ABSTRACT

MULTICLASS INTERMODAL NETWORK MODEL: THE USE OF COMBINED MODEL ON SYSTEM EVALUATIONS

by
Yi Deng

United States transportation policy has generally addressed the negative economic and social effects of the standpoint of individual transportation modes and local government involvement. Therefore, there has been an increased focus on the development of intermodal transportation. Integrating the modes and using each of them to its best advantage are strategies to optimize the existing resources and to create new capabilities.

According to the literature review performed in this research, the research in intermodal transportation system evaluation is far from mature. Most transportation performance measurements are focused on one mode rather than a whole network. In practice, the data necessary for evaluations are mostly from surveys or on-site data collection, which require a huge amount of time and cost. This study builds a combined intermodal network model and evaluation system specifically for intermodal transportation systems. It includes two main parts. The first part is to construct a combined network equilibrium model (CNEM) for multiclass travelers. The combined model projects mode split and traffic assignment/route choice simultaneously. The impact of transfer is being considered in the modeling process. In the second part, the output of CNEM model is used to evaluate an intermodal transportation system in the aspects of social, economic, environmental and transferable dimensions.

After that, a real world case study is done to demonstrate the feasibility of the methodology and show the application process. The study area is located in north New Jersey. NJ Transit is interested in updating one freight line, North Branch Line, to provide passenger service. Assuming the O-D trip matrix already exists, the mode share and route choice are projected for no build and build conditions. The transportation system evaluations are done respectively. Through the comparison of no build and build conditions, transportation planners can see the usage of the new service and its impact on the overall system performance. In additional, sensitivity analysis for years 2015 and 2030 is done to present the long term effect. The application shows the methodology is very useful in transportation planning.

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CHAPTER 1

INTRODUCTION

The United States has long enjoyed one of the best and most efficient transportation systems in the world. The system, however, is now facing significant challenges. The demand for both passenger and freight transportation continues to grow steadily, placing increasing pressure on ports, highways and airports. The transportation system is experiencing major growth pressures, which have contributed to increased traffic volumes and safety concerns. Parts of the transportation system are already approaching gridlock: urban highways are congested, the air is polluted, and we rely on foreign petroleum for the energy needs.

Intermodal transportation is considered to be a possible solution to solve the problems. Intermodal transportation refers to a system that connects the separate transportation modes—such as mass transit systems, roads, aviation, maritime, and railroads— and allows a passenger to complete a journey by using more than one mode. There has been increased focus on the development of intermodal transportation. Integrating the modes and using each to its best advantage are strategies to optimize the existing resources and to create new capabilities. Intermodalism has emerged as a major new approach to the planning of transportation systems. The U.S. has succeeded in building an extensive transportation system based on the development of individual modes-rail, road, water and air. Now the challenge of blending the separate modes into a national intermodal system is being confronted. A major goal of modern intermodal passenger transport is to reduce the dependence on the automobile as the major mode of ground transportation and promote the use of public transport.

1.1 Problem Statement

U.S. transportation policy has traditionally addressed the needs and effectiveness of public passenger transportation modes individually. The first attempt to consider intermodalism was the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). It identified the negative economic and social effects from the standpoint of individual transportation modes and local government involvement and presented an overall intermodal approach to highway and transit funding with collaborative planning requirements. It posed a major change to transportation planning and policy. ISTEA was followed by the Transportation Equity Act for the 21st Century (TEA-21) and most recently in 2005, the Safety Accountability Fairness Efficiency Transportation Equity Act: A Legacy for Travelers (SAFETY-LU). All the Acts identified the importance of the development of an intermodal transportation system.

Coming together with the intermodal planning and operation, the needs of effective intermodal performance indicators (or measures) are becoming increasingly important. For the planning aspect, choices among alternative highway and transit capital investments are often complex and politically controversial. Measuring the performance of a transit system is the first step toward efficient and proactive management. The use of performance indicators is very helpful to assist making rational and defensible choices for the investment of public funds to improve the valuation of rail and bus performance and provide more useful information for transit investment decision-makers. For the transportation operation, performance measures are yardsticks that transportation agencies use to assess how well service is being provided to their customers, the areas where improvements may be needed, and the effects of actions previously taken to improve the performance. In these cases, agencies use performance measures to help provide services as efficiently as possible, monitor whether agency and community goals are being met, and improve services so that it can attract more riders.

However, there are three main problems toward the efficient intermodal transportation system evaluations. First, most of the performance measures currently being used are specific to one transportation mode or one agency's mission and are not consistent with each other. Various evaluation performance indicators are picked for different transportation modes. There is no standard evaluation system. Few of the measures are designed to track the overall performance of the intermodal transportation system.

The second problem concerns the availability of pertinent data. According to the practice of performance measurement activities by some state Department of Transportation (DOT), data collection is an extremely costly exercise in many transportation studies. New technologies are being used to monitor the operation and collection of data, such as Global Positioning System (GPS), Automatic Vehicle Identification (AVI), Distance Measuring Instruments (DMI) and others. Survey methods are used also, such as Panel Survey, National Household Travel Survey (NHTS) and others. Transportation agencies get data from sub-agencies or contractors and integrate them together. All the data collection methods require a great amount of time and cost. Even with such a great effort, the accuracy of the data can hardly be guaranteed. Not all data, especially comprehensive performance data, can be obtained through the effort. In the condition of data absence, performance can not be able to be measured or to be measured objectively. The modeling method is a good way to provide the necessary data for performance measurements. By running a well calibrated travel forecast model, the trip flow on the roadway network can be projected, so are the travel time and cost. Those data can be used for the system evaluations.

Third, for comprehensive intermodal transportation system evaluation, the performance measurements used currently do not adequately account for the effects of transfer on transit ridership and network performance. Studies (Liu, 1997) show the presence of a transfer on a transit line can substantially reduce transit ridership and the extent of the reduction is highly dependent on the type of transfers. Including the effect of the transfer into the evaluation process can make the results closer to the real system performance and can reflect the feelings of passengers.

The goal of the study is to develop a travel forecast model to project the traveler's mode and route choice. Then the route flow, travel time and use of transportation modes are put into a comprehensive intermodal performance measurement system. Several aspects of indicators are adopted to capture the overall performance of intermodal transportation system. The travel forecast model contains highway and transit networks with the consideration of real physical infrastructure distributions and transportation mode coordination. The system evaluation results can give travelers a clearer idea of what options they have for travel and the transportation condition in the area. This study identifies a series of performance measures designed to track how effectively and efficiently an urban area's transportation system is serving the area's travelers. It is also shown that the methodology can be used to make decisions regarding transportation projects by comparing a priori evaluation with an ex post evaluation.

1.2 Research Objectives and Scope

The introduction part presents the emerging interest in the development of an intermodal transportation system and related system evaluations. A wide variety of existing performance measures have been reported in the literature. The most common measures are based on traffic volume (vehicle flow) and person movement. The traffic volume and person movement data are usually obtained from the real statistics or surveys, which cost a great amount of money, time and other resources. The accuracy of the data is still a great and can hardly be guaranteed. In the absence of data, performance can not be able to be measured or to be measured objectively.

The objective of this study is to construct a combined intermodal network model (CNEM) and an evaluation system specifically for an intermodal transportation systems. The first part, CNEM model is proposed to be used to obtain the equilibrium assignment of flows over an intermodal network by minimizing user costs. The model starts from network data, which include capacities of roadway network, rail and bus transit links, travel time, out of pocket costs (including transit fares, auto operating costs, parking fees). Assuming the trip table for each origins and destinations (O-D) is already available, the model projects the traveler's mode and route choice based on the user equilibrium principle. The results of the CNEM model include modal shares, equilibrium flow patterns, travel time and generalized cost. By running the CNEM model, road flow and transit usage information can be obtained without the effort of traditional data collection. The application of the model replaces the tedious data collection effort with the formulation and solution of the model with the relatively easier obtained input data, such as roadway links attributes, related travel time and costs.

The CNEM model differs from the traditional four steps model of forecasting the travel demand by combing the last two stages, mode split and traffic assignment into one step. Thus it takes into account the feedback effects among the two steps to make the result more reasonable. A simultaneous structure is studied together with nested combined model reflecting conditional choice probabilities. Since travel times are endogenous to the model, travel choices on a congested urban road network can be modeled. The other feature of the model proposed in the study is that it considers multi-class, multi-criterion and complete intermodal transfer options. Travelers make their own choice, typically in relation to their social and economic background.

The outputs of the CNEM model, path and link flows, mode split, link costs, and others are used as the input for the intermodal system evaluations. The evaluation system considers the network and traveler flows based on the average level since the time values for different classes' travelers are various. The result represents the features of the transportation system in social, economic, environmental and transferable dimensions.

The advantage of this intermodal framework and final indicators is that they consider all possible transportation and transfer modes in an urban area, including auto, bus transit, rail transit, and the transfers between them. Therefore the three major intermodal features: spatial (the roadway network connectivity), temporal (transit route and the schedule arrangement) and institutional (the influence of institution constitution and management) are all included into the development of the intermodal performance measures. The other advantage is that the indicators are not specific mode based, they can also be used to compare among various levels, corridors, networks or regions, regardless of area sizes and population densities.

The CNEM and the performance measurements are the conceptual part of the study. After presenting the methodology part, the dissertation modeled one real world case study to demonstrate the feasibility of the model and the application process. The study area is located in north New Jersey. New Jersey Transit is interested in upgrading one freight line, the North Branch Line, to provide passenger service. Based on the census origins-destinations trip table, the mode share and route choice for the local travelers are projected for both no build and build conditions. The transportation system evaluations are done respectively in social, economic, environmental and transferable aspects. Through the comparison between the no build with build conditions, transportation planners can find out the usage rate of the new service and its impact on the overall system performance. In addition, a sensitivity analyses for year 2015 and 2030 are done to present the long term effects. The application shows that the methodology and theory framework are very useful in transportation planning process with easy application.

This is the first time that the network equilibrium model is used for transportation system performance measurement. It widens the application of the model. Transportation agencies are required to collect and report a certain number of performance measures according to reporting and regulatory requirements. By applying the model, travel flows can be estimated and performance measures can be evaluated. Transportation agencies can have two set of data, field collected data and modeled data. They can improve the data report quality by double checking two set of data. Or in some case, model data can replace some real data, which may save cost and time and is beneficial for transportation planning professionals. Performance measures can help transportation agencies identify how well service is being provided to their customers, the areas where improvement may be needed and the effects of actions previously taken to improve performance. Priori evaluations and ex post evaluations can be made to see the impact of the improvement projects.

1.3 Organization of the Dissertation

The dissertation includes six chapters. Chapter 2 contains literature review on previous research and state of practices. In the chapter, literature about the network equilibrium model, including basic concepts, model framework, and applications are summarized. A section is devoted to research on transfer impacts on traveler behavior. Transportation performance measures being used by transportation agencies and intermodal performance measures found in literature are also presented.

Chapter 3 focuses on the CNEM model. The framework starts from the trip choice making process and user classification. Cost functions for links and paths are built, and a model is formulated under two equilibrium conditions. Then the method of solution is given. Input and output data flows are discussed on what data are needed in the model, the sources of the data and the results from the model.

Chapter 4 generates a framework for performance measures, which consists of four dimensions, social, economic, environmental and transferable. Each dimension includes several measures, for example, mobility, accessibility, safety and security, reliability, institutional impedance and environmental impact. For each measure, the notation and calculation formula are given. The data used to do the calculation are the output of the CNEM model.

Chapter 5 gives one real world case study in north New Jersey. It is used to demonstration the application of the model and performance measurement system. The model is used to project travelers' mode and route choices. System performances on both no build and build conditions are calculated and compared.

Chapter 6 presents the conclusions, contributions of the dissertation and the potential applications of the methodology and future research areas. The methodological framework is presented in Figure 1.1.

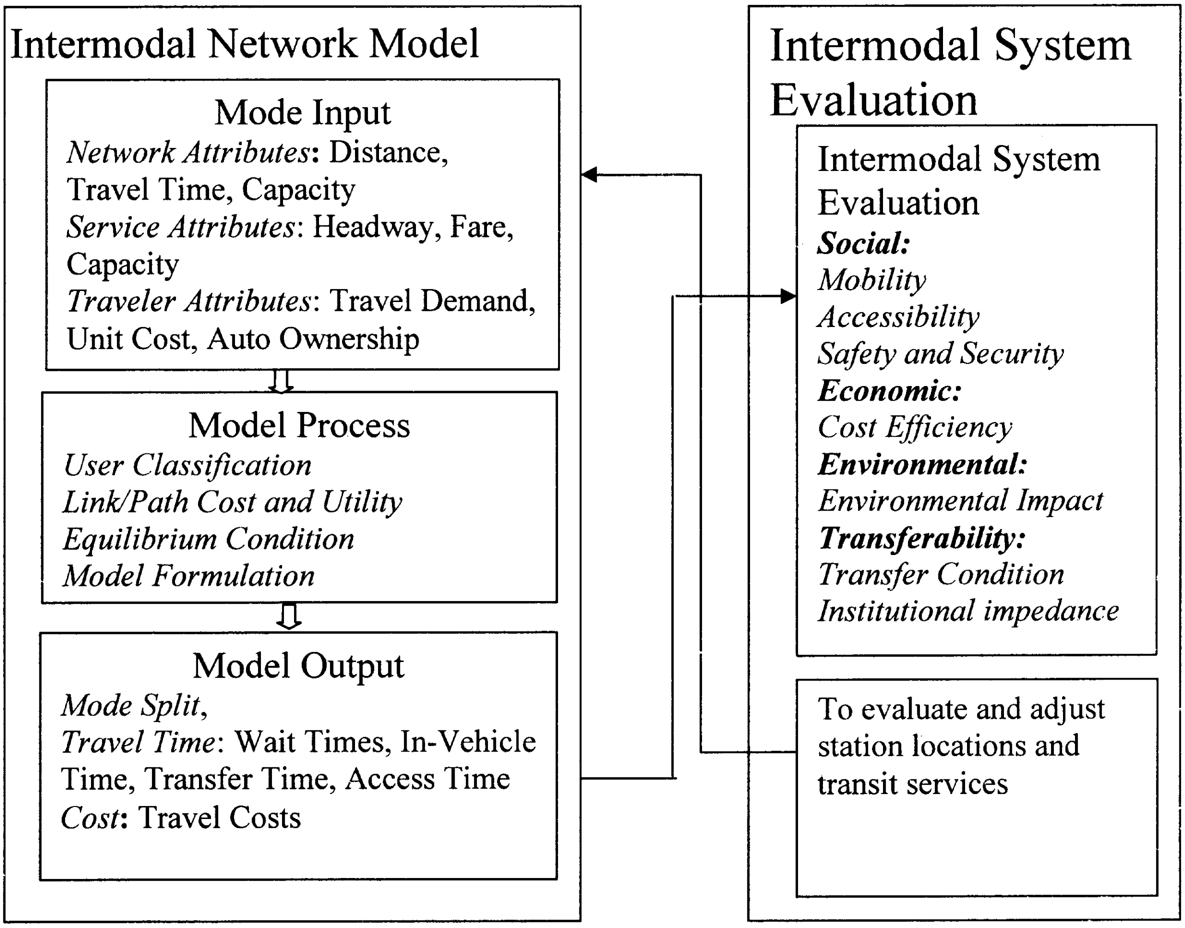

Figure 1.1 Methodological framework.

CHAPTER 2

LITERATURE REVIEW

As mentioned in Chapter 1, this study constructs one combined network equilibrium model fully considering the impact of transfer and performs intermodal system evaluations based on the output of the model. Previous studies of network equilibrium models, transfer impacts and transportation performance measurement systems are reviewed in this chapter. It includes the basic user optimization principle, the development of the model, mathematical method and application of the model. The later part is the review of research and the state of practice of performance measurement system.

2.1 Network Equilibrium Model

A classical network equilibrium problem is concerned with travelers of a congested transportation network seeking to determine their travel paths of minimal cost from origins to their respective destinations. As mentioned in Boyce (2004), "the historical development of this field, like other scientific pursuits, is complex in part because separate strands of research have now merged into more comprehensive models". Sheffi (1985) synthesized his contributions, as well as integrating the findings of other scholars. After that, an extensive historical account and mathematically rigorous synthesis of the field with over 1000 references were prepared by Patriksson (1994). Syntheses and reviews of combined models were also offered by Boyce (1990, 1998). The study examines the research from the very basic concept foundation of the network equilibrium model.

2.1.1 User Optimization Principle

The formulation of network equilibrium models has its origin in the 1950s. Wardrop (1952) firstly developed the traffic equilibrium conditions through two principles:

First Principle: The journey times of all routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route. Each user seeks to minimize his cost of transportation non-cooperatively.

Second Principle: At equilibrium the average trip journey time is minimal.

The first principle is referred to as user-optimization, whereas the second one is referred to as system-optimization. The former pattern is when travelers are free to select their routes of travel so as to minimize their individual travel cost. The latter pattern is to be established when a central authority dictates the paths to be selected or each user behaves cooperatively in choosing his/her own route to ensure the most efficient use of the whole system, so as to minimize the total system cost. Since in reality each user decides his route independently, the former solution is usually accepted as a more realistic reflection of traveler route selection.

According to the user equilibrium theory, each user chooses his own route or path to minimize his individual cost. No user has any incentive to make a unilateral decision to alter his/her travel path. A more general expression of this statement considers a generalized cost, disutility, or negative utility function including monetary, qualitative and time costs as the journey impedance. Specifically, a user-optimized equilibrium is reached when no user may lower his transportation cost through unilateral action.

Beckmann, McGuire, and Winsten (1956) were the first to formulate a mathematical model of network equilibrium, in the framework of spatial price equilibrium problems in which there were. However, no congestion effects were considered. In the study, they formulated the user equilibrium principle as a mathematical programming problem. They proved the equivalence conditions between the equilibrium and the Kuhn-Tucker conditions of an appropriately constructed optimization problem, under symmetry assumption on the underlying functions, which minimizes some objective function, subject to the equilibrium constraints. By solving the model, the equilibrium link and path flows could be obtained. It was proved that the solution of this problem is equivalent to the user equilibrium conditions.

Performance, or supply functions describe the relationship between flow, capacity, and level of service-price. Typically, average user cost-volume relationships are used to describe the performance of transport systems. Factors that need to be considered in a motorist's average user cost function include travel time, comfort, and safety, which can be collectively referred to as level of service, tolls, parking fees, and some of the operating and maintenance costs of the vehicle which comprise of the out of pocket monetary costs. A transit user's cost function would consist of similar factors, including travel time, comfort and safety, and fares as out of pocket costs. Depending on the assumed behavior of management of transportation facilities in modifying characteristics under its control such as service frequency, cost and even vehicle technology, several types of user cost-volume functions have been developed (Morlok, 1978 and 1979).

Florian (1977) developed an equilibrium model of travel by private car and one or more public transit modes. The salient features of the model were the clear distinction between the flow of vehicles and flow of transit passengers and the means of modeling the interaction that occurs between private cars and public transit vehicles that use the same road links of the network. Two classes of model structures representing the demand for each mode of travel were analyzed. For one of these classes of models, it can be proven that the equilibrium model framework permits the computation of consistent equilibrium flows. The behavioral assumptions that are imbedded in the model are clearly spelled out. Data requirements and computational aspects are discussed in detail.

Network equilibrium was defined (Friesz, 1985) as a nonnegative flow pattern occurring on a given network which is consistent with market clearing (i.e., with supply equaling demand) and with postulated behavioral principles describing decision makers active on the network, such as the user equilibrium principle.

Discrete choice models, also known as random utility models, describe the choices of individuals between competing alternatives (Oppenheim, 1995). Nested logit discrete choice models may be used to formulate the mode choice using various levels and groups of similar characteristics. Nested logit models have been tested and used in the estimation of travel volumes by mode, transit station, or both (Fan et al., 1993; Forinash and Koppleman, 1993). These models, however, only formulate the demand side and have not been implemented within a demand-supply network equilibrium context.

