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16. Abstract

A major goal of transportation planning activities targeted at reducing total automotive fuel consumption has been to attract tripmakers to use public transit to meet more of their travel and mobility needs. Bus transit networks in the U.S. have traditionally been geared to serve centralized core-area land use patterns, at the same time that these cities have become increasingly decentralized. Because of lower suburban and exurban densities, it has been difficult to provide levels of transit service that provide a meaningful alternative to the private automobile. However, increasing densification of the suburbs and the emergence of major activity nuclei outside the CBD opens opportunities for creative approaches to the supply of transit services.

The aim of this project is to develop and test computer-based design procedures for the configuration of bus route networks in areas characterized by suburban spatial patterns, so as to maximize ridership capture and serve mobility needs in a cost-effective and energy efficient manner. The methodology incorporates three service dimensions that have heretofore been left out of systematic design procedures: route coordination, variable vehicle size and demand-responsive service. All three dimensions are particularly important in the design of transit service networks for areas encompassing significant suburban and exurban spatial development patterns.

The solution approach consists of four components. A route generation procedure constructs sets of bus routes corresponding to different service concepts and trade-offs between users and operators. A network evaluation procedure determines route frequencies and vehicle sizes and computes a variety of system performance measures reflecting user and operator costs. A transit center selection procedure identifies the set of transit centers to support the implementation of timed-transfer design and demand responsive service. A network improvement procedure applies modifications to the set of routes generated by the route generation procedure to improve performance in terms of the user's and operator's perspectives. The solution approach is tested with a benchmark problem and with data generated from the transit system of Austin, Texas.

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A DESIGN METHODOLOGY FOR BUS TRANSIT NETWORKS WITH COORDINATED OPERATIONS

by

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SWUTC/94/60016-1

OPTIMAL DESIGN OF BUS TRANSIT NETWORKS FOR SUBURBAN MOBILITY NEEDS
CONCEPTUAL FRAMEWORK AND MODEL DEVELOPMENT
Research Project 60016

conducted for the

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ABSTRACT

Previous approaches to bus transit network design focused on conventional service concepts that provide fixed-route, fixed schedule, and uncoordinated systems, with the same vehicle size on all routes. As spatial trip patterns in most U.S. cities continue to evolve from a multiple origin, single destination pattern to a multiple origin, multiple destination pattern, conventional service concepts are no longer adequate to serve these new trip patterns. This report presents a network design methodology that incorporates three additional service design dimensions: route coordination, variable vehicle size, and demand responsive service, to better meet user needs and desired service levels.

The complex formulation and the combinatorial nature of the transit network design problem preclude solution by exact optimization models. A hybrid heuristic approach that relies on AI heuristics and search techniques and incorporates domain-specific human knowledge and expertise is developed. The overall approach has evolved from a design methodology developed by Baaj and Mahmassani at the University of Texas at Austin for conventional transit systems. The solution approach incorporates a trip assignment model explicitly for time-transfer (coordinated) transit systems, a frequency setting and vehicle sizing model, and a demand responsive service procedure for the integration of fixed route and fixed schedule service with demand responsive service.

The solution approach consists of four components. A route generation procedure constructs sets of bus routes corresponding to different service concepts and trade-offs between users and operators. A network evaluation procedure determines route frequencies and vehicle sizes and computes a variety of system performance measures reflecting user and operator costs. A transit center selection procedure identifies the set of transit centers to support the implementation of time-transfer design and demand responsive service. A network improvement procedure applies modifications to the set of routes generated by the route generation procedure to improve performance in terms of the user's and operator's perspectives. The solution approach is tested with a benchmark problem and with data generated from the transit systems of Austin, Texas.

EXECUTIVE SUMMARY

Traditional bus systems, which provide primarily fixed-route, fixed-schedule and uncoordinated service, has been targeted at serving centralized core-oriented land use patterns. Over the past few decades, most U.S. cities have experienced continued spatial redistribution of commercial development and population growth, with major peripheral commercial centers becoming significant activity nodes outside of the traditional CBD. Population in most U.S. cities has been growing much more rapidly in suburbs than in central cores. The resulting land use pattern has transformed the associated spatial trip pattern from a multiple-origin, single-destination pattern for a multiple-origin and multiple-destination one, evidenced in metropolitan areas like Houston and Dallas-Fort Worth.

Existing bus service systems that have resulted from successive incremental modifications to the traditional network are neither effective nor efficient at serving the new spatial trip patterns often resulting in user frustration and low ridership levels. While transit authorities have generally recognized the problem, scientific tools and systematic procedures have not been available to adequately support and facilitate attempts at major system redesign and re-engineering.

In particular, previous approaches and procedures have not been successful at incorporating alternative service concepts that are particularly suitable for spatially dispensed demand patterns, such as coordinated operation systems (e.g., time transfer systems), variable vehicle sizes (to better match areas with lower ridership levels) and demand responsive service offered in an integrated and complementary manner with conventional fixed-route service.

This report describes a systematic network design methodology that addresses the above needs for a flexible approach that integrates the service concepts that have been shown to work in lower density areas within an overall network of bus routes. Coordinated time-transfer service allows greater coverage with limited equipment through expanded transfer capabilities with little wait time at "hubs" with coordinated arrivals of buses from different routes. Variable bus sizes allows greater flexibility in frequency resulting and in serving a variety of demand levels in different markets. Demand-responsive service attempts to combine real-time operation with planned service in very low ridership areas.

The solution approach consists of four algorithmic procedures. The route generation procedure (RGP) constructs sets of bus routes for designs with or without the transit center concept. The network evaluation procedure (NETAP) determines route service frequencies and vehicle sizes and evaluates transit systems for both coordinated and uncoordinated designs. The transit center selection procedure (TCSP) identifies candidate sets of transit centers when the

network is to be configured around the transit center concept. The network improvement procedures (NIP) applies modifications to the set of routes generated by the RGP to improve performance from the user's or operator's perspective.

Numerical experiments were performed to test the solution approach on a benchmark problem. The results showed that networks generated by the RGP around the transit center concept outperformed the solutions of Mandl's and Baaj and Mahmassani's algorithm. Numerical experiments on data for the transit system of Austin, Texas, were also performed to test the design procedures and investigate the performance of alternative design. The TCSP was tested based on two application strategies and six selected combinations of demand satisfaction levels. The tests indicated that the TCSP generated consistent results in all study cases. Transit centers generated from the TCSP were either major activity centers or transit nodes within major communities in the suburban areas. The RGP and NETAP were tested using four design alternatives under six combinations of demand satisfaction levels. The tests compared the performance of coordinated vs. uncoordinated networks. The tests also investigated the performance of networks with the variable vehicle sizes vs. fixed vehicle size. The numerical results showed that 1) the coordinated design resulted in better demand satisfaction levels, total out-of-vehicle waiting time, and total system cost, but worse total in-vehicle travel time and total travel time because additional in-vehicle waiting time was generated by the route coordination, 2) designs of variable vehicle sizes greatly reduced the total system cost, fuel consumption, and out-of-vehicle waiting time, but increased the operation cost. Two possible NIP modifications were tested. The procedure that splits routes at transit centers reduced the required operational resources, but the levels of demand satisfaction were decreased. The demand responsive service procedure resulted in significant savings of operating resources and much lower reductions in the level of demand satisfaction compared to outright route discontinuation.

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CHAPTER 1.   INTRODUCTION

PROBLEM DESCRIPTION AND MOTIVATION

The significance of public transportation is revealed in several aspects. In addition to providing mobility to people who have no other options (e.g. people who do not own a car, cannot afford to drive, or are physically unable to drive), public transportation offers travel alternatives to those who might use transit for the reasons of cost, speed, comfort, convenience, traffic avoidance, or environmental principle. Public transit has been recognized as part of the solution to the growing vehicular traffic congestion problem on overloaded urban transportation systems. Increased reliance on public transit systems has been advocated as an efficient way of lowering energy consumption and reducing air pollution.

Among all transit modes, bus transit is the dominant form in American cities. As indicated in the Transit Fact Book (1991), more than 65% of the 8.9 billion annual transit trips in the US were bus trips. Buses account for almost 50% of the 41.5 billion annual transit passenger miles. In addition, there are about 2,700 bus systems in the US, of which more than one-fourth are in urbanized areas of less than 50,000 people.

The process of developing a bus service plan consists of five stages: network design, frequency setting, timetable development, bus scheduling and driver scheduling (Ceder and Wilson, 1986). The bulk of past research effort has been concentrated on bus scheduling and driver scheduling. This is understandable because these two activities are directly reflected in the operating cost and are readily amenable to computer-based procedures. However, the two most fundamental elements, namely, the design of bus routes and setting of frequencies, which critically determine the system's performance from both the operator's and users' point of view, have not been sufficiently investigated because of their inherent complexity and implementation difficulty.

Baaj (1990) pointed out five main sources of complexity that preclude finding a unique optimal solution for the transit network design problem: difficulty of formulating the problem; non-linearity and non-convexity of the mathematical formulation; inherent combinatorial complexity of the problem; multi-objective nature of the problem; and spatial layout of routes. Although decision variables such as frequency, vehicle size, and route space can be expressed in the problem formulation, the number of routes and their nodal composition are difficult to define. In addition, transit trip assignment, used to determine route demands for a bus system, cannot be expressed in a well-behaved mathematical formulation. Due to the discrete nature of the route selection problem, the choice of routes is generally a non-convex optimization problem (or an

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integer programming problem), and the selection of an optimal route structure is an NP-hard combinatorial problem (Newell, 1979). Most approaches for the transit network design problem consider operator cost and/or user cost as their objectives. In practice, service coverage, service directness, and other conflicting objectives are examined in the design process. This implies that conflicting objectives need to be addressed. Finding acceptable and good spatial layout of routes should satisfy important criteria such as route coverage, route duplication, route length, and directness of route. All the above factors contribute to the difficulty of solving the transit network design problem.

Traditional bus systems have been targeted to serve centralized core-oriented land use patterns. These bus systems provide fixed-route, fixed-schedule, and uncoordinated service, and are either radial- or grid-like. Most of the current bus transit systems in the US have evolved largely from the traditional systems, and their networks have been carried over from old streetcar operation. Expansion or deletion of elements of the bus network are highly dependent on the transit planners' judgment, experience, and knowledge of the existing land use patterns, demand patterns, service requirements, and resource constraints.

In recent years, most U.S. cities have experienced spatial redistribution of commercial development and population growth. Capitalizing on lower land values and ability to avoid traffic congestion in the downtown area, major peripheral commercial centers have been developed outside the central business district. In the same manner, population in most U.S. cities has been growing much faster in suburbs than in central cores. The resulting land use pattern of increasingly decentralized cities has transformed the associated spatial trip pattern from a multiple origin, single destination pattern to a multiple origin, multiple destination one, evidenced in metropolitan areas like Houston or Dallas-Fort Worth.

Existing bus service plans that have resulted from successive incremental modifications to the traditional network are neither effective nor efficient at serving the new spatial trip patterns, and often result in user frustration, and consequently low ridership. A nationwide survey showed that only two percent of all suburban employees commute to work by bus (Cervero, 1986). The failure to provide meaningful alternatives to the private automobile in most cities has resulted in heavy reliance on the private automobile as the only available means of mobility. The consequences are intensified traffic congestion, wasteful fuel consumption, and magnified air pollution. Some transit authorities have recognized the existing problem. However, attempts at major reevaluation and redesign have not been supported and guided by scientific tools or systematic procedures.

Previous approaches for the transit network design problem have focused on the design of

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conventional bus service, which provides fixed-route, fixed-schedule, and uncoordinated route service. Such service is no longer adequate to serve cities with a multi-centered and spatially dispersed trip pattern. Alternative design concepts, especially coordinated route service, demand responsive service, and variable vehicle sizes, have been proposed and implemented in several cities in North America and Europe with some encouraging results. The need for innovative modeling concepts to design bus transit networks is thus apparent.

The principal problem addressed in this study is how to redesign a bus transit network around a different service philosophy that recognizes the changing nature of the land use and associated travel activities. The intent is to design a bus route network and service plan that provides cost-effective quality public transportation (in terms of frequency, directness, comfort, and coverage) under the consideration of resource availability.

STUDY OBJECTIVES

The goal of the proposed work is to develop computer-based design procedures which incorporate alternative design concepts to provide good solutions to the bus transit network design problems encountered by the transit industry today. Reaching this goal entails fulfilling the following objectives:

1) To identify superior transit network designs and service planning options for the type of spatial trip pattern that prevails in most North American cities.

2) To develop and test a set of algorithmic design procedures which incorporate current practice and existing rules-of-thumb with regard to bus network design, to account for the above options.

3) To incorporate the capability to evaluate performance from both passenger and operator perspectives for various service options. In other words, the transit network evaluation model should possess the capability to determine various system performance measures which explicitly recognize the multi-objective nature of the transit network design problem.

4) To perform systematic assessments of alternative service design concepts and of the associated trade-offs in order to ascertain the conditions that determine their success.

The complex formulation and the combinatorial nature of the transit network design problem preclude solutions by exact optimization models. Baaj and Mahmassani (1991) developed a hybrid solution approach that included the following major features: 1) AI-based heuristic procedures for transit route generation and improvement, 2) a transit network evaluation model to analyze transit system performance in consideration of the multi-objective nature of transit

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network design, and 3) the use of domain-specific knowledge reflecting current practice and existing rules of thumb concerning design issues. Their model is applicable to design of conventional fixed-route, fixed-schedule, uncoordinated bus systems with the same vehicle size on all routes.

In this report, the above hybrid heuristic approach is extended and further developed to provide alternative design concepts and features oriented towards the kind of land use and transit demand patterns found in most U.S. cities. These design concepts include conventional systems with fixed-route, fixed-schedule, and uncoordinated route service; timed-transfer systems with coordinated route service; and integrated systems with conventional service for high demand areas and demand responsive service for low density areas. In addition, a variable bus size option is available with the above design concepts. Four algorithmic procedures are developed to provide these design features, namely, the route generation procedure, the network analysis procedure, the transit center selection procedure, and the network improvement procedure.

This solution approach differs from existing approaches, including Baaj and Mahmassani's, in the following meaningful aspects:

1) Ability to identify transit centers. The transit center selection procedure incorporates criteria reflecting land use pattern, transit demand, service coverage, and transfer opportunity at transit centers.

2) A route network that is heavily guided by the demand matrix, and configured with the transit center concept. The route generation procedure produces route networks that serve the demand pattern and provide good transfer opportunities at transit centers, as well as fast and direct service between transit centers.

3) Provision of alternative design concepts including conventional, coordinated, and integrated bus systems. The timed-transfer concept is intended to reduce the negative impact of transfers. Demand responsive service provides more effective service to low demand density areas than conventional fixed-route, fixed-schedule service.

4) Ability to evaluate coordinated bus operations. The network evaluation procedure assigns trips for both coordinated and uncoordinated transit systems.

5) Variable vehicle size option, which provides an additional choice dimension in designing the service configuration to better meet user needs and desired service levels.

6) A route splitting modification for coordinated systems to improve resource effectiveness.

In addition, the solution approach provides a framework to incorporate applicable service planning guidelines as well as knowledge and expertise of transit planners. Consequently, acceptable and

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operationally implementable route networks and service plans are designed.

OVERVIEW

In this chapter, the significance of transit network design in the context of transit planning activities has been described, and the study's objectives and general approach have been defined accordingly.

In Chapter 2, an in-depth background review of the transit network design problem is presented together with innovative concepts and practical guidelines for the design of bus networks and the provision of bus service. Previous approaches to the transit network problem are reviewed with regard to seven distinguishing features: objective function, demand, constraints, passenger behavior, solution techniques, decision variables, and service types. Shortcomings of these approaches are discussed as well.

Chapter 3 presents the solution framework which consists of four main procedures: the route generation procedure, the network analysis procedure, the transit center selection procedure, and network improvement procedures. An overview of these four procedures is presented. The design features that are provided by the solution approach are described as well. In addition, the motivation for implementing the procedure in the LISP computer language, intended primarily for artificial intelligence applications, is described.

Chapter 4 presents the details of the route generation procedure (RGP). It describes three main components, including the formation of initial skeletons, the expansion of skeletons to complete routes, and the termination of the RGP. Required input information for executing the RGP is described as well as the RGP's important features which ensure the generation of quality route networks.

Chapter 5 covers the network analysis procedure (NETAP). The NETAP is used to evaluate alternative bus network and service plans; it is also utilized to determine route frequencies and vehicle sizes for a given route network. The required input information for the execution of the NETAP are described as well as the resulting output that includes a variety of performance measures. The details of two main components of the NETAP, namely the trip assignment procedure and the frequency setting and bus sizing procedure are presented in detail. The chapter concludes with an illustrative application to the Austin transit network.

Chapter 6 presents the transit center selection procedure (TCSP) and network improvement procedures (NIP). The TCSP identifies suitable transit centers for the design of coordinated timed-transfer systems and the implementation of demand responsive service. The TCSP incorporates guidelines commonly used in the transit industry to select transit centers. The NIP

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improves the set of routes generated by the RGP via several possible modifications including discontinuation of service on low ridership routes, joining of routes, splitting of routes, branch exchange of routes, splitting of routes at transit centers, and implementation of demand responsive service.

Chapter 7 focuses on testing the design procedures and different design alternatives provided by the solution framework. Tests are conducted on an existing benchmark problem and on data generated from the transit network of Austin, Texas. Results of the different tests are presented and analyzed. Chapter 8 presents the conclusions from the research results and discusses directions for future research.

CHAPTER 2. LITERATURE REVIEW

Previous solution approaches to the bus transit network design problem can be categorized into optimization formulations that deal primarily with idealized situations, and heuristic algorithms for more realistic problems. In the subsequent sections, both types of approaches are reviewed. In addition, innovative practices that produce satisfactory solutions and practical guidelines that reflect operational feasibility are identified in relation to this study.

OPTIMIZATION FORMULATIONS

Existing optimization formulations of the transit network design problem are concerned primarily with the minimization of a generalized cost measure, usually a combination of user costs and operator costs. In most studies, user costs consist of access cost, waiting time cost, and in-vehicle travel time cost; operator cost is estimated by total vehicle operating miles or time. Feasibility constraints may include, but are not limited to 1) minimum operating frequencies on all or selected routes, 2) a maximum load factor on bus routes, and 3) maximum available resources (fleet size or capital).

Due to the sources of complexity of the transit network design problem described in the previous chapter, optimization methods were only applied to determine one or several design parameters (e.g. route spacing, route length, stop spacing, bus size, and headway) on a predetermined route structure, rather than determine both the route structure and design parameters simultaneously. Examples of optimization approaches include the work of Oldfield and Bly (1988), LeBlanc (1988), and Chang (1990). Consequently, heuristic approaches that do not guarantee a global optimal solution have been proposed to solve the transit network design problem.

HEURISTIC APPROACHES

Heuristic approaches include those of Lampkin and Saalmans (1967), Rea (1971), Silman, et al. (1974), Mandl (1979), Dubois, et al. (1979), Hasselstrom (1981), Ceder and Wilson (1986), Van Nes, et al. (1988), Baaj (1990), and Israeli and Ceder (1991). A thorough review of previous approaches to the bus network design problem has been conducted by Baaj. His review identifies five distinguishing features that characterize these approaches: objective function, demand, constraints, passenger behavior, and solution techniques. In this study, two additional features are included: decision variables and service type. In the following synthesis, each of the seven features is discussed individually by comparing the previous heuristic approaches and defining the most appropriate feature for the transit network design problem.

Objective Function

Most previous approaches seek to minimize generalized cost (user cost and/or operator cost)). Hasselstrom proposed maximizing consumer surplus to cope with variable demand, while Van Nes et al. maximize the number of direct trips. Instead of specifying an objective function, Rea's model seeks a solution which meets certain operator-specified performance levels. Baaj points out the importance of addressing the multi-objective nature of the transit network design problem. In Baaj's model, the total demand satisfied and its components (the total demand satisfied directly, via one transfer, via two transfer, or unsatisfied) are examined against the total travel time and its components (the total travel time that is in-vehicle, waiting, or transferring), as well as against the fleet size required to operate the system (as a proxy measure for operator cost). Israeli and Ceder consider the minimization of generalized cost and fleet size in their two objective formulation.

Demand

Demand is an essential element for transit network design. In previous approaches, except Dubois et al., Hasselstrom, and Van Nes et al., demand is assumed fixed and independent of service quality. Dubois et al. use a diversion curve based on expected travel times to estimate the public transport share from the total trip matrix. In Hasselstrom's model, a direct model is used to estimate a demand matrix for both high quality service throughout the area and less than ideal service between some origin-destination pairs. Van Nes et al. employ a direct demand model based on the simultaneous distribution-modal split model. Conceptually, the variable demand assumption is more appealing. However, the questionable accuracy of existing demand models and the added complexity of using variable demand models make the fixed demand formulation more useful practically.

Constraints

Constraints on the total operator cost, fleet size and service frequency are common to several previous approaches. Total operator cost and fleet size constraints are thought to be interchangeable since the operating cost is highly correlated with the required vehicle-miles and vehicle-hours of operation, and the number of vehicles that are needed in the service is also directly affected by the required vehicle-miles and vehicle-hours of operation. A minimum frequency is applied to provide meaningful bus service. Instead of generating real numbers for bus frequencies, Van Nes et al. use a set of possible integer-valued frequencies. The use of fleet size and service frequency constraints requires that bus allocation and frequency setting sub problems be solved simultaneously with the transit network design problem. Baaj has

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successfully implemented other service-related constraints that include the route round trip time, the directness of routes as measured by a circuity factor, load standard, and the route ridership volume. These constraints are crucial to providing quality transit service.

Passenger Behavior

Passenger behavior is reflected in the transit trip assignment formulation assumed in a particular approach. As Ceder and Wilson noted, previous transit trip assignment models can be divided into two groups, namely, single path assignment and multiple path assignment. Rea and Mandl follow single path assignment of all passengers to the least weighted cost path. All other approaches utilize multiple path assignment models that first define a set of acceptable paths, and then assign a proportion of passengers to each acceptable path equivalent to the probability that the first bus to arrive serves that path. The difference in these multiple path assignment models is the definition of path acceptability. Multiple path assignment is thought to be more appropriate for transit trips because it accounts for the waiting phenomenon at transit terminals with multiple acceptable routes.

Solution Techniques

To overcome the complexity of transit network design, most previous approaches partition the problem into two parts, route construction and frequency setting. Mandl and Baaj add a route improvement procedure to improve the initial network. Most other approaches, except those of Hasselstrom and Van Nes et al., determine route structure and assign frequencies separately by first obtaining an initial reasonable route network, and then applying mathematical formulations to solve for route frequencies. The models of Lampkin and Saalmans, Silman et al., Dubois et al., and Baaj all use a route generation procedure that starts from initial route skeletons generated by candidate nodes. Among them, Baaj's model considers demand as the criterion for selecting the initial skeletons. Additional nodes are added to these skeletons by following given insertion criteria to form complete routes. Silman et al. generate many more routes than will actually be operated, and rely on the frequency allocation procedure to define the route network. The models of Mandl and of Rea both focus on the acceptability of links that are then aggregated to form routes. Israeli and Ceder enumerate all possible routes from preset termini and apply a route length constraint to eliminate routes with travel time, between each origin-destination (O-D) pair, exceeding the least-time path by a given threshold.

Hasselstrom uses a complex two-level optimization model which first reduces the network by eliminating links that are seldom or never used by passengers. A large set of possible routes is then generated from the remaining links. Finally, the network routes are selected by assigning

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frequencies using a linear programming model which maximizes the number of transfers saved by changing from a link network (transfers at every node) to a public transit network (transfers only at intersections). Van Nes et al. assign frequencies to a pre-selected set of possible routes and increase the frequency on the route with the highest efficiency ratio, defined as the ratio of the number of extra passengers as a result of the increase to the associated cost of the increase. They point out that the ratio can be regarded as an estimate of the Lagrange multiplier of the optimization formulation which maximizes the number of direct trips with a given fleet size.

Decision Variables

All previous approaches except Mandl's consider route and frequency as their decision variables. Mandl assumes a constant frequency on all bus routes. Although this assumption simplifies the network design problem, using the same frequency on all bus routes is unrealistic. All other approaches fix the vehicle size, and use frequency as the only variable in the resource allocation process. In the transit industry, different vehicle sizes have been implemented on routes having different passenger volumes or providing different types of services. It is desirable to treat vehicle size as a decision variable in the design procedure.

Service Types

All previous approaches have focused on conventional transit service, which provides fixed-route, fixed-schedule, and uncoordinated-route service. Such service is suitable for areas with high demand density and single-centered trip patterns, but is ineffective in serving areas with low demand density and multiple-centered trip patterns. Other service types, especially those that can better serve low demand density areas (e.g. timed-transfer systems and demand responsive bus services) should be identified and incorporated in the overall bus network design.

Of the models discussed earlier, Baaj's model is presented in more detail for the following reasons:

1) Baaj's route generation procedure is highly responsive to the transit demand matrix.

2) The model effectively incorporates practical guidelines such as route length, frequency, route duplication, route directness, and load standard.

3) The model will provide a benchmark to the solutions resulting from this study.

4) The overall approach of this study has evolved from and extends Baaj's model.

Baaj (1990)

Baaj's approach consists of three parts. The first part is a route generation algorithm (RGA) which generates sets of good routes that correspond to different trade-offs between user cost

and operator cost. The second part is a transit route analysis procedure (TRUST) to evaluate a given transit network and set route frequencies for a new transit network design. The last part is the route improvement algorithm (RGA) which improves the initially generated sets of routes.

1. RGA starts by selecting high demand node pairs to form the initial set of skeletons. The skeleton of each node pair consists of either the shortest path connecting the corresponding node pair or an alternate path between them. The alternate path for a given node pair satisfies two criteria: (1) it should not be too long; and (2) its nodal composition should be substantially different from that of the shortest path. Among all acceptable paths, one may select either the path covering more network nodes or the shortest path. Each skeleton is then expanded by inserting the set of feasible nodes. These feasible nodes need to satisfy the following six conditions:

   1) Nodes do not belong to the route under expansion.

   2) Nodes still have a high percentage of their total originating demand left unsatisfied after insertion in other routes.

   3) The resulting route does not become circuitous.

   4) The ratio of the contributed demand satisfied per insertion cost exceeds a minimum demand per insertion cost value.

   5) The required frequency of service on the resulting route does not exceed the maximum operationally implementable value.

   6) The length of the resulting route does not exceed a maximum allowable value.

The route generation algorithm continues to generate routes until both the total demand satisfied and the total demand satisfied directly exceed the user specified levels.

2. TRUST performs the passenger trip assignment and the frequency setting after the set of routes is generated. The given demands between origin-destination pairs of the generated network are first assigned based on assumed initial frequencies of service on all routes . The frequency required on each route to maintain the load factor under a user pre specified maximum is then computed. If the resulting frequencies are significantly different from the initial values, TRUST reiterates with the output frequencies as the input frequencies until they converge to the same values.

3. RIA makes the following modifications to improve the set of initially generated routes so as to obtain feasible and implementable route networks.

   1) Discontinue low ridership and/or short routes.

   2) Merge low ridership and/or short routes with other routes if they can be merged.

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3) Split routes with one-way in-vehicle travel time exceeding one hour into two routes.

4) Apply a branch exchange heuristic to form a new combination of routes so as to reduce the number of transfers.

Table 2.1 summarizes all previous solution approaches discussed in this section.

INNOVATIVE PRACTICES AND PRACTICAL GUIDELINES

Transit Center Concepts

Several communities around the US, Canada, and Europe have proposed and implemented some promising approaches which provide suitable service to multi-nucleated metropolises with extensive suburban development. Most of these approaches revolve around the concept of transit centers, consisting of major community retail and/or employment centers, that function as effective hubs around which operations are structured. These centers are served by feeder bus or by paratransit, usually some form of demand responsive operation that accomplishes a regional collection-distribution function, as well as by trunk or main lines that interconnect the various centers. Schneider and Smith (1981) suggested general guidelines for the selection of such potential centers which include transit demand, area geometry, accessibility, and network structure. Their concepts have been implemented in the Seattle, Washington, area with positive results. The hubbing approach is also seen in many other cities such as Orange County, California; San Diego, California; Eugene, Oregon; Vancouver, Canada; and London, England.

Timed-Transfer Coordinated Route Service

The major disadvantage of the hubbing approach is that it might require passengers to transfer in order to complete their trips. To minimize the negative effect of transfer on ridership, the concept of timed-transfer, whereby bus schedules are coordinated at transit centers to provide for almost simultaneous (typically within a time window of 2 to 5 minutes) arrival of transit vehicles from different routes, has been proposed to reduce the transfer waiting time. To ensure synchronization, all routes must operate on the same or multiple integer headways. Accurate schedule and fairly reliable service are needed to insure the operational success of timed-transfers. Several existing transit systems have implemented the timed-transfer concept. The commonly given example of a successful North-American system is in Edmonton, Alberta (Canada). In the US, Portland, Oregon, has also introduced the timed-transfer concept at a few suburban transit centers with generally positive results (Tri-County MTD, 1982).

Although timed-transfers can reduce the waiting time incurred by transferring users, the potentially significant negative impact on existing ridership cannot be eliminated when systems

Year	Author	Objectives	Demand	Trip Assignment	Decision Variables	Solution Techniques	Service Type
1967	Lampkin and Saalmans	Generalized time	Fixed	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1972	Rea	*	Fixed	Single	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1974	Silman, Barzily, and Passy	Generalized cost	Fixed	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1976	Mandl	Generalized time	Fixed	Single	Route	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1979	Dubois, Bell, and Llibre	Generalized time	Fixed	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1981	Hasselstrom	Consumer surplus	Variable	Multiple	Route and frequency	Simultaneous	Fixed-route, fixed-schedule and uncoordinated-route
1986	Ceder and Wilson**	Generalized time	Fixed	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1988	Van Nes, Immers, and Hamerslag	Number of direct trips	Variable	Multiple	Route and frequency	Simultaneous	Fixed-route, fixed-schedule and uncoordinated-route
1990	Baaj	***	Fixed	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route
1991	Israeli Wilson	Generalized time, and fleet size	Variable	Multiple	Route and frequency	Sequential	Fixed-route, fixed-schedule and uncoordinated-route

*: No explicit objective function, but generated solutions meet certain operator specified performance levels
**: Problem formulation only
***: Multi-objective approach , generates solutions reflecting trade-offs among objectives

Table 2.1 Summary of Transit Network Design Models

are re-structured around transit centers. As indicated by Newman et al. (1983), the major source of ridership concern is the increase in the number of required transfers across most trips. Part of the problem arises from the procedures typically followed to design routes around the transit center concept. These have been driven by the need to ensure compatible vehicle cycles on the various routes. In addition to the increased number of transfers, timed transfer systems increase travel time for passengers who remain on board at the centers and thus must wait for the duration of an entire time window to accommodate transfer requirement. Therefore, the planner should examine the trade-offs between conflicting objectives in the design and implementation of timed-transfer systems.

Abkowitz et al. (1987) pointed out that operational feasibility of timed transfer in transit systems depends on the compatibility between scheduled headways and congestion levels along the route. Coordination of routes with incompatible headways results in ineffective resource allocation. Implementation of the timed-transfer concept for routes serving areas with high congestion levels is undesirable, because travel time variability and randomness due to deviations from synchronized schedules could have severe impacts on the quality of service of timed-transfer systems. It is essential to have reliable data regarding travel time for the implementation of timed-transfer systems (Bakker, Calkin, and Sylvester, 1988).

Demand Responsive Service

Recognizing the ineffectiveness of fixed-route bus service for low-density areas, the transit industry in the US has introduced demand responsive bus services. As of May 1991, about 3,900 transit systems operated demand responsive services (Transit Fact Book, 1991). Normally, the use of demand responsive instead of fixed-route bus services in low-density areas will increase transit ridership, expand transit system coverage, and provide more effective operation. Several existing transit systems integrate demand responsive bus services with fixed-route bus services so that fixed bus routes serve high-density areas and demand responsive buses serve low-density areas. Examples of such integrated operation include Ann Arbor, Michigan, and Santa Clara County, California. Both systems have experienced various levels of success (Chang and Schonfeld, 1991).

