# UC Berkeley
## Earlier Faculty Research

**Title**

A Solution Algorithm for Long Haul Freight Network Design Using Shipper-Carrier Freight Flow Prediction with Explicit Capacity Constraints

**Permalink**

https://escholarship.org/uc/item/7v1185pz

**Authors**

Apivatanagul, Pruttipong "Palm"
Regan, A C

**Publication Date**

2008

# A SOLUTION ALGORITHM FOR LONG HAUL FREIGHT NETWORK DESIGN USING SHIPPER-CARRIER FREIGHT FLOW PREDICTION WITH EXPLICIT CAPACITY CONSTRAINTS

**Pruttipong "Palm" Apivatanagul**
**Institute of Transportation Studies**
**University of California, Irvine**
**Irvine, CA 92697-3600**
papivata@uci.edu

**Amelia C. Regan**
**Department of Computer Science and**
**Institute of Transportation Studies**
**University of California, Irvine**
**Irvine, CA 92697-3600**
aregan@uci.edu

**Submission Date:**

**Word Count:** 6,137 words
**Tables:** 3 Tables
**Figures:** 2 Figures

**Total Word Count: 7,387 words**

**ABSTRACT**

Freight transportation has long been recognized as an important foundation of economic strength. Previous studies use traditional methods to examine a set of scenarios. However, due to the complexity of transportation projects which can have substitution effects in a network the number of resulting scenarios may be more than can be examined on a case by case basis.

In this paper, a sequential shipper-carrier freight flow prediction model is examined. Additionally, an explicit capacity constraint is used to divert the traffic volume from congested links. A branch and bound method is applied to obtain a solution to our model. We discuss the benefits and limitations of our method, examine its computational efficiency and provide a numerical example. The results show that project selection by the traditional case by case analysis method cannot capture the complexity of freight transportation network improvements and yields the sub-optimal solution.

## INTRODUCTION

Freight transportation has long been recognized as an important foundation of economic strength. Demands for long haul freight movements continue to grow due to increasing international trade. This increase drives the need for major infrastructure improvements at the local, state and federal level. Many states have undertaken recent freight planning studies ((NJDOT and PBQD, 2004), and (USDOT and FHWA, 2005)).

Previous studies use traditional methods to examine a set of scenarios. However, due to the complexity of transportation projects which can have substitution effects in a network, the number of resulting 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 and the 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.

In recent year, the 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, Xu and Xie, 2001) applies their model to the Chinese railway network. However, none of earlier research considers explicit freight behavior and a multimodal perspective. Our work seeks to develop a model and corresponding solution algorithm which carefully considers these two aspects of the long haul multi-modal freight network design problem. The primary focus of our paper is freight route choice behavior. A sequential shipper-carrier freight flow prediction model is used and a branch and bound method is applied to obtain a solution. Additionally, an explicit capacity constraint is used to divert the traffic volume from congested links which are unreliable. We discuss our technique, its benefits and limitations and examine its computational efficiency.

## LITERATURE REVIEW

The network design problem can be modeled as an integer programming optimization problem considering dealing the network improvement decisions. (Magnanti and Wong, 1984) shows that

many combinatorial transportation planning problems are special forms of network design problems. Network design problems can have different settings. In this paper, we model a capacitated discrete budget allocation problem with non-linear routing costs. Given an existing network and budget constraints, the problem is to choose the set of improvement alternatives to optimize the network efficiency criteria. 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. We begin our literature review with papers related to freight route choice behaviors. Then the solution algorithms for discrete budget design problems will be reviewed.

The freight flow prediction models are used to reflect the freight route choices on the transportation network. One of differences between freight and passenger movements is that the freight route choices are cooperative decisions made by multiple agents. The two primary agents in the decisions are the shipper and the carrier. The shipper is a transportation customer who wants to move commodities from one point to another. The carrier provides transportation services for these demands. There are three general approaches used to predict freight flows (Harker, 1987). 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. That model is very useful for studying the impact of various policies on the transportation market but it cannot detail the flows on transportation links. The spatial price equilibrium model focuses instead on producers, consumers, and shippers. That model predicts freight flow demand by equilibrating demand and supply in different regions through a simplified network representation. Each node represents a region and direct links represent costs to travel among all regions. The last model is the freight network equilibrium model. That type of model is the focus of our work 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 freight network equilibrium is similar to passenger traffic assignment except that many agents are considered. Two distinctive earliest models 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). The paper is explained later in (Friesz, Gottfried and Morlok, 1986). 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, Viton and Tobin, 1985) improves the model and loads both networks simultaneously. (Harker and Friesz, 1986a) and (Harker and Friesz, 1986b) 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, Cea and Soto, 2003) develops a new modeling approach to a simultaneous shipper-carrier model with more advance trip distribution and mode choice formulations.