2.1.2 Developments of the Model

Based on the efforts of Beckmann and other researchers in the early stage, more and more researchers are working in this field and yielding substantial improvement. The developments of the basic equilibrium network models are mainly in two directions. One is the consideration of more complex modes. Instead of consideration of only highway traffic, newer models include transit as a mode option, as well as intermodal systems. The other direction is in the development of algorithms, especially the creation and application of the variational inequality method.

2.1.2.1 Transit Assignment. The congestion condition of a transit system is treated different from that of highway system since transit (for example, rail transit) may operate on exclusive right of way. The transit assignment model (De Cea et al., 1993) formulated the assignment problem over congested transit networks. The congestion effects due to insufficient capacity of system elements, for example, transit lines, are considered to be concentrated at transit stops. Waiting time is dependent on passenger flow. The formulation of a transit network is used to model the congestion impact on travel time and passenger flow.

The standard transit assignment based on optimal strategies does not consider congestion effects due to limited vehicle capacity. The assignment model proposed by Spiss (1993) extended the traditional model by taking into account the vehicle capacity by means of a volume-dependent transit time function, leading to the formulation of a transit equilibrium assignment model. The paper describes how the standard version of the EMME/2 Transportation Planning Software can be used to solve this assignment model. A macro was written which implements a Frank-Wolfe descent algorithm, by combining the fixed cost transit assignment module with the network and matrix calculator modules.

While in another study (Lei, 2004), L ei studied the capacity restrained transit assignment problem with elastic demand. The urban transit network characteristics are analyzed, such as the links have finite capacities, equilibrium delay only arises when capacity is reached; and then a variational inequality model of the stochastic user equilibrium transit assignment with elastic demand under capacity constraint is proposed. The proposed model can simultaneously predict how passengers would choose their optimal routes and estimate passenger flows in a congested transit network. Based on the penalty function method, an algorithm for solving the proposed model is presented. Finally, the algorithm is illustrated with a numerical example. The results show that the algorithm is quite satisfactory.

A new formulation for the capacity restraint transit assignment problem with elastic line frequency was proposed by Lam, et al. (2002). In this case, the line frequency is related to the passenger flows on transit lines. A stochastic user equilibrium transit assignment model with congestion and elastic line frequency is proposed and the equivalent mathematical programming problem is also formulated. Since the passenger waiting time and the line capacity are dependent on the line frequency, a fixed point problem with respect to the line frequency is devised accordingly. The existence of the fixed point problem was proven. A solution algorithm for the proposed model is presented. Finally, a numerical example is used to illustrate the application of the proposed model and solution algorithm.

2.1.2.2 Combined Modes. As stated already, mathematical formulations and efficient algorithms were developed to model transportation networks. (Florian and Nguyen, 1974; LeBlanc, 1981; Fisk and Nguyen, 1981; Dafermos, 1982; Florian and Spiess, 1983). Most of these papers present highway models. "Even the percentage of intermodal passenger travel is not significant, it does exist and is increasing in magnitude and importance due to current urban transportation policies which encourage the use of transit by "park and ride" or by the development of superior transit modes, such as metro or regional transit lines, which are served by bus feeder lines" (Fernandez et al., 1994). The emerging interest on the transit system modeling results the need for models to perform an intermodal analysis. When two modes are used in one trip, traffic is assigned over overall modal networks. The connections between modes need to be considered and formulated. These choices include the choice of the combined modes versus the pure modes available. If a combined mode is used, there are choices associated with transfer nodes from one mode to the other, as well as the route choices on the corresponding modal sub-networks need to be decided.

The first combined mode network equilibrium model explicitly considered and analyzed intermodal networks was proposed by Fernandez et al. (1994). The paper presented model formulations, which consider two alternative modes available at each origin of a network and explicitly analyze intermodal trips in a network equilibrium framework. The paper presented several approaches to formulating network equilibrium models with combined modes. They proposed three model formulations with auto, metro, and auto-to-metro (or combined mode in their terminology) modes, and analyzed the resulting equilibrium conditions. The underlying assumption is that the combined mode is considered only at those origins where metro is not available. The alternatives are either auto and metro or auto and combined (auto-to-metro) modes. One of these approaches results in a new network equilibrium model, where the combined mode is considered as a distinct alternative in a demand model, and the network flows are suitably modeled on different modal sub-networks. The mathematical structure of the model was analyzed and solution algorithms were outlined.

Boile (2002) presented an intermodal network model and the model was used for analyzing and evaluating intermodal commuter networks. The model considered the interactions between modes, making predictions regarding future network activity in terms of traffic volumes and travel costs, and aiding the decision making process in terms of future transportation plans by evaluating alternative policies for improving the efficiency of high occupancy modes, mitigating congestion, reducing energy consumption, and air pollution.

2.1.2.3 Variational Inequalities Method. Mathematically, the state of equilibrium is characterized by equilibrium conditions which can be written as a variational inequality. In the special "symmetric" case, a class which contains in particular the standard model, the equilibrium conditions can be interpreted as the Kuhn-Tucker conditions of a convex minimization nonlinear programming model. Hence this case is amenable to powerful convex nonlinear programming techniques. In the more general, and very realistic "asymmetric" case, a class that contains extended as well as multimodal models, the state of affairs is less satisfactory (Dafermos, 1982). A mathematical programming approach can be used when the inverse supply, inverse demand, and cost functions are continuous and have a symmetric Jacobian matrix. However, in general, cost functions are asymmetric. A change in the flow of link "I" has a different impact on the travel cost of link "J" compared with the impact on travel cost of link I that results from a change in flow on link "J", meaning that in this case, mathematical programming techniques are not suitable. Variational Inequality (VI) is used to solve the problem where asymmetric cost interactions are involved, therefore representing more general cases (Nagurney, 1993).

Variational inequality is a mathematical theor y which attempts to serve as a methodology for the study of equilibrium problems. Variational inequality theory can be used as a tool for: formulating a variety of equilibrium problems; qualitatively analyzing the problems in terms of existence and uniqueness of solutions, stability and sensitivity analysis, and providing us with algorithms with accompanying convergence analysis for computational purposes. Variational inequality theory was introduced by Hartman and Stampacchia (1966) as a tool for the study of partial differential equations with applications principally drawn from mechanics. The breakthrough in finite-dimensional theory occurred in 1980 when Dafermos recognized that the traffic network equilibrium conditions as stated by Smith (1979) had a structure of a variational inequality.

The problem is commonly restricted to Rn. Given a subset K of Rn and a mapping F : K → Rn, the finite-dimensional variational inequality problem associated with K is finding $x \in K$ for all $y \in K$, so that

$$\langle F(x), y - x \rangle \geq 0 \tag{2.1}$$

where <·,·> is the standard inner product on Rn.

In general, the variational inequality problem can be formulated on any finite- or infinite-dimensional Banach space. Given a Banach space E, a subset K of E, and a mapping $F: K \to E^*$, the variational inequality problem is the same as above where $\langle \cdot,\cdot \rangle :$ $E^* \times E \to R$ is the duality pairing.

Florian and Spiess (1983) proposed one mode choice/ assignment model, which considers the two mode equilibrium road and transit assignment model incorporating a zonal aggregate mode choice model. This special structure network equilibrium model is reformulated as a variational inequality problem. Origin to destination demands and travel costs, link flows and link travel costs are unique when appropriate the existence of equivalent optimization formulations of special versions of this problem and study sufficient conditions for the convergence of diagonalization methods are used to obtain solutions for this model.

Peric et al. (2006) presented the formulation and solution of a combined mode choice/assignment, intermodal network equilibrium model with asymmetric link cost interactions. Auto, bus, and rail are the modes considered as travel options in the formulation, along with the combined auto-to-bus and auto-to-rail intermodal options. Using park-and-ride facilities as transfer points, travelers may switch from auto to transit. There is a two-way interaction between auto and bus transit. The presence of transit vehicles on the highway links is registered through a bus-car equivalency factor, while the transit travel time depends on the highway link congestion level. Transit travel times are also subject to congestion at the transit stops, due to boarding and alighting. Transit frequencies vary depending on the level of congestion. The solution algorithm for the variational inequality and the derivation of the decent direction for the diagonalized problem are also presented. A test network was developed and several tests were presented to show the convergence of the algorithm as well as the changes in the transit level-of-service due to transit and highway congestion.

In the study of Garcia (2005), a new model was developed for the multi-modal assignment problem with combined modes (MAPCM) to be used in the context of urban transport management. A variational inequality problem is presented to formulate the MAPCM. The model explicitly takes into account the choices of route, mode and transfer node in a nested choice structure. The model is then solved by using a disaggregate simplified decomposition algorithm. The model and the numerical approach are tested on two networks with asymmetric cost functions. The formulation and algorithm are shown to be useful for reoptimization, which is important in solving sub-models in network design problems. The algorithm also has excellent possibilities for parallel computation implementation and is a computationally tractable way of solving large-scale multi-modal assignment problems.

2.1.2.4 Multiclass Travelers. LeBlanc et al. (1982) realistically extended the general mode choice equilibrium conditions to mode choice as well. These models extend earlier combined models to the case where flows by different modes affect each other's impedance. The research considers distinct classes of travelers. By formally stratifying travelers into different groups, a more accurate analysis of the time-cost tradeoff in mode choice is possible.

There are many other papers dealing with the multiclass problem, and they are summarized by Boyce et al. (2004). They reviewed the progress in formulating, solving and implementing models with multiple user classes that combine several travel choices into a single, consistent mathematical formulation. Models in which the travel times and costs on the road network are link flow-dependent are discussed. Such models seek to represent congestion endogenously. The paper briefly summarizes the origins of this field in the 1950s and its evolution through the development of solution algorithms in the 1970s. The primary emphasis of the review is on the implementation and application of multiclass models. The paper concludes with a brief discussion of prospects for improved solution algorithms.

2.1.3 Related Algorithms

The principal objective of the network equilibrium problem is the computation of user-optimized patterns characterized by the property that, once equilibrium is established, no user has any incentive to alter his travel arrangements. In general, the incentive is measured in terms of a cost function and a demand function which depend on traffic volume (congestion effect).

In the standard (single mode) traffic equilibrium model with elastic demand, the travel cost on a link depends solely upon the flow on that link and the travel demand associated with an origin-destination (O/D) pair of modes that depends solely upon the travel cost associated with this particular O/D pair. In the extended (single mode) model, with elastic demand, the travel cost on a link is allowed to depend upon the entire flow pattern and the travel demand associated with an O/D pair is also allowed to depend upon the travel costs associated with all O/D pairs in the network.

In the multimodal extended traffic equilibrium model, with elastic demand, the link travel costs associated with each mode mainly depends upon the entire load pattern and the travel demand associated with an O/D pair and mode may depend upon travel costs associated with every O/D pair and every mode of transportation (Dafermos, 1982).

LeBlanc (1981) described two main methodologies used to solve the typical network equilibrium problem. If the travel time for each street (link) were constant, the fixed demand assignment problem could be solved by finding the least time route between each origin and destination, and incrementing the flow on each link on these routes by the specified number of trips. However, because of traffic congestion, the travel time on each link is not constant, but is a nonlinear function of the total traffic on the link. The form of the travel time function used by the U.S. Federal Highway Administration is:

$$A_{ij}(x_{ij}) = a_{ij} + b_{ij}(x_{ij})^4 \tag{2.2}$$

Where

A_{ij} : Travel time experienced by each unit of flow on link ij

x_{ij} : Flow rate on link ij, thousands of vehicles per rush hour period

a_{ij} : Travel time at free speed on link ij

b_{ij} : Congestion parameter for link ij.

In the fixed demand traffic assignment problem, the required number of trips between each origin-destination pair is a specified constant. In the elastic demand traffic assignment problem, the number of trips between an origin-destination pair depends on the travel time between the origin and destination:

$$t^{od} = g^{od}(y^{od}) \tag{2.3}$$

Where

t^{od} : Trips between origin node o and destination node d

y^{od} : Travel time between origin node o and destination node d .

The units of the trip are the same as the units of the flow variables. The functions are assumed to be strictly decreasing. The longer travel time increases, the smaller the number of trips.

2.1.3.1 Frank-Wolfe Technique LeBlanc (1981) summarized the Frank-Wolfe technology. Given a feasible set of flows and trips, (x, t), the technique solves a direction finding sub-problem of choosing flows X and trips T to

$$Min_{X,T} \nabla f(x,t) \begin{bmatrix} X \\ T \end{bmatrix} = \sum links_{ij} c_{ij} X_{ij} - \sum_{odpairs} d^{od} T^{od} \tag{2.4}$$

Here, c_{ij} and d^{od} are components of the gradient of f evaluated at the solution (x, t). The constraints in the sub-problem are the same as those in the original problem. For each origin-destination pair od , if the trips are chosen $T^{od} > 0$, then this many trips must flow along any route or routes from o to d. In addition, to prevent the subproblem from being unbounded, an upper bound on the trip variables is required:

$$T^{od} \leq U^{od} \text{ all origin-destination pairs } od \tag{2.5}$$

Or

$$T^{od} \leq U^{od} \text{ all origin-destination pairs } od \tag{2.6}$$

The solution to the direction finding subproblem is used to set up a line search; the procedure then iterates with a new solution.

The subproblem separates into a distinct problem for each different origin-destination pair. To solve it, first calculate the length of the shortest path, L^{od} , between each origin-destination pair od , using the c_{ij} as link lengths. Since there are no link capacities, all subproblem trips will follow the shortest path between o and d. If one trip is sent from o to d, the subproblem cost is $L^{od} - d^{od}$, the subproblem solution can be expressed as:

$$T^{od} = \begin{cases} 0 \ldots\ldots if \ldots\ldots L^{od} - d^{od} \geq 0 \\ U \ldots\ldots if \ldots\ldots L^{od} - d^{od} < 0 \end{cases} \tag{2.7}$$

These subproblem trips induce link flows, which follow the shortest path between the origin and destination. Observe that if it were not for the bound U, the subproblem would be unbounded; no search direction could be obtained.

2.1.3.2 Evans' Technology. An alternative solution procedure for the elastic demand assignment problem is the one proposed by Evans (Evans, 1976) for solving combined distribution-assignment problems. Her algorithm is based on Rockafellar's (1967) original work.

Evans' algorithm involves iteratively solving a direction finding sub-problem, followed by a line search in the chosen direction. In her algorithm, only the link impedance functions are linearized, not the integrals of trip demand functions. For the elastic assignment problem, the non-linear Evans sub-problem is no harder to solve than the linear Frank-Wolfe subproblem. Let L^{od} denote the length of the shortest path between o and d after linearizing the link functions, and let T^{od} denote the number of trips between o and d in the subproblem. The Evan's subproblem is:

$$MIN \int \sum_{od} [L^{od} T^{od} - \int_0^{Tod} g^{od^{-1}}(z) dz] \tag{2.8}$$

Obviously, the above Equation 2.8 is separable by origin-destination pair. Setting the derivative of it with respect to T^{od} equal to 0, the subproblem solution satisfies

$$T^{od} = g^{od}(L^{od}) \tag{2.9}$$

It is instructive to compare the subproblem trips Equation 2.9 for Evan's technique with those from the Frank-Wolfe method in Equation 2.7. In the Frank-Wolfe subproblem, we send zero trips or as many trips as possible, while in Evans' subproblem, trips are determined by the trip demand function, using origin-destination impedances based on the current solution.

2.1.4 Application of the Model

Traditionally a network equilibrium model is used to determine trip flows and mode split to forecast travel demand. In addition, network equilibrium models have been used in a number of other related applications ranging from employer location, transit frequency optimization and other aspects.

Florian et al. (1976) paper describes an application of an equilibrium trip assignment method to the 1970 road network of the city of Winnipeg, Manitoba, Canada. The validity of the method was discussed in detail. The results were encouraging and demonstrated the suitability of the method for planning purposes.

Chu (1999) presents a network equilibrium model for the simultaneous prediction of employment location, trip distribution, mode choice, and trip assignment. The employment location choice was given by a simplified form of Putman's employment allocation model. The trip distribution and mode choice were based on Wardrop's user-optimized principle. The proposed combined employment location, trip distribution, mode choice, and assignment model can itself be reformulated as an equivalent minimization problem (EMP) so that the equilibrium conditions on the network and the location and travel demand functions can be derived as Kuhn-Tucker conditions of the EMP. Under mild assumptions on the demand and link cost functions, the EMP is a convex programming problem with linear constraints, which is a great advantage from the computational respective. In addition, a unique solution of the EMP exists which is equivalent to that of the proposed combined model. When applying the Evans algorithm to the equilibrium problem, the model is expected to be usable in a realistic application at a reasonable cost and within a reasonable time period. Several areas for further extensions of the model are also discussed.

Xu's (1999) paper is concerned with the modeling of the complex demand-supply relationship in urban taxi services. A neural network model is developed, based on a taxi service situation observed in urban Hong Kong. The input consists of several exogenous variables including the number of licensed taxis, incremental charge of taxi fare, average occupied taxi journey time, average disposable income, and population and consumer price index. The output consists of a set of endogenous variables, including daily taxi passenger demand, passenger waiting time, vacant taxi headway, average percentage of occupied taxis, taxi utilization, and average taxi waiting time. Comparisons of the estimation accuracy are made between the neural network model and the simultaneous equations model. The results show that the neutral network-based macro taxi model can generate much more accurate information of the taxi services than the simultaneous equations model does. Although the data set used for training the neural network is small, the results obtained thus far are very encouraging. The neural network model can be used as a policy tool by regulators to assist with the decisions concerning the restriction over the number of taxi licenses and the fixing of the taxi fare structure as well as a range of service quality control.

From the above review, it can be seen that the combined model is still short of infallibility. Most of the papers are considering multimodal (passenger can choose different transportation mode), not intermodal (travelers finish one trip by using two or more transportation modes). The transfer impact should be included in the discussion of trip making. Besides, the difference in users has insufficiently discussion. The reality is that some passengers do not own an auto, which makes them transit compliance. This feature will have a great influence on the travel behavior.

2.2 The Role of Transfers

Transfers play a significant role in daily transit operations in relation to ridership, cost-effectiveness, and customer satisfaction. In most large transit systems in North America, at least 10% of riders make one or more transfers to reach their final destination (Crockett, 2002). Transit riders perceive transfers negatively because of their inconvenience, often referred to as a transfer penalty. By modeling actual choices, the transfer penalty can be estimated relative to its equivalence in travel time or money saved (Guo et al., 2004).

Various discrete choice models assessed the penalty using different types of data sets. Han (1987) used a binary choice model to test the influence of transfers on bus path choice in Taipei, Taiwan. Bus riders were interviewed ove r 2 months, and detailed information was obtained on their path choices for a previous trip.

A more recent intermodal transfer penalty study was conducted by Liu (1996), using data collected from the New York - New Jersey commuting corridor. In this study, both revealed and stated preference data are used to estimate logit models of mode choice reflecting the impacts of intermodal transfers. The model results suggested that: (1) An independent transfer penalty should be used in the mode choice model to reflect the impediment of the transfer itself regardless of the transfer time. (2) The penalty factors associated with transfer time should be higher than those traditionally used in travel demand models. (3) The value of the transfer penalty varies according to the type of modal transfers. For example, an intermodal transfer from auto to rail may create a transfer penalty equivalent to 15 minutes in-vehicle travel time; an intra-modal transfer from rail to rail only amount to 5 minutes of in-vehicle travel time.

Guo (2004) developed a new method to assess the transfer penalty on the basis of onboard survey data, a partial path choice model, and geographic information system techniques. This approach was applied to the Massachusetts Bay Transportation Authority subway system in downtown Boston. The new method improves the estimates of the transfer penalty, reduces the complexity of data processing, and improves the overall understanding of the perception of transfers. Because all of these studies used different definitions of the transfer penalty and different transfer contexts and characteristics, quite different results were obtained, as shown in Table 2.1.

