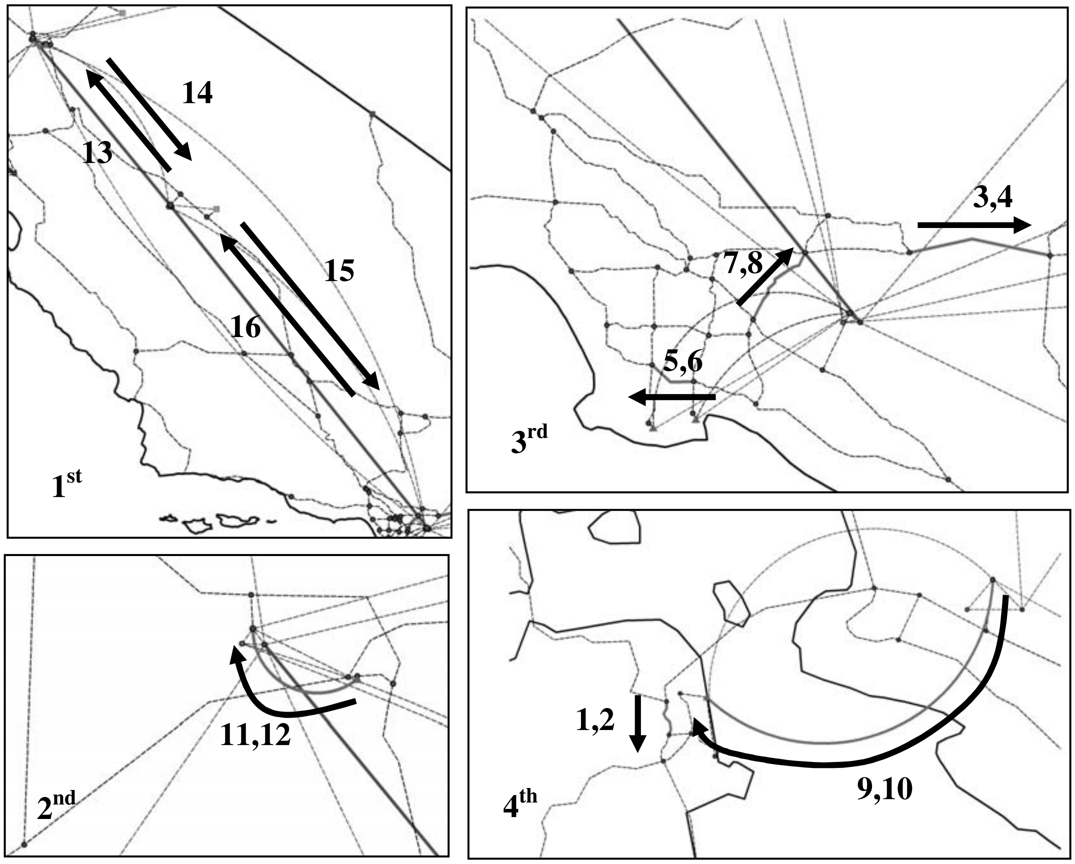
The rail links accessing the ports of Los Angles and Long Beach are reported to have densities around 40.0 -59.9 MGTM per mile. These densities are much higher than the predicted service demand. In this case study, the port access links are set to sufficiently handle the demand in year 2002 and the capacities correspond to the reported density. The port access links are improved as shown in Table 6.1. In order to create non-biased projects compared to the highway ones, the costs are set to have benefit cost ratios within the same range as the highway projects.

The other four projects are improvements on the shipper rail links. These improvements show the benefit of the shipper-carrier model which can capture the mode shift resulting from improvements. The mode shift indirectly benefits the highway network. A scenario which results in a poor outcome (a pitfall) is constructed to test the network design model from these four improvements. The model must know how to pair the projects to receive their benefits. Projects 13 and 16 together will give benefit of 30.7 truck-hours in a total travel time reduction. Projects 14 and 15 together will result 18.1 truck-hours in a total travel time reduction. Implementing such rail improvements could be accomplished by investing in improved technologies such as double stacked trains. Figure 6.4 (a) and (b) shows the projects on the network.



