ABSTRACT

A Planning Model for Intermodal Auto-Rail Transportation Assignment

by
Daniel Disario

This thesis presents a planning model for assigning trips in a corridor served by highways and commuter rail. The underlying assumption is that commuters will choose a mode (or a combination of modes) connecting the origin and destination in a way that will either minimize their individual travel times and costs (the user equilibrium principle) or minimize total system travel time and cost (system optimal principle). The model is structured as a mathematical program with a non-linear objective function and linear constraints.

The model was applied to a case study of the Raritan Valley Corridor located in Northern New Jersey. The corridor primarily serves commuters from the western part of New Jersey who are destined to Newark. Potential benefits of introducing an Advanced Traveler Information Service (ATIS) for shifting commuters form auto to rail under various management strategies and levels of congestion are also discussed. The results showed that there was total system travel time savings when auto commuters were shifted to rail. In addition, it was found that as congestion increased the mode assignments made under different management strategies became more alike.

A PLANNING MODEL FOR INTERMODAL AUTO-RAIL TRANSPORTATION ASSIGNMENT

by
Daniel Disario

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science

Interdisciplinary Program in Transportation

January, 1993

APPROVAL PAGE

A Planning Model for Intermodal Auto-Rail Transportation Assignment

Daniel Disario

Dr. Lazar Spasovic, Thesis Adviser
Assistant Professor of Management,
School of Industrial Management, NJIT

Dr. Louis J. Pignataro, Committee Member
Distinguished Professor of Civil and Environmental Engineering, and
Director of Center for Transportation Studies and Research, NJIT

Dr. Athanassios K. Bladikas, Committee Member
Associate Professor of Industrial and Management Engineering, and
Associate Director of Center for Transportation Studies and Research, NJIT

BIOGRAPHICAL SKETCH

Author: Daniel Disario

Degree: Master of Science in Transportation

Date: January, 1993

Undergraduate and Graduate Education:

- Master of Science in Transportation
  New Jersey Institute of Technology, Newark, NJ, 1993

- Bachelor of Science in Civil Engineering
  Temple University, Philadelphia, PA, 1991

Major: Transportation Engineering

This thesis is dedicated to my fiancé AnnaMarie Sanginiti who has supported me throughout my academic career.

ACKNOWLEDGMENTS

The author wishes to express his sincerest gratitude to his adviser, Dr. Lazar Spasovic, for his guidance, friendship and, above all, his patience and moral support. The author would also like to extend a special thanks to Dr. Louis Pignataro and Dr. Athanassios Bladikas for serving as members of the committee. Finally, a thank you to my family, especially my mother Susan Disario, and friends who were always there with words of encouragement.

TABLE OF CONTENTS

Chapter **Page**

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Overview

There have been great advances made in the recent past with respect to providing commuters with real-time information about traffic conditions so that they may make informed decisions concerning the mode and route they choose to make their trip. It is envisioned that in the future there will be advanced central traffic management centers responsible for disseminating this real-time information so that they may be able to manage flows through the transportation system more efficiently than it is currently possible.

The effects of management strategies that may be employed by these future traffic management centers on the operation and performance of multimodal transportation systems will be analyzed in this thesis. First, a methodological framework will be presented for evaluating the potential benefits of introducing an Advanced Traveler Information System (ATIS) service in a corridor served by highways and rail lines. Central to the methodological framework is an optimization model in the form of mathematical programming which is used to assign travel volumes over an intermodal (auto and rail) network under user equilibrium and system optimal conditions described below. The underlying assumption of the model is that commuters departing from their homes can access their final destinations via auto, rail (by walking to a station) and intermodal (auto to rail) modes. If a commuter chooses to begin the trip by auto, then there are numerous paths by which he/she can reach the final destination. Once on the highway, the commuter can switch to rail at a number of stations along the rail route. The model is developed with two separate objectives which employ Wardrop's principles (Wardrop, 1952). The user equilibrium principle encompasses minimization of total user cost, while the system optimal principle encompasses minimization of total system cost. This allows direct comparison of different management strategies to be made.

The methodological framework is then applied to a corridor that is served by multiple highways and a single commuter rail line. Four scenarios which involve varying degrees of congestion are analyzed with each of the two objectives.

The methodological framework will provide the following:

- An equilibrium assignment of flows over a network under various objectives and conditions.
- A comparison of various management strategies.
- The benefits of diverting commuters off of highways and onto rail lines.
- The rail service capacity additions (rail cars and station parking), if any, that are needed to realize the railroad's potential under equilibrium conditions.

1.2 Problem

The United States is currently facing a growing problem of congestion on its highways. It is not uncommon to hear of highway users having work-related commutes in excess of two hours due to the congestion that is occurring during the peak period. The results of such commutes are very detrimental to society for they produce air and noise pollution and high levels of driver fatigue and driver stress that have detrimental impacts on the productivity of the work force.

There has been much discussion in recent years that in order to alleviate the congestion problem on our highways, auto commuters should be induced to alter their commuting habits. For example, auto commuters should leave their autos at some point during their commute and shift to alternate modes. These alternate modes, in large part, consist of public transportation. The idea of the intermodal commute becoming more prominent in the transportation system in the future has been strengthened by our recent inability to expand highway capacity because of fiscal and environmental reasons and by the passing of the new Clean Air Act Amendments of 1990.

Identifying the benefits of such mode shifts has not been undertaken to any great extent in the past. Moreover, the effects of using user equilibrium versus system optimal principles, while providing an intermodal mode alternative, to assign flows over a network has not been examined. This research quantified the benefits of shifting commuters to rail and examined how different objectives affect the assignment of flows over a network.

1.3 Previous Studies

There have been great advances made in the past in the formulation, understanding and analysis of multimodal equilibrium models applied to transportation networks. The algorithms to solve such models have also advanced considerably (Florian, 1977; Abdulaal and Leblanc, 1979; Aashtiani and Magnanti, 1981; Dafermos, 1982; Florian and Spiess, 1983).

Despite these advances however, the models most commonly formulated and studied use a generalized abstract mode (Dafermos, 1982) or specifically only consider pure modes (Florian and Spiess, 1983). Multimodal assignment models, wherein more than one mode is used to make a trip, have not been greatly examined. Morlok (1978) identified a framework for studying auto-transit network assignment. There has also been an analysis of the choice problem of transfer facilities, and models have been developed to predict the choice of transfer facilities but outside the context of supply-demand network modeling (Florian and Los, 1979).

Intermodal modes are becoming increasingly more important with the advent of policies, especially those relating to urban transportation, that call for an increase in the market share of public transit. Evidence of this can be seen in the integrated transit systems and "park and ride facilities" that have been established. Modern urban transportation systems have developed attractive transfer facilities and integrated fare systems in order to promote the idea of using transportation modes in a complementary way.

The model that has been developed considers the intermodal mode of auto to rail when assigning volumes to a network. Commuters are able to initiate a trip by using their auto, but may switch to rail at any station along the way that has available parking capacity. The model has also been applied to a specific corridor in the form of a case study to demonstrate its features.

CHAPTER 2

METHODOLOGICAL FRAMEWORK

2.1 Introduction

This chapter presents a methodological framework developed and used in this research for analyzing the benefits of shifting commuters from auto to rail and the effects of various management strategies that may be used in assigning flows over an auto-rail intermodal network. The methodological framework, shown in Figure 2.1 in the form of a flow chart, operates by collecting data which are entered into a intermodal flow assignment model under user equilibrium and system optimal objectives. Optimized flows are then produced along with various Measures of Effectiveness (MOEs) for each objective. These MOEs are then used for the evaluation of different management strategies and determining the benefits of shifting commuters to rail

The structure of this chapter proceeds as follows. Section 2.2 describes the data that is required. Section 2.3 presents a general description of the assignment model. Section 2.4 describes the outputs that are produced. Section 2.5 describes the process that is used to evaluate the outputs.

2.2 Data

The model input consist of transportation network geometric, demand and cost data.

Network geometric data define the intermodal network to be analyzed in physical terms. Origin and destination nodes as well as transfer nodes are identified. The links that connect these nodes are also defined. Moreover, paths, defined as a sequence of links that connect origins with destinations, are defined for each origin-destination (O-D) pair. The capacities and free-flow travel times for all links are also computed.

The demands for each O-D pair are identified. The frequency and capacity of trains serving the network are also needed along with an inventory of existing rail

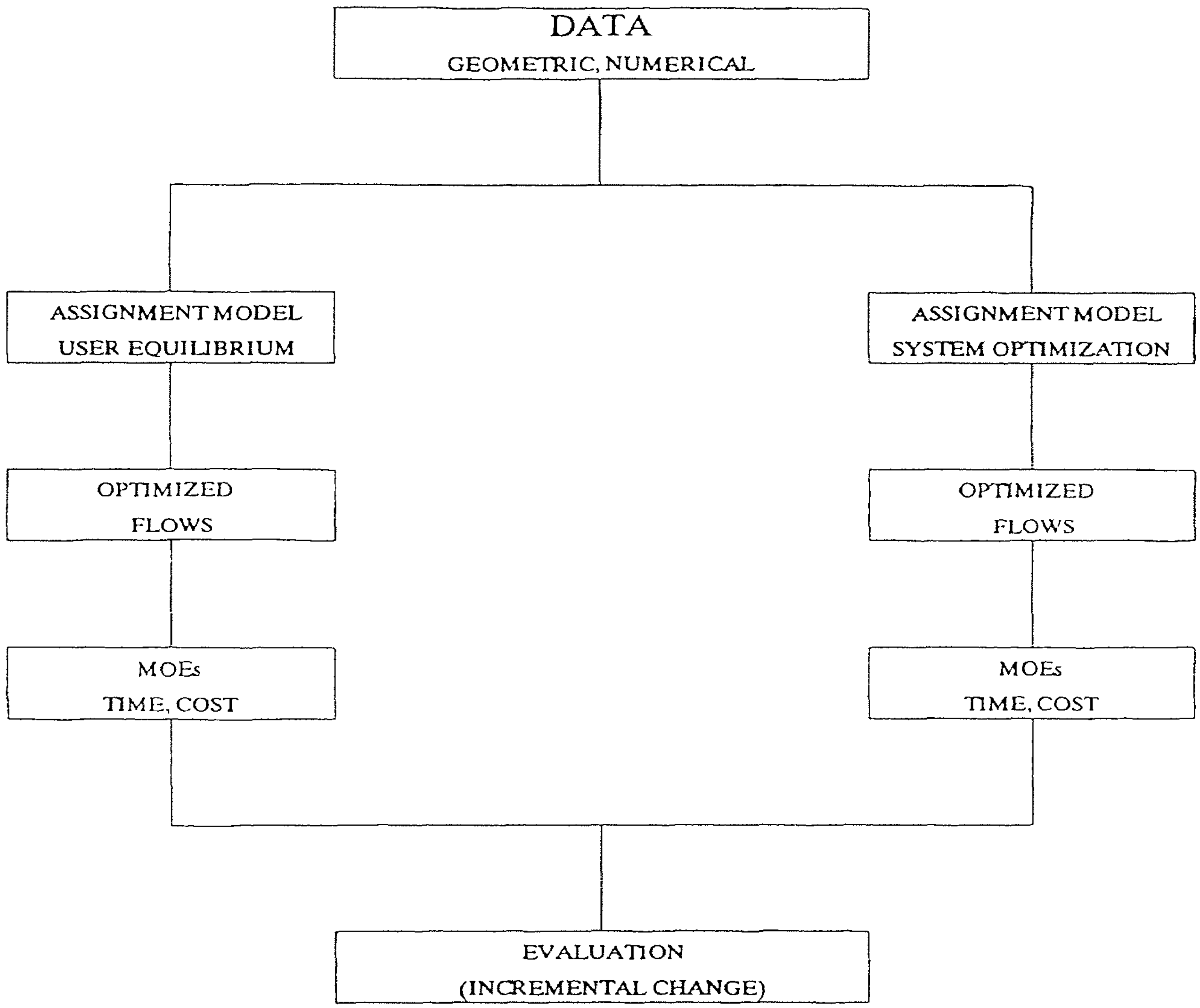

Figure 2.1 Methodological Framework

station parking capacities. In addition, existing flows in the network that originate from O-D pairs outside the network being studied and costs are determined for all links.

2.3 Assignment Model

The model has been conceptualized in the form of a mathematical programming problem consisting of an objective function that is subject to various constraints. Two objective functions were formulated according to Wardrop's first and second principles.

The first principle, also called user equilibrium, implies that users of a transportation system will use any mode as long as that mode provides them with the least cost; whether that cost is travel time, out-of-pocket cost or both. Users will keep switching paths (and thus modes) as long as they can be better off. At equilibrium, users will not be able to reduce their costs by unilaterally switching paths.