At least two freight flow prediction models have been developed and tested using real data. (Friesz, Gottfried and Morlok, 1986) uses the shipper-carrier freight flow prediction model for the US rail network. (Guelat, Florian and Crainic, 1990) assumes that shippers' behaviors is already included in OD estimation. Therefore, their model is similar to the carrier model of (Friesz, Gottfried and Morlok, 1986). Their transportation network is modified with virtual links and nodes to provide intermodal transfers. The Brazil transportation network is presented in that paper.

Network design problems can have many settings such as introduced in (Magnanti and Wong, 1984), (Friesz, Viton and Tobin, 1985) ,and (Yang and Wang, 1998). The problems can have fixed or varied costs, budget constraints, or capacity constraints. If the users' route choice behaviors cannot be controlled, bi-level optimization is usually used to simulate the different objectives of the users and the transportation agencies. In the bi-level setting, the upper level model represents the decision makers who choose the projects based on the social benefit while the lower level model represents network users who travel under route choice behavior assumptions. General network design problems are known to be NP- complete ((Johnson,

Lenstra and Rinnooy Kan, 1978)) which means there is no known algorithm to solve problems efficiently to optimality.

In this paper we examine the network design problem with discrete decision variables. The models are usually bi-level since the route choices are decided by network users. The solution algorithms for such discrete optimization problems typically use implicit enumeration and incremental solution improvements. The optimization techniques for this problem type can be Bender's decomposition ((Hoang, 1982)), and branch and bound algorithms ((Boyce, Farhi and Weischedel, 1973) and (Leblanc and Boyce, 1986)). Recently meta-heuristics have also been used ((Friesz, et al., 1992), and (Friesz, et al., 1993)). In our research, we use a branch and bound algorithm.

Branch and bound algorithms construct a binary search tree to enumerate all possible solutions but accelerate the search process by pruning the search tree and eliminating nodes that cannot contain the optimal solution. At each node, some decisions are fixed and others are explored. A lower bound will be obtained for each node. If it is worse than the current best solution, the node will be excluded from future consideration. The algorithm stops when all nodes are excluded (also known as fathomed) or explored. The current best solution at the end is the optimal solution. The branch and bound algorithm can be viewed as the upper level model while the lower level model is used to calculate the lower bound. For network design problems with fixed link costs (Boyce, Farhi and Weischedel, 1973) proposes that a lower bound for a node is the upper level objective value when all undecided projects are set to be implemented. Network users are assumed to use the shortest paths. Tighter lower bounds are proposed by (Hoang, 1973). (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 the congested network 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. For highway network design, the typical network design objective is to minimize the total delay while the road users optimize their own benefits causing the traffic conditions to converging to

user equilibrium condition. (Leblanc, 1975) uses a branch-and-bound algorithm to solve small problems optimally. The lower bound is calculated similar to (Boyce, Farhi and Weischedel, 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 the pitfall, the traffic volumes are assigned using system optimal routing instead of user equilibrium routing. This makes the lower bound looser. In order to deal with larger networks, several heuristics are developed. (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. (Haghani and Daskin, 1983) proposes an extraction algorithm for network design. In their algorithm, the links which have less traffic volume than a specific point 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. An alternative for larger networks is to use a decomposition method which moves from larger networks to smaller sub-networks. (Solanki, Gorti and Southworth, 1998) clusters the sub-networks in a hierarchical order and performs network design for each cluster separately. Although, that paper uses a fixed cost network, it can be adjusted to be applied to networks with nonlinear link costs.