(a) Summary Improvement Locations within California

Figure 6.4 Improvement Project Locations



(b) Enlarged Areas with Link Improvements

Figure 6.4Improvement Project Locations (cont.)

6.4 SOLUTION ALGORITHM

The solution algorithm for this case study is similar to the process explained in Chapter 5 and is rewritten here for the completion of this chapter.

6.4.1 The upper level model: Branch and bound algorithm

The branch and bound algorithm is a conditional tree search. The nodes in a binary search tree are either partial solution nodes or complete solution nodes. If we assume that there are P projects proposed to improve the network, then the complete binary tree will have 2^{P+1}-1 nodes with 2^P complete solution nodes at the final depth. Each node contains P decision variables. Each project has a fixed position ranging from 1 to P. If a project is selected for implementation, the decision variable at its corresponding position is set to one; otherwise it is set to zero. At the root of the tree, the node is a partial solution node which has no fixed decision variables meaning that the variables are free to set to zero or one. For each depth of the tree, a decision variable will be fixed in the order from the first project to the last one. The complete solutions are at the final depth with all decision variables having fixed values. The branch and bound algorithm is used to cut out the nodes that lose potential to develop the optimal solutions so that the complete tree need not be examined.

For the network design with the formulation as shown in Equations (6.1) to (6.3), the branch and bound algorithm is constructed as follows:

Step 0 Initialization: All decision variables at the root node will be set to zero with no fixed variables. The node is an unvisited node. The incumbent value, which is the best objective value that the search tree has found so far, is set to infinity or a high value by default. One way to obtain the initial incumbent value is to simply select network improvement projects until the budget limit is reached. Go to Step 1.

Step 1 Node Selection: Select an unvisited node. A node in the deepest level is selected, therefore the branch and bound will do a depth first search. The depth first search can be beneficial if an initial incumbent value is difficult to find. Go to Step 2.

Step 2 Check Budget Constraints: For the selected node, the budget constraint is checked. The summation of the capital costs for the projects which their corresponding decision variables fixed must be less than the budget limit. If there are multiple project levels for a link, we also check that only single project is implemented. Return to Step 1 if either constraint is violated and set this node as visited (not to be explored further), otherwise continue to Step 3.

Step 3 Check for the Completed Solution: Assume that the tree depth is equal to zero at the root. Go to Step 4.1 if the node does not have the tree depth equal to P, when there are P projects proposed for the network. Otherwise, go to Step 4.2 with the node that has the complete solution.

Step 4 Call the lower level model:

Step 4.1: Calculate the lower bound using the lower level model. Go to Step 5.1.

Step 4.2: Calculate the objective value of the updated network. The update is done by replacing the cost coefficients on the links which receive the improvements. The traffic volume used to calculate the objective value is obtained by calling the lower level model. Go to Step 5.2.

Step 5 Compare the value with the incumbent value:

Step 5.1 Pruning Decision: Go to Step 6, if the lower bound of the selected node is less than the incumbent value. Otherwise it means that its child nodes cannot produce the optimal solution. The node will be fathomed and marked as a visited node. Go to Step 7.

Step 5.2 Setting the New Incumbent Value: If the selected node has the objective value less than the incumbent value, a new incumbent value and a new current best solution are set. Otherwise, these remain the same. Set the selected node as a visited node. Go to Step 7.

Step 6 Branching: the selected node will give two child nodes with the tree depth increasing by 1. If the selected node depth equals to h, the child nodes will have the tree depths equal to $h+1$. To enumerate the solution, the improvement project at position $h+1$ will be fixed to zero for the left child node and to one for another. Set the selected node as a visited node. Go to Step 1.