The second principle, also called system optimization, states that at the optimum total system cost is at a minimum. This implies that the marginal costs of all utilized paths between an O-D pair are equal.

Constraints for the model deal with conserving flows on each link, conserving flows between each O-D pair, and insuring that facility capacities are not exceeded.

2.4 Outputs

The model produces separate outputs for each objective function which allows comparisons between different management strategies to be made. Optimized flows are produced which give insight into how the transportation system is being used. Costs (travel time, out-of-pocket) associated with these flows are also produced and are used as the Measures of Effectiveness in evaluation.

2.5 Evaluation

The optimized flows that are produced for each objective function are examined to see how the transportation system is being utilized.

The MOEs that are produced for each objective function are compared and the incremental change between system optimization and user equilibrium is computed. In addition, improvements that a rail operator needs to make in the form of increased parking and train capacity under each objective are identified.

CHAPTER 3

INTERMODAL AUTO-RAIL ASSIGNMENT MODEL

3.1 Introduction

In this chapter, the intermodal auto-rail assignment model is developed. The model operates by assigning flows over an intermodal network by optimizing various objective functions which are subject to various constraints.

This chapter proceeds as follows. Section 3.2 presents the role of the model. Section 3.3 outlines the mathematical notation that is used to develop the model as well as the choice variables and the costs that may be included in the model. Section 3.4 presents a graphical example of a flow assignment over an intermodal network. Section 3.5 develops the mathematical formulation of the model.

3.2 Role of the Model

The role of the model is to give planners a tool with which they can obtain optimized flows over an intermodal network under various objectives, compare various management strategies, identify the benefits of shifting commuters from auto to rail and identify improvements that must be made by a rail transit agency to accommodate any increase in demand. Questions that the model answers are the following:

- What is the total cost under a system optimal objective?
- What is the total cost under a user equilibrium objective?
- What is the incremental change in cost between system and user optimal objectives?
- How is the transportation system being utilized under different management strategies?
- What are the benefits of shifting commuters to rail and what improvements are needed to realize those benefits?

3.3 Mathematical Notation

The model assigns flows over an intermodal network which is composed of various types of links. The following is used to define network links:

c = centroid link that connects the centroid of an area to the network,
r = rail link that connects one rail station to another,
e = walking link that connects the centroid link of an area with a rail link,
a = highway link that connects a highway link with another highway link, centroid link or transfer link,
t = transfer link which connects a highway link with a rail link.

Demands between origins and destinations are defined as follows:

w = an origin-destination pair,
T_w = demand of trips between an origin-destination pair.

Flows are assigned over paths in a network. Paths are defined as a sequence of links that connect origins with destinations as:

p = path connecting an origin with destination.

In order to identify a link l that is in a path p the binary parameter δ_{lp} is used.

The model performs many operations over sets of like elements which are defined as follows:

W = set of O-D pairs,
R = set of all rail links,
A = set of all highway links,
T = set of all transfer links,
L = set of all links,
Pa = set of all paths via auto mode,
Pr = set of all paths via rail mode,
Pm = set of all paths via intermodal (auto to rail) mode.

There are also three constants in the model which are defined as follows:
occ = occupancy rate for autos,
$Space_l$ = existing number of parking spaces at a rail station,
$Seats$ = existing number of seats on a train.

3.3.1 Choice Variables

The choice variables designate flows on the network and are separated into flows on links and flows on paths which are defined as follows:

f_l = flow on a link,
h_p = flow on a path.

In addition, there are two choice variables which allow rail station parking capacity and train capacity to be expanded. They are defined as follows:

$Addspace_l$ = additional spaces added to a parking lot,
Addseat = additional spaces added to a train.

3.3.2 Costs

Certain costs are associated with the movement of commuters over an intermodal network. Three types of costs that may be incorporated into the assignment model are listed below:

1. Travel Time- in the form of link, path or total travel time.
2. Out-Of-Pocket Cost- in the form of link, path or total out-of-pocket cost.
3. Travel Time and Out-Of-Pocket Cost- in the form of link, path or total travel time and out-of-pocket cost.

The costs are defined as follows:

cp = cost on a path
cl = cost on a link

For this research, travel time was the only impedance incorporated into the model when it was applied to the case study. As it will be explained later, the time-volume function of the U.S. Bureau of Public Roads (BPR) was used for computing inpedances.

3.4 Graphical Example of Flow Assignment Over a Intermodal Network

In this section, a graphical presentation of a flow assignment over an intermodal network is presented to aid in the visualization of an intermodal network and to clarify the concept of modeling flows over such a network.

Figure 3.1 shows a sample intermodal network that is served by highways and a paralleling rail line. This network contains one origin and one destination which are connected by various paths that utilize various modes.

As it can be seen, the sample network is comprised of centroid, highway, transfer, walking and rail links. These links are used in sequence to form paths that connect the origin to the destination. Paths are grouped together according to mode of travel as follows:

- Auto paths
- Rail paths
- Intermodal paths

Auto paths consist of centroid and highway links. Rail paths consist of centroid, walking (for commuters that walk to and from a rail station) and rail links. Intermodal paths consist of centroid, highway, transfer (which model the parking lots at rail stations), rail and walking (which model the walk from the last station in a trip to the destination) links.

In the modeling of trips from the origin to the destination, the sum of flows on paths that connect the O-D pair must be equal to the total number of trips between the O-D pair. This insures that all trips are accounted for and that flows are indeed assigned over paths. The flow on any link in the network will be equal to the sum of flows on all paths in which the link is included. For example, the flow on link a3 is equal to the sum of flows on paths 1 and 4 since these are the only paths that use this link.

3.5 Mathematical Formulation

This section presents the assignment model which is formulated with non-linear objective functions and linear constraints. The objective functions and constraints are discussed separately and then the model is presented in its entirety.

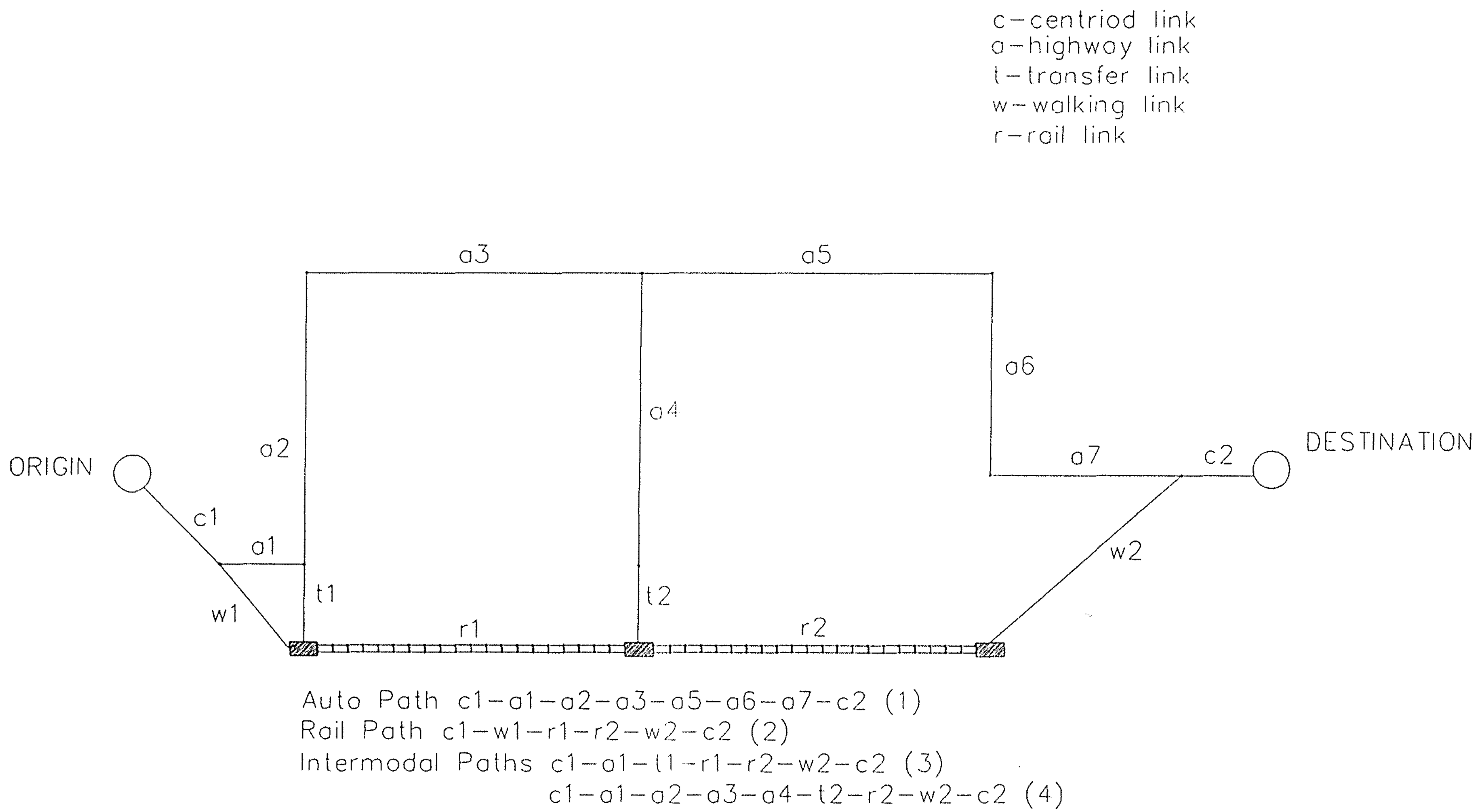

Figure 3.1 Sample Intermodal Network

3.5.1 Objective Functions

The system optimization objective function is quite easy to formulate in comparison to the user equilibrium objective function. The reason for this is that under system optimization, users are not seen as individuals but are rather seen as a collective group working for the benefit of the entire system. In order to achieve system optimization, each link cost is multiplied by the flow on that link and the total sum of the cost/flow products is then minimized. As a result of this, all paths that are utilized between an O-D pair will have equal marginal costs which is inherent when total system cost is minimized. The system optimization objective function has the following form:

$$Z = \sum_{l \in L} cl * fl$$

By comparison, the user equilibrium objective function is very difficult to formulate in mathematical terms due to the nature of the behavior it models. Beckman (1956) has developed a formulation which "mimics" user equilibrium by assigning flows over a network according to user equilibrium conditions. He developed his formulation by taking the system optimization objective above, applying the condition that all utilized paths between an O-D pair must have equal cost, and solving the resulting system which he termed the "fictitious system optimization problem." The solution to this problem results in all link costs being integrated over the flows that are on them. These integrated link costs are then summed and minimized. The user equilibrium objective function, which has no economic meaning, has the following form:

$$Z = \sum_{l \in L} \int_{0}^{fl} c(fl)\,dfl$$

which is known as Beckman's equivalent optimization problem (EOP) for fixed transportation demands.

Two points need to be made concerning Beckman's EOP. First, this formulation leads to an objective function value which has no real meaning. In order to determine the true value of the objective function, the assignment flows made under Beckman's EOP must be used to recompute a new value for the objective function. Second, this formulation is only valid for fixed demands. In this research, only demand for commuting trips was modeled, and it is valid to assume that the trip-to-work demand is fixed.

3.5.2 Constraints

The constraints of the model are as follows:

Constraint 1. Demand Conservation

This constraint insures that all trips between O-D pairs (w) are accounted for. It equates the demand for each O-D pair (T_w) with the flow on all paths (h_p) for all three modes of travel between the O-D pair. This constraint has the following form:

$$Tw = \sum_{p \subseteq Pa} hp + \sum_{p \subseteq Pr} hp + \sum_{p \subseteq Pm} hp \quad \text{for } \forall\ l \subseteq W$$

and is written for all O-D pairs being considered.

Constraint 2. Highway Link Flow Conservation

This constraint insures that the flow on every highway link is conserved. It equates the flow on each highway link (f_l) with the sum of all flows on all paths that go through that link (h_p). Paths for this constraint are derived from the auto mode and the intermodal mode since these modes are the only ones that have highway links in their paths. Paths that do go through a highway link are identified by the binary parameter δ_{lp} taking on a value of one, meaning that link l is included in path p, otherwise δ_{lp} takes on a value of zero. In addition, all flows are divided by the auto occupancy rate (occ) to convert trips into vehicles. This constraint has the following form:

$$fl = 1 / occ[\sum_{p \subseteq Pa} \delta lp * hp + \sum_{p \subseteq Pm} \delta lp * hp] \quad \text{for } \forall\ l \subseteq A$$

and is written for all highway links.

Constraint 3. Rail Link Flow Conservation.