Variable Vehicle Sizes

Due to high labor costs, transit operators in both Europe and North America tend to utilize fewer but larger buses to provide the capacity required during peak period operation. Although smaller buses cost more to operate per seat provided, their use may offer several advantages in

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some circumstances. Glaister (1985) argued that the use of small vehicles favors the provision of higher service frequencies, thereby lowering average wait times, and results in higher operation speed; the improved service levels can be expected to generate new demand for bus transit. Furthermore, smaller buses may be better suited for some types of service, such as low-demand, low-occupancy, high-quality, or special transit, as suggested by Oldfield and Bly (1988). Smaller vehicles are more acceptable to residents of certain low-density neighborhoods, and tend to cause less pavement damage on city streets. Other reasons for using different vehicle sizes are suggested by Walters (1979), Mohring (1983), Bly and Oldfield (1986), and Glaister (1986). To the extent that a given service area includes zones with different demand densities, allowing different vehicle sizes to operate on different bus routes and provide various types of services provides the transit operator with an additional choice dimension in the design of a service configuration which meets user needs better and provides desired service levels.

Although both vehicle size and route frequency are important elements of bus service plans, all previous bus network design procedures treat vehicle size as a fixed value and compute route frequency either to achieve a minimum total generalized cost or to provide the capacity needed during peak hour operation. The use of a fixed vehicle size simplifies the network design procedure, but precludes the simultaneous consideration of various vehicle sizes in the bus system design, and thus may result in ineffective resource allocation.

Practical Guidelines

Practically, transit service plans rely greatly on service planning guidelines that are mainly based on the practical experience and professional judgment of transit planners rather than on theoretical considerations. NCHRP 69 (1980) suggested constructing transit service guidelines based on interviews with transit agencies over a broad spectrum of US and Canadian cities. Particularly important guidelines for transit network design are those pertaining to the service pattern and service levels; these are summarized in Table 2.2. Although service planning guidelines are not sufficient to provide a complete solution to the design problem, violation of these guidelines may cause infeasible or ineffective operation. Properly incorporating service planning guidelines into the design model would result in a more operationally acceptable route design and service plan. Baaj (1990) pointed out that most other approaches fail to incorporate practical guidelines, and consequently have difficulty being accepted by the transit industry.

SHORTCOMINGS OF PREVIOUS APPROACHES

Major shortcomings of the previous approaches include the following:

1) Most approaches use generalized cost (time) or other types of costs as their single objective, and ignore the inherent multi-objective nature of the transit network design problem. These approaches construct bus routes only to ensure the connectivity of all demand pairs, and therefore ignore two important issues, namely, service directness and service coverage which should be considered in the transit network design.

2) Most approaches fail to utilize the demand matrix properly in constructing bus routes. These approaches either use a set of predetermined routes or a set of preselected termini in the layout of the routes. The resulting networks do not usually ensure adequate service for spatially dispersed trip patterns. A bus network should be constructed to match the spatial trip pattern so as to capture higher demand.

3) All previous approaches focus on the design of conventional bus systems which provide fixed-route, fixed-schedule, and uncoordinated-route operation. Conventional bus service is primarily used to serve areas with high demand density. However, it appears to be operationally ineffective and poor in service quality in areas with low demand density. Other service concepts, such as coordinated bus system and demand responsive service may be better suited to areas with spatially dispersed trip patterns and thus need to be addressed in the design.

4) The hubbing concept has not been addressed in any of the previous design approaches. This concept incorporates the notions of transit centers, timed-transfer service and demand responsive service, allows increased system coverage, and is specially suited to cities with multi-centered and spatially dispersed trip patterns.

5) Passenger trip assignment models used in previous approaches are limited to handling the passenger's path selection in uncoordinated bus systems. To enable the analysis and design of timed-transfer bus systems, the trip assignment model should account for the passenger's path selection in both uncoordinated and coordinated bus systems.

6) All previous models fail to consider variable vehicle sizes in the resource allocation process, and are therefore limited to the design of bus systems with the same vehicle size on all routes. A more realistic design model should consider not only frequency setting but also vehicle sizing.

7) Most previous approaches fail to incorporate practical service planning guidelines; thus the route designs and service plans generated from these approaches are sometimes operationally infeasible or uneconomical.

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Table 2.2 Suggested Service Planning Guidelines (Selected from NCHRP 69, 1980)

1. SERVICE PATTERN

1.1 Service Area and Route Coverage
   a. Service area is defined by operating authority or agency.
   b. Provide 1/4 mile coverage where population density exceeds 4,000 persons per sq mile or 3 dwelling units per acre. Serve at least 90 percent of residents.
   c. Provide 1/2 mile coverage where population density range from 2,000 to 4,000 persons per mile (less than 3 dwelling units per acre). Serve 50 to 75 percent of the population.
   d. Serve major employment concentrations, schools, and hospitals.
   e. Serve area within two-mile radius of park-and-ride lot.

1.2 Route Structure and Duplication
   a. Fit routes to major street and land use patterns; provide basic grid system where streets form grid; provide radial or radial-circumferential system where irregular or radial street pattern exists.
   b. There should be one route per arterial except on approaches to the CBD or a major transit terminal. A maximum two routes per street is desired.

1.3 Route Directness/Simplicity
   a. Routes should be direct and avoid circuitous routings. Routes should be not more than 20 percent longer in distance than comparative trips by car.
   b. Route deviation shall not exceed 8 minutes per round trip, based on at least 10 customers per round trip.
   c. Generally, there should be not more than two branches per trunk-line route.

1.4 Route Length
   a. Routes should be as short as possible to serve their markets; excessively long routes should be avoided. Route length generally shall not exceed 25 miles round trip or 2 hours.
   b. Two routes with a common terminal may become a through route if they have more than 20 percent transfers and similar service requirement, subject to (a).

2. SERVICE LEVELS

2.1 Desirable Policy Headways for Minimum Service Frequency
   a. Peak: 20 minutes-urban; 20-30 minutes-suburban.
   b. Midday: 20 minutes-urban; 30 minutes-suburban.
   c. Evening: 30 minutes-urban; 60 minutes-suburban.
   d. Night: 60 minutes.

2.2 Loading Standards
   a. Peak 30 minutes: 150 percent.
   b. Peak hour: 125-150 percent.
   c. Transition period: 100-125 percent.
   d. Midday/evening: 75-100 percent.
   e. Suburban: 100 percent.

2.2 Route Speeds
   a. Central area: 6-8 mph.
   b. Urban: 10-12 mph.
   c. Suburban: 14-20 mph.

SUMMARY

Previous approaches to the transit network design problem are either optimization models for idealized problems or heuristic models with limited applicability. Due to the complexity of the transit network design problem, optimization models are only used to determine certain design parameters on a predetermined route configuration. To design the route structure and to set route frequencies, heuristic approaches are commonly utilized. Previous heuristic approaches are reviewed with regard to seven distinguishing features: objective function, demand, constraints, passenger behavior, solution techniques, decision variables, and service types. Baaj's model has been discussed in greater detail because it has overcome some of the shortcomings of the previous models.

Non-traditional concepts for transit network design and operation include transit centers, timed-transfer, feeder bus service/demand responsive service, and variable vehicle sizes. Because of the lack of systematic design procedures for the implementation of these concepts, transit planners have to rely solely on experience and judgment. Practical service planning guidelines should be incorporated in the transit network design process. Designs that violate service planning guidelines may result in ineffective operations and poor service quality.

The shortcomings of previous approaches include:

1) failure to consider the inherent multi-objective nature of the transit network design problem.

2) limited responsiveness to the transit demand matrix in the route layout.

3) failure to incorporate the concepts of transit centers, timed-transfer, and demand responsive service.

4) failure to account for coordinated operations in the trip assignment model.

5) failure to incorporate variable vehicle sizes in the resource allocation process.

6) failure to incorporate service planning guidelines.

This study is intended to develop a transit network design model which overcomes some of the above shortcomings and produce network solutions that offer adequate service for multi-centered and spatially dispersed trip patterns of the kind encountered in most North American cities.

CHAPTER 3. SOLUTION METHODOLOGY

INTRODUCTION

The shortcomings of previous approaches were discussed in the preceding chapter. Baaj and Mahmassani (1991) attempted to overcome several of these shortcomings, and develop a procedure to design bus networks that meet certain system coverage and service directness levels, and reflect different trade-offs between user and operator costs. The procedure explicitly incorporates several practical guidelines and industry rules of thumb. The route network generated by this procedure is heavily guided by the transit demand pattern, and seeks to provide high service levels in terms of meeting passenger needs. However, like other approaches, the procedure is limited to conventional bus service, and cannot be expected to provide a superior solution for the kind of multi-centered and spatially dispersed trip patterns discussed in Chapter 1. Alternative design and service concepts that may be better suited for such trip patterns were identified in the previous chapter. These concepts include the design of the network around transit centers, the provision of timed-transfer bus service, the provision of demand responsive bus service, and the use of variable vehicle sizes.

In this chapter, a solution methodology that accounts for alternative design and service concepts is presented. This approach builds on and extends significantly Baaj and Mahmassani's procedure, adapting and modifying several of its algorithms, and adding entirely new components to achieve the desired objectives. As a result, this methodology offers a more comprehensive design procedure to develop transit networks and service plans for more general (and practically relevant) transit trip patterns.

In the next section, the solution framework and the alternative design features it provides are presented. The solution framework consists of four main procedures: a route generation procedure (RGP), a network analysis procedure (NETAP), a transit center selection procedure (TCSP), and network improvement procedures (NIP). The subsequent sections offer overviews of the RGP, NETAP, TCSP, and NIP, in this order. Section 3.7 describes the rationale for selecting the LISP computer language as the implementation tool. This chapter concludes with a summary in Section 3.8.

SOLUTION FRAMEWORK AND ALTERNATIVE DESIGN FEATURES

For a given set of input information on transit demand and street network connectivity of a projected service area, the design process starts with the generation (using the route generation procedure, RGP) of a set of routes that achieves certain service levels in terms of system service

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coverage and directness. Two network design concepts are offered by the RGP, which configure route networks either with or without the transit center concept. For the set of routes generated by the RGP, the network analysis procedure (NETAP) is then utilized to 1) assign the given transit demand and compute an array of network-level, route-level, and node-level descriptors, 2) determine frequencies and vehicle sizes for all bus routes, and 3) compute a variety of system performance measures.

The NETAP follows an iterative procedure, starting with an initial set of frequencies associated with the given routes. In each iteration, a new set of route frequencies is determined and compared to the input frequencies. If the revised frequencies are significantly different from the input values, the NETAP iterates with the revised values serving as input frequencies until they converge. When the design is desired around the transit center concept, suitable candidate centers are identified with the transit center selection procedure (TCSP) for the given route configuration, using several node-level descriptors computed by the NETAP. Given these centers, the route structure is modified by the RGP to insure good transfer opportunities at the centers, as well as fast and direct service between centers. The new route structure is evaluated by the network analysis procedure. The set of transit centers can be obtained using either only one TCSP run or iterating until two consecutive sets of candidate transit centers converge. The network improvement procedures considers a set of improvement actions which modify the previously generated bus network so that ineffective bus routes are improved, eliminated, or replaced by demand responsive service. The solution approach is summarized in Fig 3.1

Alternative designs and services are obtained using various control parameters in the above design process. The above solution framework provides the following design features:

1) Conventional transit service in the form of fixed-route, fixed-schedule, and uncoordinated service is the most basic design feature. This design feature, as shown in Figure 3.2, is a special case of the overall design process (as shown in Figure 3.1) and employs only the RGP, NETAP, and NIP. The route configuration generated under this option is not developed around the transit center concept. In this design, passenger trips are assigned according to a simpler trip assignment procedure (similar to Baaj and Mahmassani's TRUST procedure) which does not recognize the provision of coordinated route operations essential to the timed-transfer design feature.

2) Timed-transfer transit service offers fixed-route, fixed-schedule, and coordinated service. This design utilizes all four procedures. The RGP first generates a set of transit routes without using the transit center concept, since the set of transit centers

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Route Generation Procedure (RGP)
* generate a set of good routes with or without the transit center concept

User input →

↓

Network Analysis Procedure (NETAP)
* assign demand and compute network-level, route-level, and node-level descriptors
* determine frequencies and **bus sizes** **(for feature 4)**
* compute system performance measures

↓

No ← Is the design around the transit center concept?

↓ Yes

No → Has the set of transit centers been generated ?

↓ Yes

Has NIP been applied ? → **Yes** → Add the set of routes to the set of feasible solutions

↓ No

Network Improvement Procedure (NIP)
* route discontinuation
* route merging
* route splitting
* branch exchange of routes
* route splitting at transit centers
* **demand responsive service (for feature 3)**

Transit Center Slection Procedure (TCSP)
* Generate a set of transit centers

↓

* Output the set of transit centers to user
* Eliminate unsuitable transit centers

Have more sets of routes been generated? → **Yes**

↓ No

Generate non-dominated solutions from the set of feasible solutions

Figure 3.1 Solution Approach

```
                    ┌─────────────┐
                    │ User input  │
                    └──────┬──────┘
                           │
                           ▼
        ┌──────────────────────────────────────┐
        │ Route Generation Procedure (RGP)      │
        │ • generate a set of good routes       │
        │   without the transit center concept  │
        └──────────────────┬───────────────────┘
                           │
                           ▼
    ┌──────────────────────────────────────────────┐
    │ Network Analysis Procedure (NETAP)            │
    │ • assign demand and compute network-level,    │
    │   route-level, and node-level descriptors     │
    │ • determine frequencies and bus sizes (for    │
    │   feature 4)                                   │
    │ • compute system performance measures         │
    └──────────────────┬───────────────────────────┘
                       │
                       ▼
                  ╱─────────────╲          Yes    ┌─────────┐
                 ╱  Has NIP been  ╲───────────────▶│  STOP   │
                 ╲   applied ?    ╱                └─────────┘
                  ╲─────────────╱
                       │
                       │ No
                       ▼
    ┌──────────────────────────────────────────────┐
    │ Network Improvement Procedure (NIP)           │
    │ • route discontinuation                       │
    │ • route merging                               │
    │ • route splitting                             │
    │ • branch exchange of routes                   │
    │ • demand responsive service                   │
    │   (for feature 3)                             │
    └──────────────────────────────────────────────┘
```

Figure 3.2 Conventional Uncoordinated Bus System Design

is empty. The route network is then evaluated by the NETAP for uncoordinated service. Using the information provided by the RGP and NETAP, a set of candidate transit transfer centers are identified by the TCSP. The route network is then reconstructed (in the RGP) around the candidate centers. Passenger trips are assigned to the enhanced network according to a coordinated trip assignment procedure. Route frequencies are set to the same or multiple integer values for all coordinated routes. The design procedure continues iteratively until a set of convergent transit centers is found. Networks constructed around the transit center concept can be implemented using either the coordinated or uncoordinated service concepts. The timed-transfer design implements the coordinated service concept. The option of using uncoordinated service in the whole network generated around the transit center concept is also available in the solution framework.

3) The integrated bus system incorporates the demand responsive service in the NIP into the conventional and the timed-transfer service designs. The integrated system provides fixed-route, fixed-schedule, and uncoordinated (or coordinated) service for high demand density areas and demand responsive service for low demand density areas.

4) Fixed or variable vehicle sizes are available to the designer in conjunction with any of the above features.

The intent of this solution approach is to use different user specified-service levels and alternative design and service concepts to generate a set of feasible solutions. From all the resulting solutions, a set of non-dominated solutions is defined.

THE ROUTE GENERATION PROCEDURE (RGP)

Evolved from the route generation algorithm (RGA) developed by Baaj and Mahmassani, which does not incorporate the transit center concept, the RGP is capable of constructing route networks either with or without the transit center concept. If a set of transit centers is defined for the design, the network is configured around the transit center concept. Otherwise, the network is constructed without the transit center concept. Networks generated around the transit center concept are enhanced by providing better transfer opportunities at the centers, and faster and more direct service between centers. For a given street network and a given transit demand matrix, the RGP constructs a set of bus routes to satisfy certain levels of service directness and system coverage. Service directness is defined as the minimum percentage of the total demand satisfied directly without transfers. System coverage is defined as the percentage of total demand

satisfied within at most two transfers, reflecting the assumption that tripmakers would not use buses for trips that require more than two transfers.

The RGP starts by querying the designer for service directness and system coverage levels to be accomplished, and the number of initial skeletons (M). The RGP then generates M node pairs to be the seeds for initial skeletons. If any feasible transit center pairs for route generation are identified, the RGP uses them as seeds for the initial set of skeletons. However, if the number of skeleton seeds is insufficient, the RGP searches the demand matrix for high demand pairs and selects them as additional seeds for the initial set of skeletons. These skeletons are expanded to routes via different node selection and insertion strategies that are guided by the transit planner's knowledge and expertise. To provide better service quality at transit centers, higher priority for insertion is assigned to transit centers (nodes), and a lower circuity factor is utilized for routes under expansion that connect transit centers. The RGP terminates if both service directness and system coverage exceed the user specified levels. Otherwise, new routes are generated one at a time until the resulting route network satisfies pre-specified service directness and system coverage levels. Different levels of service directness and system coverage, and different node selection and insertion strategies result in different sets of routes with different user and operator costs. Details of the RGP is presented in Chapter 4; an illustrative application to data obtained for the transit network of Austin, Texas, is presented in Chapter 5.

THE NETWORK ANALYSIS PROCEDURE (NETAP)

The NETAP can be used for two purposes: system evaluation and system parameter design. For system evaluation, the NETAP computes the required fleet size, several performance measures reflecting service quality, system utilization, and the cost experienced by users and operators for a given network configuration and service plan. For design purposes, the NETAP sets route frequencies to achieve an applicable maximum allowed load factor, determines the suitable vehicle size by minimizing the total cost for each route in the bus system, and evaluates the resulting bus system.

The NETAP accomplishes the system evaluation task by assigning the given O-D trip demand to the bus network to obtain detailed route link flow information. At the same time, a variety of performance measures are computed. If the NETAP is utilized as part of a design procedure, an initial input frequency is assumed for each route before executing the trip assignment. The NETAP follows an iterative procedure to determine the vehicle size and the output route frequency for each route. If the output route frequency is significantly different from the input value, the NETAP reiterates with the output frequencies as the input frequencies until

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they converge. After determining route frequencies and vehicle sizes, the required fleet size, fuel consumption, and operation cost for the bus system are computed. The NETAP is capable of handling analysis and design for both uncoordinated and coordinated transit networks, since the trip assignment model has been developed to accommodate these special needs. In the case of timed-transfer design, a frequency adjustment procedure which sets coordinated route frequencies to the same or multiple integer values is utilized within the bus sizing and frequency setting procedures.

Chapter 5 focuses on the details of the NETAP, including the trip assignment procedure, the bus sizing and frequency setting procedure, and the computation of various system performance measures. An application to the Austin, Texas, transit network illustrates the NETAP.

THE TRANSIT CENTER SELECTION PROCEDURE (TCSP)

The TCSP incorporates several criteria that reflect commonly used guidelines in the transit industry for selecting transit centers. First, transit centers need to provide good transfer opportunities. Transfer opportunities for a demand node are measured by the number of potential routes that serve that node, or can reach it within a certain travel time. The latter ensures that the demand node can be inserted into the potential routes without incurring too much insertion cost. Second, sufficient originating trips should be generated within the feeder bus service area of each transit center. Third, each transit center should be located at a major activity center that generates high total node demand (including originating, terminating, and transferring trips). In addition, each transit center should be separate from other centers at a minimum travel time to avoid service overlap. The transit centers generated according to the above criteria are supplied to the designer so that infeasible centers violating geometric, economic, and other considerations can be eliminated. Details of the TCSP are discussed in Chapter 6.

NETWORK IMPROVEMENT PROCEDURES (NIP)

Some routes generated by the above design process may be economically and operationally infeasible, especially if the required level of demand satisfaction approaches 100%. The NIP seeks to improve a set of routes generated by the RGP. The NIP incorporates the modifications suggested by Baaj, which act on either the transit system coverage level or the route structure level; these include: 1) route discontinuation, 2) route merging, 3) route splitting, and 4) branch exchange of routes. The NIP also includes a special route splitting modification for timed-transfer system design. This modification splits routes with unequal loading on two separate segments of the routes divided by a transit center. With this split, better resource allocation can be achieved;

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the negative effect of the transfers induced by the route split is reduced by the provision of coordinated service at the transit center.

In addition, the NIP provides the option of demand responsive service (DRS) instead of fixed route operations. Under the DRS option, ineffective routes are discontinued, and unsatisfied system demand is served by DRS oriented around transit centers and associated service areas. Transit centers are identified using the TCSP. The procedure for identifying DRS areas considers two criteria: 1) the maximum DRS vehicle travel time in a service cycle, and 2) the amount of unsatisfied demand in the service area. This procedure identifies DRS areas one at a time, and terminates if pre-specified demand levels are satisfied or no feasible DRS area can be found. Details of the NIP are discussed in Chapter 6.

ARTIFICIAL INTELLIGENCE (AI) SEARCH TECHNIQUES AND DATA REPRESENTATION

LISP, an artificial intelligence computer language, is selected as the implementation tool for the solution approach. The principal motivations for selecting LISP are:

1) The nature of the computation tasks in the proposed solution approach involves numerous search processes. LISP's special "list" data structure and built-in primitives provide an effective programming environment.

2) LISP offers the simplicity and flexibility of representing graphs for the transit network design problem.

One of the core AI techniques concentrates on the efficient representation, storage, and retrieval of data so as to reduce the programming effort and speed up the search process. The advantages of using AI computer languages in solving transit network design problems come from their "list" data structure and some general primitives that test for membership, generate the intersection or union of any two lists as well as the complement of one list in another, sort a list of objectives according to some numerical properties, remove elements from a list, or execute many other functions which are created to support AI search techniques. These primitives are procedures or functions that take the necessary arguments and produce solutions; thus the programmer does not need to worry about the elemental computation and house-keeping chores, as would be the case with conventional programming languages such as FORTRAN, Pascal, and C.

LISP's "list" data structure represents different types of data for network problems more flexibly than conventional computer languages. Baaj and Mahmassani (1992) described examples of transit network data representation using the list data structure. In their examples,

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transit network connectivity is represented as a list . For example, the list (2 ((1 11.4) (3 2.9)))
indicates that one can go from node 2 to node 1 in 11.4 minutes, and to node 3 in 2.9 minutes. A
bus route or a path connecting two network nodes can be simply represented by a list including
adjacent nodes. For instance, a bus route R1 can be represented by a list (1 11 22 33 44 55 66)
which indicates that R1 starts at node 1, traverses nodes 11, 22, 33, 44, 55, and terminates at
node 66.

LISP may be relatively slow when it comes to mathematical computation. However, with the
advantages described above, LISP is thought to be very well suited for the proposed solution
approach.

SUMMARY

In this chapter, the solution methodology for the transit network design problem is presented
which accounts for the alternative design concepts specially suited to current spatial trip
distribution patterns. These alternative design concepts consist of conventional bus service
design, coordinated timed-transfer service, flexible-route and flexible-schedule demand
responsive service, and the design of variable vehicle sizes. Various design features are
achieved with different combinations of these alternative concepts. In addition, the solution
framework incorporates the knowledge and expertise of transit network planners, and adapts
superior algorithmic procedures developed by previous approaches. Four main components
have been developed to meet the special needs of this study: route generation procedure,
network analysis procedure, transit center selection procedure, and network improvement
procedures. Details of the first two procedures are described in Chapters 4 and 5, respectively.
The transit center selection procedure, and network improvement procedures are described in
Chapter 6. All the developed procedures are implemented in the LISP computer language which
provides efficient AI search techniques for the laborious path search and enumeration required to
solve the bus network design problem.

CHAPTER 4.   THE ROUTE GENERATION PROCEDURE

INTRODUCTION

The transit network design framework presented in the previous chapter consists of four main procedures, namely route generation, network analysis, transit center selection, and network improvement. This chapter focuses on the route generation procedure (RGP), which determines sets of routes for a given transit demand matrix and a description of network connectivity detailing for each node its neighboring nodes and the in-vehicle travel times on all the connecting links. Because of the inherent multi-objective nature of transit network design, the RGP generates route networks corresponding to different trade-offs among various measures of user and operator costs.

The RGP has evolved from Baaj and Mahmassani's route generation algorithm (RGA), developed primarily for uncoordinated transit networks. The RGA is heavily guided by the demand matrix; it allows the designer's knowledge to be implemented so as to reduce the search space. However, because this study seeks a more complete model that can handle both conventional (fixed-route, fixed-schedule, uncoordinated) and non-conventional (flexible-route, flexible-schedule, and coordinated) designs, the RGA is not sufficient for the objectives of this study. The RGP framework is based on that of the RGA, with the addition of significant features to configure the network around the transit center concept for non-conventional service designs. The intent is to obtain a transit network that not only heavily relies on the demand pattern but also provides better transfer opportunities at transit centers, as well as faster and more direct service between centers. In addition, dispersed demand nodes are connected to transit centers so as to reduce the total vehicle miles provided by the system, resulting in a more effective bus system.

Section 4.2 presents an overview of the RGP, including a flow chart and a summary of the RGP steps. The required input information for the RGP execution is described in Section 4.3. Section 4.4 discusses in detail the formation of initial skeletons. Section 4.5 describes the identification of candidate nodes for insertion, the node selection and insertion strategies, and the condition for the termination of route expansion. The important features of the RGP are summarized in Section 4.6.

OVERVIEW OF THE RGP

The route generation procedure is comprised of three main components: initial skeleton formation, skeleton expansion to complete routes, and RGP termination. This section describes the overall structure of each component; more detail is provided in the later sections.

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The RGP starts by generating initial skeletons. In this step, the designer's knowledge is reflected in the likely minimum number of routes (M) required for the service area (the value of M is discussed in section 4.4.1). The RGP does not check for termination until M routes are generated so as to avoid unnecessary steps and increase search efficiency.

The initial skeletons are constructed in two sub steps. First, the RGP selects M demand node pair seeds for the initial skeletons. In Baaj and Mahmassani's RGA, the M highest demand node pairs in a sorted demand matrix are selected as node pair seeds. This causes the resulting network to highly rely on the transit demand matrix. To also obtain more direct service between transit centers, the RGP first considers the feasible transit center pairs (see discussion in section 4.4.1). If the number of feasible transit center pairs (N) is insufficient, i.e. N is less than M, the RGP selects the (M - N) highest demand node pairs from the list of sorted demand node pairs with the feasible transit center pairs removed from the list. These high demand node pairs are then eliminated from the list.

After M node pairs are selected, the RGP connects each of these node pairs along either the shortest path or an alternate short path to form M initial skeletons (see section 4.4.2 for discussion). The alternate short path is the next shortest path in which the nodal composition is substantially different from that of the shortest path.

Through a node selection and insertion strategy (discussed in section 4.5.2), each skeleton is expanded to a complete route by following a selected order of expansion (discussed in section 4.5.1). In order to provide better service quality (in terms of transfer opportunity and accessibility) at transit centers, these centers receive priority for insertion. The initial M routes are examined to determine whether any route is substantially represented by one or more other routes, by checking whether its nodal composition is a subset of another route's nodal composition. Baaj (1990) suggested that this condition may be relaxed to a check on the ratio of the number of nodes of a given route that are traversed by some other route to the route's total number of nodes. If there are overlapping routes, the RGP eliminates the subset routes and removes from the list of sorted demand node pairs all elements for which the demand is satisfied directly by the current set of routes. The RGP reiterates by selecting the highest demand node pair in the remaining list of sorted demand node pairs to generate an additional route. The iterative procedure continues until M 'independent' routes are generated.

The last step of the RGP is to check for termination. The RGP terminates when the resulting set of routes collectively satisfies system service directness and system coverage levels, both user specified. In this study, the system directness level is defined as the minimum percentage of total demand satisfied directly without transfers (denoted by *dsdirmin*), and the system coverage

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level is defined as the percentage of demand satisfied within two transfers (denoted by *dsmin*). This is based on the assumption that passengers will not be willing to travel by bus if their trips cannot be completed within two transfers. The termination step first checks the system directness level. If it is not satisfied, all demand pairs satisfied directly by the current set of routes are removed from the list of sorted demand node pairs. The RGP then picks the first (highest) demand node pair in the remaining list to generate an additional route using the same criteria for forming and expanding a skeleton to a route as described above. New routes are generated one at a time until the system directness level is satisfied. The next step is to check the system coverage level. If it is not satisfied by the current set of routes, all node pairs currently satisfied within two transfers are eliminated from the remaining list. For conventional bus service design, additional routes are generated following the same process until the system coverage level is satisfied. For timed-transfer system design, the demand of each selected node pair is checked to see if it can be satisfied by connecting one of the two nodes to a transit center. If this is the case, the additional route is generated by connecting the center to the closest (least travel time) of the two nodes. The intent is to satisfy the remaining dispersed demand in the service area through the closest feasible center to reduce unnecessary vehicle miles and obtain a more effective route network. It should be noted that varying the minimum system directness level and the minimum system coverage level results in different sets of routes. This enables the designer to address different trade-offs between service directness and system coverage.

The flow chart of the RGP is shown in Figure 4.1. Given the demand matrix and street network connectivity for the service area and a set of user specified design parameters (described in next section), the steps of the RGP are summarized as follows:

Step 0 Set the initial set of bus routes, BR = {}.

Step 1 Sort the demand matrix elements to form a list of sorted node pairs (SDNP) in decreasing order of demand.

Step 2 Identify feasible transit center pairs as initial node pair seeds, and remove them from SDNP.

If N (number of feasible transit center pairs) < M (user specified initial number of skeletons), go to Step 3.

Otherwise, go to Step 4.

Step 3 Select the first (M - N) node pairs in the remaining SDNP to make up a total of M node pair seeds, and remove them from the SDNP.

Step 4 Connect node pair seeds to form route skeletons.

Step 5 Expand route skeletons to form complete routes and add them to BR.

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Formation of Initial Skeletons

- Sort the demand matrix (SDNP)
- Generate feasible transit-center pairs, and remove them from SDNP

User input
- Demand matrix
- Network connectivity
- Number of initial skeletons (M)
- Node selection and insertion strategy
- Service Type

Is N < M ? — No / Yes

- Select (M - N) highest demand node pairs from SDNP
- Remove them from SDNP

- Form skeletons using the generated node pair seeds

Expansion of Skeletons

- Insert feasible nodes to form complete routes

- Check set of generated routes for presence of subset routes and remove them

Is NR< M ? — Yes

- Select highest demand node pair from SDNP, and remove it from SDNP

No

Termination of RGP

Is SDL ok? — No

- Remove from SDNP all node pairs satisfied directly by current set of routes

Yes

Is SCL ok? — No

- Remove from SDNP all node pairs satisfied by current set of routes

Yes

- Output the set of routes

Figure 4.1 Route Generation Procedure (RGP)

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Step 6 Check for overlapping routes, and eliminate them from BR.

Step 7 Check the number of routes (NR) in BR .

If NR ≥ M, go to Step 9.

Step 8 Select the first node pair in the remaining SDNP as the next node pair seed, remove it from the remaining SDNP, and go to Step 4.

Step 9 Check system directness level.

If lower than user-specified level, remove the demand pairs satisfied directly by the current BR from the remaining SDNP, and go to Step 8.

Step 10 Check system coverage level.

If lower than user-specified level, remove demand node pairs satisfied within two transfers by the current BR from the remaining SDNP, and go to Step 8.

Otherwise, stop and obtain the resulting set of bus routes (BR), each route in the set containing a list of demand nodes.

INPUT INFORMATION

The RGP requires the same input information as Baaj and Mahmassani's RGA, as well as two additional control parameters for the selection of alternative design features. The input can be grouped into the following five categories :

1) Network: The number of bus transit nodes, the connectivity list, the shortest path list for each node pair, the next shortest path list for high demand node pairs, the number of initial skeletons (M), the set of transit centers, and the set of terminal nodes.