Step 7 Stopping Criteria: The algorithm stops when all nodes are visited. The current incumbent solution will contain the transportation network which optimizes the objective value.

A lower bound is used as criteria to decide whether a node will be explored further. The lower bound is the lowest total cost (truck travel time) that corresponds to the selected partial solution. Assume that currently undecided projects will be implemented and assign freight flows to the network. The truck volumes on the carrier network are used to calculate the total travel time lower bound. Different route choice behaviors will result in different lower bounds. The tightest lower bound can be calculated by using the lower level model to predict flow directly. Leblanc (1975) shows that the user equilibrium behavior can cause the Braess' Paradox -- meaning that implementing improvement projects can lead to worse traffic condition. In order to calculate the lower bound without the paradox problem, Leblanc (1975) uses the system optimal behavior instead. We adopt that approach to calculate our lower bound.

6.4.2 The lower level model: The Shipper-Carrier Freight Flow Prediction Model

The lower level model is a traffic assignment process. As shown in Figure 6.1, the shipper model receives the freight demand and performs its traffic assignment to yield the service demand. In our shipper network, it is assumed that there is no congestion but there are capacity limits for access to rail services. Its traffic assignment is the incremental all or nothing assignment avoiding overflow link capacities. The demand is partitioned into smaller parts. The smaller freight volumes allow the demands that travel from different origins and destinations to share the available capacity equitably. In the beginning, the truck-rail transfer links will have full capacity. When the flow is assigned to the link the capacity is reduced. This reduced capacity is called the reserve capacity.

The demands are assigned to their shortest paths using the following steps.

<u>Step 1 Calculate the Path Capacity</u> : For each pair of an origin and a destiantion, calculate the capacity of its shortest path. The capacity is equal to the least reserve capacity of all links constructing the path.

<u>Step 2 Assign the Demand Volume</u> : Compare the demand volume with the path capacity. If the volume is less than the path capacity, assign all the volume. If the volume is more than the path capacity, assign the volume equal to the path capacity.

<u>Step 3 Update the Reserve Capacity</u> : All reserve capacities are updated by minus the current reserve capacities and the assigned flow. If a reserve capacity is equal to zero, update its link cost to infinity value to prevent the future use.

<u>Step 4 Prepare the Demand Volume</u> : If all demand cannot be assigned, the remaining demand will be added to the demand considered in the next assignment iteration.

When the all or nothing assignments are implemented for all demands, the remaining demand is assgined to the truck services which do not have capacity limits.

The carrier model receives the service demand from the shipper model output, converts this to passenger car units and assigns it under the user equilibrium assumption. The assignment can be written using the Beckman Formulation and solved by the Frank-Wolfe algorithm. Ideally, the passenger demand should also be assigned to the highway network since passengers share the highway capacity with trucks. In this case study, the model is simplified by preloading the highway links with their annual average daily traffic. For the rail freight volumes that connect to ports, the volumes can use rail links directly to access ports according to predefined link capacities. These freight volumes are deducted before assigning the demand to the highway network.

6.5 RESULTS

In order to validate that our network design model can be applied to real applications, its results and computational time must be examined. If an hourly average demand is considered, the existing network condition gives the total travel time of 5273 truck-hours. The improvements reduce this total travel time.

The results are compared with the project selections when a ranking method is used. The ranking method sorts the projects from the highest benefit to the lowest and then selects projects until the budget is expended. The budget is 44.0 monetary units – for the purposes of this study this represents 50% of the cost of all candidate projects. As shown in Table 6.1, if the projects are sorted by their benefits, Projects 1, 4, 10 and 12 would be selected. The total travel time gained from these projects is 5149 truck-hours. If the projects are sorted by their benefit-cost ratios, Projects 1, 3, 5, 10, 12 will be selected and give the total travel time of 5145 truck-hours. We raise a hypothetical case in which in order to realize the full benefits of projects 13, 16 and 17, they should be implemented together. We further assume that the decision maker using the ranking method understands this situation. In that case, the ranking by benefit-cost ratio will select Projects 1, 3, 10, and 12-16 which gives a network benefit of 5127 truck-hours. In order to initialize the network design model, projects selected by the ranking by benefits is used to obtain the initial incumbent solution. The network design model then selects Projects 1, 3, 5, 7, 11, and 13-16 with a benefit of 5112 truck-hours. These results show that our model can more effectively allocate the budget more than the ranking method.