Table 2.1 Transfer Penalty Research Summary

Previous Studies	Year	Variables in the Utility Function	Transfer Types (Model Structure)	Transfer Penalty Equivalence
Algers et al. Stockholm, Sweden	1975	Walking time to stop Initial waiting time In-vehicle time	Subway-to-Subway Rail-to-Rail Bus-to-Rail Bus-to-Bus	4.4 minutes in-vehicle time 14.8 minutes in-vehicle time 23.0 minutes in-vehicle time 49.5 minutes in-vehicle time
Hunt Edmonton, Canada	1990	Walking distance Waiting time In-vehicle time Number of transfers	Bus-to-Light Rail (Path Choice)	17.9 minutes in-vehicle time
Liu et al. New Jersey	1997	Out-of-vehicle time In-vehicle time Number of transfers	Auto-to-Rail Rail-to-Rail (Modal Choice)	15 minutes in-vehicle time 1.4 minutes in-vehicle time
CTPS (Central Transportation Planning Staff) Boston, MA	1997	Walking time Initial waiting time Transfer waiting time Out-of-vehicle time In-vehicle time	All modes combined (Path and Mode Choice)	12 to 15 minutes in-vehicle time
Guo et al. Boston, MA	2004	Transfer constant Transfer walking time Transfer waiting time Assisted level change Station dummy	Rail-Rail (Path Choice)	3.5-31.8 minutes in-vehicle time

2.3 Transportation Performance Measures

The review of transportation performance measures being used by agencies is very important. The proper choice of performance measures in the study will make it more usable in industry.

2.3.1 Industry Practice

TCRP Report 88 (2003) is a guidebook for developing a transit performance-measurement system and providing a step-by-step process for developing a performance-measurement program reporting and regulatory requirements that dictate a certain number of performance measures that must be used. The guidebook identifies four points of view that transit performance measures address: customer, community, agency, and driver/vehicle. The guidebook assigns performance measures to eight primary categories, each of which relates to one or more points of view:

Availability—where and when service is provided, and having sufficient capacity available for passengers to take trips at their desired time (customer point of view).

Service delivery—including reliability, customer service, passenger loading, and agency goal accomplishment (customer).

Safety and security—reflecting the likelihood that one will be involved in an accident (safety) or become the victim of a crime (security) while using transit (customer).

Maintenance and construction—evaluating the effectiveness of an agency's maintenance program, and the impacts of construction projects on customers (customer and agency).

Economic—transit performance evaluated from a business perspective, including use, efficiency, effectiveness, and administrative measures (agency and community).

Community—measures of transit's impact on individuals and on the community as a whole (community, agency, and driver/vehicle).

Capacity—the ability of transit facilities to move both vehicles and people (community and driver/vehicle).

Travel time—how long it takes to make a trip by transit (a) by itself, (b) in comparison with another mode, or (c) in comparison with an ideal value (driver/vehicle and customer).

Shbaklo (1999) points out that the most common measures are based on traffic volume (vehicle flow) and person movement. Examples of volume-based measures include vehicle miles or vehicle hours of travel, travel time, speed, and delay measures include total travel time, running time, speed, delay rate, and delay ratio. Person movement measures include person volume and person-miles or person-hours of travel. Finally, examples of transit measures include frequency of service, riders per vehicle mile, and load factor.

In Hartgen's paper (2005), there are seven indicators: Rural interstate condition, Urban interstate condition, rural other principal arterial pavement congestion, urban interstate congestion, deficient bridges, fatality rates, narrow lanes are listed. The paper summarizes that during the six years of the federal highway program, 1998 to 2003, the state-administered US highway system improved sharply on six of seven key indicators of performance; only one indicator, urban interstate congestion, worsened. But overall expenditures on state-administered highways rose about 39 percent, about twice as fast as highway construction prices. The most spectacular gains in performance were in rural areas: the percentage of rural interstates and rural primary roads in poor condition fell by 1/2, the percentage of narrow lanes was reduced 10 percent, and the percentage of deficient bridges improved 12 percent.

2.3.2 Academic Research

Besides the industry practices, there is also much academic research in the area of transportation system evaluation.

Sanchez-Silva (2005) presented a model for optimizing the allocation of resources based on the operational reliability of transport network. The optimum assignment of resources is carried out based on a set of possible actions described in terms of the failure and repair rates of every link. Thus, the model optimizes the assignment of resources so that the accessibility of a centroid or the total network is maximized. The methodology also provides an alternative to model the decisions of the user as he/she travels between two centroids. A case study in Colombia is used to illustrate the applicability and the benefits of the model. The results can be used for the optimum allocation of resources for road maintenance and rehabilitation.

Lomax et al. (2003) pointed out that reliability is commonly used in reference to the level of consistency in transportation service for a mode, trip, route or corridor for a time period. Typically, reliability is viewed by travelers in relation to their experience. The term reliability may have a "marketable" connotation for the purposes of reporting performance measures to the public because it relates to an "outcome" of transportation—the quality of the service provided. The traveling public and a variety of companies or product sectors use the term reliability in their goal statements and it would seem this is the term that should be used with a performance measure.

The recently completed research plan on the reliability aspects of the Future Strategic Highway Research Program included a list of the sources of travel time variability. These seven sources describe the underlying conditions that change over time, and cause travel time to vary. In many “real world” situations these seven sources interact, further complicating the evaluation and prediction of reliability.

Incidents—collisions, vehicle breakdowns and debris that disrupt the normal flow of traffic, whether the event occurs on a shoulder or in the main travel lanes.

Work Zones—construction or maintenance activity.

Weather—the full range of vision-affecting events—from obscured visibility due to fog/snow/rain to bright, sunshine in driver’s eyes—to roadway surface conditions that affect driver behavior.

Fluctuations in Demand—day-to-day variations caused by changes in activity levels or patterns.

Special Events—causing dramatically different travel patterns or volumes in the vicinity of the event.

Traffic Control Devices—poorly timed signals or periodic signal events such as railroad crossings or drawbridges.

Inadequate Base Capacity—normally congested roads are more susceptible to effects from any of the other six factors.

Litman (2003) compares three approaches to measuring transportation system performance and discusses their effects on planning decisions as showed in Table 2.2. Traffic-based measurements (such as vehicle trips, traffic speed and roadway level of service) evaluate motor vehicle movement. Mobility-based measurements (such as person-miles, door-to-door traffic times and ton-miles) evaluate person and freight movement. Accessibility-based measurements (such as person-trips and generalized travel costs) evaluate the ability of people and businesses to reach desired goods, services and activities. Accessibility is the ultimate goal of transportation systems and therefore the best measure to use. The paper discussed three measurements as in Table 2.2.

Traffic Measurement: Vehicle traffic is relatively easy to measure. Most jurisdictions have data on motor vehicle registrations, drivers' licenses, and vehicle mileage. Performance indicators include traffic volumes, average traffic speeds, roadway Level of Service (LOS), congestion delay, parking supply, vehicle operating costs and crash rates.

Mobility Measurement: Mobility is measured using travel surveys to quantify person-miles, ton-miles, and travel speeds, plus traffic data to quantify average automobile and transit vehicle speeds. In recent years techniques have become available to evaluate multi-modal transportation system performance, such as transit and cycling Level of Service (LOS) ratings, although these are not yet widely used.

Accessibility Measurement: Accessibility is evaluated based on the time, money, discomfort and risk (the generalized cost) required to reach opportunities. Access is relatively difficult to measure because it can be affected by so many factors. For example, access to employment is affected by the location of suitable jobs, the quality and cost of travel options that reach worksites, and the feasibility of telecommunication (which may allow employment for a firm that is physically difficult to reach). Activity-based travel models and integrated transportation/land use models are most suitable for quantifying accessibility.

Table 2.2 Three Major Approaches to Measuring Transportation

	Traffic	**Mobility**	**Access**
Definition of transportation	Vehicle travel	Person and goods movement	Ability to obtain services and activities
Unit of measures	Vehicle miles and vehicle trips	Person miles and person trips and ton miles	Trips
Modes considers	Automobile and truck	Automobile, truck and public transit	All modes, including mobility substitutes such as telecommuting
Common performance indicators	Vehicle traffic volumes and speeds, roadway level of service, costs per vehicle mile, parking convenience	Person-trip volumes and speeds, road and transit level of service, cost per person trip, travel convenience	Multi-modal level of service, land use accessibility, generalized cost to reach activities
Assumptions concerning what benefits consumers	Maximum vehicle mileage and speed, convenient parking, low vehicle costs	Maximum personal travel and goods movement	Maximum transport options, convenience, land use accessibility, cost efficiency
Consideration of land use	Favors low density, urban fringe development patterns	Favors some land use clustering, to accommodate transit	Favors land use clustering, mix and connectivity
Favored transport improvement strategies	Increased road capacity and parking, speed and safety	Increased transportation system capacity, speed and safety	Improved mobility, mobility substitutes and land use accessibility

Source: Litman, Todd. (2003). "Measuring Transportation Traffic, Mobility and Accessibility". ITE Journal, Vol. 73, No. 10, October, pp. 28- 32.

Racca (2003) summarizes the models for public transit usage. The factor representing transit service often involves the proximity to transit stops either using walking distance buffers around transit routes or more detailed land use information. These approaches are insufficient to examine the effect transit service has on a person's travel mode decision. In work for the Delaware Transportation Institute, factors for transit level of service were developed using ArcInfo Network Models that more realistically estimate level of service between specified origins and destinations taking into account walking distances, transfers, wait times, and park and rides. Methods discussed for travel time and distance estimates are applicable for other travel modes as well. Transit ridership models using more accurate level of service estimates are discussed.

2.4 Intermodal Performance Measures in Literature

Besides general transportation measures, performance measures specifically used for intermodal systems are also being researched.

Li (2000) proposes a set of inter-modal performance indictors in which service input, service output, and service consumption are measured by total cost, revenue capacity miles/hours, and unlinked passenger raps/miles respectively based on economic principles and evaluation objectives. The proposed improvements involve the inclusion of capital as well as operating costs in such comparisons, and the recognition of the widely varying capacities of transit vehicles for seated and standing passengers. Two California cases, the Los Angeles - Long Beach Corridor and the Market/Judah Corridor in San Francisco, are used for testing their usefulness in the evaluation of the efficiency and effectiveness of rail and bus services. The results show substantial differences between performance indicators in current use and those proposed in this study. The enhanced intermodal performance indicators are more appropriate for comparing the efficiency and effectiveness of different modes or a combination of transit modes at the corridor and system levels where most major investment decisions are made.

Kenworthy and Laube (1999) listed indicators of transportation efficiency in 37 global cities in their book. In 1995, the World Bank commissioned the institute for Science and Technology Policy at Murdoch University to undertake a study on transportation efficiency in 37 global cities. Effectively, the research they requested amounted to the addition of a series of special indicators on the economy and the environment of the cities. The World Bank's request included the following items:

- Modal spilt for the journey to work
- Energy efficiency by mode of transportation
- Journey to work trip length (kilometers)
- Journey to work trip time (minutes)
- Transportation deaths
- Transportation emissions (CO, CO2, VHC, NOX, SOX, and Particulates)
- Road expenditure
- Percentage of GRP spent on the journey to work
- Public transportation operating cost recovery
- Condition of the road infrastructure

State Departments of Transportation (1996) did a survey about performance measures, which include: access limitations to intermodal facilities, coordination among modes, regulatory constraints, delivery and collection systems, safety, and economic/environmental tradeoffs. It is suggested that parameters should be identified that are suitable to measure and evaluate the efficiency of intermodal facilities and systems in moving people and goods from origin to destination.

Table 2.3 Ranking of Goals for Passenger Movement by Frequency of Use

Performance Measurements	**States**
Accessibility/Availability of intermodal facilities(Internal and external measures)	AZ CA FL HI KY MI NM OK OR PA TX
Time	AZ FL HI IN MI NM OK OR PA TX
Safety intermodal choices	CA FL HI OK OR MI MO PA TX
System Connectivity	AZ FL HI IN MI OR OK PA TX
Intermodal connectivity between modes	AZ CA HI MI NJ NM OR OK PA
Cost and affordability	CA HI KY MI OR PA TX
Encourage an increase in the percent of intermodal of alternative mode trips when the change benefits the user	CA KY MI MO OK TX
Improve intermodal effectiveness of the transportation system	CA MO OR PA TX
Define strategies for improving the effectiveness of the modal interaction	CA MI MO
Improve public knowledge of intermodal travel opportunities	MO OR PA
Improve data availability and accuracy regarding intermodal trips	MO OR PA
Legal issues and regulatory	MI OR
Reliability of facility	HI OR
Identify key linkages between one or more modes of transportation where the performance or use of one mode will affect another	MI MO
Environment	TX
Funding	TX

Source: Poister, T.H.(1997). *"Performance Measurement in State Departments of Transportation".* NCHRP Synthesis of Highway Practice. No. 238. TRB.

This goal is separated into two categories of internal and external measures. Internal measures address the actual conditions of the intermodal facility, such as queuing of vehicles. Internal measures emphasize the following issues: Queuing of vehicles, Pedestrian and bicycle access to and from intermodal facility, and facility service area.

External measures included indirect conditions, such as traffic volume on roads, level of service (LOS), traffic volume, and access to the intermodal facility. The second goal assigns a high priority to time and related measures. This goal accounts for 3 percent of the total performance measures. Measures for this goal emphasize the following issues:

Average travel time, delay time for all modes, and on-time performance. The provision of safe and secure intermodal choices was the goal ranked third by most State DOTS. These measures includes: number of accidents, injuries and fatalities by vehicle miles for all modes, security measures, conditions and percent change in statewide accidents. The goal of system connectivity ranks fourth in number of performance measures. Nine state DOTs measures: number of parking spaces, layover time for all modes, and volume-to-capacity ratio per hour of parking spaces. The goal of intermodal connectivity between modes ranks fifth in number of performance measures. Nine state DOTs provide performance measures for this goal that highlight: transfer time between modes, intermodal facility connectivity, and travel delay.

Wang (2004) established a systematic and user-oriented performance measurement system for intermodal transportation. Five major categories of performance measures are identified: mobility and reliability, safety, environmental impact, long term transportation cost efficiency, and economic impact. For each category, several quantitative measures are given to capture the features of the system and evaluate how well transportation systems can meet the needs of their travelers, who are investors (including government agents and stakeholders), individuals, industries, and society (or the public). The proposed measures are also verified by a survey conducted by this research and some industrial practices. In the thesis, a case study on the State of Mississippi is conducted based on the identified performance measures.

2.5 Shortcomings of Existing Literature

Although the previous studies cover multimodal and intermodal, the multiclass travelers, they have limited value for policy making and service planning for the following reasons:

Firstly, previous studies do not consider the impact of transfers. The previous research identified the impact of transfers on the choice of modes and routes, but the transfer penalty has not been considered in the network equilibrium model in any paper yet. Little is known about the effects. Besides, a transfer involves several components, including walking distance, waiting time, and cost. Each element is likely to contribute differently to the transfer penalty. Depending on which components are included in a model, the transfer penalty may refer to the effect of all components, the effect of only a subset of components, or the effect in addition to all quantitative components, which might be referred to as the pure transfer penalty.

Second, there is insufficient consideration of the diversity of travelers. The social economic characteristics of a traveler affect his/her travel behavior. Some of research efforts recognized the diversity of travelers by assigning different value of time to each class user. But none of the papers consider transit-captive condition. For example, the travelers having at least one auto should be distinguished from travelers don't own an auto or travelers can not drive because of physical conditions. The outcome of the multi-class model would be more accurate by separating the travelers to different classes in terms of their related features.

Third, transportation mode option is not complete. Most of research deals with the single mode. For the intermodal system, none of them give complete transfer options.

Without the complete mode options, the mode choice and route choice can not be forecasted accurately.

Last, insufficient of intermodal transportation evaluation system. For an intermodal system, the performance of each mode is very important. But the coordination between each mode can decide the overall efficiency and effectiveness. Current performance measures focus on a single mode, even for intermodal transportation system evaluations. The consideration of the transfer impact or transfer penalty is far from enough. No institutional impedance is included in the evaluations.

Therefore, from the literature review, it can be seen that the research in intermodal transportation system evaluation is far from mature. Most transportation performance measurements are focus on one mode rather than the whole network. In the practice, the data necessary for the evaluation process are from survey or on site data collection. Thus the combination of a network simulation model with an evaluation system is very necessary.

CHAPTER 3

COMBINED INTERMODEL NETWORK MODEL

This chapter presents the formulation and solution of a combined mode choice/assignment, intermodal network equilibrium model. The traditional travel demand forecast model involves four steps: trip generation, trip distribution, mode choice and trip assignment. The Combined Network Equilibrium Model (CNEM) combines the last two steps together. In the case that the first two steps are done, that the demand between each origin-destination pair is known and available, the CNEM predicts passenger flows on transportation network, which includes highway and transit, models the decision of travelers as they choose among travel options. The model takes into account the different socio- economic characteristics of travelers, like automobile ownership and various income levels.

Travel surveys indicate that in most North American communities more than 90% of households own at least one automobile and that more than 90% of trips are made by automobile. In reality, especially in urban areas, the transportation modes use can be very diverse. Many trips are taken by other modes, like bus or rail transit, even with more than one mode. These trips are increasing in magnitude and importance due to current urban transportation policies which encourage the use of transit by combined modes. Many newly developed urban transportation systems include attractive transfer facilities and integrated fare schemes that are aimed to induce passengers to undertake combined mode trips. Passengers can make the first part of the trip by a private car, then complete the trip by taking one or more public transit modes and by walking to the final destination. Even some trips taken on public transit may involve taking more than one mode, for example, bus access to a rail transit line, with a transfer at an intermodal center.

Auto, bus transit, rail transit and walking are the basic modes considered as travel options in the proposed formulation. Different from the other three modes, walking is a non-motorized mode. In urban areas, the percentage of walking is relatively low especially for long distance travel. It is considered as an access and egress mode only. People can choose one mode or make a trip on more than one mode. We call the latter "combined mode" trips. Using an intermodal transfer center as transfer points, travelers may switch between different modes, like rail-bus, bus-rail, auto-rail, and auto-bus.

There are two basic types of transfers. The first type involves a transfer within the same mode and it is referred to as an intramodal transfer. Examples include bus-bus and rail-rail. The second type involves a transfer across modes and is referred to as an intermodal transfer. Examples include bus-rail and automobile-rail. In this study, intramodel transfer is treated as pure mode. Only intermodal transfer is considered as transfer since intermodal transfers are more burdensome than intramodal transfers (Liu, 1997).

Besides the mode choice, the proposed procedure models the route choice, meaning the choice of the actual route within each of the modal options, which the traveler will follow from origin to destination. The principle is that travelers choose the route to minimize their generalized cost.

Trip generation and distribution are assumed to be exogenously given and related to the land use pattern. The mode and route choice are integrated and formulated in a mathematical programming framework. In order to model the mode choice and route choice of travelers, some assumptions are necessary to make the formulation possible and easy to conduct. The assumptions of model are:

1. Travel demand between one pair of origin and destination is fixed and known. That is, O-D flows are available. They can be used directly.

2. Travel is elastic, i.e. sensitive to travel costs on alternative modes and routes. Travelers try to choose a mode/route to minimize their generalized cost.

3. Travelers have a range of modes and route choices available to them.

4. Travelers have perfect information on travel times and costs of all routes. Travelers can choose the specific mode and route based on the information they have.

5. Travelers' preferences are considered in the mode and route choice.

6. Travelers will transfer between the different modes only once. Although sometimes travelers transfer more than one time to reach a destination, the percentage is low. The condition is not considered in the study.

7. The transit line frequencies have been adjusted to satisfy the maximum demand of each line.

3.1 Trip Mode Choice Process

In this model, the mode choice nest is formulated. A nested logit has been utilized to formulate travelers' choices. The mode choice model defines the available travel modes separately for work and non-work trip purposes. The mode choice models utilize nested-logit structure for each trip purpose, which permits the use of the denominator of the mode split model equation as a measure of impedance between zones. The nested-logit structure is shown in Figure 3.1. For the non-work trip purposes, a simple logit is used.

The models were developed using general relationships identified between the home-based work and non-work models in other regions.