**METHODOLOGY**

Our network design model is a bi-level model. An upper level model decides how to improve a given network by selecting a set of improvements. The lower model represents the transportation network users' behavior and determines traffic flows on the network. For the upper level model, implicit enumeration is performed by the branch and bound algorithm. In the branch and bound algorithm, the lower level model works as a sub-model which predicts traffic flows at each node of the branch and bound search tree. A shipper-carrier freight flow prediction model is used for the lower problem. The following variables are generally used in this paper:

**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 |
| $k$ | traveling 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 |
| --- | --- |
| $C_{mlp}(V)$ | 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 d to a destination d |
| $q_m^{od}$ | freight demand of commodity m from an origin d to a destination d |
| $u_l$ | capacity of link l |
| $\delta_{l,k}^{od}$ | link-path incidence matrix |
| $X_{lp}$ | 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 lower level problem: freight flow prediction**

The shipper-carrier freight flow prediction model is introduced in (Friesz, Gottfried and Morlok, 1986).The model develops the traffic assignments on two networks namely, the shipper network and the carrier network.

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. It is assumed that the shipper has limited information on detailed route choices. Therefore, 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.

The shipper model routes freight from one business district to another while minimizing travel costs. The shippers are assumed to be non-cooperative users. Therefore the traffic volume will result in the user equilibrium. After the shipper model routes these demands, the traffic volume on each service link will be converted to freight demands that are separated by modes and will be used by the carrier model.

The carrier model receives the freight demands data from the shipper model and routes these demands to the real world transportation network. This network includes intermediate nodes where to represent intersections, ramp locations, and different geometric designs such as differing numbers of lanes. In practice, the centroids are connected to the transportation network through centroid connectors. In addition to business centers, the freight volumes are also initiated from intermodal facilities. These volumes are secondary travel demands created by the shippers who decide to move commodities by intermodal services. Although, the intermodal facilities are explicitly shown in the carrier model, the carrier model does not decide whether the freight will use the facilities. These decisions are made by the shipper model. Therefore, the freight volumes are assigned separately for each transportation mode. The carrier behaviors differ by transportation mode. On the highway, carriers who provide truck 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 be result.

The traffic assignment for shipper-carrier freight flow prediction models can be solved using sequential (Friesz, Gottfried and Morlok, 1986) or simultaneous ((Friesz, Viton and Tobin, 1985) and (Fernandez, Cea and Soto, 2003)) models. In this research, a sequential model will be 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. Our lower level model can be considered as traffic assignment models on three separate networks. The first one is the shipper or transportation service network which combines both truck services and rail services. The routings on this network can open multi-modal routes. The second network is the highway network. The carrier will decide how to route trucks on this network. 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. The third network is the railway network. The carrier will decide to route freight volume to minimize their costs in their networks. In the case of multiple commodities, each commodity will be assigned sequentially by its priority. Therefore, the generalized mathematical model for each network and each commodity can be written by applying the Beckman's Formulation.

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

(Eq.1a)

subject to

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

(Eq.1b)

$$f_{k,m}^{od} \geq 0 \qquad \forall\; k,o,d$$

(Eq.1c)

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

(Eq.1d)

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

(Eq.1e)

In this study, the explicit link capacity constraint, Equation 1(e), is added to the traditional formulation. A major problem of the static traffic assignment is it cannot detect dynamic congestion or queues on the links. The congestion on the links is average therefore the assignment cannot indicate links' reliability. Since reliability is important for the decision on the freight route choice, 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. (Yang and Yagar, 1994) explains an algorithm to do the traffic assignment with the capacity constraints. The algorithm based on the logarithmic barrier method.

Given the barrier augmented function:

$$F(V, \gamma^n) = \sum_l \int_0^{V_{mlp}} C_{mlp}(w)\, dw \qquad \text{when the link has no limited capacity}$$

$$= \sum_l \int_0^{V_{mlp}} (C_{mlp}(w) + \gamma^n \frac{1}{u_l - w})\, dw \qquad \text{when the link has limited capacity}$$

The algorithm steps are as follows:

<u>Step 0</u> Choose a feasible solution, the vector of traffic volume $\mathbf{V^0}$. Set n = 1 (outer loop counter)

*While* ( $\mathbf{V^0}$ is not converge) *do*

    *While* (**z** is not converge) *do*

    <u>Step 1</u> Let $\mathbf{z^0} = \mathbf{V^{n-1}}$. Set g = 1 (inner loop counter)

    <u>Step 2</u> 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 $y_l$ .