Budget sensitivity is tested using budgets set at 40 % and 60% of the total potential investment cost. The results are Projects 2, 3, 7, and 12-16 (5139 truck-hours savings) and Projects 3, 5, 7, 10, and 12-16 (5089 truck-hours savings) for the 40% and 60% budgets respectively. The common selected projects are Projects 3, 7, and 12-16. The running times are 1252, 1164, and 1137 seconds for 40%, 50%, and 60% budgets respectively (performed using an Intel Pentium 1.60GHz machine with 512 MB of RAM). The branch and bound algorithm creates 1014, 1163, and 920 search nodes for the 40%, 50%, and 60% budgets. It calls the lower level model 512, 473, and 465 times, representing approximately half of the search tree each time. These results should be compared with the total possibility to construct the scenarios for 16 projects. If the 16 projects are independent, the possibility is 65536 scenarios. However, 12 of our projects are dependent (expansion levels 1 and 2), therefore the possibility is 11664 scenarios. The comparisons show that the branch and bound algorithm is able to efficiently search for the best solutions.

The next question is the maximum number of independent projects that the algorithm can practically handle. While we could examine this question empirically by iteratively adding additional projects, we can also estimate that each additional project should double the required computational time. However, we believe that effective engineers/planners could identify good initial solutions that would reduce the size of the search tree significantly. That said, if we assume that a practical time frame to run a strategic planning program is 24 hours and that in our case study, ten independent projects are input into the network design model with an approximate running time of 20 minutes. We estimate that the maximum manageable number of independent projects (without expert understanding) is16. This number is sufficient for a budget allocation for competitive projects for a strategic network within a state. However, if much larger sets are to be examined – a heuristic partitioning scheme can be used to discretize the network into smaller sub-regions and then the partitioned solutions can be combined.

6.6 CHAPTER CONCLUSION

In this chapter, a network design model for long haul freight movements are constructed based on that proposed earlier by Apivatanagul and Regan (2008) described in Section 6.4. The relationship between shippers and carriers are represented in the lower level model which is used to predict the traffic volume on the highway or railway networks. The shipper model selects the transportation services and the carrier model routes vehicles based on this demand. The lower level model will interact with transportation improvements either through route changes or mode shifts. A branch and bound algorithm is used to search for the best set of improvement projects. A case study to improve the California highway network is implemented.

Using public databases, the shipper and carrier networks are constructed. A simple calibration is implemented by setting penalty costs at transfer links. The penalty costs provide the shipper network which has a realistic market share between truck and rail services. Additionally, the link capacity limits are introduced as a means to control unrealistic use of specific facilities. The traffic assignment approaches and the branch and bound algorithm applied to our model are explained.

A comparison between the ranking method and the network design model is performed. Many criteria are used to select the projects with the ranking method, however the network design model appears to give the best answers. The result shows that the network design model can be used to efficiently allocate the budget.

Additionally, the model can capture effects of competition, substitution and synergy. The branch and bound approach works well to reduce the search time. However, the integer optimization efficiency will deteriorate fast with additional integer variables. We estimated that our model can easily handle up to 16 independent projects without resorting to project specific expert knowledge which could produce a good initial incumbent solution. If transportation agencies need to explore more projects, expert knowledge or a heuristic approach should be performed.