2) Frequencies: The maximum frequency allowed on any bus route. This is used to provide a route capacity constraint for the expansion routines.

3) Demand: A demand matrix representing the demand between each node pair, the minimum system directness level (the minimum percentage of the total demand to be satisfied directly, defined as *dsdirmin* in the computer program), and the minimum system coverage level (the minimum percentage of the total demand to be satisfied within two transfers, defined as *dsmin* in the computer program).

4) Parameters: The network design parameter for the selection of network designs with or without the transit center concept, the service parameter for the selection of uncoordinated and coordinated service design, the vehicle size parameter for the selection of the fixed vehicle size option and variable vehicle size option, the transfer penalty per transfer expressed in equivalent minutes of in-vehicle travel

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time, the bus seating capacity (assumed the same on all buses), the maximum load factor allowed by the transit planner on any bus route, the node-sharing factor (*nsf*) necessary to determine whether a node can be inserted or not (see discussion in section 4.5.2.2), and transferring flow factor necessary to determine whether a route can be further expanded (see discussion in section 4.5.3.1).

5) Node Insertion Rules: Four node selection and insertion heuristics to be selected for route expansion, including Maximum demand insertion (MD), Maximum demand per minimum time insertion (MDMT), Maximum demand per minimum route length increase insertion (MDML), and Maximum demand per minimum cost insertion (MDMC).

Table 4.1 summarizes the above input information and associated parameters and default values used in the computer program.

FORMATION OF INITIAL SKELETONS

This step consists of two components, namely, the selection of initial node pair seeds and the construction of initial skeletons from initial node pair seeds. These two components are described in turn hereafter.

Selection of Initial Node Pair Seeds

The RGP starts by sorting the given demand matrix elements into a list of sorted demand node pairs (SDNP) in decreasing order of demand. Then the RGP checks the set of transit centers, *transit-centers*, for existence of any such center. If more than one center is specified, the RGP calls for the predicate "feasible-transit-center-pairs" to determine the set of feasible center pairs such that the travel time along the shortest path between each pair is less than a preset maximum (currently 20 minutes). This maximum travel time reflects a feasibility guideline for providing coordinated bus service between centers. Scheider and Smith (1981) suggested that this time should be no greater than 20 minutes. The feasible center node pairs form seeds for initial skeletons. The list of sorted demand node pairs is updated by eliminating all feasible transit center pairs.

In the data input stage, the user is queried for the minimum possible number of routes (M) required for the project area. If the number of feasible transit center pairs (N) is less than M, the first (M - N) elements in the remaining sorted list of demand node pairs become skeleton seeds. These elements are then removed from the updated list of sorted demand node pairs.

Table 4.1 Summary of Required Input Information for the RGP

Categories	Parameters	Definition	Value
Network	*connectivity-list*	List of street network connectivity	—
	asp	List of shortest path for each demand node pair	—
	aspk	List of alternate short paths	
	M	Number of initial skeletons	1
	transit-centers	Set of transit centers	nil
	terminal-nodes	Set of terminal nodes	nil
Frequency	*max-frequency*	Maximum allowed frequency	30 bus/hr
Demand	*demand-matrix*	Demand matrix representing the demand between each node pair	—
	dsdirmin	Minimum system directness level	—
	dsmin	Minimum system coverage level	—
Parameters	*tc-network?*	Network constructed without transit center concept	1
		Network constructed with transit center concept	2
	coordinated?	Design with uncoordinated service	1
		Design with coordinated service	2
	bus-size-option	Fixed vehicle size option	1
		variable vehicle size option	2
	transfer-penalty	Transfer penalty expressed in equivalent of in-vehicle travel time	5 minutes
	seating-capacity	Bus seating capacity	40 seats
	max-load-factor	Maximum load factor	1.25
	nsf	Node-sharing factor	0.75
	tran-flow-factor	Transferring flow factor	0.25
Node Insertion rules	*sra*	Maximum demand insertion (MD)	1
		Maximum demand per minimum time insertion (MDMT)	2
		Maximum demand per minimum route length increase insertion (MDML)	3
		Maximum demand per minimum cost insertion (MDMC)	4

The selection of the value M depends on the designer's knowledge of the service area. However, if the designer's knowledge is poor or unreliable, the designer may examine data pertaining to existing transit networks of cities in which the service population and trip patterns are comparable to that of the service area. Thus, it would be desirable to compile a data bank of existing networks which can be consulted for the value of M. Alternatively, one can simply set M = 1 and let the RGP generate routes one by one.

Although the current version of the RGP selects feasible transit center pairs and high demand node pairs as seeds for route skeletons, other alternatives may also be implemented if the designer has sufficient knowledge of the network. First, the designer could specify as seeds for route skeletons those demand node pairs identified as dominant trip generators and attractors. Furthermore, the designer could also specify initial skeletons or routes directly if major corridors are identified.

Construction of Initial Skeletons From Initial Node Pair Seeds

Each node pair seed forms a route skeleton along either its shortest path or an alternate path connecting the corresponding node pair. The alternate path has a nodal composition substantially different from that of the shortest path with a travel time that does not exceed the shortest path by a given circuity factor. This factor is taken as 50% for high demand node pairs and 25% for feasible transit center pairs to ensure more direct service between transit centers. A path has significantly different nodal composition from that of a path P if the number of common links contained in both paths does not exceed a ratio (say 50 %) of the total number of links of path P.

The label-setting shortest path algorithm developed by Dijkstra (1959) is applied to generate the shortest path for all node pairs in the transit network. The label-setting k-shortest paths algorithm (Shier, 1979) is utilized to generate up to the 10th shortest path between any node pair seed. Any path longer than the 10th shortest path is expected to violate the in-vehicle travel time constraint. Thus, the shortest path for each node pair seed is defined, and the remaining nine paths (sorted in increasing order of in-vehicle travel time) are examined sequentially to find an alternate short path which meets three criteria: 1) it should not contain cycles, 2) its in-vehicle travel time meets the circuity limitation, and 3) the number of common links shared with the shortest path does not exceed 50% of the total number of shortest path links. If such a path is found for the node pair, it is assigned as an alternate path. Otherwise, the skeleton is constructed along the shortest path of the node pair. Both algorithms were implemented by Baaj (1990).

As indicated by Baaj (1990), a skeleton along the shortest path of a high demand node pair

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reduces its contribution to the total in-vehicle travel time to the minimum value but would likely have fewer nodes than longer paths. However, if the skeleton is constructed along an alternate short path comprising more nodes, it may satisfy a higher share of the total demand with only a small increase in the total trip time. Therefore, it is desirable to investigate both types of skeletons. Baaj used a typical case to examine the resulting networks, and concluded that if shortest paths are used in the procedure instead of alternate short paths, fewer buses are required, but higher total user travel time is incurred.

EXPANSION OF SKELETONS TO ROUTES

In this section, the procedure that expands skeletons to complete routes is discussed. This procedure starts by finding the set of candidate nodes for insertion into a route under expansion. Candidate nodes are inserted in the current route one at a time. The order of insertion follows a certain sorted property, described in Section 4.5.2.5. In addition, each candidate node should satisfy both the route capacity and length constraints after expansion. The procedure terminates if no candidate node is available for insertion.

The following criteria are utilized to check each node for insertion feasibility:

1) the resulting route does not form a loop after inserting the node (see Section 4.5.2.1 for more detail),

2) the node still has a low percentage of its total originating demand satisfied directly after previous insertions in other routes (discussed in Section 4.5.2.2),

3) the resulting route does not become circuitous (discussion in Section 4.5.2.3), and

4) the ratio of the contributed demand satisfied per insertion cost (in-vehicle travel time) exceeds a preset desired level (explained in greater detail in Section 4.5.2.4).

For nodes specified as transit centers, criterion 2 is relaxed since a large number of transferring trips is expected at these centers. Therefore, more routes could be routed through transit centers so as to increase accessibility and transfer opportunities.

Once the set of candidate insertion nodes is defined, the order of insertion depends on the ratio of the contributed demand satisfied to the insertion cost. The intent is to insert the node with the highest contributed demand satisfied per insertion cost into the route under expansion. Transit centers are inserted with priority because of the expected large number of transferring trips. In other words, if transit centers are contained in the set of candidate insertion nodes, the insertion procedure considers these centers first, and then other candidate insertion nodes (discussed in Section 4.5.2.4). Two constraints are checked before inserting a node:

1) the required service frequency on the resulting route does not exceed the maximum

operationally implementable value (default 30 buses/hour), and

2) the round trip time of the resulting route does not exceed a maximum allowable value (default 2 hours, suggested by NCHRP 69).

If a candidate node satisfies both constraints, it is inserted into the route under expansion. Otherwise, the route is complete, and the RGP expands the remaining skeletons. Figure 4.2 shows the flow chart of the route expansion procedure, including all the above insertion feasibility checks.

Order of Expansion

Once M skeletons have been generated, the RGP expands them sequentially to form M routes. The order of expansion determines the nodal compositions of the set of final routes for the following two reasons:

1) Some nodes previously inserted into other routes may not be available for insertion into the current route because most of their originating demand has been satisfied directly (see insertion criterion 2) .

2) If a node is inserted into a high or a low demand node seed, it will result in different contributions to the total in-vehicle travel time, and the sequence of insertion within the set of candidate insertion nodes will be altered. In other words, a node in the set of candidate insertion nodes for a low demand node seed will have higher priority for insertion than that of a high demand node seed.

For M skeletons, there are at most M! different expansion sequences. The procedure considers only two extremé cases, namely in order of decreasing demand of the seed node pairs, or in order of increasing demand. These cases have the potential to produce the most different sets of routes, with respect to the performance indicators.

Selection and Insertion of Feasible Nodes

The procedure utilizes five criteria to obtain a feasible set of candidate nodes for insertion. These criteria are route-looping, node-sharing, terminal node, route circuity, and order of insertion. The node-sharing test is not applied to transit centers because a large number of transferring trips is expected at these centers. In order to obtain good quality of service between transit centers, a lower circuity factor is used for skeletons generated using feasible transit center pair seeds. Among all candidate nodes, transit centers receive priority for insertion.

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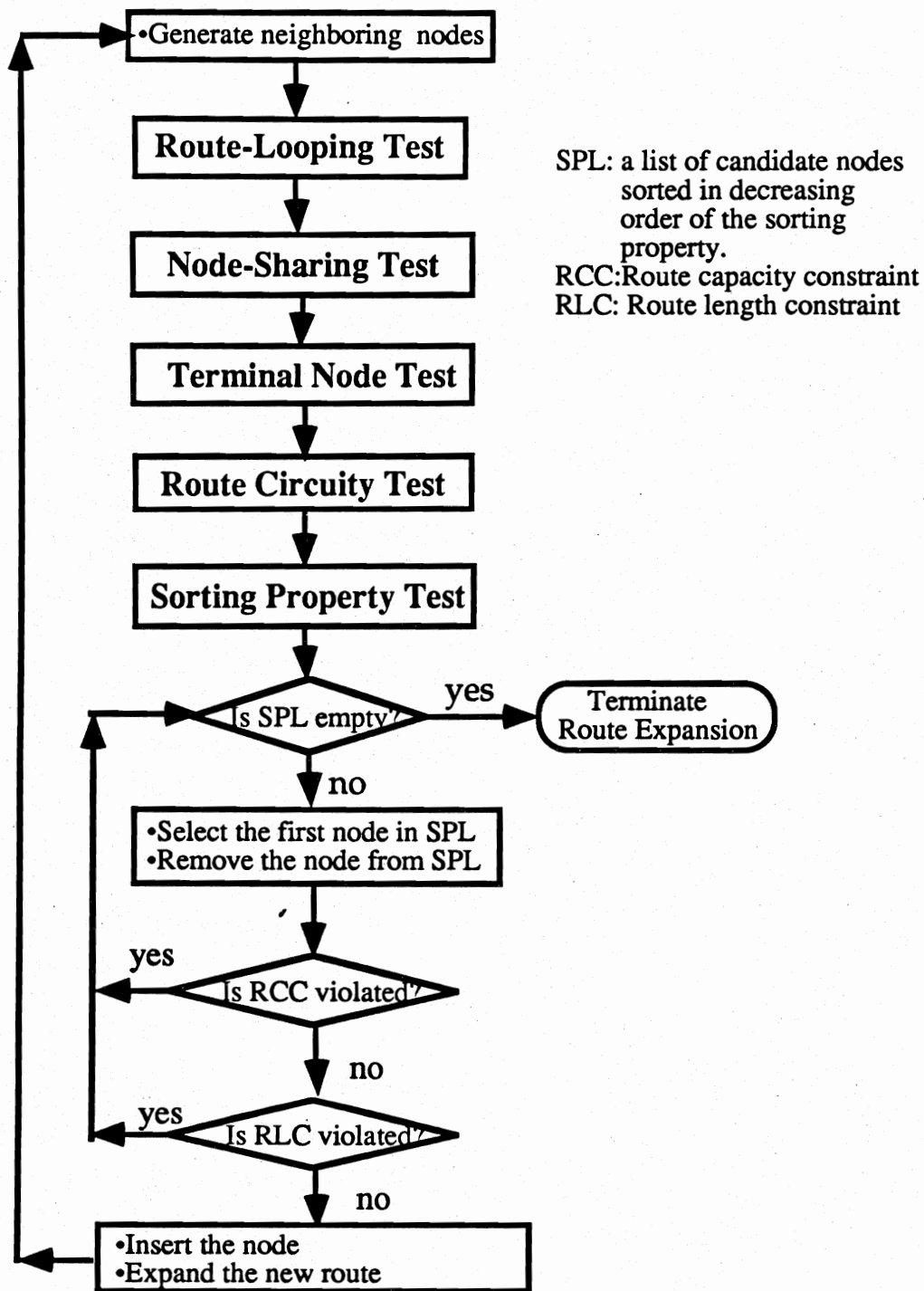
Figure 4.2 Route Expansion Procedure

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Route-Looping Test: In order to reduce the search space, the procedure checks only neighboring nodes connected via a single link to any node of the current route rather than all nodes in the network. Each neighboring node is then checked to see whether it already belongs to the route under expansion, in which case it is removed from the candidate list to avoid loops.

Node-Sharing Test: The remaining list of neighboring nodes is then checked to remove nodes that have a high percentage of their total originating demand already satisfied directly. This check is via a node-sharing factor (*nsf*, currently set at 75%) that determines when a node is no longer available for insertion into routes under expansion. Therefore, once the percentage of directly satisfied demand of any node in the remaining list is greater than *nsf*, it is removed from the list. This criterion is based on the following ideas:

    1) A node can be traversed by several routes, so insertion in one route does not preclude insertion in skeletons expanded later. As more routes traverse this node, more of the node's originating demand is satisfied. However, any further increase in the number of traversing routes will not contribute much more to the demand satisfied directly.

    2) In a transit network, passenger trips can be completed either directly or by transfers. Demand originating at a given node that cannot be completed directly could be completed via transfers. Inserting nodes with much of the originating demand already satisfied directly will not be economical.

    3) From the computational point of view, it would be burdensome to keep track of the demand originating at a given node that would be satisfied via new transfer opportunities as routes are expanded later in the process. The RGP keeps track only of the demand originating at a given node that can be satisfied directly.

The remaining list is then filtered via a terminal node test.

Terminal Node Test: The default set of terminal nodes is an empty set unless specified otherwise by the designer at the input stage. If this set is not empty, the end nodes of the current route are checked for membership in this set. The procedure then removes from the remaining candidate list all nodes for which insertion is via a connection to an end terminal node.

Route Circuity Test: Transit routes should be direct and avoid circuitous paths. Each candidate node that passes the previous three tests is examined under the route circuity test for insertion feasibility. This test compares the end to end trip time of the resulting route to the shortest trip time between those end nodes. If the trip time ratio of the resulting route exceeds a

preset circuity factor (currently set to 1.50 for all routes expanded from high demand node pair seeds and 1.25 for all routes expanded from feasible transit center node pair seeds), then the node being tested is dropped from the list. This test checks all nodes remaining in the list for circuity and generates a new candidate list.

Order of Node Insertion and Sorting Properties for Insertion: The previous screening tests generate a set of candidate nodes for insertion. The order of inserting these nodes affects not only the nodal composition of the route under expansion but also that of routes to be expanded later. Baaj (1990) has suggested that the order of expansion follow one of the following four sorting properties based on the cost and/or benefits to the user and/or the operator:

1) direct demand satisfied as a result of inserting the candidate node; this sorting property considers only user benefits without regard to cost.

2) direct demand satisfied per increase of the total in-vehicle travel time as a result of the insertion; this reflects the marginal user benefits relative to the marginal user cost.

3) direct demand satisfied per increase in round trip time of the route under expansion as a result of the insertion; this reflects user benefits versus operator costs.

4) direct demand satisfied per increase of the sum of the total in-vehicle travel time and the round trip time; this measures the user benefits versus the sum of the user cost and operator cost.

Baaj developed a specific node selection and insertion strategy associated with each sorting property, namely, Maximum Demand Insertion (MD), Maximum Demand per Minimum Time Insertion (MDMT), Maximum Demand per Minimum Route Length Increase Insertion (MDML), and Maximum Demand per Minimum Cost Insertion (MDMC), respectively. All four strategies are implemented in the RGP. The details of these strategies are discussed in Appendix A.

At the program input stage, the designer is queried to specify the selection and insertion strategy for each design execution. Candidate nodes with a sorting property value less than a pre specified value (defined for each of the four sorting properties) are discarded. The remaining candidate nodes are divided into two groups. The first group consists of all transit center nodes. The remaining candidate nodes form the second group. Each of the two groups is sorted in decreasing order of the sorting property value. The insertion procedure checks the transit center candidate list first, followed by the second list, until a feasible node is found which satisfies both route capacity constraint (discussed in section 4.5.3.1) and route length constraint (discussed in section 4.5.3.2). This feasible candidate node is inserted and the resulting new route becomes a

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candidate for further expansion. If no feasible node in the candidate list can be found, the expansion process for the route terminates and the next skeleton is selected for expansion.

Termination of Route Expansion

The route expansion procedure terminates if no node in the candidate list satisfies either the route capacity constraint or the route length constraint. These two constraints are described hereafter.

Route Capacity Constraint: The route capacity constraint is based on the idea that if the route service frequency exceeds a maximum implementable level (30 bus/hour) then the schedules will be difficult to maintain. Before a node is inserted, the maximum link flow (Q_{max}) for the route after inserting the node is compared to the allowable maximum link flow capacity (LFC_{max}). If Q_{max} is greater than LFC_{max}, the node is removed from the candidate list for insertion. LFC_{max} is the product of the maximum allowable load factor on buses, LF_{max}; the maximum implementable frequency, f_{max}; and the bus seating capacity, CAP. This can be expressed as:

$$LFC_{max} = LF_{max}f_{max}CAP \qquad (4.5.1)$$

Since it is too cumbersome to keep track of all link flows for each route under expansion, the RGP approximates the maximum link flow (Q_{max}) for the route under expansion by multiplying the route's directly satisfied flow, DF, (i.e. corresponding to node pair demands that are satisfied directly by the route) with the following factors:

1) $(1+f_{tf})$. f_{tf} is the transferring flow factor (currently set at 0.25) which accounts for the transferring flow on the route.

2) f_{lf}, maximum link flow fraction. The RGP uses the middle link's flow as the estimate of the route's maximum link flow if the number of nodes (n) of the route under expansion is even. If n is odd, the same fraction as for the case with n+1 nodes is used in the computation. In order to obtain the fraction, the same amount of originating demand is assumed for each node on the bus route except for terminating nodes which have zero originating demand. Therefore, all non-terminating nodes carry 1/(n-1) of the total demand for cases with an even number of nodes and 1/n of the total demand for cases with an odd number of nodes. It is also assumed that all the originating demand upstream of the middle link on each bus route will traverse the middle link. Therefore, the fraction, f_{lf}, is computed as follows:

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$$f_{lf} = \frac{n}{2(n-1)} \qquad \text{if n is even}$$

(4.5.2)

$$= \frac{(n+1)}{2n} \qquad \text{if n is odd}$$

where n is the number of nodes of the route under expansion.

The same formulation is used by Baaj to estimate the maximum link flow fraction. The approximate maximum link flow is then given by following equation:

$$Q_{max} = (1+f_{tf})f_{lf}DF$$

(4.5.3)

Route Length Constraint: As recommended by NCHRP 69 (1980), excessively long routes should be avoided because bus schedules for long routes are difficult to maintain. In general, the route length should not exceed two hours per round trip. The RGP checks each candidate node for insertion to see if it violates the route length constraint.

SUMMARY OF RGP FEATURES

For the purpose of this study, the RGP needs to generate quality bus route networks that allow the designer to implement alternative design concepts. The RGP achieves this requirement by providing the following important features:

1) It constructs route networks that incorporate the transit center concept. The RGP selects feasible transit center pairs as seeds for constructing initial skeletons; it also uses a lower circuity factor while generating routes between transit centers. These actions result in more direct service between transit centers. In the route expansion step, transit centers are inserted with a higher priority. This action results in more routes available at the transit centers, and thus increases accessibility and transfer opportunities at the centers. In addition, after the desired level of system directness is satisfied, routes are constructed so that the remaining unsatisfied demand (usually dispersed) can be satisfied through the closest feasible transit center to reduce unnecessary vehicle miles. As a result, the resulting route networks from the RGP are suitable for the provision of timed-transfer service and will support the implementation of demand responsive service as well.

2) It is heavily guided by the demand matrix. This can be seen in the selection of node pair seeds. The RGP selects high demand node pairs to form route skeletons. As a result, the generated bus routes directly serve large portions of the total demand.

3) It constructs the routes along the shortest path or alternate short path of high demand

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node pairs. This results in low user travel time cost and high system effectiveness.

4) It constructs different sets of routes corresponding to combinations of objectives. Guided by the designer's specifications, the RGP generates sets of routes corresponding to different system service directness levels, system coverage levels, and node selection and insertion strategies (reflecting user and/or operator costs).

5) It incorporates necessary service planning guidelines including guidelines for route length , route directness, route structure, and loop avoidance.

6) It allows the designer's knowledge to be implemented so as to possibly reduce the search space. In the RGP, the following may be specified by the designers to possibly improve the search efficiency: the minimum number of routes (M), order of expansion of the initial skeletons, the strategy for node selection and insertion, and identification of terminal nodes.

The route networks generated by the RGP are analyzed via the network analysis procedure (NETAP). This procedure assigns known demand between origin-destination pairs to the transit network, determines route frequencies and vehicle sizes (if the variable vehicle size option is chosen), and computes a variety of performance measure. In the next chapter, the NETAP will be presented along with an application to the transit data of Austin, Texas, which illustrates the RGP and the NETAP. In addition, extensive tests of the RGP are presented in Chapter 7.

CHAPTER 5. THE NETWORK ANALYSIS PROCEDURE

INTRODUCTION

The network analysis procedure (NETAP) is intended for analysis and evaluation of alternative network structures and service plans. For a given route configuration and service plan, it computes a variety of system performance measures reflecting the quality of service and the cost experienced by users. In addition, it determines the fleet size, operation cost, and fuel consumption reflecting the resources required by the operator. As an analysis and evaluation tool, the NETAP enables transit planners to evaluate existing or proposed systems.

The role of NETAP in the overall design procedure was described in Chapter 3 and illustrated in Figure 3.1. For the purpose of this study, the NETAP determines route frequencies and vehicle sizes for sets of routes generated by the RGP and evaluates the resulting system. It is also used anytime performance measures for a given network configuration are desired, such as following application of the network improvement procedure (NIP) to determine the extent of improvement and/or worsening in the performance measures of interest.

The major NETAP features that differ from other approaches are the ability to analyze coordinated bus systems and to determine coordinated bus route frequencies and variable vehicle sizes. The NETAP uses a multiple path assignment model that explicitly accounts for trip transfers at coordinated operation terminals. In addition, with minor modification, the model also handles the trip assignment for integrated bus systems. The NETAP uses an iterative procedure to achieve internal consistency of vehicle sizes and route frequencies. Route frequencies for coordinated operation are obtained by adjusting the frequencies of routes that meet at the same transit center to the same or multiple integer values after each iteration of the frequency setting and vehicle sizing procedure.

In the next section, an overview of the NETAP and a summary of its steps are presented. The required input information to execute the NETAP is presented in Section 5.3. Section 5.4 discusses the trip assignment model and the computation of network descriptors. Section 5.5 presents the frequency setting and vehicle sizing procedure, including frequency adjustment for coordinated operation. In Section 5.6, computation of system performance measures and determination of network structure are discussed. The final section presents an illustrative application using transit data from Austin, Texas. This application employs the RGP to generate a route network around the transit center concept. The NETAP is then utilized to determine route frequencies and vehicle sizes and to evaluate the resulting bus system.

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OVERVIEW OF THE NETAP

Eight types of information are determined by the NETAP; these are:

1) Network descriptors consisting of the following three types of data:

- Node information contains originating flow, terminating flow and transferring flow at each demand node. This information is used in the transit center selection procedure (discussed in Section 6.3).

- Link information includes link flows along each route. The maximum link flow on each route is used to determine route frequencies, optimal vehicle sizes, and maximum load factor (discussed in greater detail in Section 5.5).

- Route information includes the round trip time for each route and the total number of passengers on each route. This information is applied to compute the optimal vehicle size. The round trip time is also used to obtain total vehicle miles and required fleet size.

2) Demand: the total number of trips in the system as well as the percentages of demand that are unsatisfied, or satisfied with 0, 1, or 2 transfers.

3) User cost: the total travel time experienced by users in the system, and the respective percentages of in-vehicle travel time, waiting time, transfer time (reflecting a prespecified time penalty considered to be equivalent to a transfer), equivalent in-vehicle-travel time cost, and equivalent waiting cost.

4) Level of service: the service frequency, vehicle size, and load factor associated with each route.

5) Operator cost: the system operation cost and the required fleet size.

6) Fuel consumption: the total system fuel consumption.

7) System utilization: the ratio of the system actual user miles to the total user miles that can be provided by the system.

8) Network structure: classification of network as one of four network shape categories, namely, radial, spinal, grid, and delta networks. In addition, the network is classified as a one-nucleus, two-nucleus, three-nucleus, or multiple-nucleus network.

This information provides the principal measures of system efficiency, service quality, user cost, operator cost, and system utilization that are of interest in the evaluation of a particular transit route network configuration and service plan.

The NETAP is a bus transit network evaluation tool. In this study, it is also used to determine route frequencies and vehicle sizes. Once the RGP generates a set of routes, it is analyzed via the NETAP to determine route frequencies and vehicle sizes (if the variable vehicle size design

option is selected); then the resulting system is evaluated. To accomplish these tasks, the NETAP employs an iterative procedure that seeks to achieve internal consistency of frequencies and vehicle sizes. This iterative procedure consists of two major components, namely, a trip assignment model and a frequency setting and vehicle sizing procedure.

Since route frequencies are required before performing the trip assignment process, an initial set of frequencies is assumed for each route when the NETAP is used for design purposes. The NETAP then computes the round trip time of each route. Next, it utilizes the trip assignment model to assign known demand between origin-destination pairs to the transit network so as to obtain desired network descriptors. At the same time, a variety of performance measures with respect to demand and user costs are computed.

The trip assignment model at core of the NETAP was developed by modifying Baaj and Mahmassani's (1990) TRUST procedure. This model first classifies all demand pairs into 0-transfer, 1-transfer, 2-transfer, and unsatisfied (more than two transfers) demand pairs. System performance measures pertaining to demand (system demand satisfied without transfer, with 1 transfer, with 2 transfers, and unsatisfied system demand) are computed at the same time. The model then takes one node pair at a time and identifies the corresponding competing feasible paths. The definition of competing paths for a certain node pair is based on a lexicographic strategy that considers two criteria: 1) the number of transfers to reach the trip destination and 2) the trip time incurred on the alternative paths. A tripmaker is assumed to always attempt to complete his or her trip by following the path that involves the fewest possible number of transfers. When several paths have the same (minimum) number of transfers, passengers are assumed to use paths with travel times within a threshold (default 10%) of the least time path. Trips for each demand pair are assigned to competing routes at the origin and further assigned at transfer nodes if transfers are needed to complete the trip. Predicates "decide-0", "decide-1", and "decide-2" with certain rules corresponding to the assignment of the 0-transfer, 1-transfer, and 2-transfer demand pair are performed. The demand split among competing paths is computed according to certain rules that account for both uncoordinated and coordinated operations (discussed in Section 5.4.2). Network descriptors and system performance measures pertaining to user costs are updated when a given amount of demand is assigned to each competing path. The trip assignment model sequentially considers each demand pair until all demand pairs are assigned.

For integrated bus systems, the procedure ("drs-assign-demand"), is modified from the above to assign and reallocate unsatisfied fixed service demand (after performing the above trip assignment procedure) to the transit network (discussed in greater detail in Section 5.4.5). The

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role of "drs-assign-demand" in the design of integrated bus systems is presented in detail in Section 6.3.3 and illustrated in Figure 6.2.

Once the trip assignment procedure is complete, the resulting network descriptors are applied to determine the vehicle size and route frequency for each bus route. The frequency setting and vehicle sizing procedure computes the optimal vehicle size via a mathematical formulation which minimizes the total cost (operator cost and user cost) of each individual route. The total number of passenger trips, the maximum link volume, and the round trip time of a given route, determined in the trip assignment procedure, are required to calculate the optimal vehicle size. Once the vehicle size on each bus route is determined, the frequency of service is set to achieve an applicable maximum allowed load factor. For timed-transfer design, the resulting frequencies (set by the above definition) of routes that meet at the same transit center are adjusted to the same or multiple integer values for coordinated operation. Then the resulting route frequencies of service are compared to the input frequencies for each iteration. If frequencies of two consecutive iterations converge, the NETAP calculates system performance measures pertaining to operator cost, level of service, fuel consumption, and system utilization, and determines the network structure. If the revised frequencies are significantly different from the input values, the NETAP reiterates with the revised frequencies as the input frequencies. However, if the NETAP is used for evaluation purposes only, the procedure for determining service frequencies and vehicle sizes is skipped. The flow chart of the NETAP is shown in Figure 5.1. Section 5.5 describes in greater detail the frequency setting and vehicle sizing procedure.

In summary, the NETAP consists of the following steps:

Step 0 If the NETAP is used for design purposes, set an initial frequency for each bus route. Otherwise, go to Step 1.

Step 1 Compute round trip time for each bus route.

Step 2 Classify each demand pair into unsatisfied, 0-transfer, 1-transfer, or 2-transfer demand pair, and compute system demand measures for each category.

Step 3 Assign demand to the network.

3a Set $i = 0, j = 0$.

3b Assign the demand of node pair (i,j), $NP(i,j)$, according to rules associated with its demand category, and update network descriptors and system performance measures pertaining to user costs .

3c If $j < N$ (the total number of demand nodes), set $j = j + 1$ and go to 3b.

3d If $i < N$, set $i = i + 1, j = 0$, and go to 3b.

Step 4 If the NETAP is used for design purposes, determine vehicle size and service

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frequency for each route. Otherwise, go to Step 6.

Step 5 Check if two consecutive sets of route frequencies converge.

If not, set input route frequencies to the revised frequencies and go to Step 3.

Step 6 Compute system performance measures pertaining to operator cost, level of service, fuel consumption, system utilization, and network structure.

INPUT INFORMATION

When the NETAP is employed as part of the overall design procedure, its input data include part of the information supplied by the RGP and the following parameters: 1) a user specified maximum number of iterations for the frequency setting process, 2) operator cost coefficients (a and b, defined in Section 5.5.1) used in determining the optimal vehicle sizes, 3) the in-vehicle travel time value (x) and the waiting time value (w), and 4) a set of prespecified available vehicle sizes and the fuel efficiency coefficient (f_i) associated with each vehicle size i.

If the NETAP is used independently as an evaluation tool for a given bus network, its input data consists of the following four categories:

1) Network: the number of bus transit nodes, lists of nodes corresponding to each bus route and the associated name of each route, a connectivity list , and a list of transit centers.