    <u>Step 3</u> Find $\alpha^*$ to minimize $F(\mathbf{z^g} + \alpha\,(\mathbf{y}\text{-}\mathbf{z^g}), \gamma^n)$ in the range

$$0 \le \alpha \le \min\left(1, \min_{z<y} \frac{u_l - z_l^g}{y_l - z_l^g}\right)$$

    <u>Step 4</u> 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*

<u>Step 5</u> $\gamma^{n+1} = \sigma.\gamma^n\,(0 < \sigma < 1)$ 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 $\gamma$ . The high gamma value prevents the solution to violate the capacity constraints. For each $\gamma$ , the Frank-Wolfe algorithm (Step 1 to 4) is performed. In Step 3, $\alpha^*$ is

limit to a certain range to guarantee that the next solution is still a feasible solution. The $\gamma$ value is lessened in the next iteration to allow a solution which exploring 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 $\gamma \to 0$ with a unique solution.

The cost function for each link is set based on the project selected for the link. This decision is made from the upper level model. The output from the carrier network, traffic volume in each link, is fed back to the upper level model. Additionally, the shortest path information between each origin and destination is used to update the link's service travel time in the service network. The following figure shows how the lower level problem is set and integrated with the upper level problem.
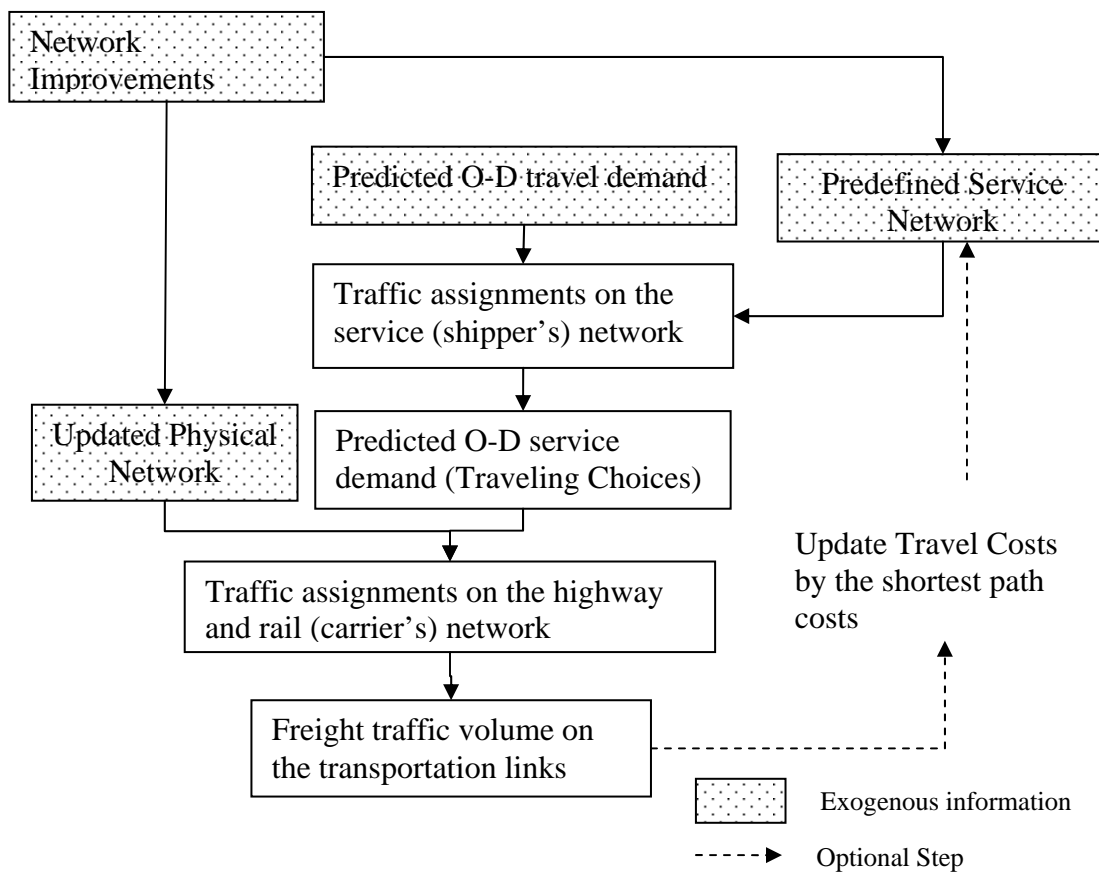


**Figure 1** Freight Flow Prediction Model

The freight flow prediction model is used in our network design model under certain assumptions. Currently, freight flow prediction models assume that the shipper network physical networks are given. However, the network design problem systematically changes the network and it should be updated corresponding to the improvements. The update can be done easily for the carrier network but it is difficult for the shipper 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.