This constraint insures that flow on each rail link is conserved. It equates the flow on a rail link (f_l) with the sum of all the flows on all the paths that go through that link (h_p). Paths for this constraint are derived from the rail mode and the intermodal mode since these modes are the only ones that have rail links in their paths. Again, the binary variable δ_{lp} is used to identify what paths go through each link. This constraint has the following form:

$$fl = \sum_{p \subseteq Pr} \delta lp * hp + \sum_{p \subseteq Pm} \delta lp * hp \quad \text{for } \forall\ l \subseteq R$$

and is written for all rail links.

Constraint 4. Transfer Link Flow Conservation

In order for intermodal mode users to transfer out of their autos and on to trains, they must go through a "transfer" link that ties the two modes of transportation (auto and rail) together. The model uses transfer links to represent the portion of an intermodal mode trip that begins with entering the station parking lot and ends with boarding the train. This constraint insures that flow on each transfer link is conserved. It equates the flow on a transfer link (f_l) with the sum of all the flows on all the paths that go through that link (h_p). Paths for this constraint are solely derived from the intermodal mode. As before, the binary parameter δ_{lp} is used to identify what paths go through each transfer link. This constraint has the following form:

$$fl = \sum_{p \subseteq Pm} \delta lp * hp \quad \text{for } \forall\ l \subseteq T$$

and is written for all transfer links.

Constraint 5. Transfer Link Capacity

This constraint insures that flows on transfer links do not exceed the capacities of parking lots at rail stations. It equates the flow on each transfer link (h_p) with the sum of the existing parking capacity ($Space_l$) and any additional parking capacity the model assigns to a transfer link ($Addspace_l$). The auto occupancy rate (occ) converts trips into vehicles. This constraint has the following form:

$$fl = 1 / occ[\sum_{p \subseteq Pm} \delta lp * hp] \leq Spacel + Addspacel \text{ for } \forall l \subseteq T$$

and is written for all transfer links.

Constraint 6. Rail Line Capacity

This constraint insures that flows on rail links do not exceed the seating capacity of the train serving these links. It equates the sum of all flows going through a critical rail link (h_p) with the sum of the existing seating capacity ($Seats$) and any additional seating capacity the model assigns to the train ($Addseats$). In a commuter rail operation with many-to-one travel patterns the critical rail link is defined as the last rail link into the destination node. This constraint has the following form:

$$\sum_{p \subseteq Pm} \delta lp * hp + \sum_{p \subseteq Pr} \delta lp * hp \leq Seats + Addseats$$

and is written only for the critical link.

The complete model statement is shown in Table 3.1.

Table 3.1. A Planning Model for Intermodal Auto-Rail Passenger Transportation Assignment

Minimize $Z = \sum_{l \in L} cl * fl$ (System Optimization)

$$Z = \sum_{l \in L} \int_0^{fl} c(fl)\,dfl \quad \text{(User Equilibrium)}$$

subject to:

1. $Tw = \sum_{p \subseteq Pa} hp + \sum_{p \subseteq Pr} hp + \sum_{p \subseteq Pm} hp$ for $\forall\ l \subseteq W$

2. $fl = 1 / occ[\sum_{p \subseteq Pa} \delta lp * hp + \sum_{p \subseteq Pm} \delta lp * hp]$ for $\forall\ l \subseteq A$

3. $fl = \sum_{p \subseteq Pr} \delta lp * hp + \sum_{p \subseteq Pm} \delta lp * hp$ for $\forall\ l \subseteq R$

4. $fl = \sum_{p \subseteq Pm} \delta lp * hp$ for $\forall\ l \subseteq T$

5. $fl = 1 / occ[\sum_{p \subseteq Pm} \delta lp * hp] \leq Spacel + Addspacel$ for $\forall\ l \subseteq T$

6. $\sum_{p \subseteq Pm} \delta lp * hp + \sum_{p \subseteq Pr} \delta lp * hp \leq Seats + Addseats$

7. $h_p, f_l \geq 0$

CHAPTER 4

CASE STUDY OF AN INTERMODAL NETWORK

4.1 Introduction

One of the objectives of this research was to use the intermodal assignment model developed in the previous chapter to assign flows over an intermodal network under various objectives and also to answer questions that were identified earlier in Section 3.2 related to such flow assignments. The approach chosen in this research was to select a real-world intermodal network and to collect the relevant data for analysis. The data included the geometric characteristics of the network, and relevant demand and cost quantities. Within the case study, several scenarios were developed which involved varying degrees of congestion. The model was then applied to these scenarios and the MOEs were evaluated. The case study of the intermodal network to which the model was applied is presented in this chapter.

This chapter proceeds as follows. Section 4.2 describes the case study and outlines the data requirements. Section 4.3 describes the data input for the model and how this data was generated for the case study. Section 4.4 outlines the scenarios used for analyses. Section 4.5 details the time cost function used in the objective functions. Section 4.6 briefly describes the model size for the case study network and the software used to solve the model.

4.2 Case Study Description And Data Requirements

The intermodal network chosen for the case study is a portion of the Raritan Valley Corridor located in Union County, New Jersey which is shown in Figure 4.1. This network contains five origins, Westfield, Garwood, Cranford, Kenilworth and Roselle Park and one destination which is Newark. The network is composed of three major highways, I-78, Route 22, and the Garden State Parkway, local county routes, which run

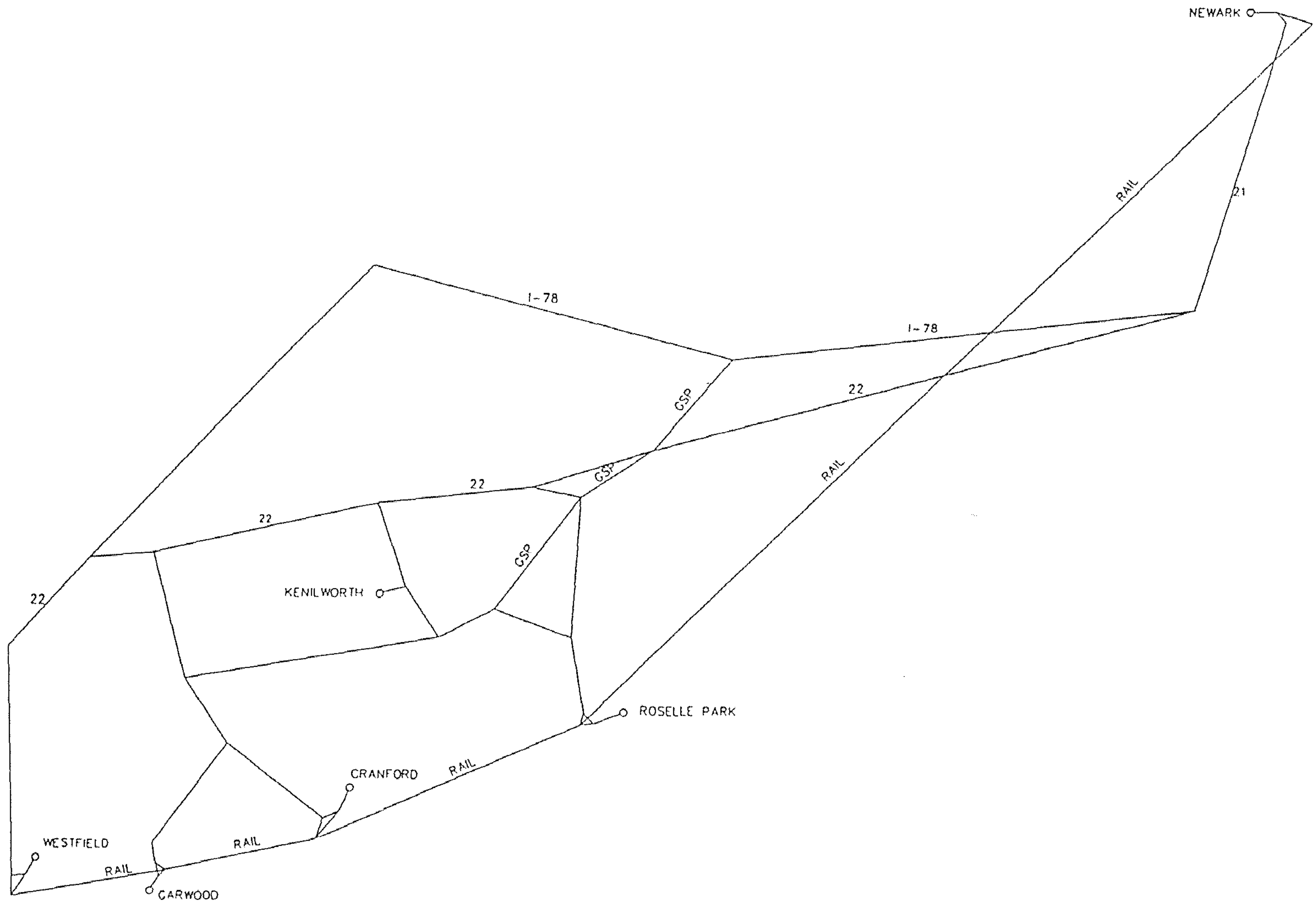

Figure 4.1 Study Network - Raritan Valley Corridor

between the major highways, and the Raritan Valley Line which provides rail service for this area.

The case study required the following data, which were classified into two groups, geometric and demand/supply.

Geometric Data:

- origin-destination pair locations
- centroids of origins and destinations
- link locations
- link capacities
- link free-flow travel times
- link costs
- paths between O-D pairs

Demand/Supply:

- origin-destination demands
- background flows originating outside of the study network
- frequency and capacity of trains
- rail station parking supplies

4.3 Data Input for Model

The data for the model were grouped into geometric and demand/supply types which are discussed further in this section.

4.3.1 Origin-Destination Pair Locations

The first step taken in defining the study network was to define areas where commuters originate their trips and to define the area they are destined to. Origins and the destination were primarily dictated by the location of rail stations. However, Kenilworth was also included as an origin because it was felt that this area was also served by the rail line even though this area is not very close to the rail line.

4.3.2 Centroids of Origins and Destination

Once the origin and destination areas were defined it was necessary to define the centroids of these areas. Generally, the centroid of an area was defined as a combination of the geometric center of the area and the center of the area's population distribution.

4.3.3 Link Locations

After all the centroids were defined, they were connected by a series of contiguous links which formed the network. These links are of the following types: centroid, walking, highway, transfer and rail.

Centroid links connect the centroid of an area with the network. They were placed between the centroid of an area and the nearest roadway and represent the origination/termination and access portions of a trip.

Walking links connect the centroid of an area with the rail station that serves that area, unless the centroid is too far away to walk as is the case with Kenilworth. These links allow a commuter to reach or leave a rail station by using the most dependable mode, walking.

Highway links connect the centroid links of an area with the centroid links of other areas. They were defined between intersections and interchanges that allow transfers between different highway facilities.

Transfer links connect the highway network with each rail station. Their purpose is to model the portion of a intermodal trip where a commuter leaves the highway network, enters a rail station parking lot and proceeds to the rail platform for boarding.

Rail links connect rail stations with each other.

4.3.4 Link Capacities

Highway link capacities are dependent upon the classification of each link (i.e., local, freeway). The highway link capacities were calculated using the methodologies set forth in the 1985 Highway Capacity Manual for each classification. Centroid links, for this research, were also considered as local highway links and have the corresponding capacities. All highway links were computed assuming a level of service C which represents a well flowing network.

The highway link capacities were calculated as follows:

Local Highway Links:
Assumptions: g/c = 0.65
2-Lane Roadways

Capacity = 1,600*0.65 = 1040 vph

I-78 and Garden State Parkway Links:
Assumptions: 70 mph Design Speed
10-Lane Roadways

Capacity = 1,550pcphpl*5lanes = 7,750 pcph

Route 22 Links:
Assumptions: 60 mph Design Speed
4-Lane Roadway

Capacity = 1,300pcphpl*2lanes = 2,600 pcph

Route 21 Links
Assumptions: g/c = 0.65
4-Lane Roadway

Capacity = 1,600*0.65*2 = 2080 vph

Walking links by definition have unlimited capacity. Transfer and rail link capacities are developed in later sections.

4.3.5 Link Free-Flow Travel Times

Highway link free-flow travel times were determined by taking the free-flow speed of each highway link and dividing by the distance of that link. Free-flow speeds were assumed as follows:

I-78 - 55 mph

Route 22 - 50 mph
All Other Highway Links - 30 mph

These values were arrived at through the author's driving experience on these links.

Transfer link free-flow travel times were assumed to be five minutes which includes parking time and waiting time for the train.

Walking link free-flow travel times were determined by the distances of each walking link. Based on this distances, free-flow travel times were calculated assuming an average walking rate of 4.5 ft/sec.