2) Demand: a symmetric demand matrix representing the demand between each transit node pair.

3) Service characteristics: the service frequency for each bus route, the vehicle seating capacity for each bus route, the allowable maximum load factor, and the vehicle operating speed.

4) Parameters: the transfer time per transfer reflecting the penalty in equivalent minutes of in-vehicle travel time, the in-vehicle travel time value (x), the waiting time value (w), operator cost coefficients (a and b), and the fuel efficiency coefficient (f_i) associated with each vehicle size i.

TRIP ASSIGNMENT MODEL AND COMPUTATION OF NETWORK DESCRIPTORS

As mentioned in Section 5.2, the NETAP consists of two major components: the trip assignment procedure and the frequency setting and vehicle sizing procedure. This section focuses on the trip assignment procedure. For a given bus route network and the associated service frequency for each route, the trip assignment procedure assigns the demand of each

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Input

Is NETAP for design?

Yes → No

Yes:
- Assign initial frequencies (Fi)

No:
- Compute route round trip times

- Classify each demand pair
- Compute system demand measures

- Set i = 0 and j = 0

Is NP (i,j) 0-transfer?

Yes →
Decide-0
- Assign NP (i,j) demand
- Update network descriptors

No

Is NP (i,j) 1-transfer?

Yes →
Decide-1
- Assign NP (i,j) demand
- Update network descriptors

No

Is NP (i,j) 2-transfer?

Yes →
Decide-2
- Assign NP (i,j) demand
- Update network descriptors

No

j < N ?

Yes →
- Set j = j+1

No

i < N ?

Yes →
- Set i = i+1
- Set j = 0

No

Is NETAP for design?

No

Yes:
- Determine bus sizes and route frequencies (Fo)

Do frequencies converge?

No →
- Set frequencies Fi = Fo

Yes:
- Compute all other system performance measures → Output

Figure 5.1 Network Analysis Procedure (NETAP)

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node pair in the network (defined by a demand matrix) to the transit routes. Therefore, the transit demand for each bus route in the network is computed and so is the flow on each link along the bus route. The significance of the trip assignment to the analysis and design of transit networks is demonstrated by three aspects: 1) the allocation of resources (vehicles) is highly dependent on the amount of trips assigned to the transit network routes; 2) the evaluation of performance needs accurate network flow information; and 3) the determination of route frequencies and vehicle sizes requires demand information on both link and route levels.

The transit trip assignment problem differs from the auto trip assignment problem because of waiting at transit stops or terminals. Due to the schedule variation for different available bus routes to the trip destination, the decision of transit passengers may be affected by the availability and the required waiting time of each available route. Many researchers have recognized these phenomena, and developed multiple path assignment models. However, all previously developed transit assignment models are limited to uncoordinated networks. In timed-transfer systems, trip assignment becomes more complicated when several routes are coordinated to arrive at a terminal within a preset time window.

As indicated by Speiss and Florian (1989), several authors have studied the transit trip assignment problem in the past, either as a separate problem (Dial, 1967; Rapp et al., 1976) or as a sub-problem of more complex models, such as transit network design (Lampkin and Saalmans, 1967; Mandle 1979; Hasselstrom, 1981), or multimodal network equilibrium (Florian and Speiss, 1983). Dial (1967) proposed a minimum weighted time path assignment, in which time spent on different modes is differentially weighted. Lampkin and Saalmans (1967) assigned a fraction of passengers to a route according to the probability that a vehicle serving this route arrives earlier than other routes. A lexicographic strategy, reflecting transfer avoidance and/or minimization as the primary criterion for passenger route choice, was recommended by Han and Wilson (1982). Their approach was motivated by systems with overlapping routes that have one or more links in common. An optimal strategy (minimum generalized cost) assignment was presented by Speiss and Florian (1989). In this model, a strategy is a set of rules for the selection of bus routes that form a path to the traveler's destination. The optimization problem in this model was solved by a label-setting algorithm. Baaj and Mahmassani (1990), in their Transit Route Analyst (TRUST), adopted Han and Wilson's lexicographic strategy and Lampkin and Saalmans's "frequency-share" rule. In addition, they used a filtering process which applies a threshold check on the travel time to eliminate any path with a trip time exceeding the minimum value among all possible paths by a specified threshold.

As mentioned above, several transit trip assignment models have been developed to

support transit network design and analysis. These models are all limited to uncoordinated transit networks. As many transit authorities have implemented timed-transfer transit systems, the need for trip assignment models for coordinated transit systems is particularly important. In addition, for the design of integrated bus systems described in this study, the trip assignment model should also account for systems with combined fixed service routes and demand responsive service routes. In this section, a more general model for uncoordinated, coordinated, and integrated systems is presented. This model primarily builds on the trip assignment algorithm developed by Baaj and Mahmassani's (1990).

Trip Assignment Characteristics In Timed-Transfer Systems

A timed-transfer transit system consists of coordinated routes in some or all transfer terminals. These transfer terminals can be divided into 1) uncoordinated operations terminals, 2) coordinated operations terminals with a common headway for all routes, and 3) coordinated operations terminals with integer-ratio headways for all routes.

At uncoordinated operations terminals, vehicles are not scheduled to arrive simultaneously. Transfer passengers usually need to wait for the next bus along the desired route to arrive. When alternative routes are available and acceptable, transfer passengers may take the first bus to arrive (among these routes) However, at coordinated operations terminals, all routes are coordinated to arrive within the preset time window such that transfer passengers will not only have shorter waiting times, but will also have a cluster of alternative routes to choose from.

Missed connections are a common occurrence at coordinated operations terminals. A vehicle becomes unavailable if it arrives behind schedule. In other words, missed connections reduce the set of vehicle routes available at a transit center, and may also cause trips to switch from the missed route to other available routes.

Assignment Rules at Transfer Terminals

Different assignment rules need to be applied to reflect passenger route choice behavior when trips involve different types of terminal operations. In our trip assignment model, the "frequency-share" rule as described in Section 5.4 is used for uncoordinated operations terminals. At coordinated operations terminals with a common headway, all competing routes are available to transit passengers in all scheduled time windows. Therefore, a "least downstream travel cost" rule which assigns all the demand to the route with the least downstream travel time is utilized. Competing routes are those that pass a screening procedure, described later in Section 5.4.3. At coordinated operations terminals with integer-ratio headways, different combinations of

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available bus routes may be available to transit passengers in different time windows. In this case, a "vehicle-availability" rule is first applied to determine the probability that a certain combination of bus routes is available. For a given combination, the "least downstream travel cost" rule is then employed. Table 5.1 summarizes the rules and logic applied to each type of transit terminal. Details of the assignment rules for the different types of terminals are described hereafter.

Uncoordinated Operations Terminals: Route assignment at uncoordinated operations terminals follows the "frequency-share" rule. The "frequency-share" rule was employed by Lampkin and Saalmans (1967), and adopted by Baaj and Mahmassani (1990). It assumes that transit passengers will always board the first arriving vehicle of any competing route. The rule stipulates that a route carries a proportion of the flow equal to the ratio of its frequency to the sum of the frequencies of all competing paths. Thus, if d_{ij} is the demand from origin i to destination j, and there are three competing routes R1, R2, and R3 with frequencies of f1, f2, and f3, respectively; then R1 carries demand $\{[f1/(f1+f2+f3)]d_{ij}\}$, R2 carries demand $\{[f2/(f1+f2+f3)]d_{ij}\}$, and R3 carries demand $\{[f3/(f1+f2+f3)]d_{ij}\}$ on all the links used by d_{ij}.

Table 5.1 Summary of Assignment Rules and Logic for Different Types of Transit Terminals

Assignment	Terminal Type		
	Uncoordinated	Coordinated with a common headway	Coordinated with multiple-integer headways
Rules	Frequency share	Least downstream travel cost	1. vehicle-availability 2. Least downstream travel cost
Logic	Transit passengers always board the first available bus among all competing routes.	All competing routes are available in all scheduled time windows. Transit pasengers choose the route with least downstream travel cost.	Different combinations of competing routes may be available in different time windows. For a certain combination of competing routes, transit pasengers choose the route with least downstream travel cost.

Coordinated Operations Terminals with a Common Headway: At coordinated operations terminals, the "frequency-share" rule becomes implausible because transit passengers may have more than one route to choose from within the preset time window. In any time window, it will be more appropriate to assign trips to the downstream route with the least travel cost among available competing routes. In case of a common headway for all coordinated routes, all competing routes will be available in all time windows. The "least downstream travel cost " rule is applied on an "all-or-nothing" basis, with all trips (between a given O-D pair) assigned to the least cost route.

Coordinated Operations Terminals with Integer-Ratio Headways: In the case of coordinated routes with integer-ratio headways, some competing routes may be available at some but not all time windows. In other words, different but still synchronized route frequencies result in different combinations of simultaneously available bus routes for transferring passengers. For example, consider two competing routes R1 and R2 with respective frequencies of one and two vehicles per hour. R1 will be available only in alternate time windows, while R2 will be available in all windows. In other words, one of every two consecutive time windows has both routes available, while the other time window has only one available route R2. Therefore, to solve the route assignment problem for coordinated operations terminals, a "vehicle-availability" rule is applied to determine the probability p_i that passengers arrive at the terminal when a particular combination of competing routes' vehicles S_i is available. The probability p_i is equal to the fraction of the time windows which contain only the set S_i. Within each set of competing routes defined in the "vehicle-availability" rule, the "least downstream travel cost" rule is applied to assign demand to the least travel cost downstream route.

To obtain S_i and p_i, the following variables are defined:

f_0 is the frequency of route R0 which carries flow into the coordinated operations terminal.

R1, R2, R3 ..., Rn are competing routes at the coordinated operations terminal.

f_1, f_2, f_3..., f_n are route frequencies for competing routes R1, R2, R3 ..., and Rn, respectively, with the relationship $f_1 \geq f_2 \geq f_3 \geq ... \geq f_n$,.

$F = \{f_0, f_1, f_2, f_3..., f_n\}$ is the set of frequencies of all coordinated routes at the transfer terminal.

A_i is equal to the ith minimum component of F, and $A_0 = 0$.

S_i is the set of available competing routes with frequencies greater than or equal to A_i.

The total number of time windows available to passengers at a coordinated operations terminal in a one-hour cycle is $Min(f_0, f_1)$. The number of time windows containing any set of

competing routes S_i (i = 1, ..., m) in a one hour cycle is equal to A_i; $(A_i - A_{i-1})$ is the number of time windows containing only the set of competing routes S_i in a one-hour cycle. From the above results, p_i can be expressed as

$$p_i = \frac{A_i - A_{i-1}}{Min(f_0, f_1)} \quad , \text{ for all } A_i \leq Min(f_0, f_1) \tag{5.4.1}$$

To illustrate this formulation, consider four competing routes R1, R2, R3, and R4, with $f_1=8$, $f_2=4$, $f_3=2$, and $f_4=1$ vehicles per hour. The frequency (f_0) of the incoming route R0 is assumed to be four vehicles per hour. From the above formulation, $Min(f_0, f_1)=4$, $A_1=1$, $A_2=2$, $A_3=4$, $p_1=0.25$, $p_2=0.25$, $p_3=0.5$, $S_1=\{R1, R2, R3, R4\}$, $S2=\{R1, R2, R3\}$, and $S_3=\{R1, R2\}$. As shown in Figure 5.2, in a one-hour cycle, transfer passengers use four time windows. This quantity is equal to $Min(f_0, f_1)=4$, the denominator in equation (5.4.1). S_1, containing R1, R2, R3, and R4, is available in only one out of the four time windows ($A_1=1$). S_2, containing R1, R2, and R3, is available in two out of four time windows ($A_2=2$). S_3, containing R1 and R2, is available in all four time windows ($A_3=4$). One out of the four time windows (A_1-$A_0=1$ and $p_1=1/4=0.25$) has S_1 as the set of available competing routes. Thus, it is clear that $(A_i$-$A_{i-1})$ is the number of time windows in the cycle containing only the set of available competing routes S_i. One out of the four time windows (A_2-$A_1=1$, and $p_2=1/4=0.25$) has S_2 as the set of available competing routes. Two out of four time windows (A_3-$A_2=2$, and $p_3=2/4=0.5$) have S_3 as the set of available competing routes.

If a coordinated operations terminal is a demand origin, where passengers do not arrive at the terminal by a coordinated route, then passengers are assumed to arrive at the terminal by a random process. In this case, the number of time windows available to transit passengers is bounded by f_1, the maximum frequency among all competing routes. Therefore, one can simply view this case as one with $f_0=\infty$, i.e. as though buses arrive continuously.

After obtaining all possible sets of available competing routes (S_i), and the associated percentages (p_i) of the time windows containing only S_i, the "least downstream travel cost " rule is applied to each S_i. The number of trips, $p_i d_{ij}$, is assigned to the route in S_i with the least downstream travel cost.

Missed Connections of Coordinated Routes: At coordinated terminals, transfer passengers transfer from the incoming route R0 to the least travel cost route Rj in each time window as described in the previous section. The situation in which vehicles of R0 or Rj arrive at transfer terminals before the preset time window has no effect on the assignment. A missed connection occurs when vehicles of R0 or Rj, or both arrive after the end of the scheduled time window.

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R0 $f_0=4$ vehicles per hour

$f_1=8$

$f_2=4$

$f_3=2$

$f_4=1$

time

TW1   TW2   TW3   TW4

One hour cycle

☐   Scheduled time windows (TW1, TW2, TW3, TW4) for R0

■   Scheduled time windows for transfer routes
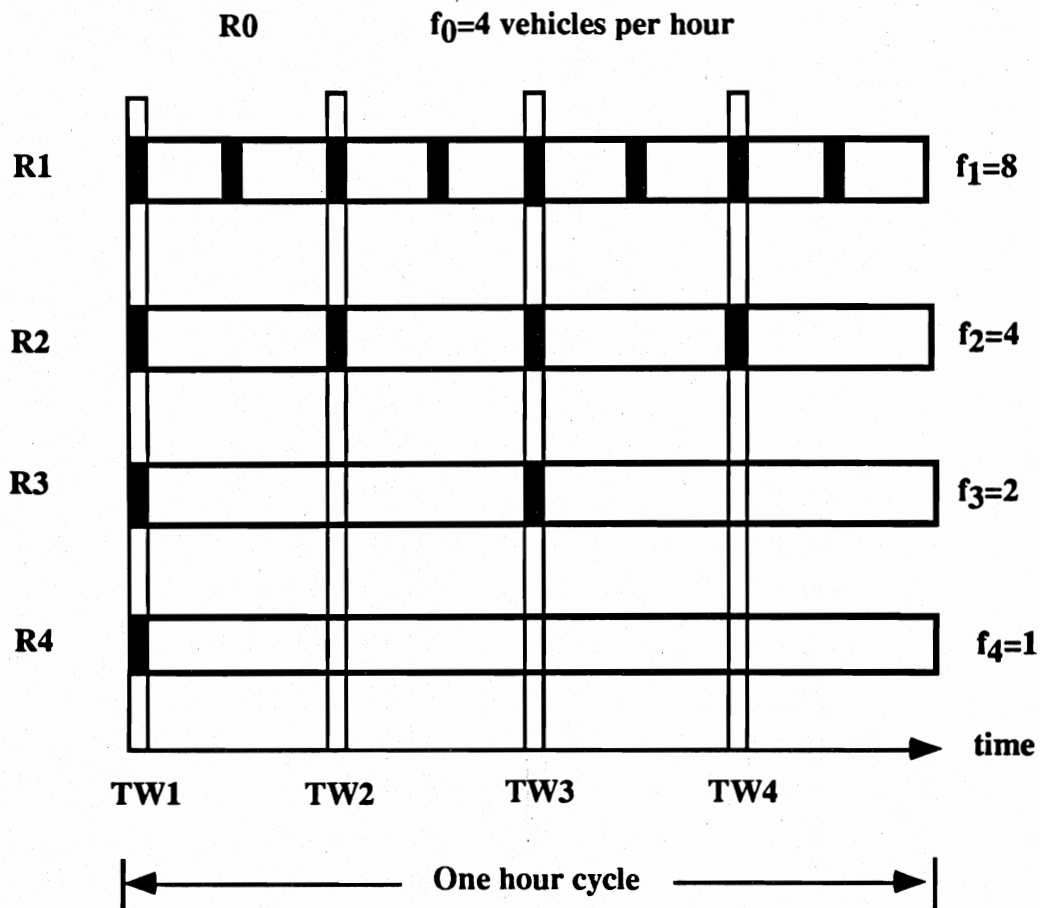
TW1 contains 4 available transfer routes {R1, R2, R3,R4}
TW2 contains 2 available transfer routes {R1, R2}
TW3 contains 3 available transfer routes {R1, R2, R3}
TW4 contains 2 available transfer routes {R1, R2}

Figure 5.2 Vehicle Availability at a Coordinated Terminal

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It is assumed that each coordinated route has the same probability of being late at all time windows. In addition, unless this probability is quite high, it is unnecessary to account for situations in which more than one coordinated route are late, since the joint probability of more than one coordinated route being late will be very low and negligible. This model assumes that at most one coordinated route may arrive behind schedule within each time window. Under these assumptions, arrival of the incoming route R0 behind schedule does not affect the trip assignment, since for any time window there will be the same amount of demand due to this kind of missed connection coming from the previous time window and going to the next window. For the case that one of the outgoing routes is behind schedule, only the least travel time cost route may result in assignment change if it is behind schedule. Under this situation, route assignment needs to consider the following two cases:

Case 1 In time windows with more than one competing routes for transferring, the lost demand of the least downstream travel cost route (due to the missed connection) will be shifted to the route with the second least downstream travel cost.

Case 2 In any time window which has only one available route R1 (usually with the highest frequency among all competing routes with integer-ratio headways), the lost demand of R1, caused by its delay, is shifted to the route with the least downstream travel cost in the next available time window. If the frequency of R1 (f_1) is greater than the frequency of the incoming route R0 (f_0), R1 must be the only available transferring route with frequency greater than f_0 for the above case to occur. Under this condition, the "lost demand" of R1 reverts back to the same route but in the next available time window, where it will be the only available route. For cases with $f_1 \pounds f_0$, R1 may not be the only available route nor the least downstream travel time route in the next available window. Furthermore, the next available window may contain different combinations S_j (j = 1, ..., m) of available competing routes. Each combination S_j contains routes with frequencies greater than and equal to A_j, the jth minimum frequency of F as defined in the previous section. Therefore, the fraction (r_j) of the lost demand of R1 that shifts to the least travel time route of a certain combination S_j needs to be defined. The fraction r_j can be obtained as the ratio of the number of "R1 only" windows followed by windows with S_j, to the number of "R1 only" windows in a one hour cycle. Since f_1 is the highest frequency among all competing routes, A_m is equal to f_1; S_m is the set of available competing routes with frequencies greater than and equal to A_m. In this case, S_m contains only R1. The number of "R1 only" time windows in a one hour cycle is equal to (A_m-A_{m-1}) as described in the previous section. The number of "R1 only" windows followed by windows with S_j for j < m

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in a one hour cycle is equal to (A_j-A_{j-1}). The number of "R1 only" windows followed by windows with S_m (window containing only R1) in a one hour cycle is equal to (A_m-2A_{m-1}). Therefore, r_j can be expressed as:

$$r_j = \frac{A_j - A_{j-1}}{A_m - A_{m-1}} \qquad \text{for } j = 1, \dots, m-1, \text{ and}$$

$$= \frac{A_m - 2A_{m-1}}{A_m - A_{m-1}} \qquad \text{for } j = m \qquad\qquad (5.4.2)$$

Thus, the previous model needs to be modified to reflect route assignment changes due to missed connections; p_{imc} denotes the probability of being late for the route in the set of available routes, S_i (defined in Section 5.4.2.3), with the least downstream travel cost path. The modification of the trip assignment procedure applies the following steps for each S_i.

Step 1 Check each S_i to see if it contains only one route R1.

   If yes, go to Step 3.

Step 2 Assign $p_i p_{imc}$ of the total trips to the route in S_i with the second least downstream travel cost, and $p_i(1-p_{imc})$ of the total trips to the route in S_i with the least downstream travel cost.

Step 3 If $f_1 > f_0$, assign p_i of the total trips to R1.

   Otherwise,

   (1) assign $p_i(1-p_{imc}) + p_i p_{imc} r_m$ of the total trips to R1, and

   (2) assign $p_i p_{imc} r_j$ of the total trips to the route in S_j (j = m-1, ... 1) with the least downstream travel cost.

Trip Assignment Procedure for Timed-Transfer Systems

The trip assignment model presented here adopts the lexicographic strategy suggested by Baaj and Mahmassani (1990), and incorporates the trip assignment concept for coordinated operations terminals described in the previous section. In this model, all origin and destination demand pairs are first classified as 0-transfer, 1-transfer, 2-transfer, or unsatisfied (more than two transfers) depending on the lowest number of transfers required for each demand pair. The demand for each demand pair classified as 0-transfer, 1-transfer, 2-transfer, or unsatisfied is added to the following demand parameters *DEMAND-0-TRANSFER*, *DEMAND-1-TRANSFER*, *DEMAND-2-TRANSFER*, and *UNSATISFIED-DEMAND-LIST*, respectively. These demand parameters are used later to compute the percentages of demand in the system that are unsatisfied, or satisfied with 0, 1, or 2 transfers.

When more than one paths have the same minimum number of transfers for a given demand node pair, a "travel cost check" rule is employed to find a set of competing paths. This rule eliminates paths with travel costs greater than a threshold above the minimum travel cost (from the minimum travel cost path among all paths with the fewest number of transfers). The assignment for each demand node pair is based on the demand category (0-transfer, 1-transfer, and 2-transfer) in which the node pair is classified. Assignment procedures applicable to each category are applied. The demand of a given node pair is first assigned at the origin terminal, then assigned at transfer terminals if necessary. Since three types of terminal operations need to be considered in timed-transfer transit systems, the various assignment rules discussed in the previous section are applied. The details of the trip assignment procedure for different demand categories are described hereafter.

Classification of Demand Node Pairs: The trip assignment procedure for timed-transfer transit systems considers each demand node pair separately. For a given pair, $NP(i,j)$, 0-transfer paths are searched for by checking the intersection of two sets of routes, SR_o and SR_d, which are the sets of routes passing through origin i and destination j, respectively. If the intersection of SR_o and SR_d is not an empty set, the routes in the set are classified as 0-transfer paths for $NP(i,j)$. A 0-transfer path is denoted by a list (R_o, i, j) which represents passengers boarding route R_o at the origin (i), and traveling on it to the destination (j). Once $NP(i,j)$ is classified as a 0-transfer node pair, the parameter, *DEMAND-0-TRANSFER*, is then updated by adding the demand d_{ij} of $NP(i,j)$. Otherwise, there is no 0-transfer path for $NP(i,j)$, and the next level of transfer paths (1-transfer paths) needs to be checked.

If d_{ij} cannot be assigned directly, paths that connect i and j with one transfer are searched for. The search process for 1-transfer paths is carried out by examining the node lists of every possible combination of route members of SR_o (i.e., that pass through node i, say R_o) and of SR_d (say R_d), for the intersection set of nodes contained in both R_o and R_d. If the intersection set is not empty, then its contents are possible transfer nodes for $NP(i,j)$. For example, if the intersection set contains $(tn_1, tn_2 ..., tn_k)$, there are k 1-transfer paths. Each of these 1-transfer paths is denoted by a list $((R_o, i, tn_k)(Rd, tnk, j))$ which represents passengers boarding route R_o at i, and staying on it until node tn_k, where the passengers transfer to route R_d, and travel on it until j. If the demand node pair can be classified as 1-transfer, *DEMAND-1-TRANSFER* is updated by adding d_{ij}.

If no 1-transfer path can be found for d_{ij} (in the absence of 0-transfer paths), then 2-transfer paths are searched for. The process begins by finding a route, R_c, that passes through neither

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node i nor j, but shares a node with a route passing through i (e.g., R_o, a member of SR_o) and another node with a route passing through node j (e.g., R_d, a member of SR_d). The set of routes, SR_c, that passes through neither node i nor node j is the complement of the union of the previously defined SR_o and SR_d, (SR_o U SR_d). For a trip to require exactly two transfers between origin i and destination j, the first route R_o, has to pass through node i (hence, R_o Œ SR_o); the second route R_c must be a member of SR_c; and the third route R_d has to pass through node j (hence, R_d Œ SR_d). Therefore, if the "list-of-nodes" of a route from SR_c (say R_c) intersects both the "list-of-nodes" of a route from SR_o (say R_o), and the "list-of-nodes" of the route from SR_d (say R_d), then possible 2-transfer paths can be defined. A possible 2-transfer path is denoted by a list with three components, $((R_o \ i \ tn_l) \ (R_c \ tn_l \ tn_k) \ (R_d, tn_k, j))$. This list means that the passengers board route R_o at i, and stay on it until node tn_l, where the passengers transfer to route R_c, and travel on it until tn_k, where the passengers transfer to route R_d, and travel on it until j. If NP(i,j) can be classified as 2-transfer, *DEMAND-2-TRANSFER* is updated by adding d_{ij}. Otherwise the demand of the node pair is unsatisfied and is added to *UNSATISFIED-DEMAND-LIST*.

Assignment for 0-Transfer Demand Pairs: For all the 0-transfer paths, the "travel cost check" rule is applied to eliminate 0-transfer paths in which the travel cost exceeds the minimum travel cost among all 0-transfer paths by a specified threshold. In the current version of NETAP, the travel cost function used in TRUST (Baaj and Mahmassani, 1990) is adapted. In this function, the travel cost is equal to the sum of three components: total passenger waiting time, total passenger in-vehicle travel time, and transfer penalties (5 minutes of equivalent in vehicle travel time for each transfer). This cost function assumes the same value for each time component. This assumption may be easily relaxed to account for different relative valuation of different cost components.

The travel cost for a 0-transfer path (TC_o) includes the waiting time at the origin i ($t_{wait,i}$) and the in-vehicle travel time from node i to node j using route R_o ($t_{invtt,i \ j|R_o}$), and can be expressed as:

$TC_0 = t_{invtt,i \ j|R_o} + t_{wait,i}$

Since the given demand d_{ij} can be assigned without a transfer, assignment will only occur at the origin node i. Thus, if node i is an uncoordinated operations terminal, the route assignment rule for uncoordinated operations terminals should be applied. Otherwise, d_{ij} should be assigned according to the rule for coordinated operations terminals. The downstream travel cost for a 0-transfer path is equal to $t_{invtt,i \ j|R_o}$.

Assignment for 1-Transfer Demand Pairs: The same travel cost check process described in the 0-transfer case is applied to all 1-transfer paths to obtain the set of competing

paths. The travel cost for a 1-transfer path, TC_1 is computed as

$$TC_1 = t_{invtt,i\ tn_k|R_o} + t_{invtt,tn_k\ j|R_d} + t_{wait,i} + t_{wait,tn_k} + t_{tp}$$

where

t_{tp} is the transfer penalty per transfer expressed in equivalent minutes of in-vehicle travel time.

In the 1-transfer case, trips are not only assigned at the origin, but also reallocated at the transfer node. At the origin, the trip assignment procedure is the same as in the 0-transfer case, except that it is now applied to classes of paths rather than to individual paths. A class of paths is formed by paths that share the same starting route (Ro) at origin. Demand is first allocated among alternative classes; within each class, demand is then equally assigned to the constituent paths. The fraction of demand that the whole class carries determines by using the assignment rules described in Section 5.4.2, based on the terminal operation type of the origin. The downstream travel cost at the origin for each path is equal to $\{t_{invtt,i\ tn_k|R_o} + t_{invtt,tn_k\ j|R_d} + t_{wait,tn_k} + t_{tp}\}$.

Trips assigned to each path at the origin need to be reallocated at the transfer node. Paths with the same starting route (R_o) and the same transfer node (tn_k) form a group G_{ok}. Paths in each group travel the same route from origin to the same transfer node, but use different routes to travel from the transfer node to the destination. Based on the transfer node type, the total trips assigned to each group are redistributed to the paths in the group using the appropriate route assignment rule corresponding to the transfer node. The downstream travel cost for each competing route at the transfer node is equal to $t_{invtt,tn_k\ j|R_d}$.

Assignment for 2-Transfer Demand Pairs: The same travel cost check is applied to obtain the set of 2-transfer competing paths. The travel cost for a 2-transfer path, TC_2 is computed as

$$TC_2 = t_{invtt,i\ tn_k|R_o} + t_{invtt,tn_l\ tn_k|R_c} + t_{invtt,tn_k\ j|R_d} + t_{wait,i} + t_{wait,tn_l} + t_{wait,tn_k} + 2t_{tp}.$$

The trip assignment at the origin and at the first transfer node follows the same procedure as in the 1-transfer case, except that the downstream travel cost for paths at the origin is $\{TC_2 - t_{wait,i}\}$, and at the first transfer node is $\{t_{invtt,tn_l\ tn_k|R_c} + t_{invtt,tn_k\ j|R_d} + t_{wait,tn_k} + t_{tp}\}$. Similarly, at the second transfer node, paths with the same upstream routes (R_o and R_c) and transfer nodes (tn_l and tn_k) form a group G_{olck}. The sum of demand that each group carries after the assignment at the first transfer node is then reassigned to the paths within that group at the second transfer node using the appropriate route assignment rule. The downstream travel cost for each path at the second transfer node is $\{t_{invtt,tn_k\ j|R_d}\}$.

Under the assumptions that 1) passengers arrive at random (uniformly), 2) passengers can always board the first available bus, and 3) vehicles arrive at regular headways, the average waiting time for passengers using a certain route is taken as half of the route's headway. This half headway assumption is used to compute the expected waiting time at trip origins and at uncoordinated transfer terminates for the computation of travel time of competing paths. At the trip origin, an average waiting time (in minutes) of $60.0/(2f_o)$ (one half Ro's headways) is used for $t_{wait,i}$. At transfer terminals tn_l and tn_k, average waiting times (in minutes) of $60.0/(2f_d)$, and $60.0/(2f_d)$ (one half Rc's and R_d's headways, respectively) are assumed for t_{wait,tn_l} and t_{wait,tn_k} if these transfer nodes are not coordinated operations terminals. Otherwise, t_{wait,tn_l} and t_{wait,tn_k} are assumed to be one half the preset time window (default 5 minutes).

The expected transit passenger waiting time for a certain bus route in an actual system depends on both the reliability of the bus schedule and the distribution of passenger arrival times. Under the assumption of uniformly distributed random passenger arrivals at bus stops, the average passenger waiting time increases as bus headways become less regular and as more passengers arrive in average during longer intervals and fewer during shorter intervals (Osuna and Newell, 1972; Larson and Odoni, 1981). However, passengers may not necessarily arrive at random in all cases. Some transit users tend, to some extent, to coordinate their arrivals with published schedules, if available, especially for routes with long headways. Bowman and Turnquist (1981) have derived an expression for the expected wait time when the population of users is a mixture of "scheduled timers" and "random arrivals". The resulting waiting time function is highly system dependent, and should be calibrated for each system, possibly for each bus route. However, the effect of schedule timing is to some extent offset by schedule unreliability, making the one-half-headway assumption an acceptable compromise. More important, from a design standpoint, virtually all procedures use that assumption for three primary reasons. First, schedule variability is not intended by design, and is usually a reduction target by system operators. Secondly, while "schedule timers" may not incur an actual physical wait time at the stop, they incur a schedule delay relative to the actual time they would have wanted to depart. From a user cost standpoint in a design procedure, it is this schedule delay cost that must be included in the objective function, and not the actual time at the stop. Evaluating waiting time on the assumption that users time their arrivals to coincide with the schedule can seriously underestimate user costs and lead to designs that do not meet user needs.