Besides the multimodal facilities in the shipper network, 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. However, the change in the link's service capacity is hard to predict since the capacity is an aggregated result from many carriers and carriers need to consider many constraints to decide the service capacity. Fortunately, the capacity of an aggregated service link is insensitive to minor changes in the physical network. Therefore, we assume that the shipper network will be changed only when a few major projects are implemented.

In conclusion, the update will be done directly for travel costs and capacities to the physical links and the multimodal facilities. Additionally, a shortest path algorithm is performed on the carrier network to feedback service links' travel costs. However, the capacities of the service links will be updated only when a major improvement is implemented. In that case, a predefined service network will be used.

**The main model– Implicit Enumeration (Branch and Bound Algorithm)**

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

$$\underset{X_{lp}}{MIN} \sum_{m} \sum_{1} \sum_{p} C_{mlp} V_{mlp} X_{lp} \qquad \text{(Eq.2a)}$$

subject to

$$\sum_{1} \sum_{p} F_{lp} X_{lp} \leq B \qquad \text{(Eq.2b)}$$

$$\sum_p X_{lp} = 1 \qquad for \text{ all } i \qquad\qquad\qquad (Eq.2c)$$

The model is a budget allocation model with $X_{lp}$ is a 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 optimized solution.

The branch and bound algorithm for this network design model is constructed as follows:
<u>Step 0</u> Initialize the first node: At the first node all project improvements are undecided. The node is set to a visited node. The lower bound is calculated. The steps to calculate the lower bound will be explained later.

<u>Step 1</u> Branch the selected node: the selected node is branched to two nodes. One node is set to implement a project and another is set not to implement that project. For each node, the budget constraint is checked and if it is violated, the node is set as a visited node (i.e. the node is stopped to branch further). If it is not violated, the lower is calculated for both nodes. If it does not, the node is set as a visited node.

<u>Step 2</u> Select an unvisited node: an unvisited node will be selected to examine further. If a node at the lowest depth is selected, the branch and bound will do a depth first search. If a node with the lowest lower bound is selected, the algorithm will do a priority first search. The depth first search can be beneficial if an initial incumbent value is hard to set.

After the selected node is set as a visited node, the node is checked to see whether it has a complete solution (i.e. all project improvements are given decisions). If all decisions are not decided, the node has a partial solution. For a partial solution node, the node's lower bound is checked with the incumbent value. If it is more than or equal to the incumbent value, it means that any solutions that are branched from the node cannot better than the current solution. The

node will be fathomed and another node is selected for examination. If the node has a complete solution, it will enter step 3 to set the new incumbent value and a new solution.

Step 3 Set the incumbent value: if the completed solution does not violate the budget constraint, its network is a candidate. Given a network, the lower level model is used to predict the freight traffic volume on the network. The total generalized costs for the freight flows are calculated and checked with the incumbent value. If it is less than the incumbent value, a new incumbent value and a new current best solution are set. Otherwise, these remain the same.

The algorithm stops when all nodes are visited. The current incumbent solution will contain the transportation network which minimizes the total generalized cost for the freight volume.

**Lower bound calculations**

A lower bound is calculated for a node that has a partial solution. Assume the undecided projects to be implemented, freight flows are routed on the network and the lower bound is calculated by substituting the flows into the objective function. Different route choice behaviors will result in different lower bounds. The tightest lower bound can be calculated if the route choices are fully controlled by the lower level model. However, this lower bound can result in the sub-optimal solution since it can cause Braess' Paradox in the network. (Leblanc, 1975) shows how to use the system optimal flow to calculate the lower bound in order to prevent the paradox. For our lower level model, the true system optimal flow can be obtained by calculating traffic assignment with the carrier network only but allow the flows to use the intermodal facilities without the shipper decisions.