Rail link travel times were determined by consulting a train schedule for the Raritan Valley Line. The trains on the route operate according to the all-stop operating regime.

4.3.6 Paths Between O-D Pairs

Paths between each O-D pair were defined through talking with people who live in the study corridor and identifying the routes they take to Newark. Though this process did not incorporate all possible paths between O-D pairs, it did eliminate from consideration circuitous routes.

4.3.7 Origin-Destination Demands

Origin-Destination demands were determined by reviewing the 1980 U.S. Bureau of Census database. The data was aggregated and the following are the O-D demands that were used for the baseline year of 1987:

Table 4.1. Origin-Destination Demands

Origin - Destination Pair	Demands (trips)
Westfield to Newark	540
Garwood to Newark	130
Cranford to Newark	620
Kenilworth to Newark	220
Roselle Park to Newark	920

According to the U.S. Bureau of Census data, these demands will not change until 2010.

4.3.8 Background Volumes

Background volumes for highway links that originate from outside the study network were determined by consulting the 1988 New Jersey Highway Straight Line Diagrams publication. Volume data was available for I-78, Route 22 and Route 21 links from this publication. In addition, volume data for the Garden State Parkway was obtained through a corridor study performed by Vollmer Associates. A baseline year of 1987 was established and a two percent per year compounded growth rate was used to expand volume data that were recorded before 1987.

Volume data for all of the local highway links was unavailable. Therefore, background volumes for these links were assumed to be sixty percent of their capacities for the year of 1987.

Rail link background volumes were determined by consulting ridership data that was provided by NJ Transit. All demands at stations west of Westfield were summed and the total was used as the background volume for the rail links of the study network.

4.3.9 Frequency and Capacity of Trains

The frequency of trains in the study network was determined to be three trains per hour for each rail station which was obtained by reviewing a train schedule for the rail line.

The capacity of each train was found to be approximately 500 seats which is based on each train consisting of four cars each having a seating capacity of approximately 125 seats.

4.3.10 Rail Station Parking Capacities

The number of parking spaces for each rail station was obtained through data provided by NJ Transit and are as follows:

Westfield - 759 spaces
Garwood - 0 spaces
Cranford - 373 spaces
Roselle Park - 239 spaces

4.4 Time-Volume Function

As mentioned previously, the only cost that was considered in this case study was travel time. The time-volume function used for each link was the Bureau of Public Roads congestion curve function:

$$t = tfl * [1 + 0.15 \text{ (link flow/capacity)}^4)]$$

where: t = travel time under current flow
tfl = free-flow travel time

This function was applied to all links in the study network. For links whose travel times are constant regardless of congestion levels (e.g., rail, transfer and walking), a capacity of 10,000 was assigned to eliminate the non-linear portion of the above function.

4.5 Scenarios

Four scenarios were developed for analysis. They involve varying degrees of highway congestion on the study network and were generated by taking the baseline scenario of 1987 and applying a two percent per year compounded growth rate to the baseline background volumes. The scenarios consist of the following years: 1987, 1992, 1995 and 2000.

4.6 Model Solver

The model was solved by using General Algebraic Modeling System (GAMS). The model code and output for Scenario 1 are presented in the appendix. For the case study network, the model consisted of 66 equations and 87 choice variables. The GAMS optimizer used to solve the model was MINOS. The total time required to generate and execute the model was 0.949 seconds. The reader is referred to the GAMS user guide for a detailed discussion of GAMS and the MINOS optimizer.

CHAPTER 5

RESULTS OF CASE STUDY ANALYSIS

5.1 Introduction

The previous chapter presented the case study of an intermodal network which consists of five origins and one destination. The case study was constructed from real-world data on commuter trip making for a portion of the Raritan Valley Corridor. Within the case study, several scenarios which involve varying degrees of congestion were developed.

In this chapter, flows are assigned over the study network for different equilibrium conditions and objectives, different management strategies are compared, the benefits of shifting commuters to rail are quantified and improvements that need to be made with respect to rail service are presented. These were done by imputing data into the model developed in Chapter 3 and solving it. The results of the model runs are presented next.

The content of the chapter is as follows. Section 5.2 presents the results of Scenario 1. Section 5.3 presents the results of Scenario 2. Section 5.4 presents the results of Scenario 3. Section 5.5 presents the results of Scenario 4. Section 5.6 presents a total cost analysis with respect to increasing congestion and the provision of rail service. Section 5.7 examines the differences between a system optimization versus a user equilibrium management strategy.

5.2 Scenario 1 Results

The results for Scenario 1 are discussed in detail in this section. The data were entered into the model and the outputs that were generated are presented in Table 5.1.

As can be seen, different objectives produce different flow assignments over the network. Overall, for this level of congestion, under user equilibrium the auto mode is the most utilized mode whereas under system optimization the intermodal mode is the most utilized mode. Furthermore, the total cost under user equilibrium is 11.3% more than the

Table 5.1 Results for Scenario 1 (1987)

	Trips Made Via			Path Time (minutes)		
	Auto	Rail	Intermodal	Auto	Rail	Intermodal
Westfield						
User	479	0	61	34.9	38.6	34.9
System	0	0	540	28.9	38.6	34.9
Garwood						
User	130	0	0	31.2	32.2	32.4
System	0	130	0	27.4	32.2	32.4
Cranford						
User	0	0	620	32.0	31.5	30.3
System	0	0	620	28.2	31.5	30.3
Kenilworth						
User	220	0	0	26.8	NA	30.4
System	0	0	220	23.0	NA	30.4
Roselle Park						
User	0	0	920	30.0	30.9	27.2
System	0	0	920	25.2	30.9	27.2
Total Cost (minutes)						
User	372,264					
System	334,512					

the total cost under system optimization. These two observations illustrate two very important points that need to be made. First, under user equilibrium commuters between each O-D pair will incur the same travel time, regardless of what path they are assigned to, for all utilized paths have the same cost. However, this does not hold true for system optimization. For example, under system optimization all commuters in Cranford are assigned to the intermodal mode even though the best auto path has a travel time which is two minutes less but has a marginal cost that is higher. Second, under user equilibrium the total cost system wide is much higher than that under system optimization which can be equated to a very inefficient use of the transportation system.

The central traffic management centers that are envisioned in the future are going to have to address the two issues just presented when determining the management strategy they will operate under.

5.2.1 Benefits of Mode Switch to Rail

The results illustrated in Table 5.1 also allow the quantification of benefits from shifting commuters to rail.

The savings that are derived from the system optimization assignment are directly attributable to shifting commuters off of highways and on to the rail line. Those commuters who were assigned to the auto mode under user equilibrium were assigned to the rail and intermodal modes under system optimization. Thus, the 37,752 minutes of travel time that were saved under system optimization is the benefit of shifting auto commuters to rail at some point during their commute.

5.2.2 Required Rail Improvements

In order for the rail line to accommodate the demand that is assigned to each rail station and corresponding parking lot, under each objective, improvements in the form of added parking capacity and train seating capacity must be made. The model has variables which enable these improvements to be identified. Table 5.2 illustrates what improvements, if any, need to be made at each rail station parking lot under each objective. In addition, under user equilibrium the required increase in rail capacity is 1,137 seats and under system optimization it is 1,966 seats.

5.3 Scenario 2 Results

The results for Scenario 2 are discussed in this section. This scenario is for the study year of 1992. The data were entered into the model and the outputs that were generated are presented in Table 5.3.

For this level of congestion, under user equilibrium the auto mode is less utilized than in Scenario 1, due to the increase in highway congestion. Again, under system optimization the intermodal mode is the most utilized mode. Moreover, the total cost under user equilibrium is 2.5% more than the total cost under system optimization, which is still indicative of inefficient use of the transportation system. As in the previous scenario, under system optimization commuters have been assigned to a mode that has a higher path time than a mode that is not utilized. As it can be seen, 540 commuters from Westfield were assigned to the intermodal mode despite the auto mode having a path with a lower travel time.

5.3.1 Benefits of Mode Switch to Rail

For this scenario, the auto mode is being utilized under user equilibrium, but under system optimization it is not. Therefore, as before, the 10,611 minutes of travel time that were saved under system optimization is the benefit of shifting auto commuters to rail at some point during their commute.

Table 5.2 Required Parking Increase for Scenario 1 (1987)

Rail Station Parking Lot	Required Increase In Parking Capacity
Westfield	
User Equilibrium	0
System Optimization	0
Garwood	
User Equilibrium	0
System Optimization	0
Cranford	
User Equilibrium	247
System Optimization	247
Roselle Park	
User Equilibrium	681
System Optimization	901

Table 5.3 Results for Scenario 2 (1992)

	Trips Made Via			Path Time (minutes)		
	Auto	Rail	Intermodal	Auto	Rail	Intermodal
Westfield						
User	4	0	536	34.9	38.6	34.9
System	0	0	540	34.5	38.6	34.9
Garwood						
User	0	130	0	33.6	32.2	32.4
System	0	130	0	31.1	32.2	32.4
Cranford						
User	0	0	620	34.4	31.5	30.4
System	0	0	620	32.0	31.5	30.4
Kenilworth						
User	220	0	0	29.3	NA	30.4
System	0	0	220	26.7	NA	30.4
Roselle Park						
User	0	0	920	31.4	30.9	27.3
System	0	0	920	29.0	30.9	27.3
Total Cost (minutes)						
User	434,686					
System	424,075					

5.3.2 Required Rail Improvements

Table 5.4 illustrates what improvements, if any, need to be made at each rail station parking lot under each objective. As expected, the number of required additional spaces remained the same as the previous scenario due to the mode assignments for Kenilworth and Roselle Park remaining unchanged. In addition, under user equilibrium the required increase in rail capacity is 1,742 seats and under system optimization it is again 1,966 seats.

5.4 Scenario 3 Results

The results for scenario 3 are discussed in this section. The study year for this scenario is 1995 and the outputs that were generated are presented in Table 5.5.

Due to the high level of highway congestion, the auto mode has been eliminated from use for every origin except Kenilworth under user equilibrium and was replaced by the intermodal mode. Under system optimization, as before, the intermodal mode is the most utilized mode. Additionally, the total cost under user equilibrium is only 0.58% more than the total cost under system optimization. This indicates that increasing levels of highway congestion induce commuters to switch to rail, promoting a more efficient use of the transportation system. Again, under system optimization commuters have been assigned to modes that do not have the lowest path times but that have the lowest marginal costs.

5.4.1 Benefits of Mode Shift to Rail

The benefit of shifting auto commuters to rail is the difference between the total costs of both objectives. This difference is 2,914 minutes, which is due to the 51 Kenilworth commuters assigned to the auto mode under user equilibrium being assigned to the intermodal mode under system optimization.

Table 5.4 Required Parking Increase for Scenario 2 (1992)

Rail Station Parking Lot	Required Increase In Parking Capacity
Westfield	
User Equilibrium	0
System Optimization	0
Garwood	
User Equilibrium	0
System Optimization	0
Cranford	
User Equilibrium	247
System Optimization	247
Roselle Park	
User Equilibrium	681
System Optimization	901

Table 5.5 Results for Scenario 3 (1995)

	Trips Made Via			Path Time (minutes)		
	Auto	Rail	Intermodal	Auto	Rail	Intermodal
Westfield						
User	0	0	540	39.0	38.6	34.9
System	0	0	540	38.3	38.6	34.9
Garwood						
User	0	0	130	34.9	32.2	32.4
System	0	130	0	34.2	32.2	32.4
Cranford						
User	0	0	620	35.8	31.5	30.4
System	0	0	620	35.1	31.5	30.4
Kenilworth						
User	51	0	169	30.4	NA	30.5
System	0	0	220	29.9	NA	30.5
Roselle Park						
User	0	0	920	32.7	30.5	27.4
System	0	0	920	32.1	30.5	27.4
Total Cost (minutes)						
User	503,054					
System	500,140					

5.4.2 Required Rail Improvements

Table 5.6 illustrates that under user equilibrium there was an increase in the number of spaces required at Roselle Park over the last scenario due to the switch of Kenilworth commuters from the auto mode to the intermodal mode. As previously, the number of spaces required under system optimization remained the same. Also, under user equilibrium the required increase in rail capacity is 1,915 seats and under system optimization it remains at 1,966 seats.

5.5 Scenario 4 Results

The results for Scenario 4 are discussed in this section. The study year for this scenario is 2000 and the outputs that were generated are shown in Table 5.7.

This level of congestion has resulted in the complete elimination of the auto mode being assigned to commuters from the five origins under user equilibrium. System optimization has again resulted in the intermodal mode being the most utilized mode, with the rail mode having the greatest utilization among all scenarios. In addition, the total cost difference between user equilibrium and system optimization is only 5 minutes indicating that as highway congestion increases the assignments made under each objective become practically identical.