In conclusion, this chapter provides evidence that the long haul freight network design model described can be implemented for real world applications. Existing public databases are sufficient to develop introductory shipper and carrier networks. The solution algorithm proposed works reasonably well.

CHAPTER 7 CONCLUSION AND FUTURE RESEARCH

7.1 SUMMARY

In this dissertation, freight network design models are developed. The model frameworks are developed considering the special nature of freight movements. The bi-level approach is used to formulate the mathematical models for this network design problem in order to represent different behaviors and their interactions between transportation agencies and network users.

Chapter 1 clarifies the problem statement, the goal, and tasks. The increasing freight demand, budget limit, and complexity to improve a transportation network leads to a necessity to develop a freight network design model. The goal is to formulate the best practice of the freight network design models by three main tasks. The first task is to develop the framework while the second task is to consider the freight route choice behaviors for the model. The final task is to develop a corresponding solution algorithm.

Chapter 2 reviews research papers and reports related to network design, freight flow prediction models, network design solution algorithms, and current practices on freight studies. The chapter provides the comparison among many network design models which are applied for different studies. It reviews number of solution algorithms that are used in different modeling situations. The limitation of current freight studies reviewed in the chapter also provides evidence of the need of the network design development.

Chapter 3 provides the background and the directions for our network design model and expected future research. The chapter begins with a discussion of the transportation network characteristics. A network can be considered as a regional network and an inter-regional network. A regional network considers the movements within a study area while an inter-regional network connects study areas together. The transportation modes for long-haul freight movements are decided based on the travel costs in the inter-regional network. However, the regional network also has a significant role on the decisions since unreliable services near origins and destinations can prevent users to select particular transportation modes. Later in the chapter, it discusses the general concept of the bi-level network design frameworks and broadened in order to embrace a wider variety of measures and points of view. Various network design models are formulated based on previous research.

Chapter 4 focuses on freight network design for long haul movements traveling between geographic regions. The chapter discusses possible analysis tools for the freight planning problem and suggests improving the local network information in the traditional four step model through centroid connectors. Simulation models can be used to substitute data needed for this improvement. The integrated network importance, which is a concept to consider both regional and inter-regional networks, is emphasized. The integrated network should maintain competition between modes therefore movements are allowed to travel into and out of the studying area through the use of external nodes. A discussion for necessary components to develop the freight network design is presented. A network design for an inter-regional freight movement is formulated. An example is given and solved by an iterative process between the upper and lower level model. The example shows the importance to develop a network design with the integrated network concept. It also suggests improving the solution algorithm.

Chapter 5 improves the freight network design by introducing a shipper-carrier freight flow prediction model into the lower level problem. The shipper-carrier model is considered to be a compromised approach to combine mode choice decision to the network design model. A branch and bound algorithm is applied to solve the problem. Additionally, certain links are controlled by capacity constraints in order to represent unreliability resulting from congestion. An example is given and solved by the branch and bound algorithm. The project selections from network design models are compared to the selections by ranking processes. The example shows that network design models can recognize the complementary effects from project improvements and consequently provide a solution which solves bottleneck issues.

Chapter 6 implements a case study based on Chapter 5 concept for a larger network. The case study focuses on the improvements on the highway and railway network in California. The long haul freight demand is decided by the shipper model which represents the truck and rail services traveling between 48 states within the US. The service demand within California is assigned into the highway network by the carrier model. Penalty values are used for simple calibration with the shipper model. It is assumed that reliability problems are most likely happen around the truck-rail transfer facilities. Therefore, capacity limits are used to prevent links connecting rail and truck services to be excessively used. An all-or-nothing assignment is used in the shipper model. A user equilibrium traffic assignment is used to route the trucks onto the carrier highway network. A branch and bound algorithm is applied to the case study. The case study shows that freight network design based on the shipper-carrier prediction model can be implemented with existing data. The project selections from the network design model shows that the model efficiently allocate the limit budget. The computational result provides evidence that a branch and bond algorithm can be used for a large network.