Numerical Application to a Single Demand Node Pair

To illustrate the assignment procedure described in the previous section, Figure 5.3 shows a

demand node pair (i,j) served by seven routes. Four examples are considered: 1) an uncoordinated network; 2) a fully coordinated network with integer-ratio headways; 3) a fully coordinated network with a common headway; and 4) a fully coordinated network with integer-ratio headways and a probability of being late p=0.1 for all routes. Link travel times are shown in Table 5.2. Examples 1, 2, and 4 use the same route frequencies, also given in Table 5.2. A five minute time window is used in all the coordinated operations examples. The threshold for the travel cost check is set at 10%. A five minute penalty per transfer is given for all cases.
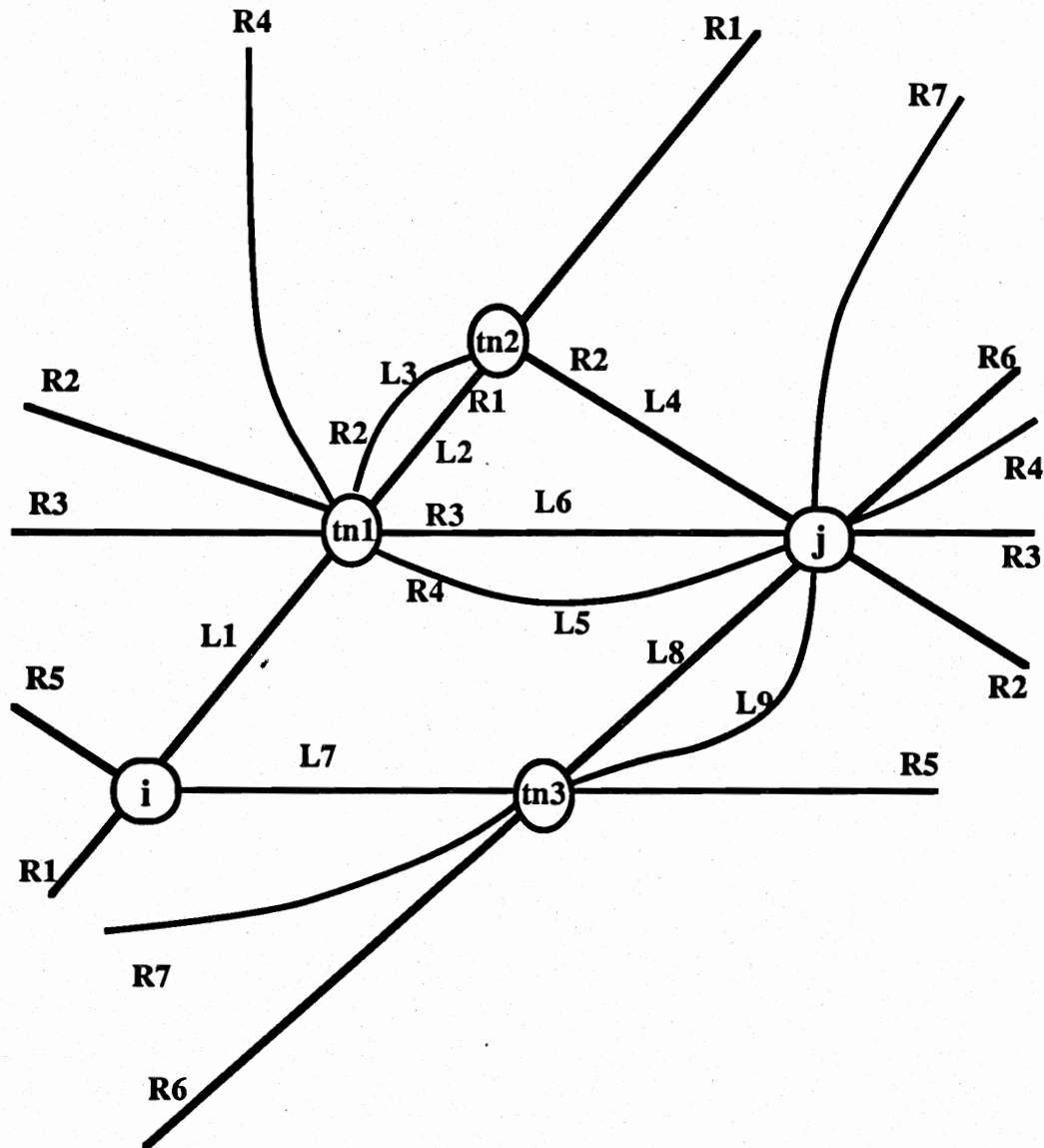
Figure 5.3 Example Route Network with Six 1-Transfer Paths

**Table 5.2 Link Travel Times (minutes) and Route Frequencies (buses/hour)
for Example of Figure 5.3**

Links	L1	L2	L3	L4	L5	L6	L7	L8	L9
Travel Times	8	4	5	6	9	8	8	7	8

Routes	R1	R2	R3	R4	R5	R6	R7
Frequencies	8	4	4	2	4	4	2

Table 5.3 Path Links and Path Travel Cost for Example of Figure 5.3

Path	List Representation	Links	Travel Cost (minutes)		
			Uncoordinated	Coordinated	Downstream
P1	((R1 i tn1)(R3 tn1 j))	L1, L6	31.8	26	8
P2	((R1 i tn1)(R2 tn1 j))	L1, L3,L4	34.8	29*	11
P3	((R1 i tn1)(R4 tn1 j))	L1, L5	40.5*	27	9
P4	((R1 i tn2)(R2 tn2 j))	L1, L2,L4	33.8	28*	6
P5	((R5 i tn3)(R6 tn3 j))	L7, L8	35	25	7
P6	((R5 i tn3)(R7 tn3 j))	L7, L9	43.5*	26	8

* **Paths eliminated by the travel cost screening process.**

No 0-transfer route can be found in the given network. Six 1-transfer paths are found in the path search process. The link components for each path are presented in Table 5.3. The path travel costs for both uncoordinated and coordinated operations and the downstream travel cost at the transfer node for coordinated operations are shown in Table 5.3 as well. After the travel cost screening process, paths P3 and P6, and paths P2 and P4 are eliminated from the set of 1-transfer paths in the uncoordinated and coordinated examples, respectively.

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Table 5.4 Proportions of Demand Between Nodes i and j
          Assigned to Paths in All Cases

Paths		P1	P2	P3	P4	P5	P6
Uncoordinated	At origin	0.22	0.22	0*	0.22	0.33	0*
	Final assignment	0.22	0.22	0*	0.22	0.33	0*
Coordinated	At origin	0.25	0*	0.25	0*	0.25	0.25
	Final assignment	0.5	0*	0	0*	0.5	0
Common Headway	At origin	0	0*	0	0*	0.5	0.5
	Final assignment	0	0*	0	0*	1	0
Missed Connection	At origin	0.25	0*	0.25	0*	0.25	0.25
	Final assignment	0.475	0*	0.025	0*	0.5	0

* Paths eliminated by the travel cost screening process.

Table 5.5 Proportions of Demand Between Nodes i and j
          Assigned to Links in All Cases

Links	L1	L2	L3	L4	L5	L6	L7	L8	L9
Uncoordinated	0.67	0.22	0.22	0.44	0	0.22	0.33	0.33	0
Coordinated	0.5	0	0	0	0	0.5	0.5	0.5	0
Common Headway	0	0	0	0	0	0	1	1	0
Missed Connection	0.5	0	0	0	0.025	0.475	0.5	0.5	0

Trip Assignment for Integrated Bus Systems

The trip assignment procedure presented in the previous sections handles both uncoordinated and coordinated bus systems with fixed-route and fixed-schedule service. However, the design of integrated bus systems is another alternative provided by the solution framework. For this purpose, the trip assignment procedure should also account for systems that combine fixed-route, fixed-schedule service with demand responsive service (DRS).

The integrated system consists of two sets of routes: fixed service routes and DRS routes. Each route of both sets consists of a list of nodes. As assumed for the fixed-route, fixed-schedule system, passengers will be willing to travel by bus if their trips can be completed within two transfers. Passengers in an integrated system are assumed to first consider the fixed route service if their trips can be completed by such service. If not feasible, passengers then consider using the demand responsive service or a combination of DRS and fixed route service. Therefore, trip assignment for integrated bus systems first employs the assignment procedure described in the previous sections for fixed route service to assign demand and identify demand node pairs with unsatisfied passengers (by the fixed route service). Then, a modified procedure is used to allocate and assign this unsatisfied demand to the integrated systems.

The modified trip assignment procedure distributes the demand unsatisfied by the fixed route system to service segments in the integrated system. For example, consider a node pair (i, j) with unsatisfied demand, d_{ij}, and served by two service segments, $(DRS_k \ i \ tn_1)$ and $(R_n \ tn_1 \ j)$, meaning that passengers board a DRS route at node i and stay on it until node tn1 where they transfer to a fixed route and travel on it until node j. In the segments served by DRS routes, the demand is satisfied by the DRS route k and thus the demand for route k is increased by an amount d_{ij}. In the fixed route segments, the demand d_{ij} is added to the demand between node pair (tn1, j) in the demand matrix. Furthermore, the demand of (i, j) is set to zero in the demand matrix. By doing this, the demand previously unsatisfied in the fixed route system can be redistributed to the fixed route network in the integrated bus system. After all the unsatisfied demand is reallocated, a new demand matrix results. This demand matrix will be used to determine the flow distribution of the fixed route service so that the service frequency and vehicle size can be set for each fixed route in the integrated bus system. In other words, a new demand matrix is used to run the fixed route trip assignment procedure.

In a DRS service area, passengers unsatisfied by the fixed route can be delivered from or to the transit center. A passenger whose destination or origin is covered by the DRS service area needs to transfer at the transit center and then use the fixed route service or other DRS to complete his or her trip. Therefore, fixed route unsatisfied passengers can be classified as drs-0-transfer, drs-1-transfer, drs-2-transfer, and drs-unsatisfied.

The trip assignment procedure considers each node pair with unsatisfied demand by the fixed route system separately. For a given node pair (i, j) with unsatisfied demand, d_{ij}, drs-0-transfer paths are searched for first by using the same procedure as described in Section 5.4.3.1 for 0-transfer paths in the fixed route service system. If d_{ij} can be completed without transfer, it must be served by at least one DRS route. Once a drs-0-transfer path (DRS_k, i, j) can be found, d_{ij}

is added to the demand of DRS route k. If more than one drs-0-transfer path is identified, d_{ij} is equally assigned to each DRS route. No adjustment to the demand matrix is needed because there is no fixed route service segment for the unsatisfied demand in this category. The demand satisfied with 0 transfer (*DEMAND-0-TRANSFER*) is updated by adding d_{ij}.

If d_{ij} cannot be assigned directly, drs-1-transfer paths are searched for. The search process for drs-1-transfer paths is similar to the process for 1-transfer paths in the fixed route service system, as described in Section 5.4.3.1, except that passengers using DRS routes can only transfer at transit centers and not at every node along the DRS route. Therefore, for any DRS route considered in the search process, only the transit center is included in the "list-of-nodes" for transferring (instead of the complete "list-of-nodes" of the route). A drs-1-transfer path can be composed of either two DRS routes,$\{(DRS_k \ i \ tn_1) \ (DRS_l \ tn_1 \ j)\}$, or a DRS route and a fixed route, $\{(DRS_k \ i \ tn_1) \ (R_n \ tn_1 \ j)\}$or $\{(R_n \ i \ tn_1) \ (DRS_k \ tn_1 \ j)\}$. In the first case, d_{ij} is added to the demand of both DRS routes. In the second case, both the demand of DRS route k and of node pair (tn_1, j) (or node pair $(i \ tn_1)$) are increased by d_{ij}. The demand of node pair (i, j) is set to zero. The demand satisfied with 1 transfer (*DEMAND-1-TRANSFER*) is updated by adding d_{ij}. If more than one drs-1-transfer path is found, passengers are assumed to choose the path with the fewest DRS segments. Therefore, d_{ij} is equally assigned to each path with the fewest DRS segments.

If no drs-1-transfer path can be found for d_{ij}, the procedure that searches for drs-2 transfer paths is invoked. The procedure is similar to the corresponding procedure in the fixed route service system, with the modification that the DRS routes can only transfer at transit centers, as described above for drs-1-transfer paths. There are two possible types of drs-2-transfer paths: those with DRS routes at both ends of the path and a fixed route in the middle, and paths with two adjacent fixed routes and one DRS route at either end of the path. The first type of path can be denoted by a list $\{(DRS_k \ i \ tn_1) \ (R_n \ tn_1 \ tn_2) \ (DRS_l \ tn_2 \ j)\}$. The second type can be denoted by $\{(DRS_k \ i \ tn_1) \ (R_n \ tn_1 \ tn_2) \ (R_m \ tn_2 \ j)\}$ or $\{(R_n \ i \ tn_1) \ (R_m \ tn_1 \ tn_2) \ (DRS_k \ tn_2 \ j)\}$. If d_{ij} is satisfied by a path of the first type, the demand of DRS routes k and route l, and the demand of node pair $(tn_1 \ tn_2)$ are increased by d_{ij}. For the second type of path, the demand of DRS route k is increased by d_{ij}. d_{ij} is added to the demand of node pair $(i \ tn_2)$ if the path starts with a fixed route service. Otherwise, d_{ij} is added to the demand of node pair $(tn_1 \ j)$. The demand of node pair (i,j) is set to zero, and *DEMAND-2-TRANSFER* is updated by adding d_{ij}. If more than one drs-2-transfer path is found, the same strategy as for the drs-1-transfer paths is applied. If no drs-2-transfer path can be found, the demand node pair remains unsatisfied.

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Computation of Network Descriptors

Through the property representation of the LISP computer language, node flows (consisting of originating flow, terminating flow, and transferring flow), link flows associated with each route, and route flow (total number of passengers served by the route) are initially set to zero. Link flow values associated with a route are represented by a property list. For example, the link flows of R1 with nodal composition (0 1 2 3 4 5) and R2 with nodal composition (4 5 6 7 8) are set to zero and represented by the lists ((l-0-1 0) (l-1-2 0) (l-2-3 0) (l-3-4 0) (l-4-5 0)) and ((l-4-5 0) (l-5-6 0) (l-6-7 0) (l-7-8 0)), respectively. Both R1 and R2 utilize the same physical link joining nodes 4 and 5, but for the purpose of assignment and flow information, link l-4-5 associated with R1 is different from link l-4-5 associated with R2. After determining the competing paths and the associated percentages of demand assigned to these paths for each demand node pair, the flow information for the node, link, and route levels is updated by adding assigned demand to the proper nodes, links, and routes that are traversed. For example, if p percent of d_{ij} is assigned via a 1-transfer path ((R1 1 4) (R2 4 7)), then the originating flow at node 1, the transferring flow at node 4, the terminating flow at node 7, and the route flows for R1 and R2 are updated by adding the quantity of demand pd_{ij}. In addition, the link flows of l-0-1, l-1-2, l-2-3, and l-3-4 on R1; and of l-4-5, l-5-6, and l-6-7 on R2 are increased by pd_{ij}.

FREQUENCY SETTING AND VEHICLE SIZING PROCEDURE

The previous sections presented the trip assignment procedure which computes network, route, link, and node descriptors. When the NETAP is utilized as part of a design tool, it also calls a procedure to determine the service frequency and vehicle size for each bus route. This section describes the iterative frequency setting and vehicle sizing procedure which yields internally consistent service frequencies and vehicle sizes using information computed from the trip assignment.

The well-known square-root rule for setting frequencies on bus routes is based on the minimization of the sum of operator cost and passenger waiting time (Mohring, 1972). Major weaknesses of the square-root formulation are that it does not account for bus capacity constraints and that it assumes demand to be independent of service frequency. In the transit industry, the frequency of service on a bus route is commonly set to achieve an applicable maximum allowed load factor (Furth and Wilson, 1981), and can be written as:

$$f_k = \frac{(Q_k)_{max}}{LF_{max}VS_k} \tag{5.5.1}$$

where

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f_k is the route frequency for route k,

$(Q_k)_{max}$ is the maximum hourly link flow of route k,

LF_{max} is the maximum allowed load factor, and

VS_k is the vehicle size (seats).

With this frequency formulation, transit operators can select the desired load factor so as to meet operational considerations (such as comfort). Note that different load factors may be set for different subsets of bus routes depending on the type of service provided, service area, and other special considerations reflecting local political preferences. Of course, when the frequency generated by this equation is unacceptably low because of low patronage, a minimum frequency policy is commonly applied in practice.

Only in a few studies have vehicle sizes been computed explicitly. Glaister (1986) developed a simulation model to compare system operations using two vehicle sizes, a large vehicle (88 seats) and a small vehicle (15 seats). Results of the simulation suggest that buses seating 35 to 45 riders would likely be most suitable for service in Aberdeen. Its level of detail notwithstanding, the computer simulation model does not explicitly describe the relationship between bus size and factors such as level of demand, operator cost, and load factor. Analytic models for finding optimal vehicle sizes have been developed for this purpose.

Previous analytic models include Jansson's (1980), Walters' (1982), Oldfield and Bly's (1988), and Chang's (1990). Jansson argued that previous analyses overweighed the producers' costs and underestimated the users' cost . He presented a model that minimizes total social cost including operator cost, passenger waiting time, and passenger riding time, subject to a peak capacity constraint satisfying a maximum occupancy rate (the ratio of the mean passenger flow to the product of the vehicle size and the service frequency). Jansson concluded that the optimal bus size determined by minimizing social cost tends to be smaller than the size used in current practice, where vehicle size is given and the number of buses is determined so as to achieve an average occupancy rate at or below a given maximum value. Walters presented a simpler model that examines the trade-off between waiting time and labor cost. He also suggested that the bus size should be considerably smaller than is typically used in cities of western Europe and North America. Gwilliam et al. (1985) and Oldfield and Bly (1988) argued that the waiting time assumption in Walters' model is questionable, and thus yields an implausible relationship between optimal bus size and demand. Oldfield and Bly's model assumes elastic demand and determines the optimal bus size by minimizing total social cost. In addition, the average passenger waiting time in their model accounts for situations where passengers are unable to board the first bus to arrive because it is full. They concluded that the optimal size lies between 55 and 65 seats (70-

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seat buses are used by most existing systems in the United Kingdom). The current cost structures could be changed to be more favorable to the operation of smaller buses, but the optimal size seems unlikely to fall below 40 seats. Chang (1990) presented analytic models to compare vehicle sizes between fixed route conventional bus and flexible route subscription bus systems. He concluded that the optimal vehicle size for flexible route service is less sensitive to the demand density than the optimal size for fixed route service.

All the previous analytic models focus on the optimization of vehicle size and frequency for an individual bus route, which is treated independently of the other routes comprising the network. In other words, the demand on a particular bus route will not be affected by the optimal bus sizes and associated route frequencies of other bus routes. This is an incorrect assumption because in a bus system, passengers may have several paths on which to complete their trips. Changes to the bus size and route frequency alter the route level of service and should lead to a redistribution of passenger flows on the bus network. Therefore, in designing route frequency and vehicle size, the systemwide effects of changes in frequency and vehicle size need to be considered.

Instead of assuming the demand on each bus route to be known and given as in all previous models, the model presented here solves for the route demands by assigning the trips in a given O-D demand matrix using the transit trip assignment model described in Section 5.4. The transit trip assignment model computes both the total passenger trips using route k (TPT_k) and the corresponding maximum link flow of route k, $(Q_k)_{max}$. The resulting maximum link flow is more reliable than the value obtained as the product of the maximum occupancy rate and vehicle seating capacity. Both TPT_k and $(Q_k)_{max}$ then form the basis for obtaining a set of optimal bus sizes (discussed in the next section) and the associated route frequencies (obtained by using Equation 5.5.1) so as to minimize the generalized cost function. For timed-transfer system design, the frequencies of coordinated routes need to be set to the same or multiple integer values. A frequency adjustment procedure is utilized to accomplish this task.

In determining vehicle sizes for different routes, it should be kept in mind that it is not practical to operate too many vehicle sizes in a system because of the resulting operational complexity and associated maintenance costs. In the process for computing vehicle sizes described above, a different vehicle size may be selected for each bus route and thus there will be too many vehicle sizes to operate practically. To overcome this disadvantage, the procedure allocates a set of prespecified vehicle sizes to each route using a simple nearest feasible integer heuristic. Five different sizes of commercially available vehicles is an appropriate guideline for the maximum number of vehicle sizes in a system. Shih and Mahmassani (1994) used an example

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based on the data generated from Austin, Texas, transit system to show that meaningful benefit can be observed even with a relatively small set of vehicle sizes.

An initial set of input frequencies is required for the trip assignment. The NETAP simply assigns the same initial frequency of 10 buses/hour to all routes. Since the procedure changes route frequencies from the input values to new values, the demand needs to be reassigned consistently with the new frequencies, and the optimal vehicle sizes and route frequencies then need to be recomputed as well. The procedure iteratively searches for internal consistency of the route frequencies and vehicle sizes. In other words, this procedure continues until the revised frequencies are not much different from the previous frequencies (up to 10 % deviation is allowed).

The computation of route frequencies to achieve a preset peak load factor is only meaningful when the demand assignment is performed over the peak hour period, especially if the network is congested. However, one would expect the NETAP to be used for different time-of-day periods. For less congested periods, the peak load factor may yield frequencies that are too low to be reasonably expected by riders. In this case, minimum policy headways would be used. The NETAP checks the output frequency for each route, which is computed to achieve the preset *MAX-LOAD-FACTOR* (currently set to 1.25). If the frequency does not exceed a *CUTOFF-FREQUENCY* (currently set to 2 buses/hour), the route belongs to the category of low ridership routes. The NETAP recomputes the frequency using a *MIN-LOAD-FACTOR* (currently set to 0.8) which represents the minimum load factor accepted by operators. If the recomputed frequency is still less than a *MIN-FREQUENCY* (currently set to 1 bus/hour), then the output frequency is set to 1 bus/hour, and the load factor is computed accordingly.

Optimal Vehicle Size for Single Route with Given Demand

The approach for determining the optimal vehicle size for each individual route is similar to the generalized cost approach used to obtain the square-root expression for frequency setting. However, instead of considering the frequency as the decision variable and the vehicle size as a constant, the vehicle size is taken as the decision variable, and the frequency is set as a function of the vehicle size consistently with equation (5.5.1).

For a given demand level on a bus route k, the optimal vehicle size is obtained by minimizing the generalized cost (C_k), which consists of the operator cost (C_{ko}) and the user cost (C_{ku}); i.e. C_k = C_{ko} + C_{ku}. The derivation of the optimal vehicle size is based on peak hour operation, which is the most critical period for determining the required system fleet size. However, the procedure could be applied to any desired operating period.

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Oldfield and Bly (1988) presented a reasonable and simple approximate formulation that expresses total operator costs as a linear function of vehicle size, as follows:

$$C_{ko} = a (1 + b \, VS_k) VM_k \qquad (5.5.2)$$

where

a is a constant which adjusts the overall cost level,

b is a constant which captures the relative rate of increase in cost with increasing vehicle size, and

VM_k is the total vehicle miles per hour operated on route k.

The total vehicle miles per hour for each route k can be expressed as:

$$VM_k = f_k \, RTM_k \qquad (5.5.3)$$

where

f_k is the frequency of service on route k, and

RTM_k is the round trip miles for route k.

Assuming that the function f_k is set according to the equal peak hour load factor rule (Equation 5.5.1), the operator's cost can thus be expressed as:

$$C_{ko} = a(1 + bS_k)RTM_k \frac{(Q_k)_{max}}{LF_{max} VS_k} \qquad (5.5.4)$$

From the passengers' point of view, the total user cost (C_{ku}) for route k consists of three components: waiting cost (WC_k), in-vehicle travel cost ($IVTTC_k$), and access cost (AC_k), as proposed by Chang (1990).

$$C_{ku} = WC_k + IVTTC_k + AC_k \qquad (5.5.5)$$

Using the half headway assumption as described in Section 5.4.3.4, the average waiting time for passengers using route k is taken as half of the route's headway. Assuming that waiting time is valued linearly (an assumption which may be easily relaxed if alternative value functions are calibrated from empirical behavioral data), the total waiting time for passengers using route k can be expressed as:

$$WC_k = wTPT_k \frac{1}{2f_k} = wTPT_k \frac{LF_{max} VS_k}{2(Q_k)_{max}} \qquad (5.5.6)$$

where

w is the value of waiting time, and

TPT_k is the total passenger trips (demand) per hour using route k (which is computed in the trip assignment procedure).

The in-vehicle travel cost is assumed independent of vehicle size, primarily because in-

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cost savings. In-vehicle travel cost reduction may arise mostly from possibly different average vehicle speeds for different vehicle sizes. Smaller buses may provide faster service for two reasons: 1) better maneuverability, and 2) fewer people getting on and off. On the other hand, they may also increase traffic congestion since more buses will be operated on the road, and thus the bus speed may decrease. Since bus speed is highly dependent on traffic conditions along the route, any improvement in the in-vehicle travel time cost of smaller buses is usually limited and insignificant relative to the potential waiting time cost saving. It should also be noted in this regard that studies on the characterization of traffic service in urban street networks have strongly suggested that the travel time and related service attributes experienced by vehicles of different types over a sufficiently long period of time tend to be very similar because of the constraining effect of traffic control and the character of urban traffic (Herman and Ardekani, 1984).

Another consideration for the constant $IVTTC_k$ assumption is the difficulty and resulting complexity of incorporating $IVTTC_k$ as a function of vehicle size in the cost function. The relationship between vehicle speed and the vehicle size is difficult to specify analytically, especially, in light of vehicle speed variation under different traffic conditions. Furthermore, vehicles with the same size but different engines may have different acceleration and deceleration characteristics. In light of the above, it seems hardly worth the effort to incorporate route-dependent and condition-dependent $IVTTC_k$.

Using the above results and assumptions, the generalized cost C_k can be rewritten as:

$$C_k = a(1 + bVS_k)RTM_k \frac{(Q_k)_{max}}{LF_{max}VS_k} + wTPT_k \frac{LF_{max}VS_k}{2(Q_k)_{max}} + AC_k + IVTTC_k$$

(5.5.7)

Note that AC_k and $IVTTC_k$ are independent of the vehicle size. The optimal bus size VS_k^* for given route demand levels can be obtained by setting $dC_k/dVS_k = 0$, and can be expressed as:

$$VS_k^* = \frac{(Q_k)_{max}}{LF_{max}} \sqrt{\frac{2aRTM_k}{wTPT_k}}$$

(5.5.8)

The relation indicates that the optimal vehicle size for a given demand level on a route is proportional to the level of the maximum link flow $((Q_k)_{max})$, and varies as the square root of round trip miles of the route (RTM_k). The optimal vehicle size is inversely proportional to the load factor (LF_{max}), as well as the square root of the total number of passenger trips (TPT_k) and the value of waiting time (w).

In the above expression, the total cost (and associated "optimal" vehicle size) for a given route depend on the flow level TPT_k. However, the latter is itself the result of the users' path choice through the network, which is a function of the vehicle sizes and frequencies not only on

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the given route k, but on all network routes k=1, ... K. The flows TPT_k, k=1.... K are given by an assignment procedure, reflecting a passenger path choice rule, which distributes a given peak-period O-D trip matrix to the various bus routes. In our procedure, the vehicle sizes on each route (and associated frequencies) are set on the basis of route flows that are consistent with the vehicle sizes and frequencies through the iterative application of an assignment algorithm along with the vehicle sizing formula developed in this paper. It should be noted however that the vehicle sizes obtained by this procedure are not necessarily optimal for the network as a whole. In other words, we do not seek to explicitly minimize the systemwide cost $C = \sum_{k=1}^{K} C_k$ subject to consistency with a given assignment rule. Because of the network level interactions described earlier, the objective function is not separable on a route by route basis. The resulting problems would be rather formidable to solve because the assignment procedure used cannot be expressed as a well-behaved mathematical formulation. Instead, we propose a practical procedure that achieves an internally consistent solution that improves on existing methods.

Frequency Adjustment for Coordinated Routes

The RGP generates the set of routes and the TCSP identifies the set of transit centers, but neither procedure determines which routes are coordinated in the design of timed-transfer systems. Generally, routes are coordinated with a prespecified time window (currently set to 5 minutes) at transit centers in timed-transfer systems. Based on this idea, all routes that pass through the same transit center are grouped into a set of coordinated routes. This task is achieved by using a predicate "coordinated-routes-at-transit-centers" which examines the "list-of-nodes" of all routes for the existence of transit centers. If the "list-of-nodes" of a route contains a certain transit center, the route is coordinated at the transit center. The predicate " coordinated-routes-at-transit-centers" generates a set of coordinated routes for each transit center.

One very important concept of the timed-transfer system is that coordinated routes need to be set to the same or multiple integer frequencies. Furthermore, since there may be some coordinated routes which serve more than one transit center, it is necessary to group all routes that are coordinated with these routes and set route frequencies in the same group to the same or multiple integer frequencies. The predicate "group-coordinated-nodes" is utilized to obtain the sets of coordinated transit centers that are connected (directly or indirectly) by coordinated routes. For each set of coordinated transit centers, a set of coordinated routes can be defined by taking the union of the sets of coordinated routes defined by the " coordinated-routes-at-transit-centers" predicate.

To illustrate how the above procedures work, a network with four transit centers t1, t2, t3, and

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To illustrate how the above procedures work, a network with four transit centers t1, t2, t3, and t4 is used. After running the " coordinated-routes-at-transit- centers" predicate, the sets of coordinated routes for t1, t2, t3, and t4 are (R1 R2 R3), (R2 R4 R5 R6), (R1 R7 R8), and (R9 R10), respectively. Applying the "group-coordinated-nodes" predicate, two sets of coordinated transit centers are found, which are (t1 t2 t3) and (t4). Routes passing through t1 should be coordinated with routes passing through t2 and t3 because R2 serves both t1 and t2 and R1 serve both t1 and t3. Therefore, a set of coordinated routes, (R1 R2 R3 R4 R5 R6 R7 R8), is defined, which contains routes serving t1, t2, and t3. A second set of coordinated routes contains only routes (R9 R10) which pass through t4.

The frequency adjustment procedure is part of the iterative process for frequency setting. In each iteration, the NETAP calls "frequency-adjuster" to adjust the frequencies of the routes in each set of coordinated routes. For the frequency adjustment, a "headway-list" is set which contains 16 possible combinations of headways with multiple integer relations between each of the components. The 16 possible combinations are: (60 30 15 7.5), (60 30 15 5), (60 30 15 3), (60 30 10 5), (60 30 10 2), (60 30 6 2), (60 30 6 3), (60 20 4 2), (60 20 10 2),(60 20 10 5), (60 12 4 2), (60 12 6 2), (60 12 6 3), (40 20 10 2), (40 20 10 5), and (40 8 4 2). The intent is to adjust each frequency determined by using Equation 5.5.1 in each set of coordinated routes to the nearest frequency in one of the combinations, and minimize the total deviation between the adjusted frequencies and the input frequencies. This task is accomplished by checking all combinations one by one to find the combination with the least total deviation, and then setting the frequency of each coordinated route to its nearest frequency in the combination. Once the frequency adjustment process is completed, the resulting frequencies are compared to the input frequencies for the termination of the frequency setting and vehicle sizing procedure.

COMPUTATION OF SYSTEM PERFORMANCE MEASURES AND CHARACTERIZATION OF NETWORK STRUCTURE

Demand

In Section 5.4, the demand parameters *UNSATISFIED-DEMAND-LIST*, *DEMAND-0-TRANSFER*, *DEMAND-1-TRANSFER*, and *DEMAND-2-TRANSFER* are updated in the process of demand pair classification. Once all demand pairs are classified, the final values of these demand parameters are divided by the total demand to obtain the percentage of demand that is unsatisfied, or satisfied with 0, 1, or 2 transfers, respectively.