5.4.1 Benefits of Mode Shift to Rail

The benefit of shifting auto mode commuters to rail at some point during the commute cannot explicitly be determined because there were no commuters assigned to the auto mode under user equilibrium. However, the difference of 5 minutes in total cost for both objectives is attributable to intermodal mode commuters under user equilibrium being assigned to the rail mode under system optimization.

Table 5.6 Required Parking Increase for Scenario 3 (1995)

Rail Station Parking Lot	Required Increase In Parking Capacity
Westfield	
User Equilibrium	0
System Optimization	0
Garwood	
User Equilibrium	0
System Optimization	0
Cranford	
User Equilibrium	247
System Optimization	247
Roselle Park	
User Equilibrium	850
System Optimization	901

Table 5.7 Results for Scenario 4 (2000)

	Trips Made Via			Path Time (minutes)		
	Auto	Rail	Intermodal	Auto	Rail	Intermodal
Westfield						
User	0	0	540	47.1	38.6	35.0
System	0	0	540	47.1	38.6	35.0
Garwood						
User	0	130	0	41.2	32.2	32.4
System	0	130	0	41.2	32.2	32.4
Cranford						
User	0	0	620	42.2	31.5	30.5
System	0	46	574	42.2	31.5	30.5
Kenilworth						
User	0	0	220	36.8	NA	30.6
System	0	0	220	36.8	NA	30.6
Roselle Park						
User	0	0	920	39.2	30.9	27.5
System	0	0	920	39.2	30.9	27.5
Total Cost (minutes)						
User	680,336					
System	680,331					

5.4.2 Required Rail Improvements

Table 5.8 illustrates that under user equilibrium the required additional number of spaces again remained unchanged. Under system optimization however, the increase in rail mode usage resulted in a decrease in the number of required additional parking spaces. Also, the required increase in rail capacity is 1,966 seats for both objectives, which was expected due to the elimination of the auto mode from use.

5.6 Total Cost Analysis

The total cost for each objective that were calculated for each scenario are presented in Table 5.9.

Interestingly, as congestion increases, the difference between the total cost of user equilibrium and system optimization decreases. The reason for this is that as highway congestion grows, the travel times for using the auto mode go up drastically causing the model to assign all O-D trips over rail and intermodal modes under both objectives. The travel times for these two modes will remain constant, for the most part, as congestion increases due to the fact that the travel time on rail is assumed to always remain constant regardless of congestion levels.

This reinforces the suggestion that rail service will play a major role in relieving congestion on U.S. highways in the future, for if commuters were not switched to rail, the travel time for auto would increase substantially as would the total system travel time under both objectives. To illustrate this point, the model was resolved for all four scenarios without any rail service. Table 5.10 presents the costs for each scenario, under each objective, with and without rail service. As can be seen, the incorporation of rail service greatly reduces total system time.

Table 5.8 Required Parking Increase for Scenario 4 (2000)

Rail Station Parking Lot	Required Increase In Parking Capacity
Westfield	
User Equilibrium	0
System Optimization	0
Garwood	
User Equilibrium	0
System Optimization	0
Cranford	
User Equilibrium	247
System Optimization	201
Roselle Park	
User Equilibrium	901
System Optimization	901

Table 5.9 Comparison of System vs. User Total Cost

Scenario Year	Total Cost (minutes)	Difference (%)
1987		
User Equilibrium	372264	11.3
System Optimization	334512	
1992		
User Equilibrium	434686	2.5
System Optimization	424075	
1995		
User Equilibrium	503054	0.58
System Optimization	500140	
2000		
User Equilibrium	680336	0.00
System Optimization	680331	

Table 5.10 Cost Comparison with Respect to Rail Service

Scenario Year	Total Cost (minutes)	Difference (%)
1987		
User Eq-Rail Service	372264	50.6
User Eq-No Rail Service	560773	
System Op-Rail Service	334512	67.6
System Op-No Rail Service	560773	
1992		
User Eq-Rail Service	434686	70.2
User Eq-No Rail Service	739869	
System Op-Rail Service	424075	74.5
System Op-No Rail Service	739869	
1995		
User Eq-Rail Service	503054	76.2
User Eq-No Rail Service	886484	
System Op-Rail Service	500140	77.2
System Op-No Rail Service	886484	
2000		
User Eq-Rail Service	680336	79.4
User Eq-No Rail Service	1220275	
System Op-Rail Service	680331	79.4
System Op-No Rail Service	1220275	

5.7 System Optimization Versus User Equilibrium

System optimization will always produce the maximum total utility, (i.e., minimum total cost) for the fact that users are not seen as individuals competing against each other but are seen as a collective group "working" toward the greatest utility for the group. However, a question of equity between users can be raised. For instance, if the flow on a particular link (or mode), say link "a" has reached its "capacity" under system optimization, is it fair to divert a user, who would experience less total travel time if permitted to use link "a" to another link which causes him to experience more total travel time but lowers the total system travel time. This inequity was illustrated in all four scenarios of the case study by commuters being assigned to modes with higher travel times than modes that were not utilized.

On the other hand, a similar argument of equity can be made under user equilibrium. In this case, users are seen as individuals who are competing against each other for the same service and who are only interested in their personal utility. For instance, a user will save travel time if he uses link "b" but he will be causing an additional delay to all other users of link "b" who are upstream from his entrance point. The price of a single user's reduction in travel time is an additional delay for many users. Is it fair for a single user to benefit at a cost to multiple users?

The author is of the belief that a user equilibrium objective is more in accordance with how users of a transportation system behave. And he is continually reminded that everyone is out for themselves when he is driving home on the Garden State Parkway during rush hour and is being continually cut off by someone who is only interested in their personal utility. Moreover, the author believes that a user equilibrium objective is most equitable in that it promotes free competition among users.

The question of system optimization versus user equilibrium can also be examined within an Intelligent Vehicle Highway Systems (IVHS) context. A central traffic management center, whose purpose is to promote the general public good, may be inclined to use a system optimization strategy. Optimal routes would be calculated at a central computing center for all users currently in the system based on real-time conditions. This strategy however, requires the central computer to solve simultaneously for every user's optimal path which may be presently technologically infeasible for large networks with many users. In addition to the large computing requirements, the necessary communication hardware that is needed to support such a system may be too overwhelming to be practical.

Consequently, some current IVHS demonstration projects, such as TravTek and Advance operate under a user equilibrium strategy (Rillet, Aerede and Macinnon 1991). Rather than concentrating the majority of intelligence in the central computer, the bulk of intelligence is placed in the vehicle. In-vehicle routing computers determine optimal routes between O-D pairs based on current link travel times that are transmitted from a central traffic management center.

Although this set up allows users to determine their own optimal routes, independent of each other, it must be realized that non-optimal decisions can result. Any routing decision that is made by a user will undoubtedly have effects on traffic conditions throughout a network. As a result, if users independently but simultaneously choose to travel over a link, that link may become over congested and non-optimal. This is a major problem for IVHS researchers in determining whether to use system optimization or user equilibrium strategies.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 Summary

In this research, three objectives were accomplished. First, a methodological framework was developed to analyze the benefits of shifting commuters to rail and the effects of various management strategies that may be used in assigning flows over an intermodal network. Second, an intermodal auto-rail assignment model was developed. Third, the model was applied to a real-world intermodal network to produce flow assignments under different objectives, evaluate the benefits of shifting commuters to rail and identify what improvements need to be made to rail service to accommodate increases in demand.

6.2 Conclusions

The case study of the four scenarios indicated that there is total travel time savings when commuters are shifted out of their cars and onto rail at some point during their commute. Moreover, when commuters do shift to rail the transportation system is more efficiently utilized.

The total cost analysis with respect to increasing congestion revealed that the difference between the total cost for user equilibrium and system optimization goes down as congestion increases due to the increase in rail use under higher congestion levels. However, it must be pointed out that this is the case because commuters that originate in the study network were indeed shifted to rail at some point during their commute, if they were not, they would have substantially added to the highway congestion and total system travel time.

6.3 Future Research

Three avenues for future research were identified during the course of this research.

First, travel time was the only cost incorporated into the model for this research. Future research should incorporate out-of-pocket costs such as tolls, rail fares and parking fees into the model to see how this would affect the flow assignments under both objectives.

Second, the travel time for rail was assumed to be constant. In reality, however, rail operators can adjust their operation so as to decrease travel time with an increase in demand for service through the introduction of local-express and accelerated service (Morlok 1978). The model can be improved by incorporating various supply functions for rail.

Third, the data that was used to develop background volumes on the highway network was not current and a growth factor had to be used to adjust the data to a common year. Also, data was only available for the major highways which forced an assumption to be made to account for background volumes on the local highways. A more current and complete data base would result in more realistic demands. Furthermore, demand was assumed to be fixed. A variable demand could be incorporated into the model through a demand function to produce more realistic demands as the level of congestion varies.