**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 mode transfer links connect o-d nodes with the transfer nodes have limit capacity. Other services have no limit. The shipper considers costs from service waiting time and delivery price which can be written as:

$$\text{Shipper cost} = \text{VOT}(\text{WT}^0)(1+0.15\left(\frac{V_{mlp}}{Capacity}\right)^4)+ \beta\,(\text{DP})^{od} \quad \text{(Eq.3a)}$$

Where VOT    Value of Time for waiting for the services

      $\text{WT}^0$    Free flow waiting time

      $\beta$       Service preference factor

      $\text{DP}^{od}$    Delivery price for a service connect an origin, o, and a destination, d.

The delays increase when the services are used 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. For example, a certain commodity type may usually 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 2a with its associated parameters.



| I | J | VOT ($/hour.unit weight) | $\text{WT}^0$ (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 |

Hwy service link
Rail service link
Access link with a limited capacity
O   Travel origin-destination node
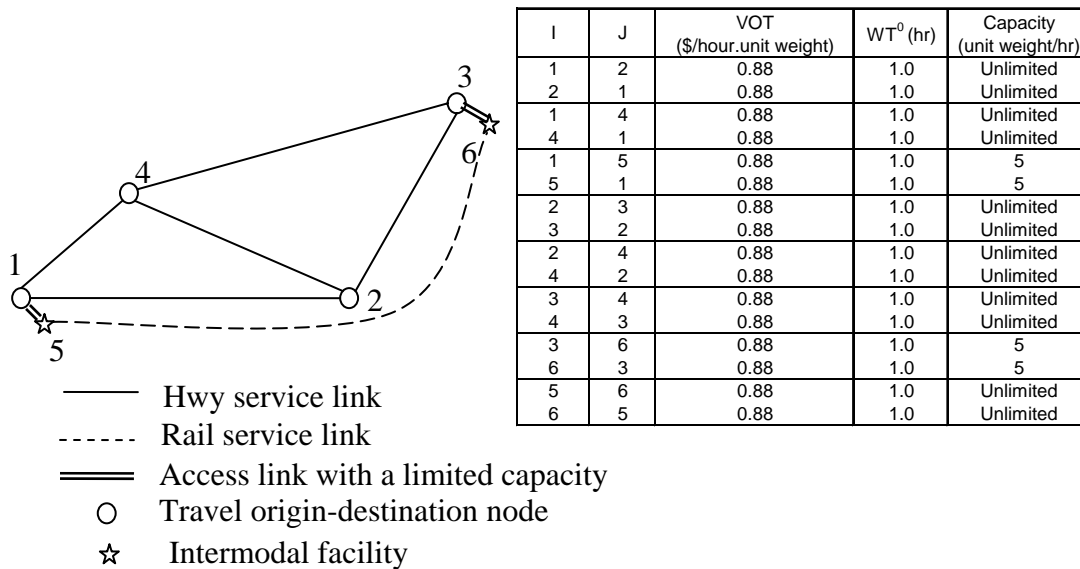☆   Intermodal facility

**Figure 2a** The studying shipper network configurations

The travel demand for each origin and destination is shown in **Table 1**. This demand will be assigned to the shipper network. The assigned demand will be converted to the travel demand by

services and is assigned to the carrier network to obtain the traffic volume in each transportation link.

**Table 1** The travel demand between each origin and destination in the shipper network

| 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:

$$\text{Carrier cost} = DP_l \left(1 + 0.15 \left(\frac{V_{mlp}}{Capacity}\right)^4\right) \qquad \text{(Eq.3b)}$$