7.2 FUTURE RESEARCH

In this dissertation, the long-haul freight network design model frameworks, formulations, and solution algorithms are developed. However, there remain some challenges for the successful implementation of our approach. The challenges can be classified into three areas which are the improvement of an upper level model, of a lower level model, and other studies.

7.2.1 Upper level model

For the upper level problem, the algorithm which can handle with the larger network and more projects is needed in order to attack the real world problem. If only the capacity expansion is considered, the continuous network design approaches (e.g Abdullal and LeBlanc (1979), and Hoang (1982)) are a good alternative. The approach has been proved to be faster but less flexible since only project improvements that change capacity can be considered. In this continuous approach, cost functions related to a capacity and a traffic volume is required with other parameters such as a fixed cost to be constant.

The meta-heuristics are another alternative since they are flexible to apply for any general problems. Furthermore, the multi-objective optimization which is an interesting possibility for network design problems can be implemented using meta-heuristics. Although the generalized cost can be converted the multi-objective optimization to the single objective optimization, the cost conversion factors are controversial. The solution at the Pareto optimal conditions for the multi-objective optimization can be more beneficial in the decision making process. If a freight network design model can consider multiple objectives, many improvement types can be considered together without the bias inherent in monetary conversion factors.

7.2.2 Lower Level Model

More advanced traffic assignment methods, such as dynamic traffic assignment, may be needed to reflect more realistic traffic conditions. However, at this time, the commodity flow survey database does not support such techniques. Further, implementing a more complicated assignment method will significantly increase computational time. A static traffic assignment is therefore considered appropriate for strategic planning at the present time. This can be improved by adding more commodity types and multiple service levels when these data become available. Note that not all traffic assignment techniques are appropriate for this network design model. Considering path based static assignment, the new route choices are predetermined and therefore the assignment cannot create new routes corresponding to new improvements.

Beside the improvements on the traffic assignment techniques, work on the relationships between the shipper and the carrier or among other agents on the freight route choice process is important. An advantage of the freight network equilibrium is the shipper and the carrier traffic assignment models can be developed as a simultaneous model. If a sequential approach is accepted, a development of logit models for the shipper decisions is an interesting possibility. Since the major travel paths from an origin to a destination are limited in reality, the uses of the freight flow equilibrium model for the shipper-carrier network in order to predict the paths may be redundant. Although the logit models have limited route information, the models have the advantage to explicitly consider the shipper's preference factors. However, it should be noted that the upper level must be adjusted to match this change.

7.2.3 Other Studies

The most important tasks that will increase the value of this research are related to network calibration. For the shipper network, information related to existing services offered by carrier companies should be used to provide a more realistic shipper network. Gathering such data is not only expensive – much of it is confidential and therefore not accessible except in aggregate forms. In addition, in an actual implementation study careful attention to setting the costs and capacities for transfer points is essential. These data too could be difficult to obtain. The carrier network should be calibrated based on truck survey data which shows the percentage of truck traffic in each highway link. In California, these data are widely available but are not updated very often (perhaps every two years) and are based on the study of a single (representative) day. However, in the future these data will be more accurate.

Another future research that should be conducted is to estimate average centroid connector costs. Centroid connectors are given significant roles as connections between local network studies and inter-regional network studies. Similarly, the service transfer links are important as a connection between different modes. If there are project improvements for a local network or an intermodal facility, a proper model should be constructed to study improvement impacts on them. The data from the study can be used to estimate typical transport costs before and after the improvements. These costs will be used to study larger impacts on the inter-regional network that connecting other local networks together. A suitable statistic approach to analysis the data from simulation model and estimate these costs is required.

Relationships between the proposed improvement actions and link performance are very important. Until now, the primary measure of link performance was the BPR function –the relationship between road expansion and traffic speed. Clearly there is a need to study other measures related to transportation improvements.

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