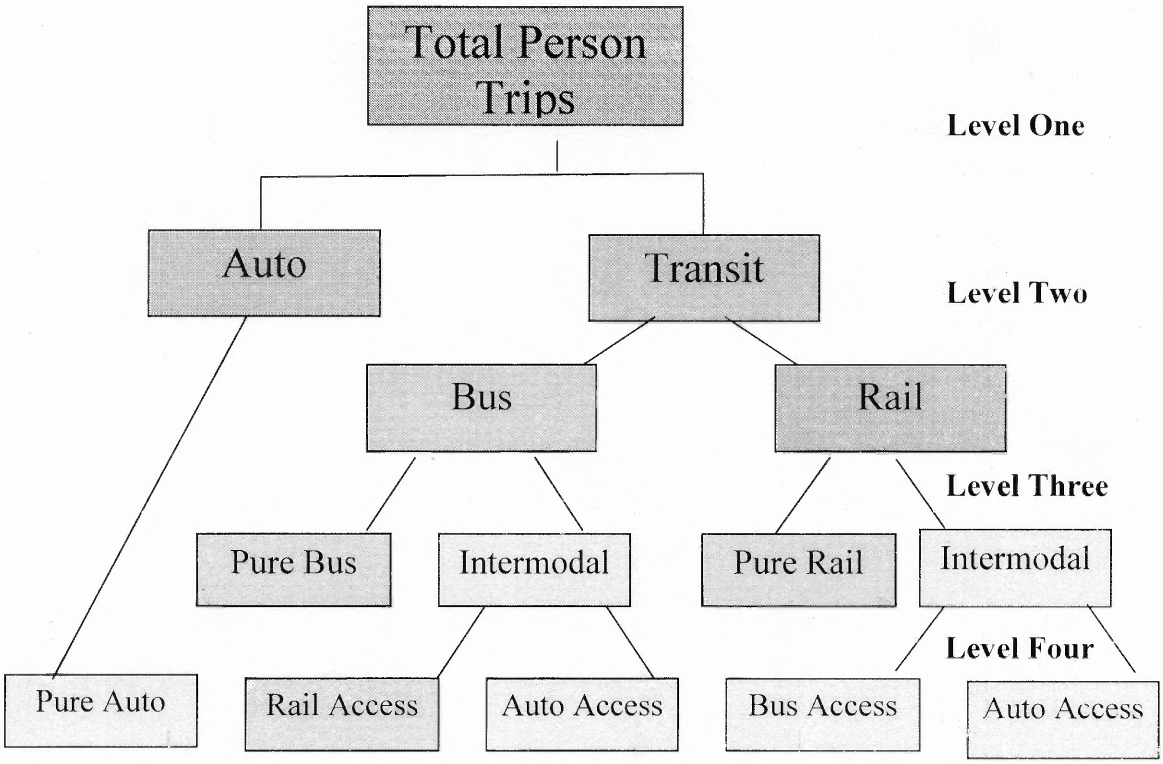

Figure 3.1 Intermodal trip making process.

The mode choice model allocates person trips for each origin-destination zonal pair into the available travel modes. Walking is not included in the process because it is treated to be access and egress use only. The access and egress process will not be treated as a transfer either.

There are two kinds of modes in the proposed model, pure mode and intermodal mode and the definitions are given as below:

Pure mode: Travelers uses only one mode to make a trip from origin to destination. This category includes pure auto, pure bus transit, and pure rail transit. The transfer between the same mode, bus or rail is not treated as transfer since the impact of intramodal transfer is much lower than that of intermodal transfer.

Intermodal: Travelers use two modes for one trip. In our case, it includes rail-bus, auto-bus, bus-rail and auto-rail. The meaning of rail-bus is that one passenger takes rail for the first part of trip and transfers to bus for the destination.

The trip mode choice process has four levels. At the first level, travelers need to decide between auto and transit, which means auto only or transit involved. If a traveler decides to use transit, then he/she make the choice between bus and rail. The reason to separate bus from rail transit is that the travel time functions are different. For bus transit, the calculation of travel time needs to consider the roadway condition, for example, the influence of congestion, since buses share roadways with automobiles. While for rail transit, the travel time is fixed because of exclusive guideways. If one passenger decides to take a bus, he/she also needs to decide that he/she wants to take a bus alone or access it by auto or rail. The same applies for travelers who want to take a train.

Therefore, there are totally seven types of possible modes that can be chosen, which are pure auto, pure bus, pure rail, rail-bus, auto-bus, bus-rail and auto-rail. All travelers are assigned among the seven modes, and the sum of seven modes demand is equal to the total demand between origin and destination flows.

3.2 Network Representation

Consider a study area that is divided into a set of zones, connected by bus and rail transit services and by a road network. The road network consists of a set of nodes and a set of directional links. There are several paths connecting one pair of origin and destination.

The network is represented by G (N, A), where N is the set of nodes and A is the set of directed links. A=RL&TL&WL&TRL, RL is railway network links, TL is the roadway network links, WL is the walk links (including access and egress links), TRL is the transfer links.

The network includes two modal sub-networks:

Pure mode: The sub-network of pure auto will include roadway network links only. The access to an auto will be eliminated since it is usually very close to the origin. The pure bus sub-network will include roadway network links and walk links because usually passengers need to walk to the bus station. Pure rail sub-network is defined as railway links and walking links.

Intermodal mode: The intermodal network contains walk links, roadway network, rail transit network and transfer links. For example, the network for rail-bus mode will include walking links, railway links, transfer links, roadway links and walking links.

3.3 Travelers Classification

Haider (1999) did a study of transit mode split in ten large Metropolitan Statistical Areas in the United States using Census Tract (CT) data extracted from the 2000 Census. Its purpose was to study public transit ridership in select US cities to determine if transit is catering to the accessibility needs of the transportation disadvantaged groups, such as low-income households. The paper draws on urban form (density, distance to the CBD), local economic health (income, unemployment, poverty, residential vacancy rate, average housing value), racial composition (% African American, % Hispanic), and auto-ownership (% of 0-vehicle households, average number of vehicles per household) to explain transit ridership at the CT level. The analysis reveals that urban form, transit supply, and poverty proxies, such as racial composition, are strong predictors of transit use in American cities. The study also showed that in large American cities, transit riders are predominantly poor individuals, who are often African Americans or Hispanics. This implies that race and poverty determine, to a great extent, transit ridership in the United States.

Various extensions of equilibrium models have been made to transportation networks with multi-class travelers. It should be clarified that the term of multi-class travelers refers to two distinct situations in the literature. The first situation is that the flows in a transportation network are divided into different classes of vehicles or modes, each of which has an individual cost-flow function, and at the same time contributes to its own and other class's cost function in an individual way. In our model, a classification of vehicle types could distinguish buses from cars. Suppose that the number of person trips by auto is converted to a number of vehicle trips by using a car occupancy factor. The number of person trips by bus and rail is converted to a number of buses and trains by using the average number of passengers.

The second situation is that all travelers or drivers are assumed to behave identically when making trips, but travelers differ from each other in different categories. First, there are some passengers who do not own an auto. Second, unobservable ways such as the value they place on time. The Value of Time (VOT) plays a central role in the network equilibrium model and network performance evaluation because it describes how travelers make tradeoffs between cost and time. Conventionally, VOTs are assumed to be identical for all travelers (homogeneous travelers).

In transportation analysis with heterogeneous travelers in terms of VOTs, various network equilibrium models are developed by assuming either a discrete set of VOTs for several distinct user classes or by a continuously distributed VOT across the whole population.

In the proposed model, the demand for travel is subdivided into m classes corresponding to groups of travelers. The first class is travelers who do not have an auto. Travelers who own at least one auto can be grouped to classes according to different socio-economic characteristics (for example, income levels). Average VOT is used for travelers in class m and demand for travel of class m between O-D pair. For simplicity and clarity, assume that the demand is given and fixed. The case study deals with the fixed-demand multi-class traffic network equilibrium problem.

Assuming each traveler chooses a path that minimizes his/ her generalized cost based on his/her own particular perception, the research examines the multi-class multi-criteria or cost versus time network equilibrium in a network with a discrete set of VOTs for several user classes.

This study is Deterministic User Equilibrium (DUE). Travelers of each class perceive cost identically, requiring perfect knowledge and foresight of the conditions and costs on the network, thus excluding error in perception.

3.4 Generalized Cost/Utility

Traffic flow distribution in the tolled network is forecasted using bi-criterion traffic assignment models in which travelers select their routes according to two criteria: travel time and travel cost (toll, parking, fare). Individuals will choose a mode of travel as if they were attempting to minimize the disutility associated with travel. A generalized cost function considering out of pocked costs in addition to the elements of travel time (which can be converted to cost using the value of time), similar to those presented in Fernandex et al. (1994), could be used as a more general and realistic expression of the cost functions.

There are four types of links, which are roadway links, railway links, access and egress links and transfer links. Total cost is composed by out of pocket costs and time value.

3.4.1 Auto Link

Both automobiles and buses can use roadway network links. To account for congestion, traffic assignment models use the notion of user equilibrium or Wardropian equilibrium. The travel time used to define the distance between the connection nodes is a function of the length and the capacity of each link of the path, and the total flow of the path. For the roadway, the travel time is subject to roadway network congestion and is flow dependent. The amount of passenger flow will influence the travel time on the link because of congestion. Thus, the fact that many travelers can travel along a link will affect the time it takes any particular user to traverse the link. On each link of the roadway network, the travel time has an associated flow-dependent travel time, which is determined by volume/delay functions $t(v)$. The functions denotes the travel time per unit flow or average travel time on each link. The travel time function is assumed to be differentiable, convex, and monotonically increasing with the amount of flow v. As it can be seen in Figure 3.2, the travel time increases when passenger flows increase.

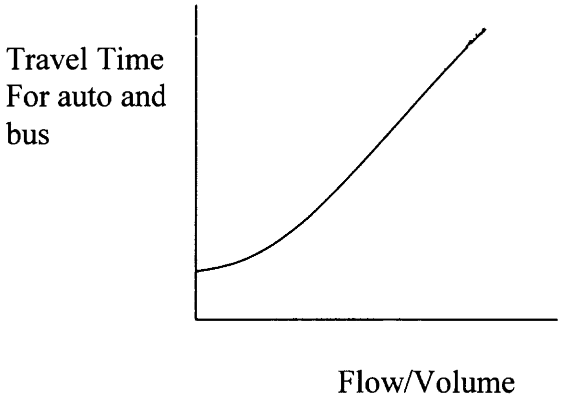

Figure 3.2 Flow-travel time relationship for automobiles and buses.

The roadway system is coded according to facility type, including such parameters as number of lanes, median type, and corresponding operating speed. The capacity of each highway link is coded according to the latest edition of the Highway Capacity Manual (HCM).

Additional attributes, such as free-flow travel time and travel cost, are also attached to individual links of the network. Total flow on link l includes auto flow and bus transit flow. Automobile travel time can be calculated by using the standard BPR form as below. Automobile travel time for link l,

$$t(l) = fft(l)(1 + a(\frac{f(l)/AOR}{ca(l)})^{b}) \tag{3.1}$$

Where

l : Link

$t(l)$: Travel time on link l

$fft(l)$: Free flow travel time on link l

$f(l)$: Passenger flow on link l

$ca(l)$: Capacity on link l

AOR: Average occupancy rate

Generally, a=0.15, b=4.

In order to determine the effect of a bus in the roadway network, assume that a transit vehicle is equivalent to a multiple of private cars. The conversion factor, γ_w , may be determined empirically. In traffic engineering studies (HCM), a bus is equivalent to 3 or 4 private cars. Certain links of the two networks can be considered to coincide in the sense that all the bus transit lines that use the road network share the use of the road links with the private cars. Let

$$\delta_{lk} = \begin{cases} 1, \text{ if link a belongs to path k} \\ 0, \text{ otherwise} \end{cases} \tag{3.2}$$

Thus the total flow on link l is

$$f^m(l) = \sum \delta_{lk}^m \bullet f_b^m(l) \bullet \gamma_w + \sum \delta_{lk} \bullet f_o^m(l) \tag{3.3}$$

for all links l , class m

Where

$f^m(l)$: Passenger flow on link l for user class m

δ_{lp}: Element of the link/path incidence matrix

γ_w: Bus-car equivalency factor.

Auto link travel time can be obtained as:

$$t(l) = fft(l)(1 + a(\frac{\sum_m f^m(l) / AOR}{ca(l)})^b) \tag{3.4}$$

Auto link generalized cost is expressed as:

$$c^m(l) = fft(l) \bullet (1 + a(\frac{\sum_m f^m(l)/AOR}{ca(l)})^b)(VOT^m + OPT) \tag{3.5}$$

Where

$c^m(l)$: Cost on link l for user class m

VOT^m : Value of time for class m

OPT : Operation cost.

3.4.2 Bus Link

Although buses share the same links with autos, usually bus travel time will be longer. The interaction of the transit vehicles and private cars on the road links affects the speed of the transit vehicles. The bus transit vehicle travel time over a line segment coinciding with link l is related to the automobile. For example, the bus travel time plus a constant penalty per mile to allow for stopped time (Florian, 1977). In the reality, bus stops per mile are not as easy to obtain and accurate as bus stop numbers on a specific link. In this study, bus stop numbers on a specific link are adopted. Total link bus dwell time is the production of average bus dwell time per stop and the real bus stop numbers. Bus travel time is the summation of general link travel time and bus dwell time.

$$t(l) = fft(l)(1 + a(\frac{\sum_m f^m(l)/AOR}{ca(l)})^b) + Del \bullet Sto(l) \tag{3.6}$$

Where

Del : Bus dwell time at one station

Sto : Bus stops in link l.

Bus link generalized cost is:

$$c^m(l) = (fft(l)(1 + a(\frac{\sum_m f^m(l)/AOR}{ca(l)})^b) + Del \bullet Sto(l)) \bullet VOT^m + fare \qquad (3.7)$$

Where

Fare : Transit fare.

3.4.3 Rail Transit Link

Rail travel time is not a function of the rail transit passenger link volumes. The capacity of a line is not considered explicitly. The line frequencies are assumed to be adjusted to satisfy the maximum demand of each line. This is justifiable if there is always sufficient capacity to transport all passengers who wish to travel. Since rail transit has its own network system and own right-of-way, rail in-vehicle travel time will not be affected by the influence of congestion and it is not a function of flow as shown in Figure 3.3.

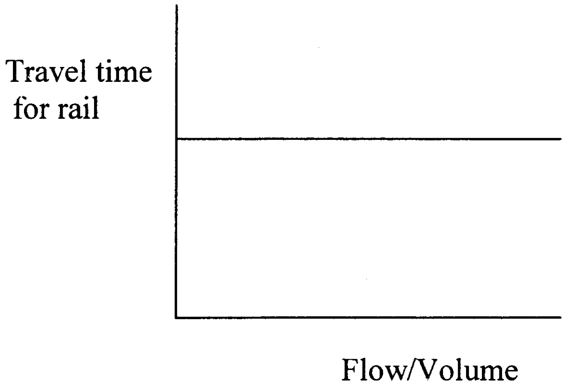

Figure 3.3 Flow-travel time relationship for rail transit.

Rail transit link travel time =Distance/ average travel speed. Then rail transit link generalized cost can be estimated as:

$$c^{m}(l) = t(l) \bullet VOT^{m} + fare \qquad (3.8)$$

3.4.4 Transfer Link

Usually transfer time includes walking time and waiting time. In this research, extra transfer penalty is also being considered. Transfer walking time is defined as the walking time from the transfer station arrival platform to the transfer station departure platform, which varied across transfer stations and by the direction of the transfer movement.

Transfer mean waiting time was calculated as half the headway of the transit to which the rider transferred if the passenger arrivals are assumed to follow an uniform distribution. Frequency of a bus transit line is defined as a number of transit vehicles dedicated to that transit line divided by the total journey time (Lam et al., 2002). The line frequencies for bus transit are assumed to be constant.

According to the study conducted by Liu (1996), rider satisfaction may be substantially reduced when a long walk is involved in transferring to transit. Consequently, transit ridership may be considerably reduced. Liu used data collected from the New York - New Jersey commuting corridor and used both revealed and stated preference data to estimate logit models of mode choice reflecting the impacts of intermodal transfers. The model results suggested that the value of the transfer penalty varies according to the type of modal transfers. For example, an intermodal transfer from auto to rail may create a transfer penalty equivalent to 15 minutes in-vehicle travel time;

an intra-modal transfer from rail to rail may only amount to 5 minutes of in-vehicle travel time.

Indeed, the mode-choice model specification, which includes an automobile-to-rail transfer dummy, clearly shows that an automobile to-rail transfer is more burdensome than a rail-to-rail transfer (omitted dummy variable).

The likelihood that rail will be used when an automobile-to-rail transfer must be made is less than that when only a rail-to-rail transfer must be made. Based on previous studies, the transfer penalties used in the research are listed as Table 3.1.

Table 3.1 Transfer Penalty Equivalence by Types

Transfer Types (Model Structure)	**Transfer Penalty Equivalence**
Rail-to-Rail	14.8 minutes in-vehicle time
Bus-to-Rail	23.0 minutes in-vehicle time
Bus-to-Bus	49.5 minutes in-vehicle time
Auto-to-Rail	15 minutes in-vehicle time
Rail-to-Rail	1.4 minutes in-vehicle time
Auto-Bus	15 minutes in-vehicle time

The transfer link generalized cost can be obtained as:

$$c^m(l) = t(l) \bullet VOT^m \tag{3.9}$$

3.4.5 Access and Egress Link

The access and egress link travel time is the walk time on access and egress links. Walking time is defined as the walking time from the origin to transit station and from transit station to the destination. In this study, all travelers are assumed to start from the centriod of the origin and end at the centroid of the destination. Access and egress link generalized cost is defined as Equation 3.10.

$$c^m(l) = t(l) \bullet VOT^m \tag{3.10}$$

3.4.6 Generalized Cost

The generalized cost of a path is the total cost of all the links used in the path. One bus mode path cost is given as an example. Consider a bus transit network that consists of nodes and a set of access links, transfer links and egress links. The bus transit path is subdivided into several bus links between the connecting nodes. Each link has its own travel demand and travel time. For bus transit network, the total travel time includes the total travel time includes in-vehicle travel time for each bus transit link, walking time on access and egress links, and bus waiting time at the boarding station.

1. In-vehicle travel time for each bus transit link can be found by using the above function;

2. Walking time on access and egress links is quiet straightforward, can be get by using the distance divided by the average walking speed;

3. Bus waiting time at the boarding station. The line frequencies are assumed to be adjusted to satisfy the maximum demand of each line.

3.5 Model Formulation

The number of trips by type is determined in the trip generation step. Within this step, both trip productions and trip attractions are estimated for each zone. In this simulation effort, the number of trips generated (produced or attracted) is not affected by the addition, deletion, or change in transfer penalty. As such, the simulation assumes that the number of trips produced and attracted by each zone is fixed. It is conceivable. However, that trip generation is affected by transfer penalties on transit networks. This is related to the issue of induced and suppressed trips.

The dependence of the number of trips on the cost of travel between the O-D pair is expressed by the demand function. This function is assumed to be monotonically decreasing as shown in Figure 3.4.

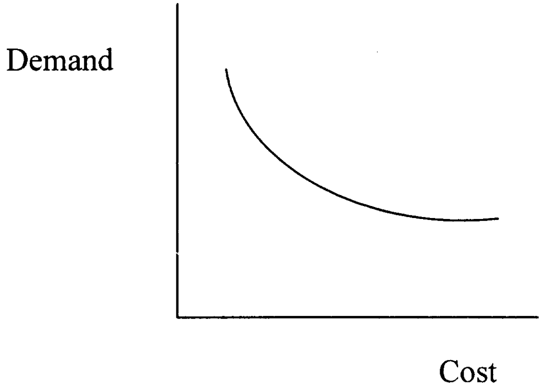

Figure 3.4 Cost-demand relationship.

Assume that the inverse function of the demand function exists, then, the user optimized equilibrium flows, are those that maximize the consumer's surplus or equivalently, minimize the total cost.

3.5.1 Equilibrium Conditions

The equilibrium conditions are given by the intersection of the following three subsets of conditions.