APPENDIX

GENERAL ALGEBRAIC MODELING SYSTEM (GAMS) CODE AND OUTPUT

GENERAL ALGEBRAIC MODELING SYSTEM (GAMS) CODE AND OUTPUT

This appendix contains the GAMS code and the output in which the model was implemented and solved for Scenario 1. In GAMS language, the equations (objective functions and constraints) are written concisely and in algebraic form. The choice variables (i.e., link flows and path flows) and equations are not input individually. Rather, the choice variables and equations are defined over sets of link types. The program generates a choice variable by performing summations over these sets (i.e., generating the pair-wise combinations of the elements in each set). It also generates a pre-specified number of equations for each element of a set (i.e., a link).

```
GAMS 2.25  SUN 4/SPARC                    11/28/92 13:24:04  PAGE     1
General Algebraic Modeling System
Compilation
OPTION LIMROW = 0;
OPTION LIMCOL = 0;
OPTION ITERLIM = 3000;
SETS
I ORIGINS /WEST,GARW,CRAN,KENL,ROSP/
J DESTINATIONS /NEWARK/
L LINKS /1*55/
CD(L) CENTROID LINKS /1*6/
R(L)  RAIL LINKS /7*10/
CR(L) CRITICAL RAIL LINK /10/
X(L)  HIGHWAY LINKS /17*27, 29*52, 54/
T(L)  TRANSFER LINKS /15,16,28,55/
W(L)  WALKING LINKS /11*14, 53/
P     PATHS /P1*P26/
PA(P) AUTO ONLY PATHS /P1,P2,P3,P8,P9,P13,P14,P17,P18,P20,P21/
PM(P) AUTO-RAIL PATHS /P4*P6,P10,P11,P15,P22,P23,P24,P25,P26/
PR(P) RAIL ONLY PATHS /P7,P12,P16,P19/;
TABLE VOLUME(I,J,*) DEMAND BETWEEN ORIGINS AND DESTINATIONS
             TRIPS
 WEST.NEWARK  540
 GARW.NEWARK  130
 CRAN.NEWARK  620
 KENL.NEWARK  220
 ROSP.NEWARK  920;
PARAMETER CAP(L) LINK CAPACITITES-EXCLUDING TRANSFER AND RAIL LINKS
/
 (1*5)   1040
 6      10000
 (7*16) 10000
 17      7750
 18      7750
 (19*24) 2600
 (25*27) 1040
 28     10000
 (29*48) 1040
 49      2080
 50      1040
 51      7750
 52      7750
 53     10000
 54      1040
 55     10000 /;
PARAMETER SPACE(T) TRANSFER LINK CAPACITITES
/15 373
 16 239
 28 0
 55 759/;
```

```

PARAMETER FF(L) FREE-FLOW TRAVEL TIME ON LINKS IN MINUTES
/1 0.5, 2 0.2, 3 0.4, 4 1.0, 5 0.5, 6 1.0, 7 2.0, 8 3.0, 9 3.0, 10 15.0,
11 9.0, 12 5.0, 13 7.0, 14 9.0, 15 5.0, 16 5.0, 17 2.9, 18 3.9, 19 1.0,
20 0.3, 21 1.9, 22 1.3, 23 0.5, 24 5.7, 25 3.2, 26 3.0, 27 2.2, 28 5.0,
29 0.9, 30 1.6, 31 0.6, 32 1.6, 33 0.9, 34 2.2, 35 1.7, 36 0.2, 37 1.7,
38 3.0, 39 0.7, 40 1.0, 41 1.0, 42 0.7, 43 1.0, 44 1.7, 45 0.7, 46 0.2,
47 0.7, 48 1.7, 49 3.8, 50 0.7, 51 1.9, 52 1.6, 53 5.0, 54 0.2, 55 5.0/;

TABLE LP(L,P) LINK-PATH MATRIX
GAMS 2.25  SUN 4/SPARC                11/28/92 13:24:04  PAGE    2
General Algebraic Modeling System
Compilation


    P1 P2 P3 P4 P5 P6 P7 P8 P9  P10 P11 P12 P13 P14 P15 P16 P17 P18 P19 P20
1   1  1  1  1  1  1  1  1  1
2                     1  1  1   1   1
3                               1   1   1   1
4                                                   1
5                                           1   1   1
6   1  1  1  1  1  1  1  1  1   1   1   1   1   1   1   1   1   1   1   1
7               1
8              1  1             1
9         1    1  1     1   1           1
10        1  1  1  1    1   1   1       1   1           1
11                1
12                            1
13                                      1
14                                              1
15        1            1
16           1             1            1
17  1
18  1  1            1               1               1
19  1  1  1  1  1  1
20     1  1  1  1  1
21     1  1    1     1               1
22     1  1    1     1               1                  1
23     1  1          1               1          1       1
24     1             1               1          1       1
25  1  1  1  1  1  1
26  1
27        1   1
28            1
29        1   1
30        1             1
31                              1   1   1
32                              1   1   1
33                   1  1    1     1   1   1
34                   1              1
35            1
36                   1  1  1  1
37                   1  1  1  1
38                      1     1         1   1
```

```
39                      1      1          1   1
40                            1             1
41                                                   1
42
43                                                          1
44            1
45            1                1             1
46                                                1   1
47       1                                         1  1
48                                                1   1
49  1  1               1  1             1   1         1   1       1
50  1  1  1            1   1            1   1          1   1      1
51                      1                1             1
52       1               1                1             1
53         1   1  1  1        1   1   1         1   1          1
54  1  1  1  1     1

 + P21 P22 P23 P24 P25 P26
1         1
2             1
3                1
4   1   1             1
GAMS 2.25  SUN 4/SPARC                    11/28/92 13:24:04  PAGE     3
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n

6   1   1   1   1   1   1
7         1
8         1   1
9         1   1   1
10      1   1   1   1   1
15                1
16      1             1
18  1
28             1
31                1
36             1
39  1    1
40      1
42  1    1
45      1
46                   1
49  1
50  1
51  1
52  1
53      1   1   1    1  1
54         1
55         1 ;

PARAMETER IJP(I,J,P) ORIGIN-DESTINATION PATH MATRIX
/(WEST.NEWARK.P1)  = 1
 (WEST.NEWARK.P2)  = 1
 (WEST.NEWARK.P3)  = 1
```

```
(WEST.NEWARK.P4)  = 1
(WEST.NEWARK.P5)  = 1
(WEST.NEWARK.P6)  = 1
(WEST.NEWARK.P7)  = 1
(WEST.NEWARK.P23)  = 1
(GARW.NEWARK.P8)  = 1
(GARW.NEWARK.P9)  = 1
(GARW.NEWARK.P10)  = 1
(GARW.NEWARK.P11)  = 1
(GARW.NEWARK.P12)  = 1
(GARW.NEWARK.P24)  = 1
(CRAN.NEWARK.P13)  = 1
(CRAN.NEWARK.P14)  = 1
(CRAN.NEWARK.P15)  = 1
(CRAN.NEWARK.P16)  = 1
(CRAN.NEWARK.P25)  = 1
(ROSP.NEWARK.P17)  = 1
(ROSP.NEWARK.P18)  = 1
(ROSP.NEWARK.P19)  = 1
(ROSP.NEWARK.P26)  = 1
(KENL.NEWARK.P20)  = 1
(KENL.NEWARK.P21)  = 1
(KENL.NEWARK.P22)  = 1/;

PARAMETER BG(L) BACKGROUND VOLUMES ON HIGHWAY LINKS
/ (1*5)    624
  17       6035
  18       4250
  19       4933
  20       4933
  21       5393
  22       5174
```



```
  23       4726
  24       4153
  (25*27)  624
  (29*48)  624
  49       3923
  50       624
  51       6805
  52       6805
  54       624 /;

VARIABLES
F(L)  FLOW ON A LINK
H(P)  FLOW ON A PATH
ADDSPACE(T) ADDITIONAL PARKING SPACES REQUIRED AT A STATION
ADDSEAT     ADDITIONAL SEATS REQUIRED ON TRAIN
UE   USER OBJECTIVE FUNCTION
SE  SYSTEM OBJECTIVE FUNCTION
POSITIVE VARIABLES F,H,ADDSPACE,ADDSEAT;
```

```
SCALAR
SEATS SEAT CAPACITY OF TRAIN /1500/;
EQUATIONS
OBJSE  OBJECTIVE FUNCTION UNDER SYSTEM EQUILIBRIUM
OBJUE  OBJECTIVE FUNCTION UNDER USER EQUILIBRIUM
DEMAND(I,J) NUMBER OF TRIPS BETWEEN ORIGIN AND DESTINATION
FLOW(L) FLOW ON EACH LINK
TRANS(T) FLOW INTO TRANSFER LINKS
RAIL(CR) FLOW INTO TRAIN;
DEMAND(I,J) .. SUM(P$IJP(I,J,P), H(P)) =E= VOLUME(I,J,'trips');
FLOW(L) .. SUM(P$LP(L,P), H(P)) +BG(L) =E= F(L);
TRANS(T) .. SUM(P$LP(T,P), H(P)) =L= SPACE(T) + ADDSPACE(T);
RAIL(CR) .. SUM(P$LP(CR,P), H(P)) + 1036 =L= SEATS + ADDSEAT;
*SYSTEM EQUILIBRIUM
OBJSE .. SE =E= SUM(L, F(L)*FF(L)*(1+0.15*POWER((F(L)/CAP(L)),4)));
*USER EQUILIBRIUM OBJECTIVE (NO ECONOMIC MEANING)
OBJUE .. UE =E= SUM(L, F(L)*FF(L)*(1+0.03*POWER(F(L),4)/POWER(CAP(L),4)))
                                          ;
MODEL SYS /OBJSE, DEMAND, FLOW, TRANS, RAIL/;
SOLVE SYS USING DNLP MINIMIZING SE;
PARAMETER SYSREPORT(*,*) REPORT ON SYSTEM LINK, PATH AND TRAVEL TIMES;
PARAMETER USEREPORT(*,*) REPORT ON USER LINK, PATH AND TRAVEL TIMES;
*DISPLAY RELEVANT INFORMATION
SYSREPORT("LINKFLOW",L) = F.L(L);
SYSREPORT("LINKTIME",L) = FF(L)+FF(L)*0.15*POWER((F.L(L)/CAP(L)),4);
SYSREPORT("TRUETIME","SYSTEM") = SUM(L, F.L(L)*SYSREPORT("LINKTIME",L));
SYSREPORT("PATHTIME",P) = SUM(L$LP(L,P), SYSREPORT("LINKTIME",L));
SYSREPORT("PATHTFLOW",P) = H.L(P);
SYSREPORT("MARGINALSY",P) = SUM(L$LP(L,P), FLOW.M(L));
DISPLAY SYSREPORT;
GAMS 2.25 SUN 4/SPARC              11/28/92 13:24:04 PAGE    5
General Algebraic Modeling System
Compilation

MODEL USER /OBJUE, DEMAND, FLOW, TRANS, RAIL/;
SOLVE USER USING DNLP MINIMIZING UE;
USER.OPTFILE=1; OPTION NLP=MINOS5;
*DISPLAY RELEVANT INFORMATION
```

```
USEREPORT("LINKFLOW",L) = F.L(L);
USEREPORT("LINKTIME",L) = FF(L)*(1+0.15*POWER((F.L(L)/CAP(L)),4));
USEREPORT("TRUETIME","USER") = SUM(L, F.L(L)*USEREPORT("LINKTIME",L));
USEREPORT("PATHTIME",P) = SUM(L$LP(L,P), USEREPORT("LINKTIME",L));
USEREPORT("PATHTFLOW",P) = H.L(P);
USEREPORT("MARGINALUS",P) = SUM(L$LP(L,P), FLOW.M(L));
DISPLAY USEREPORT;
```

```
COMPILATION TIME     =       0.317 SECONDS        VERID SUN-00-044
GAMS 2.25  SUN 4/SPARC                  11/28/92 13:24:04  PAGE     9
General  Algebraic  Modeling  System
Model Statistics    SOLVE SYS USING DNLP FROM LINE 231

MODEL STATISTICS

BLOCKS OF EQUATIONS        5     SINGLE EQUATIONS       66
BLOCKS OF VARIABLES        5     SINGLE VARIABLES       87
NON ZERO ELEMENTS        425     NON LINEAR N-Z         55
DERIVATIVE POOL           59     CONSTANT POOL          36
CODE LENGTH             1861

GENERATION TIME      =       0.150 SECONDS

EXECUTION TIME       =       0.150 SECONDS        VERID SUN-00-044
GAMS 2.25  SUN 4/SPARC                  11/28/92 13:24:04  PAGE    10
General  Algebraic  Modeling  System
Solution Report    SOLVE SYS USING DNLP FROM LINE 231

          S O L V E      S U M M A R Y

   MODEL   LAZSYS          OBJECTIVE  SE
   TYPE    DNLP            DIRECTION  MINIMIZE
   SOLVER  MINOS5          FROM LINE  231

**** SOLVER STATUS      1 NORMAL COMPLETION
**** MODEL STATUS       2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE          336097.8215

 RESOURCE USAGE, LIMIT          0.320     1000.000
 ITERATION COUNT, LIMIT        15         3000
 EVALUATION ERRORS              0            0

   M I N O S    5.3    (Nov 1990)        Ver: 225-SUN-02
   = = = = =

   B. A. Murtagh, University of New South Wales
     and
   P. E. Gill,  W. Murray,  M. A. Saunders and M. H. Wright
   Systems Optimization Laboratory, Stanford University.
```

Work space allocated -- 0.08 Mb

EXIT -- OPTIMAL SOLUTION FOUND
MAJOR ITNS, LIMIT 1 200
FUNOBJ, FUNCON CALLS 16 0
SUPERBASICS 1
INTERPRETER USAGE 0.08
NORM RG / NORM PI 1.932E-08

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU OBJSE	.	.	.	1.000

OBJSE OBJECTIVE FUNCTION UNDER SYSTEM EQUILIBRIUM

---- EQU DEMAND NUMBER OF TRIPS BETWEEN ORIGIN AND DESTINATION

	LOWER	LEVEL	UPPER	MARGINAL
WEST.NEWARK	540.000	540.000	540.000	35.579
GARW.NEWARK	130.000	130.000	130.000	32.297
CRAN.NEWARK	620.000	620.000	620.000	31.591
KENL.NEWARK	220.000	220.000	220.000	34.335
ROSP.NEWARK	920.000	920.000	920.000	30.762

---- EQU FLOW FLOW ON EACH LINK

	LOWER	LEVEL	UPPER	MARGINAL
1	-624.000	-624.000	-624.000	-1.088
2	-624.000	-624.000	-624.000	-0.241
3	-624.000	-624.000	-624.000	-1.014
4	-624.000	-624.000	-624.000	-4.172
5	-624.000	-624.000	-624.000	-0.707

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 11
General Algebraic Modeling System
Solution Report SOLVE LAZSYS USING DNLP FROM LINE 231

EQU FLOW FLOW ON EACH LINK

	LOWER	LEVEL	UPPER	MARGINAL
6	.	.	.	-1.003
7	.	.	.	-2.000
8	.	.	.	-3.000
9	.	.	.	-3.001
10	.	.	.	-15.039
11	.	.	.	-9.000
12	.	.	.	-5.000
13	.	.	.	-7.000
14	.	.	.	-9.000
15	.	.	.	-5.000
16	.	.	.	-5.000