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

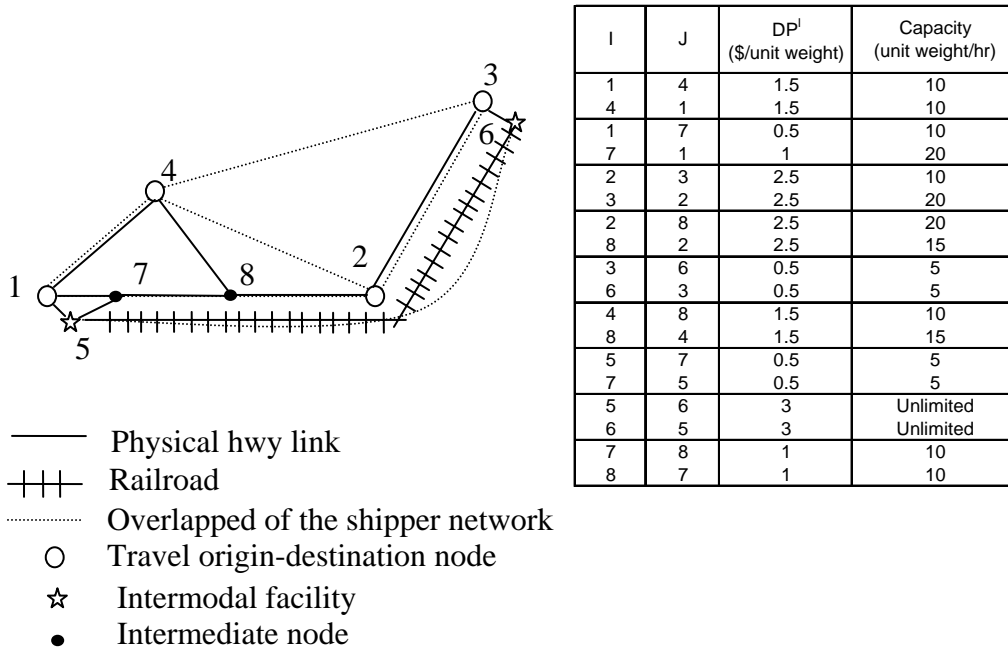The carrier network has the overlapped nodes from the shipper network. The network is shown in Figure 2b.

| I | J | DP$^I$ ($/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 |

Legend:
—— Physical hwy link
+++ Railroad
.......... Overlapped of the shipper network
O Travel origin-destination node
☆ Intermodal facility
• Intermediate node

**Figure 2b** The studying 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 2. The budget is set to three units of project improvements. When a project is implemented, it is counted as a unit. The lower model will be used to calculate the lower bound at each searching tree node. The results from the network design will be compared to the traditional method which prioritizes each project separately by its benefit cost ratio. 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 2** Details of the improvement projects

| Project | Related Network | Related Link From | Related Link To | Capacity Existing | Capacity Improved | Cost* | Benefit ** | Improvement Note |
|---|---|---|---|---|---|---|---|---|
| 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

The result shows that the traditional method yields the sub-optimal solution for the network design. By considering projects in a case-by case manner, the traditional method fails to capture the benefit of combining project 3 and project 4 which will solve a bottleneck problem to access the rail mode. It proposes to implement Project 1, 2, and 3 which give the total carrier cost of 497.0 money 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 Project 1, 3, and 4 which give the total carrier cost of 469.9 unit costs. The branch and bound algorithm accelerates the optimization by exploring only 12 nodes which are less than all feasible solutions (26 feasible solutions for the budget set to 3 improvement units). Table 3a and 3b shows the link flows on the shipper and carrier networks for the existing condition, the condition when implementing the projects proposed by the traditional method, and the optimal condition given the solution from the network design model.

**Table 3** The 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 |

**Table 3a:** 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 |

**Table 3b:** The carrier network flows

* The improvement proposed by the traditional case by case analysis

** The improvement proposed by the network design model

**CONCLUSION AND FUTURE RESEARCH**

In this paper, the network design model for the long haul freight movements is proposed. The 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 traditional formulation in order to alleviate a problem of the static traffic assignment. The capacity limit indicates how much the link can be used without loosing its 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. A numerical example is provided. The results show that the traditional method yields only sub-optimal solution. Our network design model is powerful enough to identify bottlenecks and propose the best solution.

Future work for the freight network design problem includes studies on both the upper level and lower level problems. 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 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.

The lower level model can be developed for more realistic freight flow prediction model. 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 is needed to be adjusted to match this change. The development of the freight network design with the logit model is our future research topic.

**REFERENCE**

ABDULLAL, M. and LEBLANC, L. J. (1979) Continuous equilibrium network design models, *Transportation Research,* 13B, pp. 19-32.

BEN-AYED, O., BLAIR, C. E., BOYCE, D. E. and LEBLANC, L. J. (1992) Construction of a real-world bilevel linear programming model of the highway network design problem, *Annals of operations research,* 34, pp. 219-254.

BOYCE, D. E., FARHI, A. and WEISCHEDEL, R. (1973) Optimal network problem: a branch-and-bound algorithm, *Environment and planning A,* 5(4), pp. 519-533.

DIONNE, R. and FLORIAN, M. (1979) Exact and approximate algorithms for optimal network design, *Networks,* 9, pp. 37-59.