1) The choice of route. The basic assumption under user equilibrium is that, for each origin destination pair, all used paths will have a cost equal to the minimum cost path, while the unutilized paths will have a cost equal to or higher than the minimum cost path. In other words, at equilibrium, no traveler has an incentive to unilaterally change

routes for he/she cannot reduce the travel cost. Assume that Wardrop's user-optimal principle governs the route choice in every subnetwork. This condition takes the mathematical form:

$$GC_k^{wm} - GC^{wm} = \left\{ \begin{array}{l} = 0\mathrm{K}\ \mathit{if}\mathrm{K}\ p_k^{wm} \geq 0 \\ \geq 0\mathrm{K}\ \mathit{if}\mathrm{K}\ p_k^{wm} = 0 \end{array} \right\} \tag{3.11}$$

Where

GC^{wm} : Minimum cost of traveling between O-D w for class m

GC_k^{wm} : Generalized cost flow on path k between OD w for class m

p_k^{wm} : Passenger flow on path k.

This condition indicates that path p from origin i to destination j is utilized (i.e., has a nonnegative flow, or p_k^{wm} **> 0**) only if the generalized cost on this path is equal to the minimum generalized cost for that user class and that O-D pair.

2) The choice of mode of transport. The proportion of travelers in every mode, for each pair, is given as a demand function. For example, at the first level, the demands are assigned on automobiles and transit. The utility for an alternative is defined as:

$$U = -\beta GC - \alpha \tag{3.12}$$

Where

U : Utility

GC : Generalized cost

α, β : Utility coefficients.

A logit model of mode choice is used to determine the modal split and the total number of trips that will be made by auto as:

$$T_a^{wm} = T^{wm} \frac{\exp(U_a^{wm})}{\exp(U_a^{wm}) + \exp(U_t^{wm})} \tag{3.13}$$

Where

T^{wm} : Demand between O-D pair w for user class m

T_{mode}^{wm}: Travel demand between O-D pair w for user class m by some mode

U_a^{wm}: Utility for O-D pair w for user class m by auto

U_t^{wm}: Utility for O-D pair w for user class m by transit .

Then get

$$T_a^{wm} = T^{wm} \bullet \frac{\exp(-\beta_1 GC_a^{wm} - \alpha_a)}{\exp(-\beta_1 GC_a^{wm} - \alpha_a) + \exp(-\beta_1 GC_t^{wm} - \alpha_t)} \tag{3.14}$$

$$GC_a^{wm} - GC_t^{wm} = -\frac{1}{\beta 1}(\ln \frac{T_a^{wm}}{T_t^{wm}} + \alpha_a - \alpha_t) \tag{3.15}$$

That is for level one. Same logic is for level two

$$GC_{t,b}^{wm} - GC_{t,r}^{wm} = -\frac{1}{\beta 2}(\ln \frac{T_{t,b}^{wm}}{T_{t,r}^{wm}} + \alpha_{t,b} - \alpha_{t,r}) \tag{3.16}$$

Level three

$$GC_{t,b,i}^{wm} - GC_{t,b,p}^{wm} = -\frac{1}{\beta 3}(\ln \frac{T_{t,b,i}^{wm}}{T_{t,b,p}^{wm}} + \alpha_{t,b,i} - \alpha_{t,b,p}) \tag{3.17}$$

$$GC_{t,r,i}^{wm} - GC_{t,r,p}^{wm} = -\frac{1}{\beta 4}(\ln \frac{T_{t,r,i}^{wm}}{T_{t,r,p}^{wm}} + \alpha_{t,r,i} - \alpha_{t,r,p}) \tag{3.18}$$

3) The choice of the transfer node. The proportion of combined mode travelers that choose each transfer point, for each pair OD is given by the demand function. Level four:

$$GC^{wm}_{t,b,i,a} - GC^{wm}_{t,b,i,r} = -\frac{1}{\beta 5}(\ln \frac{T^{wm}_{t,b,i,a}}{T^{wm}_{t,b,i,r}} + \alpha_{t,b,i,a} - \alpha_{t,b,i,r}) \tag{3.19}$$

$$GC^{wm}_{t,r,i,a} - GC^{wm}_{t,r,i,b} = -\frac{1}{\beta 6}(\ln \frac{T^{wm}_{t,r,i,a}}{T^{wm}_{t,r,i,b}} + \alpha_{t,r,i,a} - \alpha_{t,r,i,b}) \tag{3.20}$$

When these proportions are achieved, none user has an incentive unilaterally to change the transfer point chosen.

3.5.2 Asymmetric Cost

The derivative of highway link cost with respect to transit link flow is not equal to the derivative of transit link with respect to highway flow, as in Equation 3.21:

$$\frac{\partial c_i}{\partial v_j} \neq \frac{\partial c_j}{\partial v_i} \tag{3.21}$$

Therefore, the problem is asymmetric and non-convex, and no equivalent mathematical programming method can solve the problem. Therefore, the variation inequality method is used to express the equilibrium conditions for the combined mode split/assignment problem.

3.5.3 Model Statement

The objective function of the mathematical model is:

$$\begin{aligned} & c(l^*)^t(f(l) - f(l)^*) - G_1^{-1}(T_t^*)^t(T_t - T_t^*) - G_2^{-1}(T_{t,b}^*)^t(T_{t,b} - T_{t,b}^*) \\ & -G_3^{-1}(T_{t,r,p}^*)^t(T_{t,r,p} - T_{t,r,p}^*) - G_4^{-1}(T_{t,b,p}^*)^t(T_{t,b,p} - T_{t,b,p}^*) \\ & -G_5^{-1}(T_{t,r,i,a}^*)^t(T_{t,r,i,a} - T_{t,r,i,a}^*) - G_6^{-1}(T_{t,b,i,a}^*)^t(T_{t,b,i,a} - T_{t,b,i,a}^*) \geq 0 \end{aligned} \tag{3.22}$$

Where

G_1^{-1} : Inverse demand function for demand between auto and transit

G_2^{-1} : Inverse demand function for transit demand between bus and rail transit

G_3^{-1} : Inverse demand function for rail demand between pure and intermodal rail transit

G_4^{-1} : Inverse demand function for bus demand between pure and intermodal bus transit

G_5^{-1} : Inverse demand function for bus demand between auto and bus transfer rail transit

G_6^{-1} : Inverse demand function for bus demand between auto and rail transfer bus transit

This mathematical construct will minimize average user cost according to the user equilibrium principle as these are described by the equilibrium conditions stated above. The first three components are the mathematical expression of the user equilibrium principle (Sheffi, 1985) while the last three components are the integrals of the inverted demand functions, Dl, D2 and D3, which account for traveler preference between auto and transit, and between rail and intermodal. The total demand conservation constraint indicates that the total demand between each origin-destination (O-D) pair is equal to the sum of the auto and transit trip rates for this O-D pair:

$$T^{wm} = T_a^{wm} + T_t^{wm} \tag{3.23}$$

The auto demand conservation constraint indicates that the auto trip rate for an O-D pair is equal to the sum of flows on all auto paths of this O-D pair:

$$T_a^{wm} = \sum_k p_k^{wm} \tag{3.24}$$

Where:

p_k^{wm} : path flow between O-D pair w for user class m by mode m.

Transit path

$$T_t^{wm} = \sum_k p_k^{wm} \tag{3.25}$$

The same constraint is written for the rail and intermodal trip rates.

$$T_t^{wm} = T_{t,b}^{wm} + T_{t,r}^{wm} \tag{3.26}$$

Bus transit path

$$T_{t,b}^{wm} = \sum_k p_k^{wm} \tag{3.27}$$

Rail transit path

$$T_{t,r}^{wm} = \sum_k p_k^{wm} \tag{3.28}$$

The demand for transit conservation constraint indicates that the transit trip rate between each O-D pair is equal to the sum of rail and intermodal trip rates between this O-D pair.

$$T_{t,b}^{wm} = T_{t,b,p}^{wm} + T_{t,b,i}^{wm} \tag{3.29}$$

Pure bus transit path

$$T_{t,b,p}^{wm} = \sum_k p_k^{wm} \tag{3.30}$$

Intermodal bus transit path

$$T_{t,b,i}^{wm} = \sum_k p_k^{wm} \tag{3.31}$$

Intermodal rail transit path

$$T_{t,r}^{wm} = T_{t,r,p}^{wm} + T_{t,r,i}^{wm} \tag{3.32}$$

Pure rail transit path

$$T_{t,r,p}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.33}$$

Intermodal rail transit path

$$T_{t,r,i}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.34}$$

$$T_{t,b,i}^{wm} = T_{t,b,i,a}^{wm} + T_{t,b,i,r}^{wm} \tag{3.35}$$

Auto-bus path

$$T_{t,b,i,a}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.36}$$

Rail-bus path

$$T_{t,b,i,r}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.37}$$

$$T_{t,r,i}^{wm} = T_{t,r,i,a}^{wm} + T_{t,r,i,b}^{wm} \tag{3.38}$$

Auto-rail path

$$T_{t,r,i,a}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.39}$$

Bus-rail path

$$T_{t,r,i,b}^{wm} = \sum_{k} p_{k}^{wm} \tag{3.40}$$

The constraint of the formulation is the non-negativity constraint which ensures that the model does not generate negative path flow values:

$$p_{k}^{wm} \geq 0 \tag{3.41}$$

The model is summarized as Appendix A. It can be proven mathematically that a solution to this model satisfies the equilibrium conditions.

3.6 Solution of the Model

The specific package used in this study was General Algebraic Modeling System (GAMS) in the solve process. GAMS is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows the travelers to build large maintainable models that can be adapted quickly to new situations. Similar optimization software like AMPL, LINGO can also used in solving application. The CNEM model is Nonlinearly Constrained Optimization Problem (NCOP). The minos solver is chosen to solve the CNEM model. The calculation is processed by NEOS solvers.

3.7 Data Needs

The availability of input data is very important for the success of the model. The output data decides the application of the model. The data categories and sources are discussed below.

3.7.1 Input Data

Input data can be divided into several categories:

1. Network Attributes (Transportation supply characteristics). Usually the above data can be obtained from local transportation agency. The data includes:

Centroid of each origin and destination

Path (route) between each OD pair

Location of parking lot

Each link in the network is described by the following parameters: Link type, Link length in miles, number of lanes, capacity and free flow speed.

2. Transit Service.Usually the category data can be obtained from local transportation agency. It includes:

Location of bus and rail transit stations

Frequency of bus and rail transit

Location of Transfer station

Out of pocket cost, which may include transit fare, and parking fee.

3. Travel Demand. The data can be obtained from Census data or from local planning agency. The category has:

Travel demand between O-D trips (OD flow), which can be obtained from Census Transportation Planning Package (CTPP).

Value of time of each user class. The data is usually a function of average hourly income of traveler.

4. Statistical Data. The data is available from National Transportation Statistics. Bureau of Transportation Statistics (BTS) publishes the data every year. It includes:

Average safety and security record for each mode

Average automobile, bus and rail energy consumption

Average automobile, bus and rail emissions

Average automobile operation cost.

3.7.2 Output Data

The output of the model is the equilibrium flow. By reaching the equilibrium, no traveler may lower his/her transportation cost through unilateral action. The generalized cost of the paths used by travelers is lowest. The output of the model gives the traffic flow on each link. By using the traffic flow, travel time and cost on each link can be derived. Links can be connected to each other to compose a path (route). Therefore for each path, travel flow and cost can be obtained.

CHAPTER 4

INTERMODAL TRANSPORTATION EVALUATION SYSTEM

Performance indicators are practical ways of measuring progress toward objectives. Per capita travel statistics, traffic counts, level-of-service (LOS) ratings, cost per mile, and customer satisfaction survey results are examples of performance indicators used for transport planning. State of practice of the performance measures is very important. The identification of appropriate performance measures is a critical component of successful decision making because inappropriate performance measures generally lead to poor decisions and poor outcomes. If choose the similar indicators with the ones used in the industry, there is a higher probability they will be used by transportation planners. Performance measures for sustainable transportation are also used as a method to assist decision-makers in making informed decisions regarding projects, programs and policies.

Transportation can be evaluated from many aspects. Some of them conflict with each other. For example, the use of automobiles can increases mobility, vehicle traffic and associated benefits and costs. However, automobile dependency reduces the range of solutions that can be used to address problems such as traffic congestion, road and parking facility costs, crashes and pollution. Intermodal and multimodal indicators are necessary for comprehensive evaluations.

Literature review shows the state of practice of transportation system performance measures, which most likely include mobility, accessibility, cost efficiency, institution impedance, safety, security, and environmental impact. This can be served as a guideline of choosing performance measures.

The necessary data for performance measures are obtained from the CNEM model. The output of the CNEM can be used to establish a systematic and user-oriented performance measurement system for intermodal transportation. Based on the literature review and the state of practice, the dimensions of social equity, economic development, environmental impacts and transferability stewardships are chosen to evaluate transportation system. For each category, in order to meet the goals to improvement the transportation performance, several quantitative measures are given to capture the features of the system and evaluate how well transportation systems can meet the needs of their travelers. In the study, the unique of the evaluation system is that it fully considers the difference and interaction between the modes and the intermodal impact on transportation performance.

These measures were then used to determine the index values at a link level, so that various links within the corridor could be compared, as well as at the corridor level, so that various corridors could be compared. It was also illustrated that different index values can be obtained at the corridor level depending on whether it was viewed from the perspective of the individual driver or the system as a whole. The performance measures are summarized in Table 4.1.

Table 4.1 Transportation System Goals and Performance Measures

Dimension	Goals	Performance Measures
Social	Maximize accessibility	Travel time to reach transit service and activities
	Maximize Mobility/ Minimize travel time	Average travel speed
	Maximize safety	Accidents per 100 million vehicle miles of travel
	Maximize security	Incidents of crime per 100 million vehicle miles of travel
	Maximize transit usage/ Minimize auto usage	Person-miles of transit travel Person-miles of automobile travel
Economic	Maximize affordability/ Minimize travel cost	Travel cost per person mile
Environmental	Minimize air pollution	VOC, OC and NO_X emissions
	Minimize energy use	Fuel Consumption (Per capital fuel consumption)
	Minimize noise impact	Noise levels
Transferable	Minimize transfer times	Average time spend on transfer
	Minimize number of transfers	Average number of transfers
	Institution impact	

4.1 Social Dimension

The social dimension includes mobility, accessibility, safety, security and transit usage. Each aspect has its own measures.

4.1.1 Mobility

Mobility refers to the movement of people or goods. Providing mobility for passengers is the transportation system's most essential function. Mobility is important because it widens the geographic horizon of employment, housing, shopping and recreation opportunities. In other words, mobility is valuable because it provides access to jobs, services and markets.

In the study, mobility is measured door-to-door, taking into account each link of a trip, including walking to a transit station or transfer time. Since each path has its own travel time, for automobile, travel time is in-vehicle time; for bus and transit, travel time is in-vehicle time, access time and waiting time; for intermodal mode, additional transfer time should be added into.

Mobility can be measured in person-miles, ton-miles, and travel speeds. Average travel speed is picked up to measure mobility in the study, which can be represented as Sum (Path length* path flow) / sum (path flow* path travel time). The path travelers choose, which is the minimum generalized cost path, is generated from the CNEM model. The path flow is also from the result of the model. The computation equation is as Equation 4.1.

$$\frac{\sum_{m}\sum_{l} f^{m}(l) * L(l)}{\sum_{m}\sum_{l} f^{m}(l) * t(l)} \tag{4.1}$$

4.1.2 Accessibility

From the customer point of view, service availability is where and when service is provided, and having sufficient capacity available for passengers to take trips at their desired time. It refers to the ability to reach desired goods, services, activities and destinations (collectively called opportunities). Opportunities for fulfillment of travel objectives can be represented by employment (jobs), housing, shopping, community services, or other destinations of interest.

Accessibility is most readily calculated using transportation planning computer networks and demographic data for a corridor or region. It has been extensively used for assessing relative quality and equity in transit service, but can be applied to any mode. The strongest feature of accessibility is that it is particularly useful in examining the joint performance of the transportation and land use system.

Accessibility is evaluated based on the time, money, discomfort and risk (the generalized cost) required reaching opportunities. Individuals often think of it in terms of convenience, that is, the ease with which they can reach what they want. Accessibility is relatively difficult to measure because it is affected by a variety of transportation, economic and geographic factors. For example, access to employment is affected by an individual's physical and economic abilities, the quality and cost of travel options that reach worksites, the feasibility of telecommunication (which may allow employment for a firm that is physically difficult to reach), and the geographic location of suitable jobs. Activity-based travel models and integrated transportation/land use models using detailed travel survey data are most suitable for quantifying accessibility.

At the regional level, accessibility is affected by street connectivity, transit service, geographic density and mix. A more accessible region will have a network of many roads (rather than just a few major arterials) and efficient transit service that makes it convenient to travel within the region by car or transit.

In the study, accessibility is measured by the average time to access transit and activities. That can be express as: sum (access/egress link travel time* link flow)/ total flow. The link flow and access/egress link travel time can be obtained from the CNEM model. The measure can be calculated by Equation 4.2.

$$\frac{\sum_{m}\sum_{l} f^{im}(l) * t(l)}{T} \qquad (4.2)$$

4.1.3 Safety and Security

Safety is a qualitative evaluation method, meaning there is no easy way to measure the effects each alternative has on potential safety hazards or existing safety deficiencies using calculated methods. Rather, each alternative is evaluated based on the perceived impact (good or bad) it may have on the safety of the corridor. The safety component has been separated into two categories: Auto and Pedestrian. The auto safety is being evaluated on potential conflict points at signalized and unsignalized intersections, as well as the potential for increased or decreased vehicle volumes on a corridor. The measures reflect the likelihood that one will be involved in an accident (safety) or become the victim of a crime (security) while using transit (customer).

Researchers over the past two decades have developed a variety of statistical methods to predict the crash rates at different roadway sections and establish the relationship between vehicle crashes and the characteristics of traffic on the roadway. Different models have different advantages and disadvantages. It is important to evaluate how those models can be integrated into the safety planning process in terms of their underlying assumptions, data requirements, and model performance (Qin, 2006). Average fatal and injury rate for different modes, passenger car, bas and train can be obtained from the BTS data (BTS) as Table 4.2.

Table 4.2 Fatal and Injury Rate by Different Modes

Mode	Fatal Rate (times/million miles)	Injury Rate (times/million miles)
passenger car	0.0159719	1.1479198
Bus	0.0002364	0.1072802
Train	0.0055657	1.1229676

Source: USDOT, 2005

The total intermodal system fatal and injury number equals: sum (mode link flow* link length) * mode fatal rate/ Sum (link flow*link length) .Each mode link flow is summarized from the result of the CNEM model. Fatal and injury number can be obtained by using Equation 4.3 and 4.4.

$$\frac{\sum_m \sum_l f^m(l) * L(l) * fatalrate}{\sum_m \sum_l f^m(l) * L(l)} \tag{4.3}$$

$$\frac{\sum_m \sum_l f^m(l) * L(l) * injurerate}{\sum_m \sum_l f^m(l) * L(l)} \tag{4.4}$$

4.1.4 Auto Usage

In order to reduce the dependence on automobiles, auto usage rate is an important measure for sustainable developments. The goal is to reduce the amount of auto usage or get people to switch from cars to buses. The auto usage rate is the proportion of auto usage to overall trips. The calculation is as follows:

$$\frac{\sum_m \sum_{l \in auto} f^m(l) * L(l) + \sum_m \sum_{l \in bus} f^m(l) * L(l) + \sum_m \sum_{l \in rail} f^m(l) * L(l)}{\sum_m \sum_l f^m(l) * L(l)} \tag{4.5}$$

4.2 Economic Dimension

Economic dimension can be represented by a transportation affordability measure. Affordability refers to people's ability to purchase goods and services considered important or essential. Transportation affordability refers to people's ability to purchase transport that provides access to goods, services and activities considered important or essential, such as medical service, basic shopping, education, employment and social activities. An affordability analysis should generally be as comprehensive as possible, taking into account all related costs, and based on total rather than unit costs. For example, transportation affordability is ultimately based on total vehicle costs, not just fuel costs, and reductions in per-gallon fuel prices may provide little overall increase in affordability if it encourages vehicle purchasers to select less fuel-efficient vehicles or stimulates more dispersed, automobile-dependent land use development. Transportation affordability should also account for indirect costs, such as residential parking costs.