17	-6035.000	-6035.000	-6035.000	-3.700
18	-4250.000	-4250.000	-4250.000	-4.165
19	-4933.000	-4933.000	-4933.000	-10.719
20	-4933.000	-4933.000	-4933.000	-3.216
21	-5393.000	-5393.000	-5393.000	-28.278
22	-5174.000	-5174.000	-5174.000	-16.590
23	-4726.000	-4726.000	-4726.000	-4.594
24	-4153.000	-4153.000	-4153.000	-33.529
25	-624.000	-624.000	-624.000	-3.511
26	-624.000	-624.000	-624.000	-3.292
27	-624.000	-624.000	-624.000	-2.414
28	.	.	.	-5.000
29	-624.000	-624.000	-624.000	-0.987
30	-624.000	-624.000	-624.000	-1.756
31	-624.000	-624.000	-624.000	-1.521
32	-624.000	-624.000	-624.000	-1.756
33	-624.000	-624.000	-624.000	-0.987
34	-624.000	-624.000	-624.000	-2.414
35	-624.000	-624.000	-624.000	-1.865
36	-624.000	-624.000	-624.000	-0.219
37	-624.000	-624.000	-624.000	-1.865
38	-624.000	-624.000	-624.000	-3.292
39	-624.000	-624.000	-624.000	-0.928
40	-624.000	-624.000	-624.000	-1.325
41	-624.000	-624.000	-624.000	-1.097
42	-624.000	-624.000	-624.000	-0.928
43	-624.000	-624.000	-624.000	-1.097
44	-624.000	-624.000	-624.000	-1.865
45	-624.000	-624.000	-624.000	-0.928
46	-624.000	-624.000	-624.000	-0.535
47	-624.000	-624.000	-624.000	-0.768
48	-624.000	-624.000	-624.000	-1.865
49	-3923.000	-3923.000	-3923.000	-39.863
50	-624.000	-624.000	-624.000	-0.768
51	-6805.000	-6805.000	-6805.000	-2.747
52	-6805.000	-6805.000	-6805.000	-2.313
53	.	.	.	-5.013
54	-624.000	-624.000	-624.000	-0.435
55	.	.	.	-5.000

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 12
General Algebraic Modeling System
Solution Report SOLVE LAZSYS USING DNLP FROM LINE 231

---- EQU TRANS FLOW INTO TRANSFER LINKS

	LOWER	LEVEL	UPPER	MARGINAL
15	-INF	373.000	373.000	EPS
16	-INF	239.000	239.000	EPS
28	-INF	.	.	EPS
55	-INF	540.000	759.000	

---- EQU RAIL FLOW INTO TRAIN

	LOWER	LEVEL	UPPER	MARGINAL
10	-INF	464.000	464.000	EPS

---- VAR F FLOW ON A LINK

	LOWER	LEVEL	UPPER	MARGINAL
1	.	1164.000	+INF	.
2	.	754.000	+INF	.
3	.	1244.000	+INF	.
4	.	844.000	+INF	.
5	.	1544.000	+INF	.
6	.	2430.000	+INF	.
7	.	540.000	+INF	.
8	.	670.000	+INF	.
9	.	1290.000	+INF	.
10	.	2430.000	+INF	.
11	.	.	+INF	.
12	.	130.000	+INF	.
13	.	.	+INF	.
14	.	.	+INF	.
15	.	620.000	+INF	.
16	.	1140.000	+INF	.
17	.	6035.000	+INF	.
18	.	4250.000	+INF	.
19	.	4933.000	+INF	.
20	.	4933.000	+INF	.
21	.	5393.000	+INF	.
22	.	5174.000	+INF	.
23	.	4726.000	+INF	.
24	.	4153.000	+INF	.
25	.	624.000	+INF	.
26	.	624.000	+INF	.
27	.	624.000	+INF	.
28	.	.	+INF	.
29	.	624.000	+INF	.
30	.	624.000	+INF	.
31	.	1244.000	+INF	.
32	.	624.000	+INF	.
33	.	624.000	+INF	.
34	.	624.000	+INF	.
35	.	624.000	+INF	.
36	.	624.000	+INF	.
37	.	624.000	+INF	.
38	.	624.000	+INF	.
39	.	844.000	+INF	.
40	.	844.000	+INF	.

VAR F FLOW ON A LINK

	LOWER	LEVEL	UPPER	MARGINAL
41	.	624.000	+INF	.
42	.	844.000	+INF	.
43	.	624.000	+INF	.
44	.	624.000	+INF	.
45	.	844.000	+INF	.
46	.	1544.000	+INF	.
47	.	624.000	+INF	.
48	.	624.000	+INF	.
49	.	3923.000	+INF	.
50	.	624.000	+INF	.
51	.	6805.000	+INF	.
52	.	6805.000	+INF	.
53	.	2430.000	+INF	.
54	.	1164.000	+INF	.
55	.	540.000	+INF	.

---- VAR H FLOW ON A PATH

	LOWER	LEVEL	UPPER	MARGINAL
P1	.	.	+INF	32.964
P2	.	.	+INF	108.014
P3	.	.	+INF	41.868
P4	.	.	+INF	17.602
P5	.	.	+INF	56.671
P6	.	.	+INF	20.712
P7	.	.	+INF	3.565
P8	.	.	+INF	98.055
P9	.	.	+INF	26.095
P10	.	.	+INF	0.840
P11	.	.	+INF	3.544
P12	.	130.000	+INF	.
P13	.	.	+INF	100.726
P14	.	.	+INF	28.766
P15	.	.	+INF	6.215
P16	.	.	+INF	0.479
P17	.	.	+INF	52.870
P18	.	.	+INF	25.069
P19	.	.	+INF	EPS
P20	.	.	+INF	67.280
P21	.	.	+INF	22.551
P22	.	220.000	+INF	.
P23	.	540.000	+INF	.
P24	.	.	+INF	0.219
P25	.	620.000	+INF	.
P26	.	920.000	+INF	.

---- VAR ADDSPACE ADDITIONAL PARKING SPACES REQUIRED AT A STATION

LOWER LEVEL UPPER MARGINAL

```
15    .   247.000     +INF       .
16    .   901.000     +INF       .
28    .      .        +INF       .
55    .      .        +INF      EPS
GAMS 2.25  SUN 4/SPARC                  11/28/92 13:24:04  PAGE    14
General Algebraic Modeling System
Solution Report    SOLVE SYS USING DNLP FROM LINE 231

                     LOWER    LEVEL    UPPER    MARGINAL

---- VAR ADDSEAT              1966.000   +INF         .
---- VAR SE          -INF    3.3451E+5   +INF         .

 ADDSEAT    ADDITIONAL SEATS REQUIRED ON TRAIN
 SE         SYSTEM OBJECTIVE FUNCTION

**** REPORT SUMMARY :        0    NONOPT
                     0 INFEASIBLE
                     0 UNBOUNDED
                     0   ERRORS
GAMS 2.25  SUN 4/SPARC                  11/28/92 13:24:04  PAGE    15
General Algebraic Modeling System
Execution

----   243 PARAMETER SYSREPORT     REPORT ON SYSTEM LINK

                 1           2           3           4           5

LINKFLOW    1164.000     754.000    1244.000     844.000    1544.000
LINKTIME       0.618       0.208       0.523       1.065       0.864

     +           6           7           8           9          10

LINKFLOW    2430.000     540.000     670.000    1290.000    2430.000
LINKTIME       1.001       2.000       3.000       3.000      15.008

     +          11          12          13          14          15

LINKFLOW                 130.000                             620.000
LINKTIME       9.000       5.000       7.000       9.000       5.000

     +          16          17          18          19          20

LINKFLOW    1140.000    6035.000    4250.000    4933.000    4933.000
LINKTIME       5.000       3.060       3.953       2.944       0.883

     +          21          22          23          24          25

LINKFLOW    5393.000    5174.000    4726.000    4153.000     624.000
LINKTIME       7.176       4.358       1.319      11.266       3.262

     +          26          27          28          29          30
```

LINKFLOW	624.000	624.000		624.000	624.000
LINKTIME	3.058	2.243	5.000	0.917	1.631

+	31	32	33	34	35
LINKFLOW	1244.000	624.000	624.000	624.000	624.000
LINKTIME	0.784	1.631	0.917	2.243	1.733

+	36	37	38	39	40
LINKFLOW	624.000	624.000	624.000	844.000	844.000
LINKTIME	0.204	1.733	3.058	0.746	1.065

+	41	42	43	44	45
LINKFLOW	624.000	844.000	624.000	624.000	844.000
LINKTIME	1.019	0.746	1.019	1.733	0.746

+	46	47	48	49	50
LINKFLOW	1544.000	624.000	624.000	3923.000	624.000
LINKTIME	0.346	0.714	1.733	11.013	0.714

+	51	52	53	54	55
LINKFLOW	6805.000	6805.000	2430.000	1164.000	540.000
LINKTIME	2.069	1.743	5.003	0.247	5.000

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 16
General Algebraic Modeling System
Execution

243 PARAMETER SYSREPORT REPORT ON SYSTEM LINK

+	P1	P2	P3	P4	P5
PATHTIME	29.869	44.799	28.930	41.756	47.730
MARGINALSY	-68.543	-143.594	-77.448	-53.182	-92.250

+	P6	P7	P8	P9	P10
PATHTIME	44.858	38.629	42.150	27.358	32.787
MARGINALSY	-56.291	-39.144	-130.352	-58.392	-33.137

+	P11	P12	P13	P14	P15
PATHTIME	34.688	32.219	42.943	28.151	35.481
PATHTFLOW		130.000			
MARGINALSY	-35.841	-32.297	-132.317	-60.356	-37.806

+	P16	P17	P18	P19	P20
PATHTIME	31.534	28.968	25.168	30.875	32.754
PATHTFLOW					
MARGINALSY	-32.070	-85.640	-57.840	-32.377	-98.769

+	P21	P22	P23	P24	P25
PATHTIME	23.048	30.378	34.876	32.423	30.318
PATHTFLOW		220.000	540.000		620.000
MARGINALSY	-54.040	31.489	-35.579	-32.516	-31.591

+	P26	SYSTEM
TRUETIME		334512.417
PATHTIME	27.221	
PATHTFLOW	920.000	
MARGINALSY	-29.306	

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 17
General Algebraic Modeling System
Model Statistics SOLVE USER USING DNLP FROM LINE 247

MODEL STATISTICS

BLOCKS OF EQUATIONS 5 SINGLE EQUATIONS 66
BLOCKS OF VARIABLES 5 SINGLE VARIABLES 87
NON ZERO ELEMENTS 425 NON LINEAR N-Z 55
DERIVATIVE POOL 59 CONSTANT POOL 31
CODE LENGTH 2026

GENERATION TIME = 0.216 SECONDS

EXECUTION TIME = 0.433 SECONDS VERID SUN-00-044
GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 18
General Algebraic Modeling System
Solution Report SOLVE USER USING DNLP FROM LINE 247

SOLVE SUMMARY

MODEL USER OBJECTIVE UE
TYPE DNLP DIRECTION MINIMIZE
SOLVER MINOS5 FROM LINE 247

**** SOLVER STATUS 1 NORMAL COMPLETION
**** MODEL STATUS 2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE 237504.5677

RESOURCE USAGE, LIMIT 0.310 1000.000
ITERATION COUNT, LIMIT 9 3000
EVALUATION ERRORS 0 0

M I N O S 5.3 (Nov 1990) Ver: 225-SUN-02
= = = = =

B. A. Murtagh, University of New South Wales
and
P. E. Gill, W. Murray, M. A. Saunders and M. H. Wright
Systems Optimization Laboratory, Stanford University.

Work space allocated -- 0.08 Mb

EXIT -- OPTIMAL SOLUTION FOUND
MAJOR ITNS, LIMIT 1 200
FUNOBJ, FUNCON CALLS 24 0
SUPERBASICS 2
INTERPRETER USAGE 0.08
NORM RG / NORM PI 8.755E-09

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU OBJUE	.	.	.	1.000

OBJUE OBJECTIVE FUNCTION UNDER USER EQUILIBRIUM

---- EQU DEMAND NUMBER OF TRIPS BETWEEN ORIGIN AND DESTINATION

	LOWER	LEVEL	UPPER	MARGINAL
WEST.NEWARK	540.000	540.000	540.000	34.867
GARW.NEWARK	130.000	130.000	130.000	31.212
CRAN.NEWARK	620.000	620.000	620.000	30.310
KENL.NEWARK	220.000	220.000	220.000	27.951
ROSP.NEWARK	920.000	920.000	920.000	28,590

---- EQU FLOW FLOW ON EACH LINK

	LOWER	LEVEL	UPPER	MARGINAL
1	-624.000	-624.000	-624.000	-0.618
2	-624.000	-624.000	-624.000	-0.208
3	-624.000	-624.000	-624.000	-0.523
4	-624.000	-624.000	-624.000	-2.242
5	-624.000	-624.000	-624.000	-0.510

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 19
General Algebraic Modeling System
Solution Report SOLVE USER USING DNLP FROM LINE 247

EQU FLOW FLOW ON EACH LINK

	LOWER	LEVEL	UPPER	MARGINAL
6	.	.	.	-1.001
7	.	.	.	-2.000
8	.	.	.	-3.000
9	.	.	.	-3.000
10	.	.	.	-15.001
11	.	.	.	-9.000
12	.	.	.	-4.001
13	.	.	.	-7.000
14	.	.	.	-7.078
15	.	.	.	-5.000
16	.	.	.	-5.000