FERNANDEZ, J. E., CEA, J. D. and SOTO, A. (2003) A multi-modal supply-demand equilibrium model for prediction intercity freight flows, *Transportation research,* 37B, pp. 615-640.

FRIESZ, T. L., ANANDALINGAM, G., MEHTA, N. J., NAM, K., SHAH, S. J. and TOBIN, R. L. (1993) The multiobjective equilibrium network design problem revisited: simulated annealing approach, *European journal of operational research,* 65, pp. 44-57.

FRIESZ, T. L., CHO, H.-J., MEHTA, N. J., TOBIN, R. L. and ANANDALINGAM, G. (1992) A simulated annealing approach to the network design problem with variational inequality constraints, *Transportation Science,* 26(1), pp. 18-26.

FRIESZ, T. L., GOTTFRIED, J. A. and MORLOK, E. K. (1986) A sequential shipper-carrier network model for predicting freight flows, *Transportation Science,* 20(2), pp. 80-91.

FRIESZ, T. L., VITON, P. A. and TOBIN, R. L. (1985) Economic and computational aspects of freight network equilibrium models: a synthesis, *Journal of regional science,* 25(1), pp. 29-49.

GUELAT, J., FLORIAN, M. and CRAINIC, T. G. (1990) A multimode multiproduct network assignment model for strategic planning of freight flows, *Transportation science,* 24(1), pp. 25-39.

HAGHANI, A. E. and DASKIN, M. S. (1983) Network design application of an extraction algorithm ofr network aggregation, *Transportation research Record,* 944, pp. 37-46.

HARKER, P. T. and FRIESZ, T. L. (1986a) Prediction of intercity freight flows, I: theory, *Transportation research,* 20B(2), pp. 139-153.

HARKER, P. T. and FRIESZ, T. L. (1986b) Prediction of intercity freight flows, II: mathematical formulations, *Transportation researh,* 20B(2), pp. 155-174.

HOANG, H. H. (1973) A computational approach to the selection of an optimal network, *Management science,* 19(5), pp. 488-498.

HOANG, H. H. (1982) Topological optimization of networks: A nonlinear mixed integer model employing generalized benders decomposition, *IEEE Transaction on automatic control,* 27(1), pp. 164-169.

JOHNSON, D. S., LENSTRA, J. K. and RINNOOY KAN, A. H. G. (1978) The complexity of the network design problem, *Networks,* 8(4), pp. 279-285.

KUBY, M., XU, Z. and XIE, X. (2001) Railway network design with multiple project stages and time sequencing, *Journal of geographical systems,* 3, pp. 25-47.

LEBLANC, L. J. (1975) An algorithm for the discrete network design problem, *Transportation Science,* 9, pp. 183-199.

LEBLANC, L. J. and BOYCE, D. E. (1986) A bi-level programming algorithm for exact solution of the network design problem with user-optimal flows, *Transportation Research,* 20B(3), pp. 259-265.

MAGNANTI, T. L. and WONG, R. T. (1984) Network design and transportation planning: models and algorithms, *Transportation Science,* 18(1), pp. 1-55.

NJDOT and PBQD (2004) Developing a framework to assess goods movement in New Jersey.

PETERSON, E. R. and FULLERTON, H. V. (1975) The railcar network models, *Report 75-11, Canadian Insittute of Guided Ground Transport*.

POORZAHEDY, H. and TURNQUIST, M. A. (1982) Approximate algorithms for the discrete network design problem, *Transportation Research,* 16B(1), pp. 45-55.

ROBERTS, P. O. (1966) Transport planning: Models for developing countries, *Northwestern Unviersity*.

SOLANKI, R. S., GORTI, J. K. and SOUTHWORTH, F. (1998) Using decomposition in large-scale highway network design with a quasi-optimization heuristic, *Transportation Research,* 32 B(2), pp. 127-140.

USDOT and FHWA (2005) The freight story: A national perspective on enhancing freight transportation.

YANG, H. and WANG, J. Y. T. (1998) Models and algorithms for road network design: A review and some new developments, *Transport reviews,* 18(3), pp. 257-278.

YANG, H. and YAGAR, S. (1994) Traffic assignment and traffic control in general freeway-arterial corridor systems, *Transportation research,* 28B(6), pp. 463-486.