Each path and mode has its own generalized cost, for automobile, cost is fuel, parking fee, in- vehicle time (convert to cost), for transit user, cost includes fare and travel time cost, for intermodal mode, transfer cost should be considered. Cost efficiency = sum (volume of passengers of each path * travel cost) / all the travel demand* travel distance.

$$\frac{\sum_{m}\sum_{l} f^{m}(l) * C(l)}{\sum_{m}\sum_{l} f^{m}(l) * L(l)} \tag{4.6}$$

4.3 Environmental Dimension

4.3.1 Emission

Transportation is a major contributor to air pollution, with motor vehicles accounting for a large share of nearly all the major pollutants found in the atmosphere. Despite significant improvements in fuel and engine technology, road vehicles continue to be one of the primary sources of urban pollution. The pollutants examined in this research are volatile organic compounds (VOC), carbon monoxide (CO), and nitrogen oxides (NOX) because they are most commonly associated with health problems in urban areas. Emission can be calculated as: (Autos numbers* travel distance*emission rate + buses numbers* travel distance* emission rate+ train numbers* travel distance* emission rate)/ (total passenger miles).

$$\frac{\sum_{m}\sum_{l} f^{m}(l) * L(l) * emissonrate}{\sum_{m}\sum_{l} f^{m}(l) * L(l)} \tag{4.7}$$

4.3.2 Energy Consumption

Different mode has different energy consumption, emission rate. Only auto links, bus links and rail links are chosen for analyses, since walking links will have no energy consumption and emission. Energy consumption part can be calculated as: (Autos miles*energy consumption rate + buses miles* energy consumption rate+ train miles* energy consumption rate)/ total passenger miles. Equation is 4.8.

$$\frac{\sum_{m}\sum_{l} f^{m}(l) * L(l) * energyuserate}{\sum_{m}\sum_{l} f^{m}(l) * L(l)} \tag{4.8}$$

Table 4.3 Fuel Consumption by Different Modes

Mode	**BTU/Pass. Mile**
Passenger car	3489.55386
Bus	987.475748
Transit	396.064371

Source: USDOT, 2005

4.4 Transferable Dimension

Transferability is an important factor to measure the coordination between different transfer modes and the transfer penalty to travelers. There are two kinds of changer: one is traditional change, including changing transportation mode or changing vehicles within one same mode; the other type is the change of institution. All local transportation agency has its own area. The change of authority area will bring some differences.

4.4.1 Transfer Evaluation

For travelers changing mode or changing vehicle during the trip, two measures are used to evaluation the transfer condition

1. Average transfer rate. The measure is average number of transfer. Since all travelers are assumed to transfer at most one time, the measure gives the percentage of travelers who change the mode during their trip.

$$\frac{\sum_{W}\sum_{M} T_{t,r,i}^{wm} + T_{t,b,i}^{wm}}{\sum_{W}\sum_{M} T^{wm}} \tag{4.9}$$

2. Average time. Time spend on transfer, which including the walking time to a transfer center, the waiting time and the transfer penalty at the transit station.

$$\frac{\sum_{m}\sum_{transferlink} f^{m}(l)*T(l)}{\sum_{m}\sum_{l} f^{m}} \tag{4.10}$$

4.4.2 Institutional Impedance

The institutional impedance focuses on how the allocation of institution will affect the traveler's utility. For example, transfer policy between different institutions, is there an extra fare charged for transfer or not? A score can be given to evaluate the impedance caused by the allocation of institution. Then the institution impedance = total score/transit network length.

The measures can be used to compare different transportation systems. They provide the transportation planer with the needed information to find the shortcomings of the system (like the location of the intermodal transfer center, the headway of the transit) and to improve it.

CHAPTER 5

CASE STUDY

The CNEM model and evaluation systems provide the methodology framework to forecast travel demand, mode choice, route choice and the system performance. This chapter gives one case study. The study area is located in north New Jersey (NJ). NJ Transit has long been interested in using the Northern Branch rail line between North Bergen and Tenafly to develop a rail transit service improving passenger mobility in the corridor with connections to Manhattan, Downtown Jersey City, Hoboken and Bayonne. Until recently planning had focused on extending the Hudson Bergen Light Rail Transit System (HBLRTS) north along the Northern Branch from Tonnelle Avenue to Tenafly. NJ Transit is now considering developing Self-Propelled Rail Car (SPRC) service to improve mobility in this corridor in a more economically attractive manner. NJ Transit's vision for the SPRC service entails an 11.3 mile route running from Tonnelle Avenue in North Bergen to Madison Avenue in Tenafly. The SPRC service would share track with existing CSXT freight operations, serve 11 stations, operate with 15 to 20 minute peak headways and 30-40 minute off-peak headways, carry 1,800 passengers arriving at Tonnelle in the peak morning hour.

5.1 Case Study Network

The study corridor for the Northern Branch Line has several proposed stops located in Tenafly, Englewood, Leonia, Palisades Park, Ridgefield and North Bergen. Figure 5.1 shows the existing CSXT rail line from North Bergen to Tenafly. The rail line runs through a variety of residential, commercial, and industrial areas. This study area, located to the west of the Hudson River, is densely populated and very close to New York City. The proposed Northern Branch Line is located in the southeast part of Bergen County and extents to the northern portion of Hudson County, which is even more populous in the region.

According to the 2000 US Census, there are almost 270,000 inhabitants living along the corridor within the area of 43 square miles. The average population density is more than 6,000 persons per square mile. There are 15 towns or municipalities located along or close to the Northern Branch Line corridor, as shown in Figure 5.1.

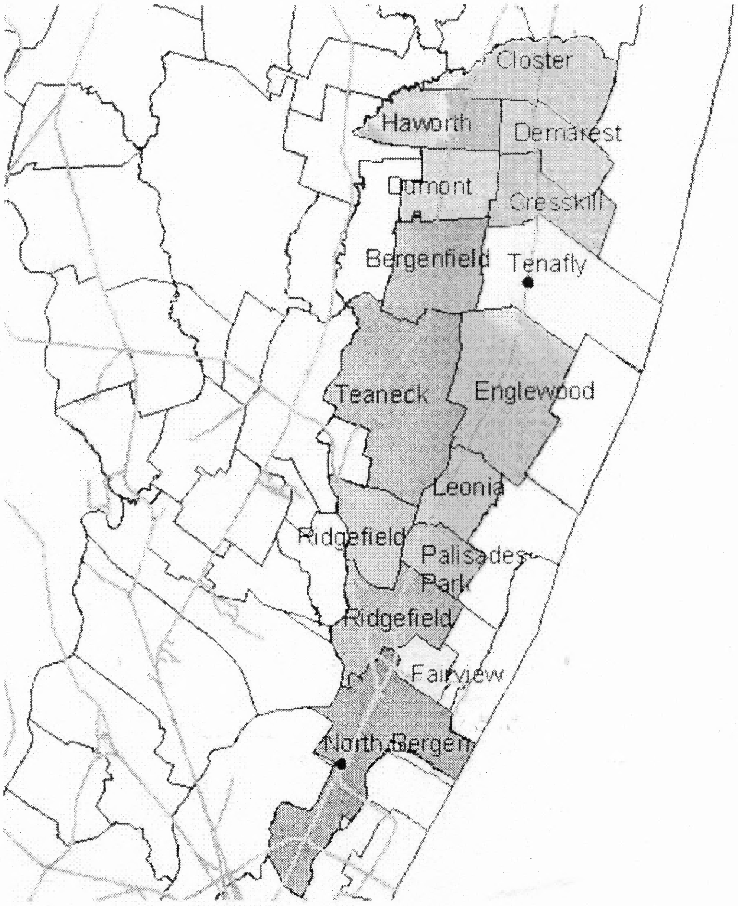

Figure 5.1 North Branch Line corridor map.

In this study area, Dumont, Tenafly, Ridgefield Park, and Fairview are chosen as the originals and Jersey City is chosen as the destination. The centroids are identified to stand for the location of the community. It is assumed that all the trips are from and to the centroid of the communities.

The roadways, busways and rail lines can be represented as a link network as shown in Figure 5.2. Route names are shown in the figure. In order to see the impact of the new transit service, the no build (before) network is used to generate the mode split and traffic flows and system performance measurements. Then the same procedures are repeated for the build (after) network with new light rail service. The performance measure results are compared to identify how the new facility will impact the existing system in terms of social, economic, environmental and transferable performances.

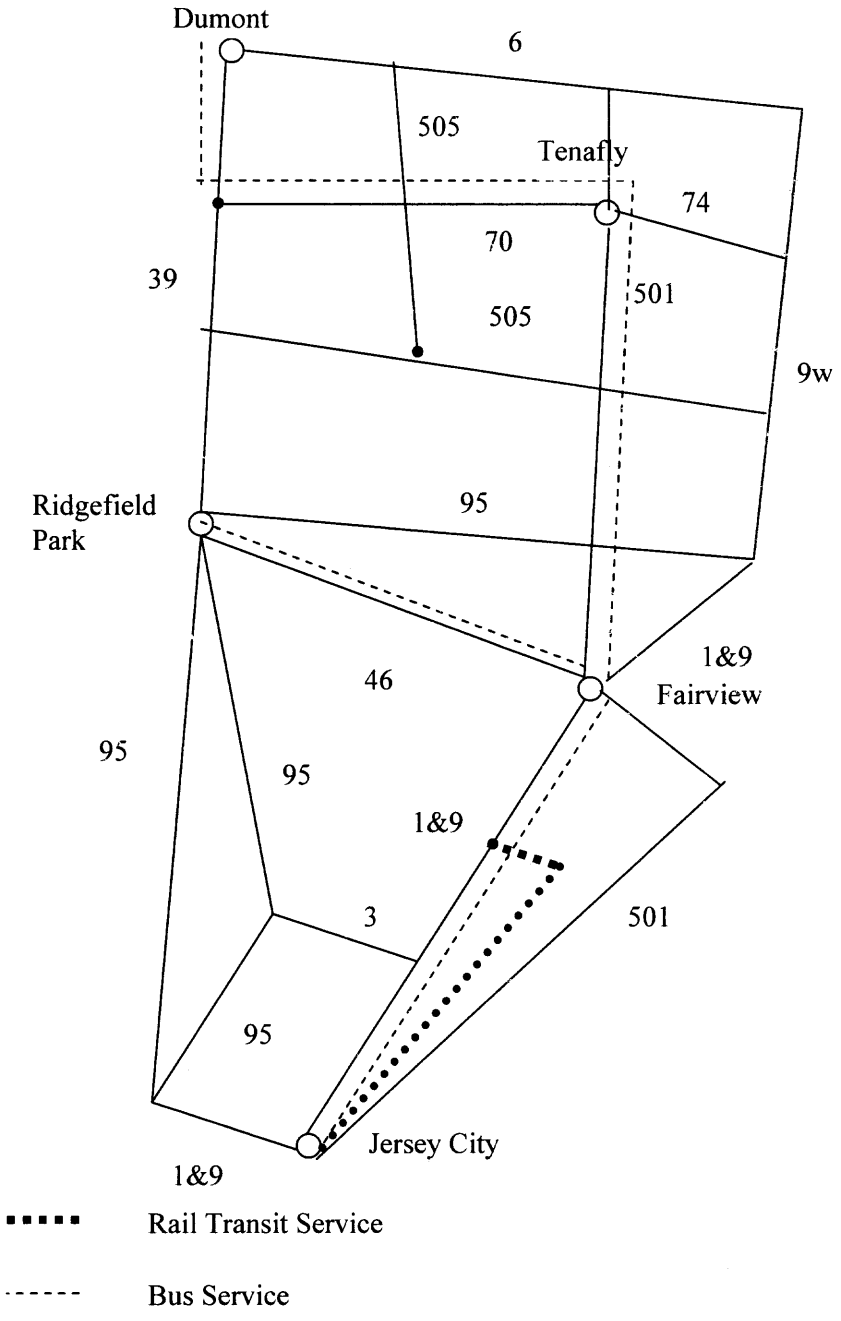

Figure 5.2 Network conceptual map with route name.

5.2 Network Link and Path Identification

The intermodal transportation network includes roadway and railway subnetworks. The link attributes can be obtained from transportation agencies. Then the information should be derived to the data can be used in the model process.

5.2.1 Base Link Information

In the study area, the roadway subnetwork includes five functional classes from Urban Collector to Urban Interstate level as shown in Table 5.1.

Table 5.1 Roadway Subnetwork Classes

Roadway Class	Roadways Name
Urban Interstate	I-95, N.J.Turnpike, I-95, N.J. Turnpike- West alignment
Urban Freeway/Expressway	NJ3, US1
Urban Principal Arterial	Route505, Route501, Bergen County 70, Bergen County72, US 46, Bergen County 39, US9W
Urban Minor Arterial	Bergen County 74
Urban Collector	W. Palisade Ave, W. Clinton Ave

Source: NJDOT, 2007

The existing roadway subnetwork (no build) contains 34 auto roadway links. Although buses share the roadway with automobiles, the bus links should be separated from the auto links since the time functions are different. There are 10 exclusive links for busways. For the no build condition, there is only one link for rail transit from North Bergen to Jersey City. The roadway network has 34 links, 10 bus links plus one light rail track, totally 45 links.

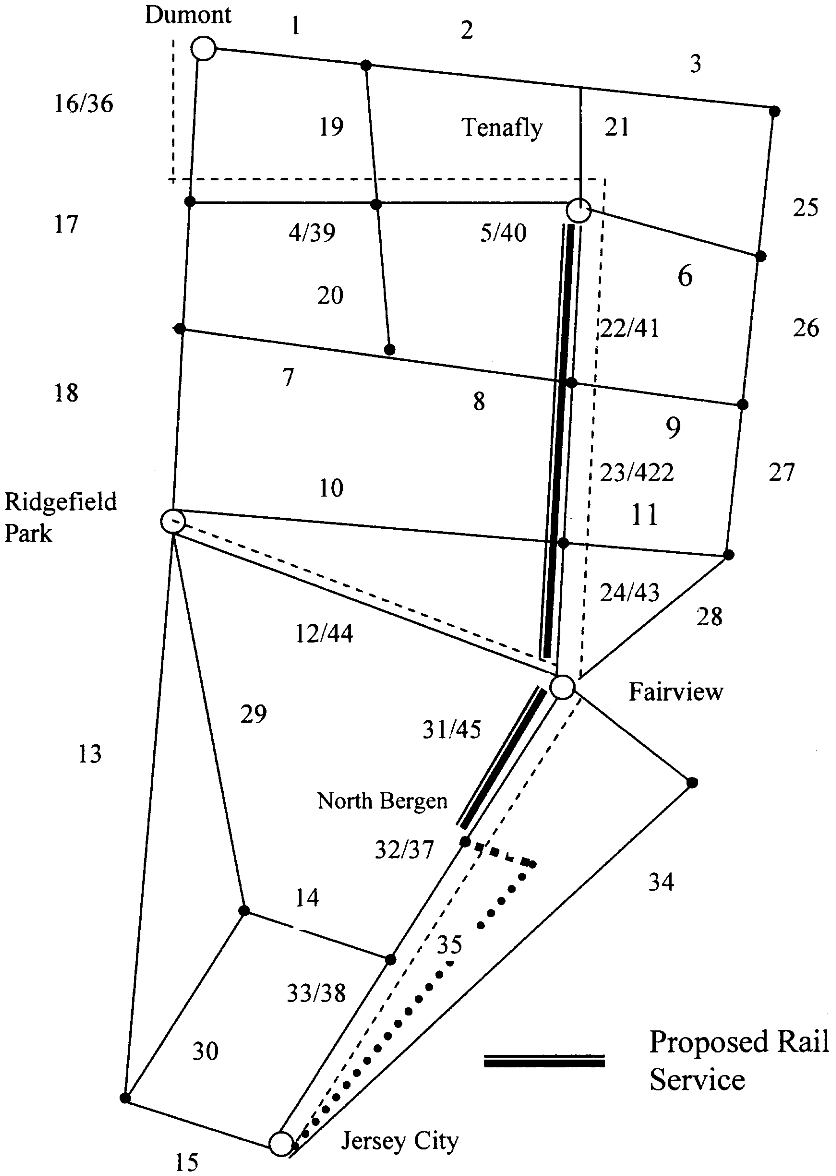

Figure 5.3 Transportation network with link number.

For build condition, assuming the auto and bus roadway subnetworks keep same. The only change is that there will be another rail transit service from Tenafly to North Bergen. Two rail links will be added into the network. There will be totally three rail links. The roadway links are numbered in Figure 5.3. The link numbers are shown in the figure.

The roadway link attributes are obtained from the Straight Line Diagrams, which is published on the New Jersey Department of Transportation's (NJDOT) website. The Straight Line Diagrams give the basic information of roadway, which includes: street name, functional class, number of lanes, speed limit, traffic volume and other information.

There are also bus services and light rail service. The bus stop, service time, headway, fare information can be obtained from NJ Transit's website. Bus routes run across this study area include:

Route 159: Fairview-North Bergen

Route 166: Dumont –Tenafly- Fairview- North Bergen

Route 155: Dumont-Ridgefield Park-North Bergen

Route 84, 86: North Bergen- Jersey City

Table 5.2 Bus Transit Service

Route Name	Distance (Miles)	Travel Time (Min)	Headway (Min)	Fare ($)
159	4.9	16	24	1.35
84,86	5.6	25	20	1.35
155	4.1	20	50	1.35
166	8.5	40	20	1.95

Source: NJ Transit, 2007

The light rail service's information, including service distance, travel time, headway, fare, is gotten from NJ Transit's website.

Table 5.3 Rail Transit Service

Mode	Distance (Miles)	Travel Time(Min)	Headway (Min)	Fare($)	Other
Rail	20.6	33	5	1.9	Daily Parking + Transportation $6.50

Source: NJ Transit, 2007

Table 5.4 Roadway Basic Information

Link	Road Name & Location	Distance	Speed Limit	Number of Lanes	Level
1	74(between 39 & 505)	0.9	25	2	Urban minor arterial
2	74(between 505 &501)	1	25	2	Urban minor arterial
3	74(between 501 &9w)	1.9	30	2	Urban minor arterial
4	70(between 39 &505)	1	25	2	Urban principal arterial
5	70(between 505&501)	0.7	25	2	Urban principal arterial
6	72(between 501&9w)	2	25	2	Urban principal arterial
7	W.Palisade(39&505)	0.6	25	2	Urban collector
8	505(between 505&501)	1.3	25	3	Urban principal arterial
9	505(between 501&9w)	0.7	40	2	Urban principal arterial
10	95(between 46&501)	2.9	55	3	Urban interstate
11	95(between 501&9w)	1.5	55	2	Urban interstate
12	46(between 95&501)	4.4	50	3	Urban principal arterial
13	95w(between 1&46	9.7	65	4	NJ turnpike
14	3(between 95&1)	1	50	3	Urban freeway
15	1(between 95&139	3.1	45	2	Urban freeway
16	39(between 70&74)	2.4	25	2	county road
17	39(between74&W.Palisade)	1.7	30	2	county road
18	39(between 95&W.Palisade)	4	30	3	county road
19	505(between 74&70)	1	35	2	Urban principal arterial
20	505(between 70&505)	2.1	30	2	Urban principal arterial
21	501(between 74&70)	1.1	35	2	Urban principal arterial
22	501(between 70&505)	2.5	30	2	Urban principal arterial
23	501(between 505&95)	1.5	35	2	Urban principal arterial
24	501(between 95&46)	5.3	30	2	Urban principal arterial
25	9w(between 74&70)	2.9	40	2	Urban principal arterial
26	9w(between 70&505)	1.8	35	4	Urban principal arterial
27	9w(between 505&95)	2.2	30	3	Urban principal arterial
28	505(between 95&1)	7.5	35	3	Urban principal arterial
29	95(between 46&3)	4.5	55	4	Urban interstate
30	95(between 3&1)	5.8	55	4	Urban interstate
31	1(be46&80th St, north Bergen)	2.9	35	3	Urban principal arterial
32	1(80th St, north bergen&3)	2.3	40	4	Urban principal arterial
33	1(3&1)	3.7	40	2	Urban principal arterial
34	501(46&1)	10.2	25	4	Urban principal arterial

Source: NJDOT, 2007

The Straight Line Diagrams give the basic information of roadway. It can be used to check each link's street name, functional class, number of lanes, speed limit, traffic volume and other information. The 34 links information is summarized in Table 5.4. Bus links in Table 5.5 and rail links in Table 5.6.