17	-6035.000	-6035.000	-6035.000	-3.062
18	-4250.000	-4250.000	-4250.000	-4.008
19	-4933.000	-4933.000	-4933.000	-3.815
20	-4933.000	-4933.000	-4933.000	-1.132
21	-5393.000	-5393.000	-5393.000	-9.212
22	-5174.000	-5174.000	-5174.000	-5.595
23	-4726.000	-4726.000	-4726.000	-1.686
24	-4153.000	-4153.000	-4153.000	-11.266
25	-624.000	-624.000	-624.000	-3.807
26	-624.000	-624.000	-624.000	-3.066
27	-624.000	-624.000	-624.000	-2.243
28	.	.	.	-5.000
29	-624.000	-624.000	-624.000	-0.917
30	-624.000	-624.000	-624.000	-1.631
31	-624.000	-624.000	-624.000	-0.784
32	-624.000	-624.000	-624.000	-1.631
33	-624.000	-624.000	-624.000	-0.937
34	-624.000	-624.000	-624.000	-2.243
35	-624.000	-624.000	-624.000	-1.733
36	-624.000	-624.000	-624.000	-0.208
37	-624.000	-624.000	-624.000	-1.770
38	-624.000	-624.000	-624.000	-3.124
39	-624.000	-624.000	-624.000	-0.781
40	-624.000	-624.000	-624.000	-1.019
41	-624.000	-624.000	-624.000	-1.019
42	-624.000	-624.000	-624.000	-0.746
43	-624.000	-624.000	-624.000	-1.019
44	-624.000	-624.000	-624.000	-1.733
45	-624.000	-624.000	-624.000	-0.714
46	-624.000	-624.000	-624.000	-0.346
47	-624.000	-624.000	-624.000	-0.823
48	-624.000	-624.000	-624.000	-1.733
49	-3923.000	-3923.000	-3923.000	-14.144
50	-624.000	-624.000	-624.000	-1.100
51	-6805.000	-6805.000	-6805.000	-2.107
52	-6805.000	-6805.000	-6805.000	-1.824
53	.	.	.	-5.000
54	-624.000	-624.000	-624.000	-0.247
55	.	.	.	-5.000

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 20
General Algebraic Modeling System
Solution Report SOLVE USER USING DNLP FROM LINE 247

---- EQU TRANS FLOW INTO TRANSFER LINKS

	LOWER	LEVEL	UPPER	MARGINAL
15	-INF	373.000	373.000	EPS
16	-INF	239.000	239.000	EPS
28	-INF	.	.	EPS
55	-INF	61.306	759.000	.

---- EQU RAIL FLOW INTO TRAIN

	LOWER	LEVEL	UPPER	MARGINAL
10	-INF	464.000	464.000	EPS

---- VAR F FLOW ON A LINK

	LOWER	LEVEL	UPPER	MARGINAL
1	.	1164.000	+INF	.
2	.	754.000	+INF	.
3	.	1244.000	+INF	.
4	.	844.000	+INF	.
5	.	1544.000	+INF	.
6	.	2430.000	+INF	.
7	.	61.306	+INF	.
8	.	61.306	+INF	.
9	.	681.306	+INF	.
10	.	1601.306	+INF	.
11	.	.	+INF	.
12	.	.	+INF	0.999
13	.	.	+INF	.
14	.	.	+INF	1.922
15	.	620.000	+INF	.
16	.	920.000	+INF	.
17	.	6055.071	+INF	.
18	.	5078.694	+INF	.
19	.	5411.694	+INF	.
20	.	5391.623	+INF	.
21	.	5851.623	+INF	.
22	.	5632.623	+INF	.
23	.	5184.623	+INF	.
24	.	4153.000	+INF	.
25	.	1102.694	+INF	.
26	.	644.071	+INF	.
27	.	624.000	+INF	.
28	.	.	+INF	.
29	.	624.000	+INF	.
30	.	624.000	+INF	.
31	.	1244.000	+INF	.
32	.	624.000	+INF	.
33	.	754.000	+INF	.
34	.	624.000	+INF	.
35	.	624.000	+INF	.
36	.	754.000	+INF	.
37	.	754.000	+INF	.
38	.	754.000	+INF	.
39	.	974.000	+INF	.
40	.	624.000	+INF	.

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 21
General Algebraic Modeling System
Solution Report SOLVE USER USING DNLP FROM LINE 247

VAR F FLOW ON A LINK

	LOWER	LEVEL	UPPER	MARGINAL
41	.	624.000	+INF	.
42	.	844.000	+INF	.
43	.	624.000	+INF	.
44	.	624.000	+INF	.
45	.	624.000	+INF	.
46	.	1544.000	+INF	.
47	.	1082.623	+INF	.
48	.	624.000	+INF	.
49	.	4293.071	+INF	.
50	.	1452.694	+INF	.
51	.	7155.000	+INF	.
52	.	7613.623	+INF	.
53	.	1601.306	+INF	.
54	.	1164.000	+INF	.
55	.	61.306	+INF	.

---- VAR H FLOW ON A PATH

	LOWER	LEVEL	UPPER	MARGINAL
P1	.	20.071	+INF	EPS
P2	.	.	+INF	18.755
P3	.	458.623	+INF	EPS
P4	.	.	+INF	8.545
P5	.	.	+INF	17.761
P6	.	.	+INF	11.647
P7	.	.	+INF	3.753
P8	.	.	+INF	18.158
P9	.	130.000	+INF	.
P10	.	.	+INF	1.608
P11	.	.	+INF	3.553
P12	.	.	+INF	.
P13	.	.	+INF	19.812
P14	.	.	+INF	1.654
P15	.	.	+INF	5.207
P16	.	.	+INF	1.216
P17	.	.	+INF	5.750
P18	.	.	+INF	1.756
P19	.	.	+INF	3.654
P20	.	.	+INF	10.101
P21	.	220.000	+INF	.
P22	.	.	+INF	3.553
P23	.	61.306	+INF	.
P24	.	.	+INF	1.207
P25	.	620.000	+INF	.
P26	.	920.000	+INF	.

---- VAR ADDSPACE ADDITIONAL PARKING SPACES REQUIRED AT A STATION

```
   LOWER    LEVEL    UPPER   MARGINAL

15    .        247.000    +INF         .
16    .        681.000    +INF         .
28    .            .      +INF         .
55    .            .      +INF        EPS
GAMS 2.25  SUN 4/SPARC                 11/28/92 13:24:04  PAGE    22
General Algebraic Modeling System
Solution Report    SOLVE USER USING DNLP FROM LINE 247

                     LOWER    LEVEL    UPPER   MARGINAL

---- VAR ADDSEAT       .     1137.306    +INF         .
---- VAR UE          -INF    2.3750E+5   +INF         .

 ADDSEAT   ADDITIONAL SEATS REQUIRED ON TRAIN
 UE        USER OBJECTIVE FUNCTION

**** REPORT SUMMARY :       0    NONOPT
                     0 INFEASIBLE
                     0  UNBOUNDED
                     0    ERRORS
GAMS 2.25  SUN 4/SPARC                 11/28/92 13:24:04  PAGE    23
General Algebraic Modeling System
Execution

----   257 PARAMETER USEREPORT    REPORT ON user LINK

                  1          2          3          4          5

LINKFLOW    1164.000    754.000   1244.000    844.000   1544.000
LINKTIME       0.618      0.208      0.523      1.065      0.864

      +           6          7          8          9         10

LINKFLOW    2430.000     61.306     61.306    681.306   1601.306
LINKTIME       1.001      2.000      3.000      3.000     15.001

      +          11         12         13         14         15

LINKFLOW                                                  620.000
LINKTIME       9.000      5.000      7.000      9.000      5.000

      +          16         17         18         19         20

LINKFLOW     920.000   6055.071   5078.694   5411.694   5391.623
LINKTIME       5.000      3.062      4.008      3.815      1.132

      +          21         22         23         24         25

LINKFLOW    5851.623   5632.623   5184.623   4153.000   1102.694
LINKTIME       9.212      5.595      1.686     11.266      3.807

      +          26         27         28         29         30
```

LINKFLOW	644.071	624.000		624.000	624.000
LINKTIME	3.066	2.243	5.000	0.917	1.631

+	31	32	33	34	35
35					
LINKFLOW	1244.000	624.000	754.000	624.000	624.000
LINKTIME	0.784	1.631	0.937	2.243	1.733

+	36	37	38	39	40
LINKFLOW	754.000	754.000	754.000	974.000	624.000
LINKTIME	0.208	1.770	3.124	0.781	1.019

+	41	42	43	44	45
LINKFLOW	624.000	844.000	624.000	624.000	624.000
LINKTIME	1.019	0.746	1.019	1.733	0.714

+	46	47	48	49	50
LINKFLOW	1544.000	1082.623	624.000	4293.071	1452.694
LINKTIME	0.346	0.823	1.733	14.144	1.100

+	51	52	53	54	55
LINKFLOW	7155.000	7613.623	1601.306	1164.000	61.306
LINKTIME	2.107	1.824	5.000	0.247	5.000

GAMS 2.25 SUN 4/SPARC 11/28/92 13:24:04 PAGE 24
General Algebraic Modeling System
Execution

257 PARAMETER USEREPORT REPORT ON user LINK

+	P1	P2	P3	P4	P5
PATHTIME	34.867	53.622	34.867	43.413	52.629
PATHTFLOW	20.071		458.623		
MARGINALUS	-34.867	-53.622	-34.867	-43.413	-52.629

+	P6	P7	P8	P9	P10
PATHTIME	46.515	38.620	49.371	31.212	32.821
PATHTFLOW				130.000	
MARGINALUS	-46.515	-38.620	-49.371	-31.212	-32.821

+	P11	P12	P13	P14	P15
PATHTIME	34.765	32.211	50.122	31.963	35.516
MARGINALUS	-34.765	-31.212	-50.122	-31.963	-35.516

+	P16	P17	P18	P19	P20
PATHTIME	31.525	32.962	28.969	30.867	36.876

MARGINALUS	-31.525	-32.962	-28.969	-30.867	-36.876

+	P21	P22	P23	P24	P25
PATHTIME	26.774	30.327	34.867	32.419	30.310
PATHTFLOW	220.000		61.306		620.000
MARGINALUS	-26.774	-30.327	-34.867	-32.419	-30.310

+	P26	USER
TRUETIME		372263.933
PATHTIME	27.213	
PATHTFLOW	920.000	
MARGINALUS	-27.213	

EXECUTION TIME = 0.200 SECONDS VERID SUN-00-044

USER: Dr. L.N. Spasovic S920608-1928AX-SUN
NJIT, School of Industrial Management

**** FILE SUMMARY

INPUT /home/users/lazar/case1.gms
OUTPUT /home/users/lazar/case1.lst

BIBLIOGRAPHY

Aashtiani, H.Z., and T.L. Magnanti. "Equilibria on a Transportation Network." *Algebraic Discrete Methods* 4 (1981): 213-216.

Abdulaal, M., and M.J. Leblanc. "Methods for Combining Modal Split and Equilibrium Assignment Models." *Transportation Science* 13 (1979): 292-314.

Beckman, H.M., C.B. McGuire, and C.B. Winsten. "Studies in the Economies of Transportation." Yale University Press (1956).

Brooke, A., D. Kendrick, and A. Meeraus. "GAMS A User's Guide." The Scientific Press (1988).

Dafermos, S.C. "The General Multimodal Network Equilibrium Problem with Elastic Demand." *Networks* 12 (1982): 57-72.

Florian, M. "A Traffic Equilibrium Model of Travel by Car and Public Transit Modes." *Transportation Science* 8 (1977): 166-179.

Florian, M., and M. Los. "Determining Intermediate Origin-Destination Matrices for the Analysis of Composite Mode Trips." *Transportation Research* 13-B (1979): 91-103.

Florian, M. and, H. Spiess. "On Binary Mode Choice/Assignment Models." *Transportation Science* 17-1 (1983): 32-47.

Jewell, W.S. "Optimal Flows Through Networks with Gains." *Operations Research.* 10 (1962): 476-499.

Morlok, E.K. "Introduction to Transportation Planning and Engineering." McGraw Hill (1978).

Rillet, Aerde and, Macinnon. "Simulating the TravTek Route Guidance Logic Using the Integration Traffic Model." Vehicle Navigation and Information Systems Conference Proceedings (1991).

Transportation Research Board. "Highway Capacity Manual." Special Report 209 (1985).

U.S. Bureau of Public Roads. "Traffic Assignment Manual." U.S. Department of Commerce (1964).

Vollmer Associates. "Garden State Parkway Comprehensive Traffic Study." (1987).

Wardrop, J.G. "Some Theoretical Aspects of Road Traffic Research." Proceedings Institute of Civil Engineers Part II,(1952).