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User Costs

NETWORK-IN-VEHICLE-TRAVEL-TIME, *NETWORK-WAITING-TIME*, and *NETWORK-TRANSFER-TIME* are initially set to zero. During the trip assignment, the above user cost measures are updated after the associated percentages of demand are assigned to the competing paths for each demand pair. Using the example from Section 5.4.5, *NETWORK-IN-VEHICLE-TRAVEL-TIME* is increased by multiplying pd_{ij} by the sum of the travel time from node 1 to node 4 on R1 and by the sum of the travel time from node 4 to node 7 on R2; *NETWORK-WAITING-TIME* is increased by multiplying pd_{ij} by the sum of the waiting times at node 1 and at node 4; *NETWORK-TRANSFER-TIME* is increased by multiplying pd_{ij} by the transfer penalty. Once all the elements of the demand matrix are assigned, the *NETWORK-TOTAL-TRAVEL-TIME* is obtained by summing over the final values of the above three components.

In Section 5.4.3.4, the evaluation of the expected waiting time as one half the headway was discussed and proposed for passengers using a certain bus route at uncoordinated terminals. At uncoordinated terminals or at any origin where there are several possible routes, and the passenger is assumed to board the first "feasible" route to arrive, the headway is derived from the pooled process for all possible routes. Therefore, the expected headway is equal to 60.0 (minutes) divided by the sum of all competing routes' frequencies. The expected waiting time is equal to half this expected headway.

At coordinated terminals, if the terminal is an origin node, all competing routes are coordinated and have common or integer-ratio headways. The duration between two consecutive time windows with outgoing competing routes is equal to the minimum headway of all the competing routes. In this case, the average waiting time is set to one half this minimum headway, i.e. $60/(2f1)$, where f1 is the maximum frequency of all the outgoing competing routes as defined in Section 5.4.2.3. If the terminal is a transfer node, the average waiting time for each passenger is assumed to be one half the preset time window when the frequency (f_0, as defined in Section 5.4.2.3) of the incoming route (R_0) is less than or equal to the maximum frequency (f_1) of all the outgoing competing routes. However, if $f_0 > f_1$, transferring passengers on average have to wait more than one half the preset time window. The average waiting time (in minutes) for each passenger can be expressed as:

$$t_{wait} = 0.5tw + 60.0(n - 1)/2f_0 \qquad\qquad (5.6.1)$$

where

n is equal to f_0/f_1

tw is the preset time window.

For example, if f_1 = 1/hour and f_0 = 3/hour at a transfer terminal, one third of the passengers need to wait for 42.5 minutes, one third of the passengers need to wait for 22.5 minutes, and the remaining one third need to wait for 2.5 minutes. Therefore, on average, each passenger has to wait for 22.5 minutes which is 7.5 minutes less than the average waiting time for the uncoordinated condition.

Level of Service

The details of the computation of the route frequency, vehicle size and load factor for each bus route are presented in Section 5.5.

Operator Cost

Once the route frequency (f_k) and vehicle size (VS_k) for each route k are determined, the required fleet size, N_{sk}, for each route can be computed by using:

$$N_{sk} = f_k RTT_k/60 \qquad\qquad (5.6.2)$$

where

RTT_k is the round trip time of route k

The required number of each vehicle size i, Ni, is obtained by summing up the number of buses required for all the routes in the system that have the same bus size, i.e., $N_i = \sum_{s=i}^{over\ all\ k} N_{si}$.

The operating cost for each bus route is a function of vehicle size and vehicle-miles and can be determined from equation 5.5.2. The system operating cost can thus be calculated by summing over all route operating costs, i.e., $C_o = \sum_{over\ all\ k} C_{ko}$.

Fuel Consumption

Fuel consumption per hour for a bus route k, FC_k, can be readily computed as the product of the fuel efficiency coefficient f_i (gallons/miles) for vehicle type (size) i and the vehicle-miles per hour VM_k.

$$FC_k = f_i VM_k \qquad\qquad (5.6.3)$$

The fuel consumption for the overall bus system is then obtained by summing over all FC_k.

System Utilization

The system utilization is defined as the ratio of the total actual user miles (*total-user-miles*) to the maximum user miles (*max-user-miles*) that could be provided by the system. The total actual user miles for a bus system is computed in the trip assignment procedure. When a certain amount of demand (d) is assigned to a link with distance (s), the *total-user-miles* is increased by the product of d and s. Once all the demand pairs are assigned, the total actual user miles for the

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bus system is determined. The "max-user-miles" is calculated by summing over all the maximum amount of user miles that could be provided by each route. The maximum user miles provided by each route is equal to the product of the route frequency, route round trip mile, and vehicle size (seating capacity). The utilization of a transit system is an index of effectiveness of the service provided and resource allocation of the system.

Network Structure Descriptor

The classification of network structure is an important aspect of the overall evaluation of bus systems. To facilitate comparison of alternative networks generated by the RGP, summary descriptors of the network shape are included. The NETAP incorporates the identification model developed by Liu (1994). In the following section, a brief discussion of this model is presented.

The identification model establishes several criteria based on planar graph theory for classifying bus networks. This model includes three sequential parts. In the first part, it determines the number of nucleus-nodes in a network based on the frequency distribution of routes. Depending on the number of nucleus-nodes, a network is classified as a one-nucleus, two-nucleus, three-nucleus, or multiple-nucleus network. Once the number of nucleus-nodes is determined, the second part of procedure seeks to identify the shape of the network.

The second part of the procedure classifies a network based on the frequency distribution of modified-routes. A modified-route is defined by a pair of edges incident on a non-terminal node. An edge is different from a transit link since there is at most one edge between any given pair of nodes, but more than one transit links may be present between two nodes. The procedure first checks whether the network has one intersection-node. If this is the case, the network is classified as a radial network. Otherwise, the procedure checks whether the maximum number of modified-routes that pass through any node is larger than or equal to $\max\{3, k_1\}$. If the above condition is satisfied, the network is classified as a radial network. The value of k_1 varies with different network sizes. A nonlinear relation between k_1 and the total number of routes in the network was also given by Liu. However, if the condition is not satisfied, the procedure checks the number (frequency) of nodes with two and three modified-routes. If nodes with two modified-routes passing through them are the most frequent in the network, the network is classified as a grid network. If nodes with three modified-routes passing through them are the most frequent in the network, the network is classified as a delta network. If none of the above conditions are satisfied, the procedure moves to the third part.

The third part of the procedure classifies a network using two measures, namely, the circuity index (f_c) and intersection-node index (f_{id}). The circuity index is given by :

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$$f_c = \frac{N_e - N_d + 1}{2(\sqrt{N_d} - 1)^2}$$ (5.6.4)

where

N_d: the number of nodes in the bus transit network, and

N_e: the number of edges in the bus transit network.

The expression of the intersection-node index is as follows:

$$f_{id} = \frac{2N_{id}}{N_R^2}$$ (5.6.5)

where

N_{id}: the number of intersection-nodes in the bus transit network, and

N_R: the number of routes in the bus transit network.

The procedure checks the sum of the circuity index and the intersection-node index. If the sum is between 0 and 0.5, the network is considered to be a spinal network. If the sum is larger than 0.5 and the circuity index is less than or equal to 0.75, the network is classified as a grid network. If the circuity index is greater than 0.75, the network is classified as a delta network.

Additional detail regarding the network shape classification procedure is available in the report by Liu (1994).

ILLUSTRATIVE APPLICATION

In this section, the Austin, Texas, urban area serves to illustrate the RGP for generating networks around the transit center concept. Using the resulting route network, NETAP is utilized to illustrate the design and analysis of a coordinated bus system with variable vehicle sizes.

Data Preparation

In order to execute the RGP and NETAP, four important data lists must be made available, namely, the network connectivity list, the transit demand matrix list, the shortest path list between all demand nodes, and the list of alternate paths for high demand nodes.

A total of 177 nodes are defined to describe the service area and associated network connectivity. All 177 nodes are selected from the existing transit network which consists of 40 routes with fixed schedules, operated by the Capital Metropolitan Transit Authority (Capital Metro, for short). The list of locations associated with these 177 nodes is presented in Appendix B. The network connectivity is generated from street links that connect these 177 nodes and are suitable for bus operations. This network connectivity is represented by a list, *connectivity-list*, also shown in Appendix B.

The generation of the demand matrix is based on Tsygalnitzky's fluid analogy model (Tsygalnitzky, 1979), tested successfully by Simon and Furth (1985) against actual origin-destination data, and coded in LISP by Baaj (1990). Tsygalnitzky's fluid analogy model has been widely used by transit agencies because of its simplicity and relative reliability. This model estimates a route O-D matrix from on-off surveys that are regularly conducted by many transit agencies. The main assumption for this model is that at a given bus stop, every qualified passenger is equally likely to alight. A qualified passenger at a given bus stop needs to have been on board a certain minimum distance. At a given stop, the alighting ratio of the number of qualified passengers boarding from an upstream stop to the total number of qualified passengers is determined. The demand from a certain bus stop to the given bus stop is obtained by multiplying the associated alighting ratio and the number of alighting passengers at the given stop. The LISP computer program implementing Tsygalnitzky's algorithm developed by Baaj (1990) is presented in Appendix C.

Tsygalnitzky's model was applied to existing boarding and alighting data obtained from Capital Metro. These data correspond to a typical weekday peak hour demand in 1993 for all 177 demand nodes defined above. There were a total of 5784 transit demand trips; the highest node pair demand was 25 hourly transit trips.

The shortest paths were generated from each node to all other nodes using the given network connectivity for the Austin transit network; 113 high demand node pairs in which the demand exceeds 7 trips/hour are used in the process of generating the alternate short path list. The LISP codes of the shortest path algorithm and the alternate short path algorithm developed by Baaj (1990) are presented in Appendix D.

Nine transit centers, as shown in Figure 5.4, are specified for this example; these include node 2 in downtown Austin, nodes 9, 19 and 36 in the north, nodes 87 and 101 in the east, and nodes 73, 78 and 84 in the south. These nodes are generated by the transit center selection procedure (TCSP), described in Chapter 6, based on information from the current transit system. The maximum demand per minimum route length increase insertion strategy (MDML) is followed in the route expansion process. No pre-determined set of terminal nodes is assigned. The number of initial skeletons is chosen as 25. The shortest paths are used in the layout of initial skeletons. The minimum system directness level is set at 60%, and the minimum system coverage level is set at 80%. In addition, the maximum operational bus frequency, the transfer penalty, the load factor on all routes, and the bus seated capacity are set to the default values namely 30 buses/hour, 5 minutes of in-vehicle travel time, 1.25, and 40 seats, respectively.

The coefficients, a and b , in the operator's cost function are derived from the operator costs associated with different bus sizes which were provided by Capital Metro; they are equal to 2.96 and 0.0078, respectively. These coefficients should be recomputed for other cities because wage rates and gasoline costs vary from city to city. The maximum load factor for peak hour service is chosen to be 1.25 (i.e., up to 10 standing passengers are allowed at any time if the bus seating capacity is 40 passengers) which is suggested by NCHRP 69 (1980). The value of out-of-vehicle waiting time (w), is set to $9 per hour. The value of the in-vehicle travel time is set to $3 per hour (one third of the waiting time value). Three commercially available vehicle sizes with 37, 27, and 15 seats, and with fuel efficiency coefficients of 3, 6, and 9 miles per gallons, respectively, are considered in this application.
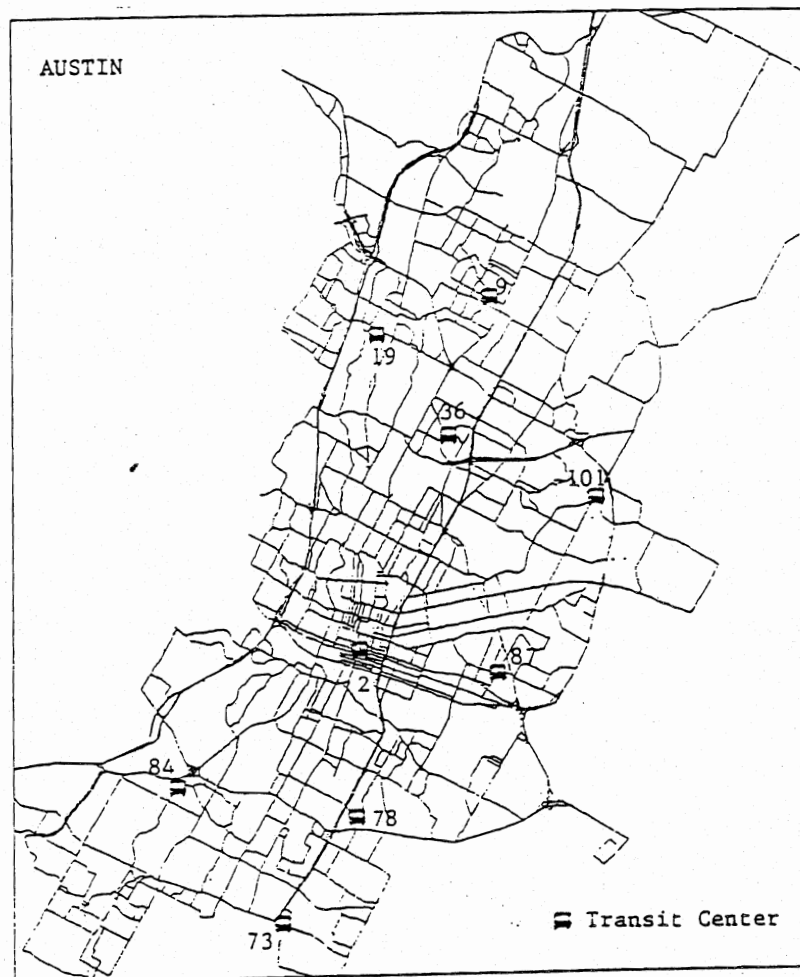
Figure 5.4 Transit Centers for Austin Study Case

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==============================================================================
                          OUTPUT SUMMARY FOR RGP
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Set of transit centers = (2 36 19 73 78 9 101 87 84)

Set of terminal nodes = NIL

Number of initial skeletons = 25

Layout of skeletons uses the shortest paths

Apply MDML rule for node selection and insertion

The minimum system directness level = 60%

The minimum system coverage level = 80%

Maximum route frequency = 30.0

Maximum load factor = 1.25

Node pairs are (((73 78) 18) ((2 78) 15) ((19 36) 4) ((1 2) 25) ((2 73) 22) ((2 67) 21) ((66 67) 20) ((2 36) 19) ((73 78) 18) ((5 9) 18) ((107 108) 17) ((5 176) 17) ((2 64) 17) ((1 73) 17) ((2 121) 16) ((86 103) 15) ((78 121) 15) ((73 121) 15) ((5 6) 15) ((2 78) 15) ((40 41) 14) ((8 9) 14) ((73 120) 13) ((4 9) 13) ((2 65) 13))

The initial 25 skeletons after expansion met only 54.98% of the total demand directly.

The resulting 27 routes satisfied 60.30% of the total demand directly.

The resulting 27 routes satisfied 87.14% of the total demand.

Route Generation required 2373.86 CPU seconds.

Figure 5.5 Output Summary for Application of the RGP

5.7.2 Results of RGP and NETAP Illustrative Application

Figure 5.5 shows the output from the RGP. The output first shows the values of all the use control parameters given in the previous section. 25 demand node pairs are used as seeds for the initial skeletons, which include 3 feasible transit center node pairs and 22 high demand node pairs. The demand node pair (1,2) has the highest demand of 25 hourly trips. After expansion of the 25 initial skeletons, the network meets 54.98% of the total demand directly (system directness level). This indicates that more routes need to be generated to reach the desired minimum system directness level of 60%. A total of 27 routes are generated with 60.30 % of demand satisfied directly and 87.14% of the total demand satisfied, meeting the required minimum system directness level of 60% and the required minimum system coverage level of 80%, respectively.

Information for all 27 routes is shown in Table 5.6, which includes route round trip time, service frequency, load factor, vehicle size, and nodal composition. Other information, including the number of buses required, the operator cost, the waiting cost, and the link flows for each route are also provided by the computer output, but not listed in the table. One set of 21 coordinated routes resulting from the design consists of R1, R2, R4, R5, R6, R8, R9, R10, R11, R12, R13, R14, R15, R16, R17, R20, R22, R23, R24, R26 and R27..

Table 5.7 shows the summary of system performance measures, which include the demand information, user cost, operator cost, fuel consumption, and system utilization. The bus system satisfies 60.30% of demand without transfer, 23.96% with one transfer, 2.87% with two transfers; 12.86% of demand is unsatisfied. The total in-vehicle travel time is 149,769 minutes which is equivalent to $7,488.44 for x = $3 per hour, and the total out-of-vehicle waiting time is 43,229 minutes which is equivalent to $6,478.02 for w = $9 per hour. The network transfer penalty is equal to 8,590 minutes. The network total user cost, which is the sum of the total in-vehicle travel time, total out-of-vehicle waiting time, and network transfer penalty, is equal to 201,588 minutes. The system operates at a cost of $6,593.59, requires 91 15-seat buses, 52 27-seat buses and 16 37-seat buses, and consumes 289.53 gallons of fuel per peak hour. The system utilization is equal to 0.56.

Table 5.8 presents the result of the network structure identification model for the network generated by the RGP. The output includes three parts. In the first part, the first line shows the "diagnosis" reached by the model. The network is classified as a "three-nucleus spinal" network. The following lines list the value of the circuity index, the intersection-node index, the number of routes, the alpha-index, and the gamma index, which are 0.275, 0.192, 27, 0.233, and 0.491, respectively. The second part of the output shows the frequency distribution of routes. Since there are three nodes in downtown Austin (nodes 1, 2, 108) with the maximum number of routes (11 routes) passing through them, the network is classified as a three-nucleus network. The frequency distribution of modified-routes is shown in the third part of Table 5.8. The network has 57 nodes which have only one modified route passing through them. Therefore, the shape of the network cannot be determined using this information. Instead, the sum of the circuity index and the intersection index is checked. Since the sum is equal to 0.467 (less than 0.5), the network is classified as a spinal network.

Table 5.6 Route Information

ROUTE	RTT	FREQ	LF	BS	NODAL COMPOSITION
R1	101.0	4.0	1.45	27	(140 176 171 175 3 21 2 15 108 63 1 52 154 75 68 76 78 70 72 73)
R2	89.0	4.0	1.35	27	(3 21 2 15 108 1 52 53 54 83 66 122 84 138 139 67 57)
R3	28.6	1.0	0.27	15	(66 139 67)
R4	37.2	2.0	1.47	15	(107 140 2 108 1 52 81 64)
R5	100.4	8.0	1.23	15	(5 94 16 85 26 4 175 3 21 171 176 2 108 15 14 1 63 86 23 24 41 117 25)
R6	93.0	4.0	1.31	15	(3 2 108 1 52 53 82 71 73 121)
R7	22.0	1.33	1.25	15	(41 86 103)
R8	51.4	2.0	1.27	15	(73 78 77 40 120)
R9	114.8	8.0	1.54	15	(4 170 26 5 105 27 6 35 80 36 7 28 29 8 37 114 9)
R10	116.6	4.0	1.21	15	(90 22 15 2 108 1 52 81 53 82 129 65 84 138 137 145)
R11	117.2	4.0	1.29	27	(63 1 14 15 108 2 21 3 168 10 22 90 23 41 24 87 89 88 33 92 102 143)
R12	117.8	4.0	1.31	27	(19 29 36 80 35 61 104 60 59 20 30 11 23 24 87 41)
R13	61.6	1.0	0.6	15	(2 108 1 52 53 54 55 83 66)
R14	119.4	8.0	0.94	37	(3 2 15 168 10 74 34 62 79 104 61 35 80 36 8 37 114 9 113 155)
R15	60.4	2.0	0.93	15	(120 40 77 78 169 121)
R16	119.6	4.0	0.98	27	(154 52 1 14 10 74 34 62 79 104 35 80 36 29 164 162 161)
R17	92.8	4.0	1.27	15	(36 80 142 46 45 44 101 102 143 144)
R18	32.2	1.0	0.87	15	(67 160 159)
R19	53.6	4.0	1.24	15	(130 40 120 41 87 42)
R20	102.6	4.0	1.47	15	(34 74 141 10 15 14 1 52 53 82 71 73 121)
R21	100.6	2.13	1.25	15	(115 8 113 112 164 156 158 157)
R22	90.6	4.0	0.96	27	(3 2 108 1 52 154 75 53 68 69 70 54 55 56 57)
R23	118.4	8.0	0.96	27	(108 2 21 3 175 171 4 16 85 26 5 105 27 17 6 7 28 18 19 109 165)
R24	118.2	8.0	1.03	15	(140 108 15 22 90 10 141 62 59 20 91 100 43 44 101 102 143)
R25	60.6	1.0	1.21	15	(65 66 72 56 57 139 67)
R26	67.0	2.0	1.0	15	(19 29 8 36 46 115)
R27	74.8	2.0	1.33	15	(19 29 112 8 37 114 149)

RTT: ROUND TRIP TIME

FREQ: FREQUENCY

LF: LOAD FACTOR

BS: BUS SIZE

Table 5.7 Summary of System Performance Measures

Demand Information

	DEMAND	PERCENTAGE
NETWORK TOTAL DEMAND	5784.0	100
PERCENTAGE OF DEMAND SATISFIED WITHOUT TRANSFER	3488.0	60.30
PERCENTAGE OF DEMAND SATISFIED WITH 1 TRANSFER	1386.0	23.96
PERCENTAGE OF DEMAND SATISFIED WITH 2 TRANSFERS	166.0	2.87
UNSATISFIED DEMAND	744.0	12.86

User Cost

	MINUTES	PERCENTAGE
NETWORK TOTAL USER COST	201588	100
NETWORK IN-VEHICLE TRAVEL TIME	149769	74.29
NETWORK WAITING TIME	43229	21.44
NETWORK TRANSFER PENALTY	8590	4.26

FOR WAITING TIME VALUE = 9 $/hour

TOTAL WAITING COST = 6478.02 $/hour

FOR IN-VEHICLE TRAVEL TIME VALUE = 3 $/hour

TOTAL IN-VEHICLE TRAVEL COST = 7488.44 $/hour

Operator Cost

SYSTEM OPERATION COST = 6593.59 $/hour

NUMBER OF 15 SEAT BUSES REQUIRED : 91 buses

NUMBER OF 27 SEAT BUSES REQUIRED : 52 buses

NUMBER OF 37 SEAT BUSES REQUIRED : 16 buses

Fuel Consumption

TOTAL SYSTEM FUEL CONSUMPTION : 289.53 gallons/hour

System Utilization

SYSTEM UTILIZATION : 0.56

Table 5.8 Output Summary for Network Structure Descriptors

●●

This bus transit network is THREE-NUCLEUS GRID network

●●

CIRCUITY-INDEX :	0.275
INTERSECTION-NODE-INDEX :	0.192
NUMBER-OF-ROUTES :	27
ALPHA-INDEX :	0.233
GAMMA-INDEX :	0.491

==================FREQUENCY DISTRIBUTION OF ROUTES ===================

NO. OF ROUTES PASS THROUGH	FREQUENCY
1	42
2	36
3	29
4	6
5	6
6	2
7	0
8	1
9	2
10	0
11	3

=============== FREQUENCY DISTRIBUTION OF MODIFIED-ROUTES ==============

NO. OF MODIFIED-ROUTES PASS THROUGH	FREQUENCY
1	57
2	55
3	14
4	1

SUMMARY

The NETAP is a procedure that serves the following two purposes: 1) bus transit system analysis and evaluation, and 2) system design for route service frequencies and vehicle sizes. For system analysis and evaluation purposes, the NETAP assigns known demands between origin-destination pairs to the bus transit network, and computes a variety of performance measures reflecting the quality of service, the cost experienced by the users, and the resources required by the operator for a given network configuration and service plan. In addition, the shape of the bus transit network is classified via a network structure identification model. For design purposes, the NETAP sets the service frequency and determines appropriate vehicle size for each bus route for particular transit route network configurations under different service concepts.

Two major components, namely, the trip assignment procedure and the frequency setting and vehicle sizing procedure, form the core of the NETAP. The main feature of the trip assignment procedure is its capability to handle coordinated, uncoordinated, and integrated systems. The frequency setting and vehicle sizing procedure utilizes an iterative process which searches for internal consistency of both frequencies and vehicle sizes.

The NETAP differs from existing approaches in several aspects: 1) the ability to handle trip assignment for coordinated, uncoordinated, and integrated transit systems, 2) the ability to determine frequencies for coordinated routes in the frequency setting process, 3) variable vehicle sizes which provides the transit operator with an additional choice dimension to better meet user needs and desired service levels, and 4) computation of a broader range of system performance measures and network descriptors. 5) classification of the network structure to facilitate the comparison of alternative bus transit network configurations.

CHAPTER 6. TRANSIT CENTER SELECTION AND NETWORK IMPROVEMENT PROCEDURES

INTRODUCTION

For a given set of transit centers, the route generation procedure (RGP) generates sets of bus routes with improved transfer opportunities at transit centers and faster and more direct service between transit centers. The network analysis procedure (NETAP) analyzes and sets frequencies for timed-transfer (coordinated) transit systems based on a given set of transit centers. These procedures were discussed in Chapters 4 and 5, respectively. In this chapter, the transit center selection procedure (TCSP) is described; it identifies suitable transit centers for the implementation of timed-transfer designs and demand responsive services that were described in Chapter 2.

In the design of timed-transfer systems, transit centers are essential facilities that help to coordinate the movement of buses and other transit vehicles. Different combinations of transit centers result in different route network configurations, and different levels of demand coverage. Careful selection of transit centers will result in transit network designs with better service quality and resource allocation. Based on the network connectivity, demand matrix, and route information generated by the RGP, as well as node information provided by the NETAP, the TCSP incorporates several criteria that in part reflect guidelines suggested in the transit industry for the selection of transit centers.

In addition to the TCSP, this chapter describes the network improvement procedures (NIP). The primary objective is to improve the set of routes generated by the RGP so that operationally and economically implementable solutions can be obtained. If the RGP is used to satisfy a high percentage of total demand (approaching 100%), then some of the resulting routes may either suffer from low ridership or be too short or both. The same situation occurred in Baaj and Mahmassani's route generation algorithm (RGA). To overcome this problem, four improvement modifications were developed in their route improvement algorithm (RIA), namely: discontinuation of service on low ridership routes, route joining, route splitting, and branch exchange of routes. The NIP adapts all four of these procedures and adds two new procedures for the purpose of this study, namely: splitting routes at transit centers and demand responsive service procedures. The procedure that splits routes at transit centers improves transit system effectiveness when unbalanced loading on two route segments divided by a transit center are detected. However, the above modifications can improve the system only to a certain extent, since low demand density areas cannot be served effectively by conventional fixed route and fixed schedule bus

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service. The NIP accounts for this problem by incorporating demand responsive service, considered to be more cost-effective for low demand density areas.

In the next section, details of the transit center selection procedure are presented. Section 6.3 focuses on the network improvement procedure. In this section, the improvement modifications considered by the RIA are reviewed; the procedures for splitting routes at transit centers and for demand responsive service are described in detail and illustrated by numerical examples. Summaries of these procedures are given in Section 6.4.

THE TRANSIT CENTER SELECTION PROCEDURE (TCSP)

As suggested by Taylor-Harris and Stone (1983), the extent to which a transit center is used is primarily determined by its location. The latter should reflect land use, costs, availability, bus and street patterns, traffic conditions, and passenger interchange volumes. Ideally, the transit centers should be located at sites near busy activity generating centers (Schneider and Smith, 1981). Major activity centers are well-known and visible to the public. Locating transit centers at these locations will improve the perceived accessibility of the centers to the user. In light of the above, high levels of transit service can be provided. Moreover, locations near major activity centers will provide opportunities for joint development. It is also critical that transit centers should be well-distributed with respect to the region's population and employment, which in turn influence the transit demand density. A transit center should be allocated to every identifiable population cluster or major community to minimize the distance between the population and the transit center. However, a large number of transfer centers may be operationally and economically impractical. Therefore, a minimum travel time between transit centers should be imposed to avoid route overlap, scheduling difficulties, and unnecessary duplication. Transit centers should provide sufficient transfer opportunities, which could be facilitated through timed-transfer service. Of course, other factors such as accessibility, land availability, and geographical limitations should be considered as well. In summary, the guidelines for the location of a transit center include:

1) proximity to a major activity center that generates high transit demand.

2) population cluster or major community coverage in service area.

3) separation from other centers by a minimum travel time.

4) good transfer opportunities.

5) feasibility considerations such as accessibility, land availability, and geographical limitations.

The TCSP incorporates several criteria that reflect the above guidelines, using data that is either prepared for or generated by the RGP and NETAP. Since major activity centers usually

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generate high transit demand, the TCSP seeks to identify them by calculating the total node transit demand, obtained by summing over the originating node demand, terminating node demand, and transferring demand, all determined in the trip assignment procedure described in Section 5.4.5. Demand nodes with high total node transit demand are identified as major activity centers.

To identify population clusters and major communities, the TCSP considers the originating demand generated within the service area of a demand node. The service area is defined by the travel time from the demand node to other demand nodes. If other demand nodes can be reached from the demand node within a certain travel time (default is 15 minutes), they are assumed to be within the service area. By summing the originating demand at all demand nodes within the service area, the originating demand in the service area of a given node is defined. The originating demand at a node is obtained by summing over all O-D pairs with the given node as origin. The TCSP identifies demand nodes with high originating demand in their service areas as possible population clusters and major communities.

Transfer opportunities at a node are defined by the number of potential routes. Potential routes for a given demand node are those passing through the node and those reachable from this node within a certain travel time (default is 5 minutes). The latter case ensures that the potential route can be rerouted to serve the demand node without incurring too much cost. Using the set of routes generated by the RGP, the number of potential routes for each demand node can be computed. Demand nodes with a larger number of potential routes normally provide better transfer opportunities.

The TCSP starts with a screening process that eliminates all nodes that do not meet certain requirements in terms of transfer opportunities, originating demand covered by the service areas, and total node transit demand. The procedure first identifies all nodes with a number of potential routes exceeding a prespecified value (default is 3 routes) to form a set of candidate nodes for transit centers. The procedure then removes candidate nodes with insufficient originating demand within their service areas (default is 150 passenger trips/hour) and candidate nodes with low total node demand (default is 100 passenger trips/hour). No guidelines are available for these minimum levels. The selection of suitable values highly relies on the designer's knowledge of the service area. However, if information is insufficient or unreliable, the designer may perform sensitivity analysis and evaluate the resulting transit centers.

A sequential selection process is then used to identify transit centers one by one by checking the minimum separation travel time constraint. The order of center selection is based on total node demand, with the highest total demand node (among all candidate nodes) considered

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first. Initially, the set of transit centers (TC) is empty. In each iteration, the procedure checks the node with the highest total demand and removes it from the set of candidate nodes. If the shortest travel time between the node under consideration and each center already in the set of transit centers is less than a prespecified minimum separation (default is 15 minutes), this node is added to the set of transit centers. The selection process continues until the set of candidate nodes is empty. In the final step, the selected transit centers are supplied to the designer in order to eliminate infeasible nodes due to other factors such as accessibility, land availability, and geographical limitations, as discussed earlier in this section.

The flow chart of the TCSP is shown in Figure 6.1. In summary, the TCSP consists of the following steps:

Step 0 Set the initial set of transit centers, TC = {}.

Step 1 Compute the number of potential routes (NPR) for each demand node, and generate a set of demand nodes (S) with NPR greater than a prespecified level (3 routes).

Step 2 Eliminate all nodes in S with originating demand covered by their service areas less than a prespecified level (default is 150 trips per hour).

Step 3 Eliminate all nodes in the remaining set S with total node demand less than a prespecified level (default is 100 trips per hours).

Step 4 Check if the remaining set S is empty. If yes, go to Step 6.

Step 5 Check the node in S with the highest total node demand to see if it violates the minimum separation travel time constraint (default is 15 minutes).

If yes, remove the node from S, and go to Step 4.

Otherwise, add the node in TC, remove it from S, and go to Step 4.

Step 6 Output TC to the designer to remove unacceptable transit centers, and obtain the resulting TC.

The framework of the TCSP can be readily modified to reflect additional information on location feasibility due to land availability, geographical limitations, traffic conditions, and other factors. The procedure can also be enhanced by incorporating a geographic information system (GIS) to provide accurate population and other useful information.