Table 5.5 Bus Transit Link Information

Link	Location	Distance (Miles)	Speed limit(MPH)	Number of Lanes	Level
36	39(between 70&74)	2.4	25	2	County
37	1(80th St, north bergen&3)	2.3	40	4	County
38	1(3&1)	3.7	40	2	County
39	70(between 39 &505)	1	25	2	Urban principal arterial
40	70(between 505&501)	0.7	25	2	Urban principal arterial
41	501(between 70&505)	2.5	30	2	Urban principal arterial
42	501(between 505&95)	1.5	35	2	Urban principal arterial
43	501(between 95&46)	5.3	30	2	Urban principal arterial
44	46(between 95&501)	4.4	50	3	Urban principal arterial
45	95(between 3&1)	5.8	55	4	Urban interstate

Source: NJ Transit, 2007

Table 5.6 Rail Transit Link Information

Link	Location	Distance	Speed limit(MPH)	Number of Lanes	Level
35	74(between 39 & 505)	0.9	25	2	Urban minor arterial

Source: NJ Transit, 2007

5.2.2 Derived Data

The information collected in the above step needs to be derived to the data can be used for model process.

5.2.2.1 Free Flow Time. The link speed limit can be obtained from the Straight Line Diagrams. According to Highway Performance Monitoring System (HPMS), Base Free Flow Speed (BFFS) is based on the coded speed limit (Data Item 80) and guidance from the HCM 2000. To be consistent with the HCM 2000 methodology, the BFFS is not allowed to go below 40 mph or above 70 mph. This conflicts with guidance in the HCM 2000 which states that the methodology is valid for free flow speeds between 45 mph and

60 mph. However, the HCM 2000 methodology is geared to estimating performance characteristics, not capacity. For the purpose of capacity, these restrictions were relaxed.

BFFS = 40 mph, for posted speed limits < 40 mph

BFFS = Speed Limit + 7, for posted speed limits 40-45 mph

BFFS = Speed Limit + 5, for posted speed limits >= 50 mp

Free flow time = link distance/ Free flow speed.

5.2.2.2 Link Capacity. The Base Capacity (passenger cars per hour per lane; PCPHPL) of a multilane facility is based on information found in HCM Exhibit 21-3. The following equations were developed based on this information:

Base Cap = 1,000 + 20FFS; for FFS <= 60 (10)

Base Cap = 2,200; for FFS > 60.

5.2.2.3 Bus Dwell Time. The dwell time at a bus stop is one of the major components of bus travel time, and it is highly correlated with numbers of boarding and alighting passengers. According to the research done by Li, et al. (2006) and Rajbhandari. et al. (2003), service time per passenger is about 4-7 seconds. Since boarding and alighting passengers varies in each stop, it is assumed that average stop dwell time is 30 seconds. The bus stop numbers are obtained from New Jersey Transit website, bus information. Link dwell time is the production of bus stop number and average dwell time per stop.

Table 5.7 Bus Link Dwell Time

Link	Location	Distance (Mile)	Number of Bus Stops	Stop Dwell Time(s)	Link Dwell Time(Min)
36	39(between 70&74)	2.4	1	30	0.5
37	1(80th St, north bergen&3)	2.3	3	30	1.5
38	1(3&1)	3.7	4	30	2
39	70(between 39 &505)	1	1	30	1
40	70(between 505&501)	0.7	1	30	1
41	501(between 70&505)	2.5	2	30	1
42	501(between 505&95)	1.5	1	30	0.5
43	501(between 95&46)	5.3	3	30	1.5
44	46(between 95&501)	4.4	2	30	1
45	95(between 3&1)	5.8	4	30	2

Source: NJ Transit, 2007

5.2.2.4 Background Flow. Background flows are those vehicle trips with origins or destinations outside the study network. They are using the links in the network and contribute to the total traffic flow and congestion. They should be considered as background flows and added into the existing system. The data can be obtained from Roadway Information and Traffic Counts, shown as Appendix B.

The mode choices for travelers are auto only, auto- bus, auto-rail, and bus-rail. Network attributes, including speed limit, link length, and traffic counts can be obtained from the Straight Line Diagrams. Link capacity, free flow speed can be calculated by using the Highway Performance Monitor System (HPMS) Field Manual. Bus transit and light service and fare information are obtained from the NJ Transit website.

5.2.2.5 Travel Demand. Travel demand between origins and destination data is obtained from Census Transportation Planning Package (2000) as shown in Table 5.8. The data capture journey to work data. It is assumed that the trips occur in one hour in peak time. The trips either have their origin or destination outsides of our study area and are using the transportation links in our network are considered as background traffic flow. The data are from the Straight Line Diagrams and are being considered in our modeling process.

Table 5.8 O-D Travel Demand Matrix

Origins and Destinations	**Travel Demand (Pass.Trips)**
Dumont-Jersey City	125
Tenafly-Jersey City	245
Ridgefield Park-Jersey City	200
Fairview-Jersey City	65

Source: CTPP, 2000

Above is the information for the no build condition. After the proposed rail service from Tenafly to North Bergen is build, two rail links will be added to the existing network, providing travelers additional options.

5.3 No Build and Build Comparison

By running the CNEM model and calculating the performance measures, the system no build and build conditions can be compared as shown in Table 5.9. It can be seen that the construction of new rail transit will have a big influence on the system. The average cost, access time will be reduced, same as the fatal and injury possibilities. The average speed and auto usage will decrease. Travelers will switch to transit since the auto usage will decrease. Overall the new rail service can improve the accessibility, mobility, safety and security. The increasing use of rail transit will also improve the environment impact by lowing energy use and emissions. But at the same time, the new service provides travelers more options which will increase the average transfer rate. Although the average transfer time will decrease, this should remind the planners to try to reduce the transfer time by carefully setting the location of transit services and coordinating the transit headways to improve the transfer conditions.

Table 5.9 shows the comparisons between the no build and build conditions. In Figure 5.5, all of the no build measures are converted to one then the ratios of build measures to no build measures represent the changes of before and after. gives the trend of the performance measures change. The results show that the CNEM model and related transportation evaluation system is an efficient way to measure traffic changes and system performance. It can be done without the effort of on site survey and field traveler counting. It can be regarded as a good alternative for transportation planners.

Table 5.9 No Build and Build Performance Measure

	No-Build	**Build**	**Change**
Average Speed (MPH)	13.621	16.657	22%
Access Time (Min)	3.287	2.901	-12%
Auto Usage Rate (%)	77.7%	62.9%	-19%
Fatal (Person)	1.118E-04	8.567E-05	-23%
Injury (Person)	0.00806	0.00628	-22%
Average Cost($)	1.930	1.496	-23%
Energy Use (BTU)	24265891.63	18679252.15	-23%
Transfer Rates (/person trip)	21.3%	36.5%	71%
Transfer Time (Min)	6.625	5.431	-18%

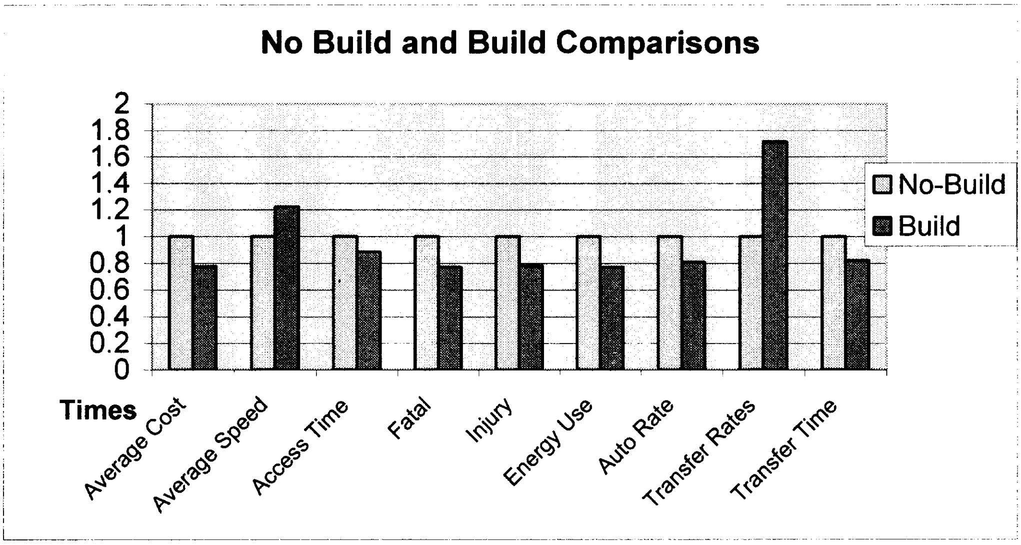

Figure 5.5 No-build and build performance measures.

5.4 New Rail Service Cost and Benefit Analysis

By comparing the no build with build conditions, the usage and four dimensions impacts of the new rail service can be estimated. However, the results are not enough for a complete priori evaluation. The construction of a new facility needs a great amount of money. An improvement project can not be implemented if not economic effectively even it can improve the system performance measures greatly. The cost benefit analysis is a necessary part to assess possible economic impacts to make the new infrastructure effect projection more comprehensive.

Since this case study is not a feasibility study but a sample to demonstrate the CNEM model and performance measures, plus the absence of necessary economic data, the detailed cost benefit analysis can not be done in this study. But the cost benefit framework and some primary data are provided for further research.

According to the study (KKO & NJIT, 2005), the Colorado Railcar DMU train would be one of the possible vendors to provide rolling stock for the proposed service. It is proposed that the operations be limited to 30 mph over the shared track. The local SPRC service between North Tenafly and 47th Street is proposed to make eight intermediate stops. It is presumed that service would be peak service ranging between four trains per hour, 15 minutes headway in peak hours, 3 cars per train. Estimated end-to-end running time for this service is 24 minutes. The system would require five sets of SPRC equipment to provide the peak period services. This following part provides the components of the capital costs and operating costs associated with developing the proposed Northern Branch SPRC. The total cost and benefit can be generated when the data are ready to use.

5.4.1 Cost Analysis

Total costs include capital costs and operation costs.

5.4.1.1 Capital costs. They may include:

1. Rolling stock: The number of vehicles required was determined by the frequency of service and minimum estimated train turning time. The total train cost is the production of estimated units and unit costs. Single Level SPRC Unit is about $2,900,000 Colorado Railcar Corporation. Assume that 20 cares are needed, the rolling stock cost is $58,000,000.

2. Track and train control improvements

3. Grade Crossings

4. Stations

5. Parking

6. Maintenance facility

7. Contingency and Support Costs: A contingency factor added to the directly estimated cost items to account for unforeseen circumstances.

5.4.1.2 Operation Costs. The Operating Costs are generally estimated in three main categories: transportation, maintenance of equipment and administrator cost.

Transportation operating costs include the direct costs for service provision including train crews, all trains would operate with a two-person crew, supervisors and dispatchers, propulsion energy and train supplies.

Maintenance of Equipment (MOE). The mechanical costs include labor and materials for vehicle maintenance. According to Colorado Railcar Manufacturing LLC (CRM), the DUM maintenance cost is about $134,279 per vehicle for the first year of operation.

Administrative Expense: Administration costs include revenue collection and accounting, marketing, personnel, training and safety.

5.4.2 Benefit Analysis

Transit benefits quantification is complicated by the fact that many transit benefits are indirect or external and so are not perceived by users or capitalized in property values. The other issue is that some impacts overlap. Transit benefit can be defined from the following aspects:

User benefits: result from improved convenience, speed, comfort or financial savings to transit users. Since some of passengers will switch from auto to automobiles, costs of traffic congestion condition can be improved, that saves highway travel time. The benefit can be measured from the total travel time savings. As stated in above section, the results of CNEM model results shows that the average speed in the network increased from 13.6 mph to 16.6 mph. The average cost reduced from $1.93 per trip to $1.5 per trip. So the total saving for the users can be $200,000.

Mobility benefits: reply the additional mobility provided by a transportation service, particularly to people who are physically, economically or socially disadvantaged.

Environmental benefits: result from energy conservation and emission reductions, noise impacts and can lower accidents and pollution emissions. Reducing the amount of land that must be paved for roads and parking facilities

There can be other benefits from the property values increase, business development chances and so on. The benefits are hard to be represents in monetary values.

The primary cost benefit analysis shows that with huge investment on the new rail line service, the direct benefits to user travel time saving are not comparable. Even it is true that the transit can bring benefits in the aspects of environment and mobility improvement, the construction decision should be made after further detail feasibility study is implemented.

5.5 Sensitivity Analyses

To fully evaluate the effects of the new facility, a long-term comparison is necessary since the population keeps increasing in the northern New Jersey Area. Table 5.10 gives the NJTPA Population Forecast by County and Municipality. It is used as the source of the increase of the population and travel demand.

Table 5.10 Population Growth in Study Area

Population	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**
Dumont	17,500	17,510	17,570	17,690	18,110	18,620	19,080
Growth Rate	-	**0.057%**	**0.400%**	**1.086%**	**3.486%**	**6.400%**	**9.029%**
Ridgefield Park	12,870	13040	13090	13170	13440	13770	14170
Growth Rate	-	**1.321%**	**1.709%**	**2.331%**	**4.429%**	**6.993%**	**10.101%**
Tenafly	13,810	14220	14310	14400	14710	14890	15140
Growth Rate	-	**2.969%**	**3.621%**	**4.272%**	**6.517%**	**7.820%**	**9.631%**
Fairview	13,260	13930	14120	14210	14540	14780	15280
Growth Rate	-	**5.053%**	**6.486%**	**7.164%**	**9.653%**	**11.463%**	**15.234%**

Source: NJ TPA, 2007

It is assumed that traffic demands will increase by the same rate as the population increase. Years 2015 and 2030 are chosen to be the target future years for comparisons. Performance Measures in both years are calculated and compared.

1. Mobility

Mobility is represented by average speed in the study. When the transit service are put into use, the average speed can increase from 13.5 MPH to 17MPH , which is about 20% higher than the no build condition. That means the new transit service can relieve congestions and improve the area mobility. The effect of improvement will be very stable for both years 2015 and 2030, as shown in Figure 5.6.

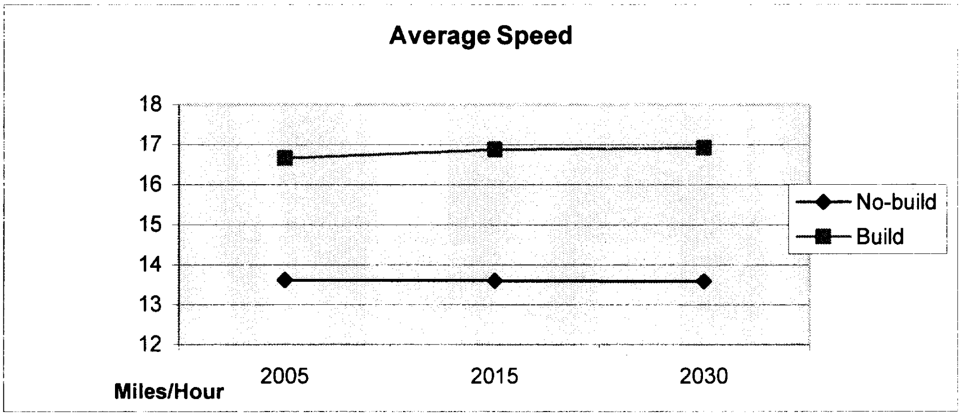

Figure 5.6 Average speed trend comparison.

2. Accessibility

The average access time to transit service and destination represents the accessibility. In the build condition, the access time will be about 10% shorter than the no build condition currently, years 2015 and 2030. The decrease of access time means that the area accessibility condition can be improved. Travelers can reach transit service easier. The differences between the no build and build conditions increase with time as shown in Figure 5.7.

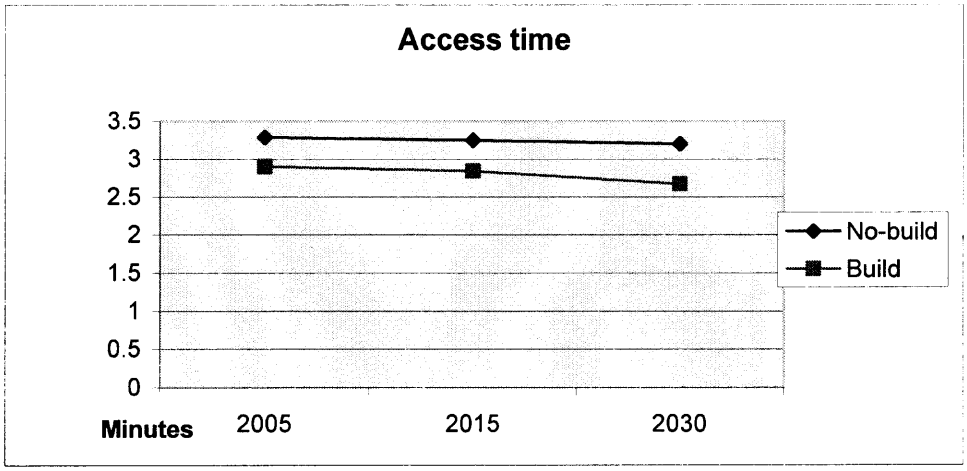

Figure 5.7 Average access time trend comparison.

3. Safety and Security

Both fatal and injury will increase with the increase of demand for both no build and build conditions. The rate of increase for the build condition is not as fast as that of the no build condition. Transit fatal and injury rates of the build condition are lower than that of autos. Since more people will use the transit, safety and security condition will be improved with the construction of the new transit service as shown in Figure 5.8 and 5.9.

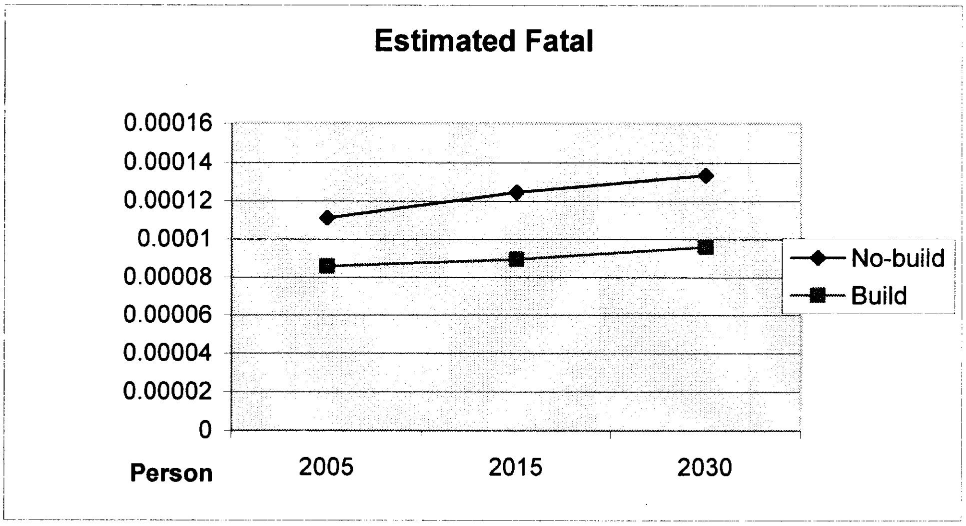

Figure 5.8 Estimated fatal trend comparison.