In the design of a timed-transfer transit network, as described in Section 3.2, the RGP and NETAP are initially executed with an empty set of transit centers. The resulting information is then employed by the TCSP to generate a set of transit centers. Using the resulting centers, the RGP generates a new set of routes that are subsequently analyzed by the NETAP. Since the route and node information for the new set of routes will be different from those in the initial run, the new information should be supplied to the TCSP to generate another set of centers. The

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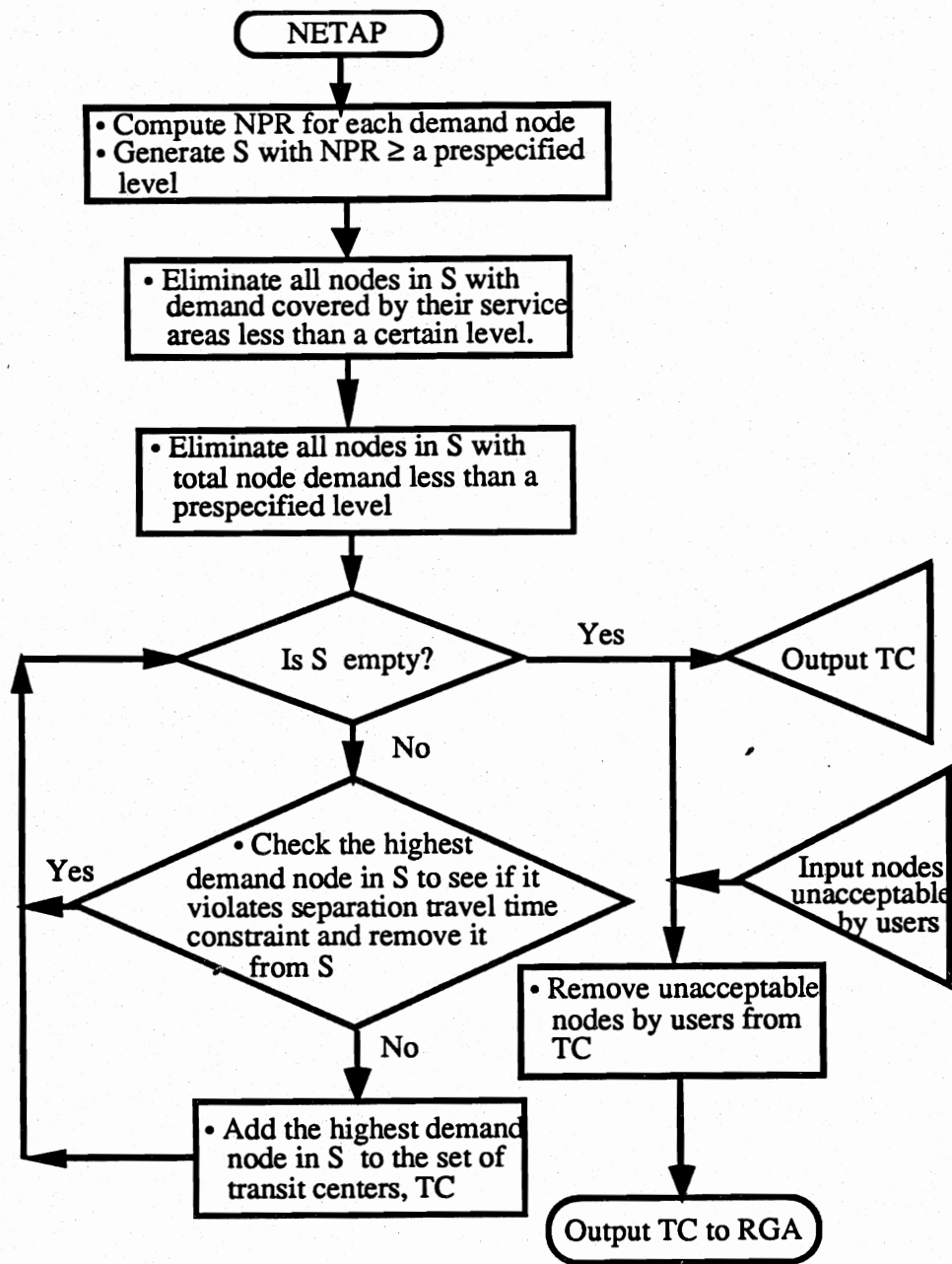
Figure 6.1 Transit Center Selection Procedure (TCSP)

process should iterate until convergence of the transit center set is reached. However, each iteration of the transit center selection process requires running both the RGP and NETAP, which is time consuming. By default, this model performs only one iteration to save the required

computation time. The option of running the procedure iteratively until the set of transit centers from two consecutive iterations is the same is also available in the TCSP.

To illustrate the TCSP, an example shown in Table 6.1, with six nodes N1, N2, N3, N4, N5, and N6 is presented. The node information, include the number of potential routes, the originating demand within the service area, and the total demand for each node, as obtained following execution of the NETAP. The screening process eliminates N6, N5, and N4 because N6 has fewer than three routes (2 routes), N5 has insufficient demand (140 passenger trips) within its service area, and N4 has insufficient total node demand (80 passenger trips per hour). Therefore, the set of candidate nodes consists of N1, N2, and N3. The shortest travel times between N1 and N2, N1 and N3, and N2 and N3 are assumed to be 12, 18, and 10 minutes, respectively. N1 has the highest total demand in the set of candidate nodes; it is selected first as a transit center and removed from the set of candidate nodes. N2 has the highest total demand in the remaining set of candidate nodes. However, the shortest travel time between N1 and N2 is 12 minutes (less than 15 minutes). N2 violates the minimum separation travel time constraint. The process removes N2 from the set of candidate nodes without adding it to the set of transit centers. The procedure then considers the last node N3 in the set of candidate nodes. Since the shortest travel time between N1 and N3 is 18 minutes (greater than 15 minutes), N3 is added to the transit center set. The procedure identifies N1 and N3 as transit centers and supplies these to the designer to remove unacceptable centers.

Table 6.1 Node Information for the TCSP Illustrative Example

Node	Number of potential routes	Total demand within service area (passengers/hour)	Total node demand (passenger/hour)
N1	5	400	200
N2	4	300	150
N3	3	180	130
N4	3	160	80
N5	3	140	120
N6	2	180	100

THE NETWORK IMPROVEMENT PROCEDURES (NIP)

As indicated by Baaj (1990), the transit network grows rapidly, both in the number of routes and the total route mileage when the network designer tries to achieve a high coverage level (approaching 100%). Results from his example showed that many routes would be either too short or carry low ridership. Such routes are not desired by the transit operator because their marginal contribution to the demand satisfaction is outweighed by the resources required to provide adequate service acceptable to the transit user. These and similar types of problems are also encountered in existing actual transit networks. Wilson and Gonzalez (1982) explored the current practice in the design of bus service, identified problems in the existing system, and suggested improvement modifications to overcome these problems. Transit system modifications suggested by them can be grouped into four levels:

1) At the system level, feasible actions include implementation of new routes, extension of existing routes, replacement of a small set of routes with a new set, and discontinuance of service on routes.

2) At the route-structure level, actions include the splitting of a route into two segments, joining of two routes into one new route, and splitting a route into zones or segments with different types of service (e.g. local and express service).

3) At the route frequency level, the major action available is the modification of the service frequency to meet prevailing needs at different times of day.

4) At the control level, actions are mainly concerned with maintaining closer adherence to the schedule; these include installation or removal of control points, alteration in the running time, and change in the layover time.

In addition to the above modifications, Mandl (1979) suggested a branch exchange algorithm which creates new combinations of routes in such a way that the number of transfers at the intersection node of two routes is reduced. Baaj and Mahmassani's (1991) RIA adopted four improvement modifications from Wilson and Gonzalez, as well as Mandl. These modifications include an action at the system level (discontinuation of service on low ridership routes) and three actions at the route-structure level (joining of routes, splitting of routes, and branch exchange of routes). The improvement modifications considered by the RIA are discussed in the following sections.

The RGP, modified from Baaj and Mahmassani's RGA, produces networks that exhibit the same problems of short and/or low ridership routes when a high system coverage level is desired. All existing fixed route transit network designs model exhibit the same problem. Baaj and Mahmassani showed that their modifications had positive results in most of their experiments.

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The NIP incorporates all the modifications provided by the RIA to improve the route network. In addition, it contains a procedure for splitting routes at transit centers, intended to improve system effectiveness under the timed-transfer design concept. However, these modifications can improve the system only to a limited extent. For low demand density areas, a large portion of routes still remain short and/or have low ridership. To overcome this problem, the option to provide demand responsive service (DRS), which may be more effective in low demand density areas, has been added to the NIP. Details of the DRS modification are discussed in Section 6.3.3.

Review of RIA Improvement Modifications

The improvement modifications carried out by the RIA have the following two objectives: 1) make the set of routes generated by the RGA operationally and economically feasible, and 2) test existing improvement modifications suggested by others. For the first objective, the RIA discontinues service on low ridership routes and joins low ridership routes with medium routes. For the second objective, the RIA allows testing the route splitting strategies suggested by Wilson and Gonzalez, and branch exchange of routes suggested by Mandl. These modifications were tested by Baaj and Mahmassani. In the following sections, these modifications and their effects on transit systems are briefly discussed.

Discontinuation of Service on Low Ridership Routes: The objective of this action is to eliminate low ridership routes generated by the RGA and obtain an operationally and economically feasible set of routes. A route is low in ridership if its load factor (determined in the frequency setting and bus sizing procedure) falls below a threshold (default use 1.0, corresponding to the minimum service frequency of 1 bus/hour) set by the transit planner. Alternatively, this action allows the user to sequentially eliminate individual routes in increasing order of ridership. The planner determines the trade-off between the operator cost and the level of demand satisfaction.

After removing the low ridership routes, the NETAP can then measure the effect of this modification. In general, discontinuation of service on low ridership routes reduces the fleet size and the total vehicle miles required by the system (thus reducing the operator costs and fuel consumption), and increases the system utilization, but lowers the levels of system coverage (total demand satisfied) and system directness (total demand satisfied directly).

Route Joining: The purpose of the route joining action is to eliminate routes with low ridership. For each route identified as having low ridership, the RIA searches for other routes that have a common terminal node with the route under consideration. If such routes can be found,

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the procedure joins the low ridership route with the route that requires the minimum number of extra buses to operate. The joining process is repeated for each low ridership route.

Joining low ridership routes to other routes results in a decrease in the number of transfers since some passengers who previously may have had to transfer at the common terminal node can travel through the node without transferring. As a result, the total waiting time and transfer time will be reduced. Route joining may also increase the level of demand satisfaction because some unsatisfied demand may be satisfied by the elimination of a transfer at the common terminal node. However, more buses are required since higher route frequencies are provided to the low ridership segments.

Route Splitting: Route splitting has been recognized as an important action at the route-structure level by Wilson (1982) and Wilson and Gonzalez (1982). Splitting certain routes may be desirable if one or more of the following factors occur:

1) The route suffers from poor schedule adherence.
2) The route exhibits unequal loading on two segments.
3) The route includes a natural break point such that few passengers travel from one segment to the other.
4) The route's length greatly exceeds the mean passenger trip distance.

A set of indicators was suggested by Wilson to measure the extent of each factor. The route splitting procedure implements two of these indicators. First, the procedure selects routes for splitting consideration by requiring them to exceed one hour in one-way route in-vehicle travel time. It selects nodes for possible splitting locations, by requiring that each of the proposed routes exceeds 20 minutes in one way in-vehicle travel time. The above actions greatly reduce the number of routes and nodes selected for splitting. Second, the procedure utilizes an indicator that identifies possible candidates for splitting location. The indicator is the ratio of the product of the peak load point counts on the proposed two new routes obtained by splitting at a particular node to the square of the peak load point count on the splitting route. The lower the value of the indicator, the higher the possibility that the second and third factors will occur, as mentioned above. The procedure accepts as possible splitting locations only those nodes in which the value of the indicator does not exceed a certain value (default is 0.5). The indicator is also used in the procedure for splitting routes at transit centers as will be described in Section 6.3.2.

In general, route splitting results in better resource allocation and system effectiveness, reflected in the reduction in fleet size, operator costs and fuel consumption. All the above

positive effects result from a decrease in service frequency on the lower ridership segment of the splitting route. With regard to demand satisfaction, splitting a route results in a decrease in the percentage of demand satisfied directly and an increase in the percentage of demand satisfied by one or more transfers. In light of the above, route splitting generally causes an increase in the total waiting time and transfer penalty, because more transfers are required after a route split.

Branch Exchange of Routes: The purpose of the branch exchange heuristic is to reduce the number of transfers at the intersection node of two routes by devising new combinations of the branches. Two routes, (A E B) and (C E D), with intersection node E have a total of four branches, AE, EB, CE, and ED. By exchanging the branches, two alternative combinations, (A E C) and (B E D); and (A E D) and (B E C), can be found. The procedure computes the number of transfers at the intersection node of the three possible layouts, and utilizes the one with the fewest number of transfers. To reduce the search space, the RIA restricts the branch exchange process to intersecting routes with medium to high ridership (in implementation it considers only routes with frequencies over 3 buses/ hour, since they generally involve more transfers at their intersection node).

This procedure generally results in a decrease in the total number of transfers, and thus reduces the total transfer time. Due to the reduction in the total number of transfers, the system will provide better service in terms of the percentages of demand satisfied directly, via one transfer, and via two transfers. Changes in the total in-vehicle travel time and the required fleet size are expected to be slight because the flow on each route will remain approximately the same.

Splitting Routes at Transit Centers

The procedure for splitting routes at transit centers is intended for timed-transfer system design, to avoid transfer waiting time through coordinated route operations at the centers. This procedure consists of two steps and is similar to the route splitting procedure described in Section 6.3.1.3. First, it selects routes containing transit centers for splitting. Transit centers are the only possible splitting locations for each selected route. In order to prevent infeasible short routes, it requires that each of the proposed routes resulting from the split exceeds 20 minutes in one way in-vehicle travel time. Second, the indicator used in Section 6.3.1.3 for determining unequal loading on two route segments is calculated to identify possible candidate transit centers for splitting locations. The procedure accepts as possible splitting locations only those transit centers in which the value of the indicator does not exceed a user specified value (acceptable splitting ratio).

Demand Responsive Service

One of the major disadvantages of the fixed route design is its inability to cover a high percentage of the total demand without including low ridership routes. These low ridership routes are not acceptable to most transit planners. Demand responsive service (DRS) has been shown to be more cost-effective than fixed-route transit service in low demand density areas (Chang, 1990). The DRS concept is implemented in the present improvement procedure.

The DRS modification procedure starts by discontinuing routes that suffer from low ridership. The network analysis procedure (NETAP) is then applied to evaluate the resulting network and to identify all unsatisfied demand which cannot be completed within two transfers. A procedure for identifying suitable DRS service areas (or routes) and their corresponding transit centers is applied to the unsatisfied demand nodes. Each resulting DRS route is represented by a list of nodes in which the first node is the transit center (TC_i) associated with the DRS route and the rest of the nodes are unsatisfied demand nodes within its service area. Routing of the DRS vehicle, which requires real time information, is not considered in this study.

The procedure sequentially identifies DRS service areas which cover the highest unsatisfied demand until one of the following two conditions is met. First, the sum of the unsatisfied demand covered by the DRS routes is greater than the unsatisfied demand that should be satisfied in order to reach the desired demand coverage level (denoted by *demand-to-be-satisfied*). Second, no more suitable DRS areas can be identified. The procedure to identify DRS routes is described later in this section. Then, the DRS procedure calls the predicate "drs-assign-demand" (described in Section 5.4.5), a modification of the trip assignment procedure for the conventional fixed route service described in the NETAP, to assign the unsatisfied demand to the integrated system and reallocate unsatisfied demand to the demand matrix. In addition, it checks the demand levels (demand satisfied directly and demand satisfied within two transfers) for termination. If the demand levels are not satisfied, the procedure to identify the DRS routes is called again to generate more DRS routes. This process continues until the demand levels are satisfied or no more suitable DRS routes can be identified. Finally, the modified demand matrix is assigned to the fixed route network by the NETAP which computes the route service frequencies and vehicle sizes and determines the extent of the improvement and/or worsening in the performance measures of interest.

The procedure for identifying DRS routes is based on the two following criteria:

1) The DRS service area should cover as much unsatisfied demand as possible.
2) The DRS vehicle travel time (DRSTT) in a service cycle should be no more than the maximum travel time ($DRSTT_{max}$) so as to provide a certain service level.

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The procedure starts by forming a set of feasible seeds (nodes with unsatisfied demand) for each transit center (generated by the transit center selection procedure) where the travel time between each seed and the transit center is less than one half of $DRSTT_{max}$ (default is 20 minutes), and each seed node is not connected directly by a conventional fixed route to the transit center. Each seed is then expanded to form a candidate service area that contains the closest seed nodes corresponding to the same transit center one by one until the condition ($DRSTT_{max} > DRSTT$) is violated. The DRSTT in a service cycle can be approximated using geometric probability (Daganzo, Hendrickson, and Wilson, 1977). Since the transit center may be located either inside or outside the service area, DRSTT can be expressed as:

$$DRSTT = 1.01rt\sqrt{\pi(n+1)}$$ for transit centers inside the service area

$$DRSTT = 1.01rt\sqrt{\pi n} + 2T_c$$ for transit centers outsider the service area

where

> r is the route factor, which is the ratio of network distance to airline distance (default is 1.27 for 2-directional grid networks in circular areas).

> t is the travel time to go from the center node to the furthest node in the service area.

> n is the number of unsatisfied demand nodes in the service area

> T_c is the travel time from the transit center to the closest node in the service area.

Once the unsatisfied demand nodes covered by each candidate service area are defined, the procedure eliminates the candidate service areas covering insufficient unsatisfied demand, i.e. less than a predetermined minimum level for feasible implementation (default is 5 passenger trips per hour). Among those remaining, the procedure selects the service area which would cover the most unsatisfied demand as a DRS service area. The unsatisfied demand covered by the resulting service area is then added to the cumulative covered (otherwise) unsatisfied demand (*covered-unsatisfied-demand*), which is initially set to zero. The procedure iteratively selects the candidate service area with the next highest unsatisfied demand until either one of the two following conditions is met: 1) *covered-unsatisfied-demand* is greater than *demand-to-be-satisfied*, or 2) all candidate DRS service areas are selected. The procedure then goes back to call "drs-assign-demand" to assign the covered unsatisfied demand and check the demand satisfied levels for termination.

The flow chart of the DRS modification procedure is shown in Figure 6.2. In summary, the DRS procedure consists of the following steps:

> Step 0 Initialize the set of DRS service areas (DRSSA) to empty, and *covered-unsatisfied-demand* equal to zero.

```
                                                    ┌─────────────────┐
┌──────────────────────────┐                        │ • Input the set │
│ • Set DRSSA = empty      │◀───────────────────────│   of routes     │
│ • Set *covered-unsatisfied-│                       └─────────────────┘
│   demand* = 0            │
└──────────────────────────┘
            │
            ▼
┌──────────────────────────┐
│ • Discontinue low        │
│   ridership routes       │
└──────────────────────────┘
            │
            ▼
┌──────────────────────────────────┐
│ "drs-assign-demand"              │
│ • reallocate unsatisfied demand  │
│ • identify unsatisfied demand nodes│
│ • compute *demand-to-be-satisfied*│
│ • compute the demand levels      │
└──────────────────────────────────┘
            │
            ▼
      ╱ • Are demand levels ╲        Yes
     ◀     satisfied?         ▶──────────────┐
      ╲                     ╱                │
            │ No                             │
            ▼                                │
┌──────────────────────────┐                │
│ • Generate the sets of transit │           │
│   centers and seed pairs, P │               │
└──────────────────────────┘                │
            │                                │
            ▼              Yes               │
      ╱ Is P empty ? ╲────────────▶┌──────────────────────────┐
     ◀               ▶             │ • Analyze the resulting  │
      ╲             ╱              │   network by NETAP       │
            │ No                   └──────────────────────────┘
            ▼                                │
┌──────────────────────────────┐            │
│ • Determine the DRSSA for each │           ▼
│   transit center and seed pair in P │  ┌──────────────────────────┐
└──────────────────────────────┘      │ • Obtain an integrated   │
            │                          │   bus system             │
            ▼                          └──────────────────────────┘
┌──────────────────────────────┐
│ • Eliminate candidate DRSSA with │
│   insufficient unsatisfied demand │
└──────────────────────────────┘
            │
            ▼
┌──────────────────────────────────┐
│ • Add the candidate DRSSA one by │
│   one to the DRSSA until *covered-│
│   unsatisfied-demand* > *demand-  │
│   to-be-satisfied* or all candidate│
│   DRSSA are added                │
└──────────────────────────────────┘
```
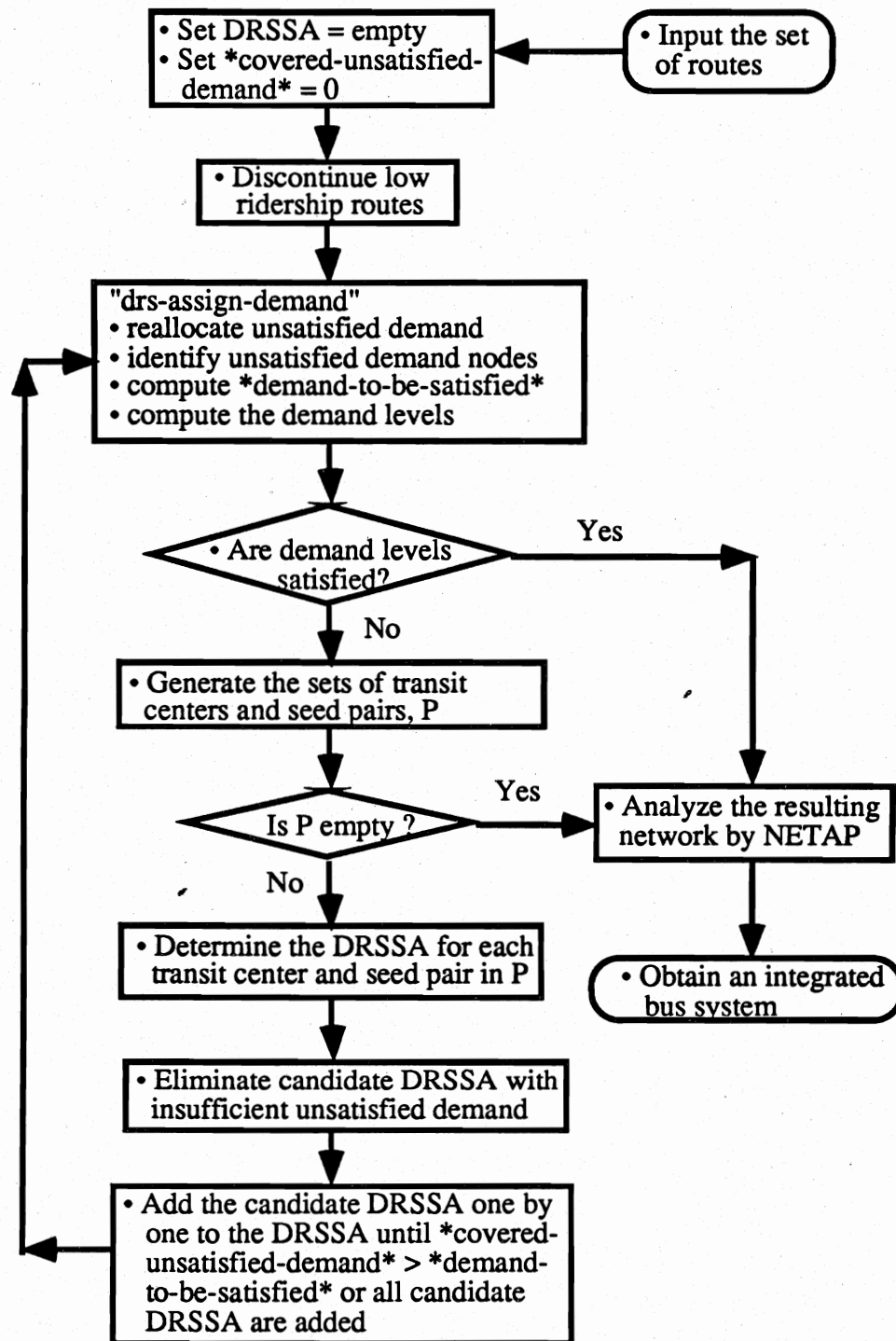
Figure 6.2 Demand Responsive Service Precedure

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Step 1 Discontinue low ridership routes, and generate a new set of routes.

Step 2 Call "drs-assign-demand" to reallocate unsatisfied demand, identify unsatisfied demand nodes, and compute *demand-to-be-satisfied* and the demand levels.

Step 3 If the demand levels are satisfied, go to step 9.

Step 4 Generate sets of transit centers and seed pairs, P.

Step 5 If P is empty, go to Step 9.

Step 6 Determine the candidate DRS service area for each transit center and seed pair in P.

Step 7 Eliminate candidate DRS service areas covering insufficient unsatisfied demand.

Step 8 Add candidate DRS service areas one by one to DRSSA until one of the following two conditions is met:

    a) *covered-unsatisfied-demand* is greater than *demand-to-be-satisfied*.

    b) all candidate DRS service areas are selected.

    Set *covered-unsatisfied-demand* to zero and go to Step 2.

Step 9 Assign the resulting demand matrix to the fixed route network using the NETAP.

The NIP provides six modifications which include four actions developed by Baaj and Mahmassani (1991), in addition to route splitting at transit centers, and conversion to demand responsive service. These actions are implemented in modules which can be applied individually or in any sequence. The demand responsive service provides an additional service dimension to the designer. However, the integration of fixed route and flexible route service increases the complexity of the bus system. Therefore, the DRS action should be used last in the modification sequence.

Computation of Number of DRS Buses

Once the demand for each DRS route k (DRSQ$_k$) has been determined, the procedure then computes the number of buses required on each DRS route k to achieve the applicable maximum allowed load factor defined for DRS route:

$$DRSN_k = \frac{DRSQ_k DRSTT_k}{60.0 * DRS-MAX-LF * *DRS-VEHICLE-SIZE*}$$

where

DRSTT$_k$ is the estimated travel time for the DRS route k as described in Section 6.3.3.

DRS-MAX-LF is the maximum allowed load factor for DRS routes (default is 1.0).

DRS-VEHICLE-SIZE is the DRS bus seating capacity (default is 15 seats).

Since DRSN$_k$ may not be an integer value, it is rounded up to the closest integer. The minimum DRS fleet size necessary for the whole DRS system is equal to the sum of DRS buses over all DRS routes.

Numerical Example for the Demand Responsive Service Procedure

To illustrate the demand responsive service procedure, Figure 6.3 shows a small network with nine demand nodes and six conventional fixed routes obtained after discontinuing all low ridership routes. Nodes 1 and 2 are transit centers. The demand matrix associated with this network is presented in Figure 6.3. The shortest travel time (in minutes) for each demand pair is shown in Table 6.2, where M denotes demand pairs with shortest travel time greater than 20 minutes. In the demand matrix, all demand node pairs satisfied directly have 10 passenger trips; demand node pairs satisfied with either one or two transfers have 3 passenger trips; and unsatisfied demand pairs have either one or two passenger trips. The total demand is 236 transit trips per hour. The demand satisfied directly is 140 passenger trips or 59 percent of the total demand. A total of 206 passenger trips are satisfied within two transfers, equivalent to 87 percent of the total demand. The remaining 30 passenger trips are unsatisfied. All nine demand nodes are identified as unsatisfied demand nodes, since each of these nine nodes is the origin or destination of some of the unsatisfied demand pairs. The desired demand directness and coverage levels are 60% and 95% corresponding to 142 and 225 passenger trips, respectively. Therefore, at least 19 unsatisfied passengers ("demand-to-be-satisfied") should be served by the DRS routes to reach the desired demand coverage level.

Because the demand levels are not satisfied, the procedure generates a set of seeds for each transit center. Since the shortest travel time between each seed and transit center should be less than 20 minutes (one half of $DRSTT_{max}$), and each seed node is not connected directly by conventional fixed route to the transit center, seed node 4 is identified for transit center node 2 and seed nodes 7, 8, and 9 are identified for transit center node 1. In the next step, each seed node is expanded to form a candidate service area. Since node 4 is the only seed node for transit center node 2, a candidate service area is obtained which contains nodes 2 and 4. For candidate service areas corresponding to transit center node 1, node 7 first expands to contain node 9. Since DRSTT after adding node 9 the service area is equal to 36 minutes (less than $DRSTT_{max}$), node 9 is added to the candidate service area under expansion. The procedure then attempts to expand the service area by considering node 8. Since DRSTT after adding node 8 to the service area is greater than 40 minutes, the expansion procedure stops. Consequently, the candidate service area expanded from seed node 7 contains nodes 1, 7, and 9. Following the same process, expansion of seed node 9 yields the same candidate service area containing nodes 1, 7, and 9; candidate service area generated from seed node 8 contains nodes 1 and 8. Thus, three candidate service areas (1, 7, 9), (1, 8), and (2, 4) are obtained, covering 14, 12, and 8 unsatisfied passenger trips, respectively. The above candidate service areas are shown in Figure 6.4.