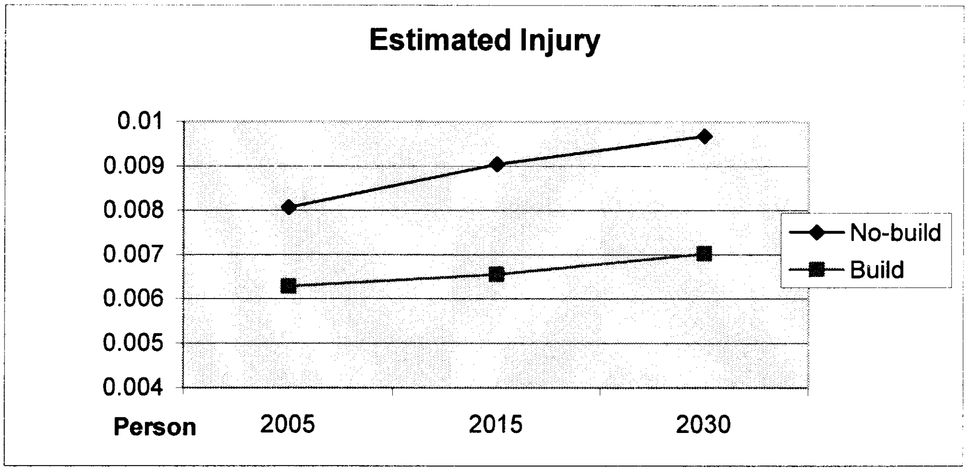

Figure 5.9 Estimated injury trend comparison.

4. Auto Usage Rate

The auto usage rate for the build condition is lower than that of no build condition. That means some travelers will switch to transit service and the service does attract travelers. Transportation planner can use the measure to check if the service is designed properly or not. In this study, the effect extend keeps fairly stable for year 2015 and 2030, as shown in Figure 5.10.

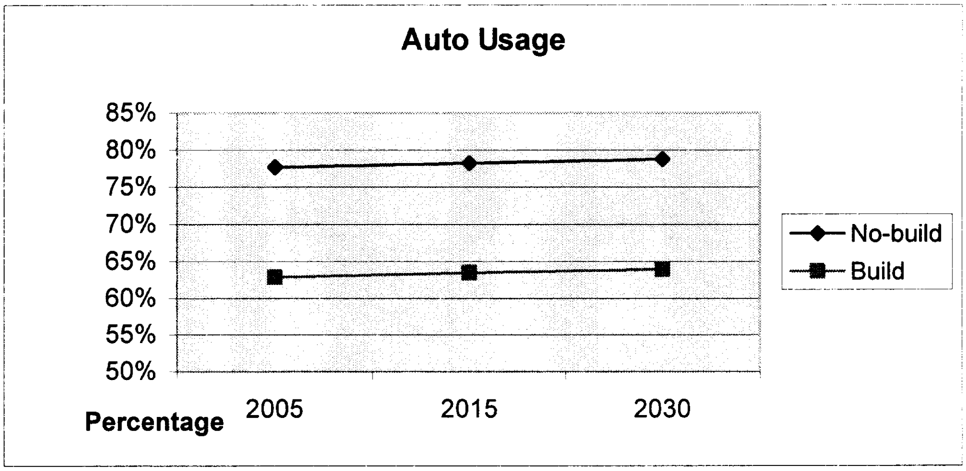

Figure 5.10 Average auto usage trend comparison.

5. Transportation Affordability

The comparisons between the no build and build travel costs shows that the average travel cost for travelers get lower. The new rail service does provide more affordable transportation modes to travelers. The new construction of transit service will improve the affordability by reducing the average cost as shown in Figure 5.11.

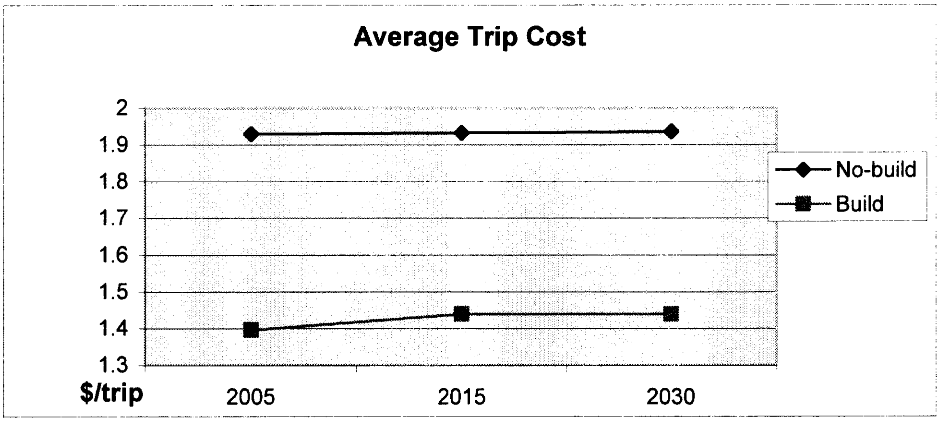

Figure 5.11 Average cost trend comparison.

6. Environmental Impact

Environmental impacts include several aspects, such as energy consumption, emission, noise and others. Only energy consumption data are presented here since the other data are not available. Since travelers switch from auto to transit with the build of transit service, the overall environment impact caused by transportation system can be improved. The total energy consumption comparison is shown in Figure 5.12. The extent of improvement in 2030 is greater than in 2015. It shows that the transit will become more necessary with the demand increases.

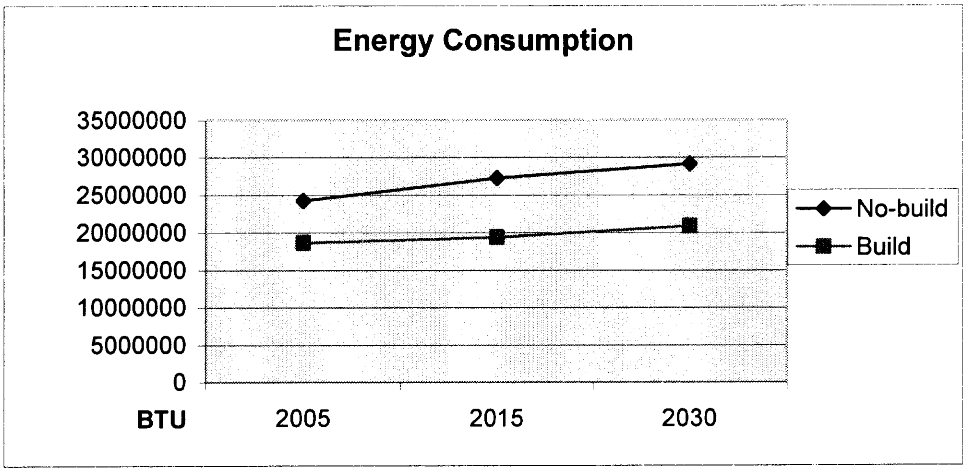

Figure 5.12 Average energy consumption trend comparison.

7. Transfer Condition

The transfer rate will increase, as shown in Figure 5.13, since more travelers will choose transit services. While the transit service coverage is limited, travelers need to make transfer from other modes. The average transfer time is lower as shown in Figure 5.14.

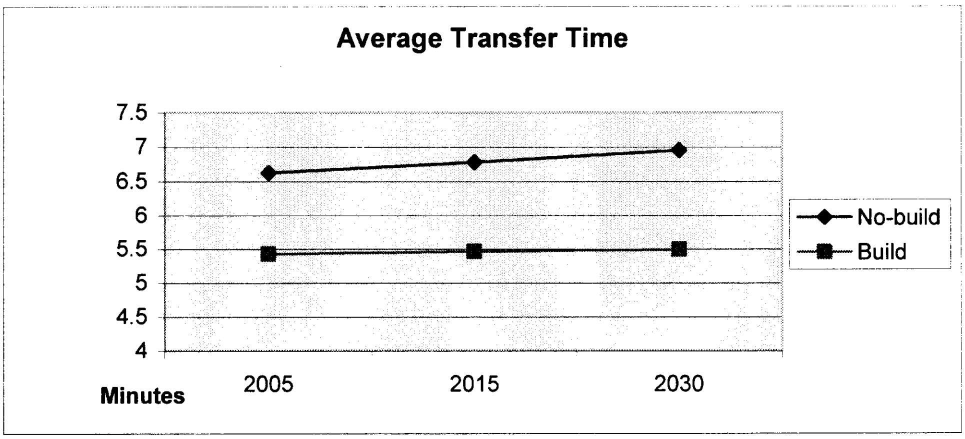

Figure 5.13 Average transfer time comparison.

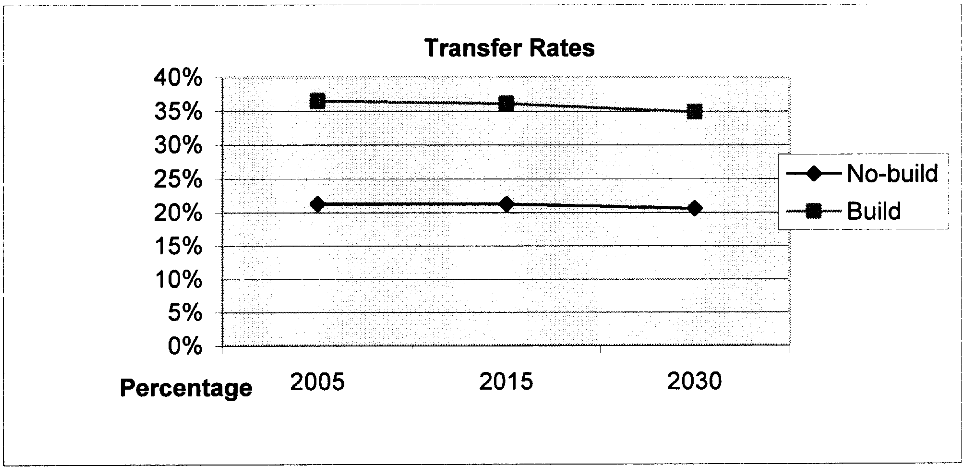

Figure 5.14 Average transfer rate trend comparison.

The sensitivity analyses for years 2015 and 2030 shows that the impacts of new transit service will be relatively stable in the future. The new transit service will improve the overall transportation system in terms of social, economic, environmental and transferable dimensions.

CHAPTER 6

SUMMARY AND FUTURE WORKS

6.1 Conclusions

A Combined Network Equilibrium Model (CNEM) was presented in this study. The advantage over the traditional four-step model is that the interaction between mode split and assignment phases, namely, the effect of congestion on trip decision-making, is formally recognized. This model divides travelers to multiple classes according to their social economic condition, auto ownership condition and income levels. Transfer effects are considered in the model formulation process. Different effects are chosen based on the transfer types.

The outcome of the CNEM model is the major input data to a performance measurement system. The intermodal transportation system is evaluated from four dimensions: social, economic, environmental and transferable. Each dimension contains several measures, for example, mobility, accessibility, cost efficiency and so on.

A real world case study is done to demonstrate the feasibility of the model and the application process. The study area is in northern New Jersey. New Jersey Transit is interested in updating one freight line, North Branch Line, to provide passenger service. Assuming the O-D trip matrix already exists, the mode share and route choice are projected for the no build and build conditions. The transportation system evaluations are done respectively. Through the comparisons between the no build and build conditions, transportation planners can find out the usage of the new service and its impact on the overall system performance. In addition, sensitivity analyses for years 2015 and 2030 are done to present the long term effects. The application shows the methodology is very useful in transportation planning.

The measures generated by the case study can help to quantitatively demonstrate the benefits of intermodal transportation and promote transportation intermodalism. The proposed measures differ in many aspects from traditional measures. The proposed set of performance measurement system can have a significant impact on the development of U.S. transportation systems.

6.2 Contributions

The research has contributions in both theory and practice aspects. From the methodological aspect, the research develops a network equilibrium model and an intermodal transportation system. From the practical aspect, the output of the model is being used for performance measurements, which widens the application of the network equilibrium model. The model can be used to estimate the traffic that the will utilize newly improved roadways or transit services and measure the system performance after the new facility is constructed.

6.2.1 Development of Network Equilibrium Model

This study has added the below features to the traditional network equilibrium model:

1. The socio-economic characteristics of a traveler affect his/her travel behavior. The CNEM model recognizes the diversity of the travelers. For example, the travelers who own at least one auto should be distinguished from the travelers who do not own an auto since they are transit-captive. Besides auto ownership, the other important criterion

is the value of time which is generally determined by income levels. Different values of time are chosen to represent the user differences. By using the multiclass method, the model can project travelers' behavior more accurately.

2. The model considers relatively complete transportation mode options. In the previous researches, bus and rail were treated same as transit services. While in reality, buses and rail transit have different operation features. Buses are more possible subject to congestions since they share roadways with automobiles, whiles trains have less probability for congestion since they have their exclusive right of ways. The volume time functions for buses and trains are different. Thus the separation of modes is necessary to generate accurate time functions for each mode. In the CNEM model, the basic modes are auto, bus and rail.

3. The mode options include pure modes and intermodal modes. Travelers are free to transfer at most once between different basic modes. For intermodal modes, complete access modes are provided. Travel can transfer from another basic mode. For example, a rail trip can be transferred from an auto or a bus trip. Complete possible transfers between various modes are given in the model process, which makes the model result closer to reality.

4. The model considers the impact of transfers on the travelers' behavior. By adding an additional transfer penalty to transfer links, the model is sensitive to the presence of transfers by incorporating the different values of time spend on transfer.

5. The output of the model is used to generate evaluation criteria and a performance measurement system. This attempt widens the application of the network equilibrium model.

6.2.2 Development of Intermodal Transportation Evaluation System

An intermodal transportation evaluation system is developed to measure overall transportation performance. Besides social, economic and environmental dimensions, the evaluation includes the transferability dimension. In this dimension, transfer rates, transfer time and institution impedance are considered. For an intermodal system, the performance of each mode is very important. But the coordination between modes influences the overall system efficiency and effectiveness.

6.3 Future Work

The research improves on the existing network equilibrium model and system evaluation. However, there still more work could be done to achieve further progress. The future directions were found during the research process, but have not been done due to time and space limitations.

First, a combine Geographic Information System (GIS) can be incorporated into the research. GIS can be used to generate accurate data and information. For example, network attributes, centroid of each community, link length, location of transit stops and other information, can be obtain from GIS. GIS can be used to extract the transfer information and to help understand the pedestrian environment. By using GIS, the data collection process can become easier and cheaper and the quality of data can be improved.

Second, the trip distribution step can be combined into the CNEM model to reflect the congestion impact on trip demand. By combining the trip distribution step, the model can project the destination of travelers. Then the traditional four-step model can be separated to trip generation, and the combined network equilibrium model. Since the last three steps, trip distribution, mode choice and route assignment are generated from one combined model, the interaction and feedback between them can be fully used.

The four dimensions of the transportation system performance measurements can be further developed to obtain a comprehensive transportation performance index. The main problem is how to weight the different measures and generate a new single index which represents all the features. Once a single index is generated, it can be used to compare transportation systems between different corridors, regions and areas. When the model is used in priori and ex post evaluations, additional detailed cost and benefit analysis should be done to demonstrate the economic impacts.

APPENDIX A

CONBINED INTERMODAL NETWORK MODEL

The model can be summarized as

$$\begin{aligned}&c(l^*)^t(f(l)-f(l)^*)-G_1^{-1}(T_t^*)^t(T_t-T_t^*)-G_2^{-1}(T_{t,b}^*)^t(T_{t,b}-T_{t,b}^*)\\&-G_3^{-1}(T_{t,r,p}^*)^t(T_{t,r,p}-T_{t,r,p}^*)-G_4^{-1}(T_{t,b,p}^*)^t(T_{t,b,p}-T_{t,b,p}^*)\\&-G_5^{-1}(T_{t,r,i,a}^*)^t(T_{t,r,i,a}-T_{t,r,i,a}^*)-G_6^{-1}(T_{t,b,i,a}^*)^t(T_{t,b,i,a}-T_{t,b,i,a}^*)\geq 0\end{aligned}$$

$$T^{wm}=T_a^{wm}+T_t^{wm}$$

$T_a^{wm}=\sum_k p_k^{wm}$, auto path

$T_t^{wm}=\sum_k p_k^{wm}$, transit path

$$T_t^{wm}=T_{t,b}^{wm}+T_{t,r}^{wm}$$

$T_{t,b}^{wm}=\sum_k p_k^{wm}$, bus transit path

$T_{t,r}^{wm}=\sum_k p_k^{wm}$, rail transit path

$$T_{t,b}^{wm}=T_{t,b,p}^{wm}+T_{t,b,i}^{wm}$$

$T_{t,b,p}^{wm}=\sum_k p_k^{wm}$, pure bus transit path

$T_{t,b,i}^{wm}=\sum_k p_k^{wm}$, intermodal bus transit path

$$T_{t,r}^{wm}=T_{t,r,p}^{wm}+T_{t,r,i}^{wm}$$

$T_{t,r,p}^{wm}=\sum_k p_k^{wm}$, pure rail transit path

$$T^{wm}_{t,r,i} = \sum_k p^{wm}_k$$, intermodal rail transit path

$$T^{wm}_{t,b,i} = T^{wm}_{t,b,i,a} + T^{wm}_{t,b,i,r}$$

$$T^{wm}_{t,b,i,a} = \sum_k p^{wm}_k$$, auto-bus path

$$T^{wm}_{t,b,i,r} = \sum_k p^{wm}_k$$, rail-bus path

$$T^{wm}_{t,r,i} = T^{wm}_{t,r,i,a} + T^{wm}_{t,r,i,b}$$

$$T^{wm}_{t,r,i,a} = \sum_k p^{wm}_k$$, auto-rail path

$$T^{wm}_{t,r,i,b} = \sum_k p^{wm}_k$$, bus-rail path

$$p^{wm}_k \geq 0$$

APPENDIX B

BASE LINK DATA

Link	Location	Free Flow Speed	Free Flow Time	Base capacity	Capacity	Travel Volume
1	74(between 39 & 505)	40	2.2	1800	3312	10234
2	74(between 505 &501)	40	2.4	1800	3312	14320
3	74(between 501 &9w)	40	3.8	1800	3312	9832
4	70(between 39 &505)	40	2.4	1800	3312	12903
5	70(between 505&501)	40	1.7	1800	3312	11289
6	72(between 501&9w)	40	4.8	1800	3312	8906
7	W.Palisade(39&505)	40	1.4	1800	3312	7590
8	505(between 505&501)	40	3.1	1800	4968	18455
9	505(between 501&9w)	47	1.1	1940	3570	11873
10	95(between 46&501)	60	3.2	2200	6072	82346
11	95(between 501&9w)	60	1.6	2200	4048	98230
12	46(between 95&501)	55	5.3	2100	5796	79433
13	95w(between 1&46	70	9.0	2200	8096	82786
14	3(between 95&1)	55	1.2	2100	5796	100542
15	1(between 95&139	52	4.1	2040	3754	63523
16	39(between 70&74)	40	5.8	1800	3312	11187
17	39(between74&W.Palisade)	40	3.4	1800	3312	10237
18	39(between 95&W.Palisade)	40	8.0	1800	4968	12572
19	505(between 74&70)	40	1.7	1800	3312	14897
20	505(between 70&505)	40	4.2	1800	3312	11703
21	501(between 74&70)	40	1.9	1800	3312	37876
22	501(between 70&505)	40	5.0	1800	3312	46193
23	501(between 505&95)	40	2.6	1800	3312	40910
24	501(between 95&46)	40	10.6	1800	3312	22383
25	9w(between 74&70)	47	4.4	1940	3570	12845
26	9w(between 70&505)	40	3.1	1800	6624	22609
27	9w(between 505&95)	40	4.4	1800	4968	32896
28	505(between 95&1)	40	12.9	1800	4968	40981
29	95(between 46&3)	60	4.9	2200	8096	98276
30	95(between 3&1)	60	6.3	2200	8096	87109
31	1(46&80th St, North Bergen)	40	5.0	1800	4968	21734
32	1(80th St, North Bergen&3)	47	3.5	1940	7139	33858
33	1(3&1)	47	5.6	1940	3570	61072
34	501(46&1)	40	24.5	1800	6624	22383

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