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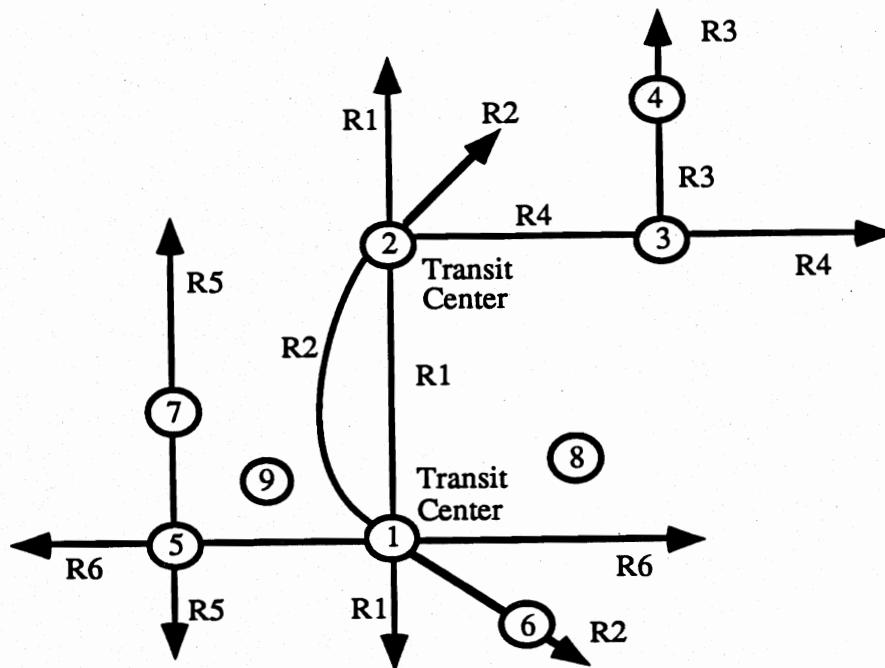
	N1	N2	N3	N4	N5	N6	N7	N8	N9
N1	0	10	3	3	10	10	3	2	2
N2	10	0	10	3	3	10	3	1	1
N3	3	10	0	10	3	3	2	1	0
N4	3	3	10	0	2	3	2	0	0
N5	10	3	3	2	0	3	10	1	0
N6	10	10	3	3	3	0	3	1	0
N7	3	3	2	2	10	3	0	0	0
N8	2	1	1	0	1	1	0	0	0
N9	2	1	0	0	0	0	0	0	0

Figure 6.3 Network and Transit Demand Matrix for the Illustration of the Demand Responsive Service Procedure

Table 6.2 Shortest Travel Time Between Node Pairs For Network In Figure 6.3

	N1	N2	N3	N4	N5	N6	N7	N8	N9
N1	0	M	M	M	10	10	15	10	15
N2	M	0	10	15	M	M	M	M	M
N3	M	10	0	5	M	M	M	M	M
N4	M	15	5	0	M	M	M	M	M
N5	10	M	M	M	0	20	5	5	M
N6	10	M	M	M	20	0	M	20	10
N7	15	M	M	M	5	M	0	M	5
N8	15	M	M	M	M	10	M	0	M
N9	10	M	M	M	5	20	5	M	0

Shortest Travel Times are in minutes
M denotes shortest travel time greater than 20 minutes

Table 6.3 New Demand Matrix for Fixed Route Service After the Reallocation of Unsatisfied Demand

	N1	N2	N3	N4	N5	N6	N7	N8	N9
N1		M	M	M	10	10	15	10	15
N2		0	10	15	M	M	M	M	M
N3		10	0	5	M	M	M	M	M
N4		15	5	0	M	M	M	M	M
N5		M	M	M	0	20	5	5	M
N6		M	M	M	20	0	M	20	10
N7		M	M	M	5	M	0	M	5
N8		M	M	M	M	10	M	0	M
N9		M	M	M	5	20	5	M	0

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The procedure then checks if any candidate service area covers insufficient unsatisfied demand. All three candidate service areas satisfy this condition, since they all cover more unsatisfied demand than the default value (5 passenger trips per hour). The procedure first selects (1, 7, 9) as a DRS service area because it covers the highest unsatisfied demand. Since this DRS service area covers only 14 unsatisfied passenger trips, which is less than *demand-to-be-satisfied* (19 unsatisfied passenger trips), the procedure continues and selects (1, 8), the area with the second highest unsatisfied demand, to be a DRS service area. The sum of the unsatisfied demand (*covered-unsatisfied-demand*) covered by both areas is greater than *demand-to-be-satisfied*. The procedure then calls "drs-assign-demand" to reallocate unsatisfied demand and check the demand levels.
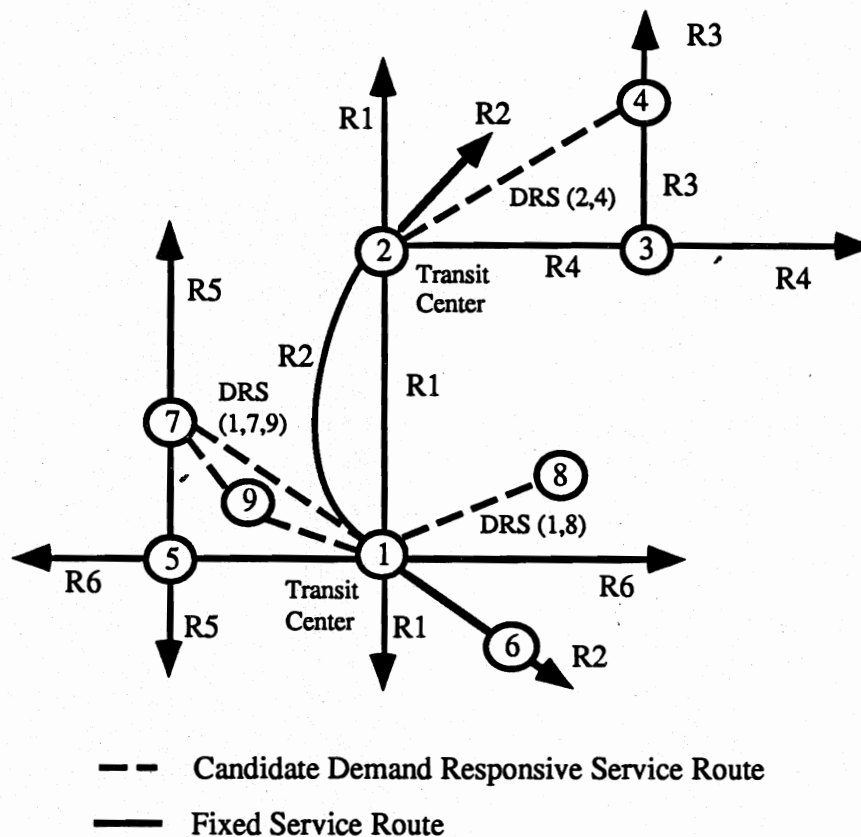

**Figure 6.4 Candidate Demand Responsive Service Routes
for the Illustrative Example**

The new integrated system contains six conventional fixed routes and two DRS routes. To illustrate "drs-assign-demand", four unsatisfied demand pairs (1, 8), (2, 9), (3, 7), (4, 7) are used as examples. The demand of (1, 8) is satisfied directly by DRS route (1, 8). Therefore, *DEMAND-0-TRANSFER* is updated by adding 2 passenger trips; no adjustment to the demand matrix is needed. Demand pair (2, 9) is satisfied with one transfer. Passengers between this demand pair board either R1 or R2 at node 2, and stay on until node 1, where they transfer to DRS route (1, 7, 9), and travel on it until node 9. *DEMAND-1-TRANSFER* is updated by adding 1 passenger trip. Since the passengers between demand node pair (2, 9) use fixed routes from node 2 to node 1, the demand of (2, 1) is increased by 1 passenger trip, and the demand of (2, 9) is set to zero in the demand matrix. Demand pair (3, 7) is satisfied with two transfers. Passengers between this demand node pair board R4 at node 3, stay on it until node 2, then transfer to either R1 or R2, travel on them until node 1, where the passengers transfer to DRS route (1, 7, 9), and stay on it until node 7. *DEMAND-2-TRANSFER* is updated by adding 2 passenger trips. The demand between (3, 1) is increased by 2 passenger trips, and the demand between (3, 7) is set to zero in the demand matrix. Demand pair (4, 7) remains unsatisfied in the new integrated system, since more then two transfers are needed. After executing "drs-assign-demand", a new demand matrix for the conventional fixed route service is obtained as shown in Table 6.3. Four demand pairs (4, 5), (4, 7), (5, 4), and (7, 4) remain unsatisfied. Demand pairs (1, 8), (1, 9), (8, 1), and (9, 1) are not satisfied by the conventional fixed routes, but satisfied directly by the DRS routes. The demand directness and coverage levels for the integrated bus system are 63% and 97%, respectively. Since both demand levels are greater than the desired levels, no additional DRS route needs to be generated.

In the trip assignment process, the demand for DRS routes (1, 7, 9) and (1, 8) are found to be 10 and 12 passenger trips per hour, respectively. Travel times for the above two routes are estimated to be 30 and 36 minutes. From the equation for computing the number of buses required on each DRS route described in Section 6.3.4, 0.4 buses are required for each DRS route. By rounding up to the closest integer value, both DRS routes require one bus.

SUMMARY

This chapter describes the transit center selection and network improvement procedures. The transit center selection procedure identifies suitable transit centers that are utilized in the design of timed-transfer service and demand responsive service. The network improvement procedures modify networks generated by the RGP and NETAP so that better system effectiveness and service levels can be achieved.

CHAPTER 7. COMPUTATIONAL EXPERIMENTS

INTRODUCTION

The transit network design framework incorporates four main procedures, namely, the route generation procedure (RGP), network analysis procedure (NETAP), transit center selection procedure (TCSP), and network improvement procedures (NIP), all of which have been described in the previous chapters. Using these procedures, alternative design concepts, including conventional systems, coordinated services, integrated systems, and variable vehicle sizes are implemented in the solution framework as described in Chapter 3. In this chapter, the results of extensive computational experiments are presented to test and illustrate the above design procedures and alternative design features on cases representing different levels and spatial distributions of demand.

The computational tests have two primary objectives. The first is to investigate and compare the character and performance of the solution networks generated with the transit center concept relative to other proposed solutions, namely those generated by Mandl's and Baaj and Mahmassani's algorithms, for a benchmark problem. The second objective is to test the solution framework and investigate its performance with respect to an actual transit network. This objective is achieved by testing the design procedures and alternative design concepts with data generated for the transit system of Austin, Texas. In addition, sensitivity analyses with respect to key design features and parameters of the procedures are performed. The design features tested include uncoordinated vs. coordinated, fixed vs. variable vehicle sizes, and conventional fixed route vs. integrated services; the design parameters tested include minimum system directness level, minimum system coverage level, application strategy for the TCSP, and acceptable splitting ratio.

The benchmark network was originally reported by Mandl (1976) and tested by Baaj and Mahmassani (1991) for comparison. The network is small and dense; it comprises only 15 nodes within a 33 minute shortest travel distance between the two furthest nodes. Although this network may not be very representative of many real-world urban bus transit networks, it is still useful possibly as a regional subnetwork. The demand matrix used by Mandl and Baaj and Mahmassani contains relatively heavy ridership. This base network was used to test the solution framework during the development stage. In the next section, the solutions to the benchmark transit network are reported and compared to the solutions of Mandl's and Baaj and Mahmassani's algorithms.

In section 7.3, the design procedures and alternative design concepts are tested with data from the Austin transit system. Six different combinations of the desired minimum system

coverage and directness levels are used for the tests. Section 7.3.1 presents tests of the transit center selection procedure (TCSP). Sets of transit centers generated from the different combinations and from different application strategies are reported and investigated. In Section 7.3.2, the route generation procedure (RGP) and network analysis procedure (NETAP) are tested in a performance comparison of four design alternatives: uncoordinated design with fixed vehicle size, uncoordinated design with variable bus sizes, coordinated design with fixed vehicle size, and coordinated design with variable vehicle sizes. The comparison is based on four categories of performance measures: 1) demand satisfaction levels, 2) user travel costs, 3) operator costs, and 4) total system cost. In Section 7.3.3, the modification procedure which splits routes at transit centers for the coordinated network is tested and its sensitivity to the value of the acceptable splitting ratio is analyzed. Section 7.3.4 describes the performance of the "integrated" system design that allows for demand responsive service as a modification to two of the solutions presented in Section 7.3.2. Section 7.3.5 presents a summary discussing the conclusions of the computational experiments with the data from the transit system of Austin, Texas.

EXPERIMENTS ON BENCHMARK PROBLEM

Mandl's transit network is based on a real network in Switzerland. There are no acceptable benchmark networks in the transit network design literature, and Mandl's is the only one for which the author has reported all pertinent information to allow replication and comparative testing, making it a de facto benchmark. This network has been utilized by Baaj and Mahmassani as a benchmark problem to compare their results with Mandl's solutions. In this section, the performance of the solution networks generated by the route generation procedure (RGP) with the transit center concept are investigated using this same network.

Mandl's Transit Network

In Figure 7.1, the network connectivity and demand matrix for Mandl's Swiss network are shown. The in-vehicle travel time between two adjacent nodes is in minutes. The demand matrix shows the average number of passenger trips per day for each transit node pair. The total demand is 15570 transit trips; the highest node pair demand is 880 transit trips. In this matrix, 82% of the demand node pairs have non-zero demands.

Mandl presented two solutions (before and after improvement) which satisfied 100% of the total demand in the given network. Figure 7.2 shows Mandl's final solution network after improvement. Baaj and Mahmassani produced three solutions for this network shown in Figure 7.3, Figure 7.4, and Figure 7.5, and compared them to Mandl's solutions. Their solutions

0   8 (in-vehicle travel time, minutes)
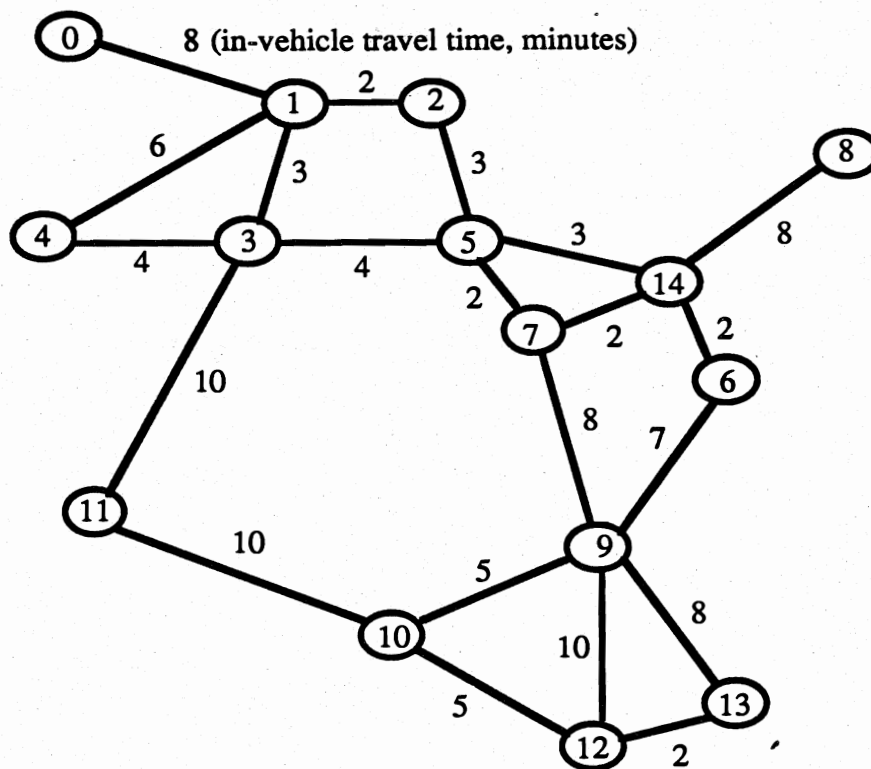
Transit Demand Matrix in List Form :

(0 400 200 60 80 150 75 75 30 160 30 25 35 0 0)
(400 0 50 120 20 180 90 90 15 130 20 10 10 5 0)
(200 50 0 40 60 180 90 90 15 45 20 10 10 5 0)
(60 120 40 0 50 100 50 50 15 240 40 25 10 5 0)
(80 20 60 50 0 50 25 25 10 120 20 15 5 0 0)
(150 180 180 100 50 0 100 100 30 880 60 15 15 10 0)
(75 90 90 50 25 100 0 50 15 440 35 10 10 5 0)
(75 90 90 50 25 100 50 0 15 440 35 10 10 5 0)
(30 15 15 15 10 30 15 15 0 140 20 5 0 0 0)
(160 130 45 240 120 880 440 440 140 0 600 250 500 200 0)
(30 20 20 40 20 60 35 35 20 600 0 75 95 15 0)
(25 10 10 25 15 15 10 10 5 250 75 0 70 0 0)
(35 10 10 10 5 15 10 10 0 500 95 70 0 45 0)
(0 5 5 5 0 10 5 5 0 200 15 0 45 0 0)
(0 0 0 0 0 0 0 0 0 0 0 0 0 0 0)

Figure 7.1 Mandl's Swiss Network and Transit Demand Matrix
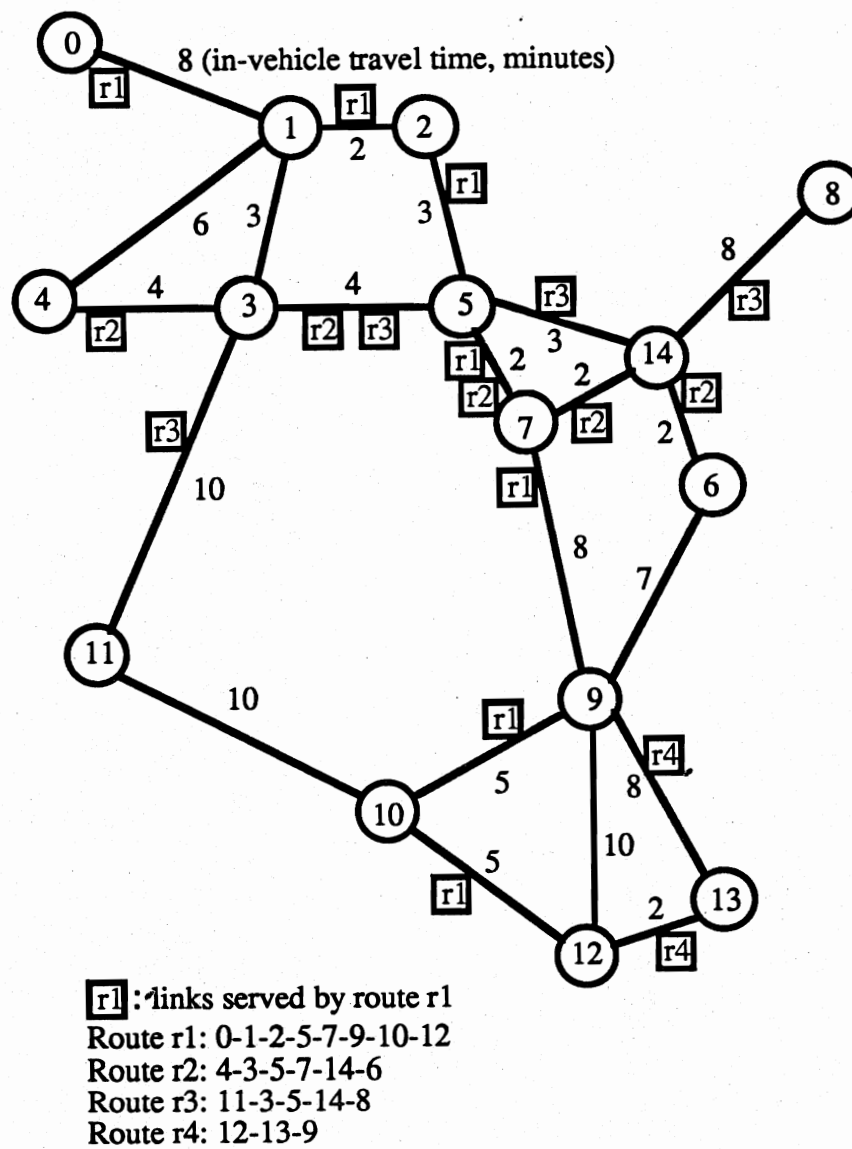
Figure 7.2 Route Layout Generated by Mandl's Algorithm
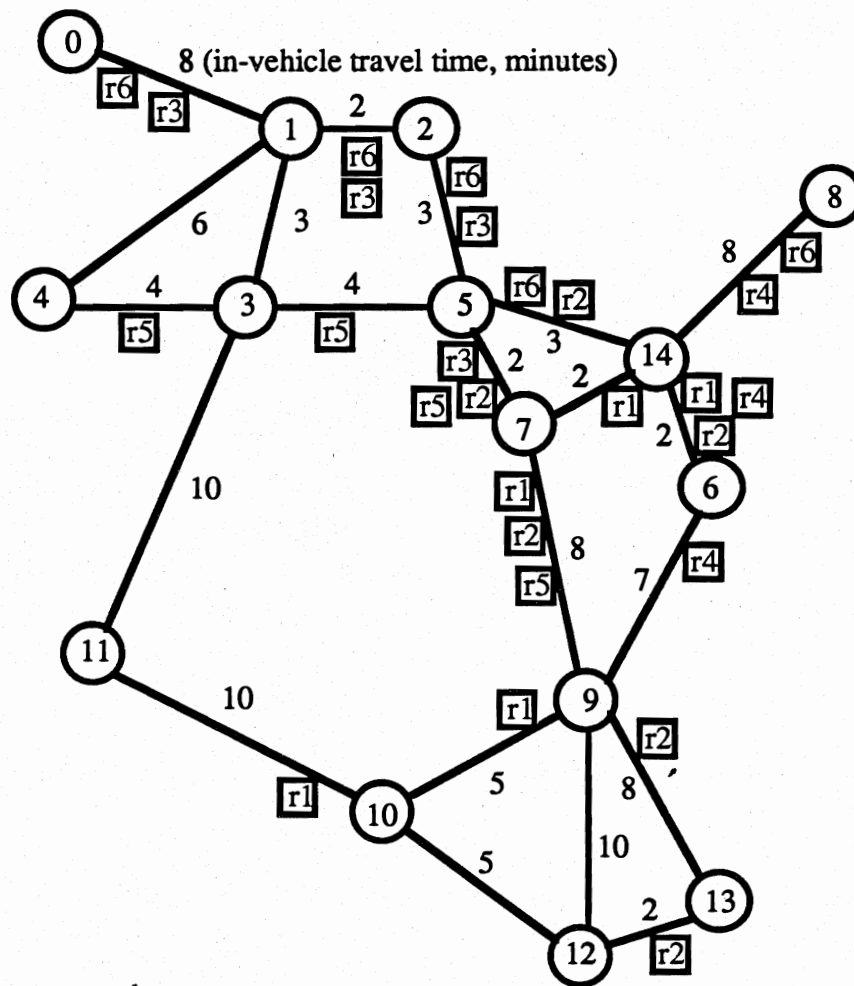
8 (in-vehicle travel time, minutes)

[r1] : links served by route r1
Route r1: 0-1-2-5-7-9-10-12
Route r2: 4-3-5-7-14-6
Route r3: 11-3-5-14-8
Route r4: 12-13-9

8 (in-vehicle travel time, minutes)

- MD Insertion
- Shortest Paths for Skeleton Layout
- *dsdirmin* = 50%

[r1] : links served by route r1

Route r1: 6-14-7-9-10-11
Route r2: 6-14-5-7-9-13-12
Route r3: 0-1-2-5-7
Route r4: 8-14-6-9
Route r5: 4-3-5-7-9
Route r6: 0-1-2-5-14-8

**Figure 7.3 Route Layout Generated by Baaj and Mahmassani's
RGA for First Set of Design Parameters**

Figure 7.4 Route Layout Generated by Baaj and Mahmassani's RGA for Second Set of Design Parameters

- MDMT Insertion
- Alternate Shortest Paths
  for Skeleton Layout
- *dsdirmin* = 50%

r1 : links served by route r1
Route r1: 0-1-3-11-10-12-13
Route r2: 2-5-7-14-6-9
Route r3: 9-10-12
Route r4: 9-10-11
Route r5: 7-9-13
Route r6: 0-1-3-5
Route r7: 8-14-5-7-9
Route r8: 4-1-2-5-14-6-9

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- MD Insertion
- Shortest Paths for Skeleton Layout
- *dsdirmin* = 70%

$\boxed{\text{r1}}$: links served by route r1

Route r1: 9-12
Route r2: 9-10-11
Route r3: 9-3
Route r4: 0-1-2-5-7-9
Route r5: 8-14-6-9
Route r6: 4-3-5-7-9
Route r7: 0-1-3-4

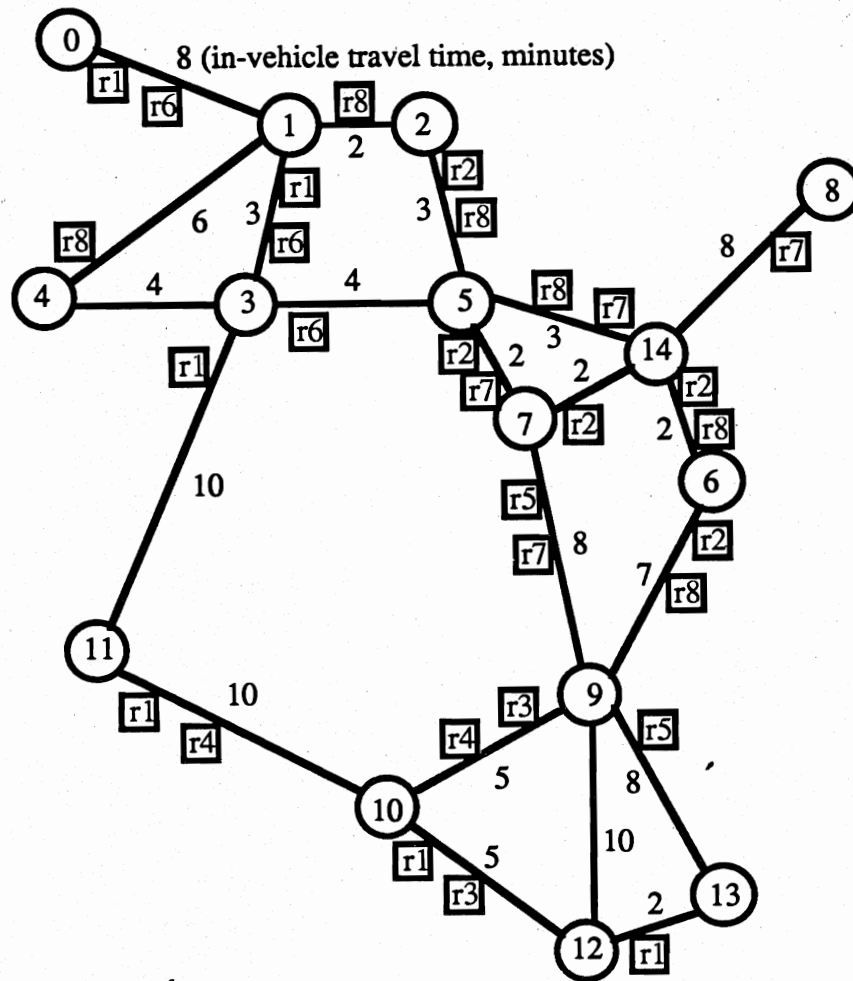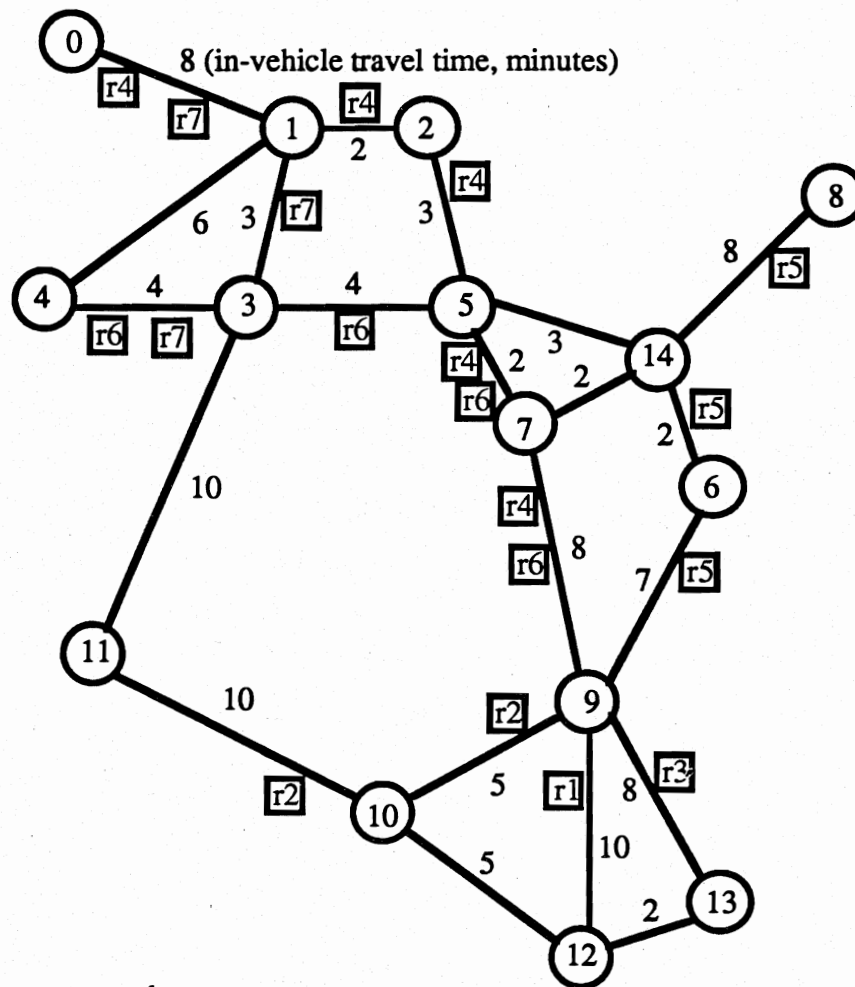**Figure 7.5 Route Layout Generated by Baaj and Mahmassani's RGA for Third Set of Design Parameters**

dominated the networks generated by Mandl's design algorithm in terms of the levels of demand satisfaction, in-vehicle travel time, and required resource (fleet size) but not in terms of the total waiting time. In the following section, the solutions generated by the RGP with the transit center concept for coordinated and uncoordinated service are compared to Mandl's and Baaj and Mahmassani's solutions for uncoordinated transit network designs.

The solutions were generated by RGP using the same three sets of design parameters that were tested by Baaj and Mahmassani. These are summarized in Table 7.1. In the first case, the desired minimum system directness level (the minimum total demand satisfied directly, *dsdirmin*) was set at 50%, the shortest path was used for the initial layout of skeletons, and the maximum demand (MD) node selection and insertion heuristic was followed. In the second case, the same *dsdirmin* was specified, the alternate shortest path was used to form skeletons where feasible, and the maximum demand per minimum time (MDMT) insertion heuristic was employed. The third case increased the desired minimum system directness level (*dsdirmin*) to 70% and used the shortest path and the MD heuristic. The desired minimum system coverage level (the minimum total demand satisfied, *dsmin*) for all three cases was set to 100%.

Table 7.1 Summary of Design Parameters for Three Test Cases

Case	Minimum System directness level	Skeleton Formation	Insertion Heuristic	Minimum System Coverage level
1	50%	shortest path	MD	100%
2	50%	alternate shortest path	MDMT	100%
3	70%	shortest path	MD	100%

The resulting sets of routes from the RGP were evaluated using the NETAP for both coordinated and uncoordinated designs. The NETAP was also used to evaluate all the solutions suggested by Mandl as well as by Baaj and Mahmassani. In all the NETAP runs, the bus seating capacity was selected at 40 seats, the transfer penalty was set at 5 minutes of in-vehicle travel time, and a bus load factor of 1.25 was selected. Operation cost coefficients, a and b, were set to 2.962 and 0.0078, respectively, the same values used in the illustrative application for Austin

case in Section 5.7. The minimum separation distance (travel time) between transit centers was selected to be 10 minutes; the minimum total demand for a transit center was set to 100 passengers; the minimum demand covered by a transit center was set to 150 passengers.

Numerical Results and Conclusions

Two sets of routes were generated by the RGP using the above three sets of input design parameters, as the route networks generated for the first and third cases are the same. Figures 7.6 and 7.7 show the networks generated by the RGP. Tables 7.2, 7.3, and 7.4 show the results of the solutions generated by the RGP and by Baaj and Mahmassani's algorithms using the first, second, and third sets of design parameters, respectively, as well as Mandl's final solution.

All the networks generated by the RGP for the different sets of design parameters had a higher percentage of total demand satisfied directly (82.59, 87.73, and 82.59) than Baaj and Mahmassani's solutions (78.61, 79.96, and 80.99) and Mandl's solution (69.94). Consequently, the percentage of transferring passengers was less in all three of the RGP solutions (17.4, 12.27, and 17.4) than Baaj and Mahmassani's (21.39, 20.04, and 19.04) and Mandl's (30.06).

In all networks utilizing the timed-transfer (route coordination) concept, the total in-vehicle travel times were much higher than Baaj and Mahmassani's and Mandl's solutions. In the worst case, the total in-vehicle travel time was 14% more than Baaj and Mahmassani's solution and 8% more than Mandl's solution. As a result, higher total travel times were required by the timed-transfer cases. The increase of in-vehicle time resulted from additional in-vehicle waiting incurred by passengers who remain on board at transit centers during a time window (for coordinated operations). The additional in-vehicle waiting times for the three timed-transfer networks were 20933, 19574, and 20933 minutes, respectively, based on a five-minute time window. One may reduce this in-vehicle time by using a smaller time window, which however will increase the possibility of missing connections. Therefore, the reliability of bus operations must be traded-off against in-vehicle as well as out-of-vehicle waiting time in determining the time window for coordination at the transit centers. The cases with coordinated route operation had lower out-of-vehicle waiting time than Baaj and Mahmassani's solutions. The differences ranged from 6% to 16%. Mandl's solution had a total out-of-vehicle waiting time that was 8% lower than the best case of timed-transfer networks because the service frequencies on Mandl's routes were much higher than all the coordinated networks. All the coordinated networks had lower aggregate transfer penalties (time) than Baaj and Mahmassani's solutions (39 % lower in the best case) and Mandl's solution (59% lower). The computation of the aggregate transfer penalty was based on the assumption that each transfer is equivalent to five minutes of in-vehicle travel time. It might be

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8 (in-vehicle travel time, minutes)
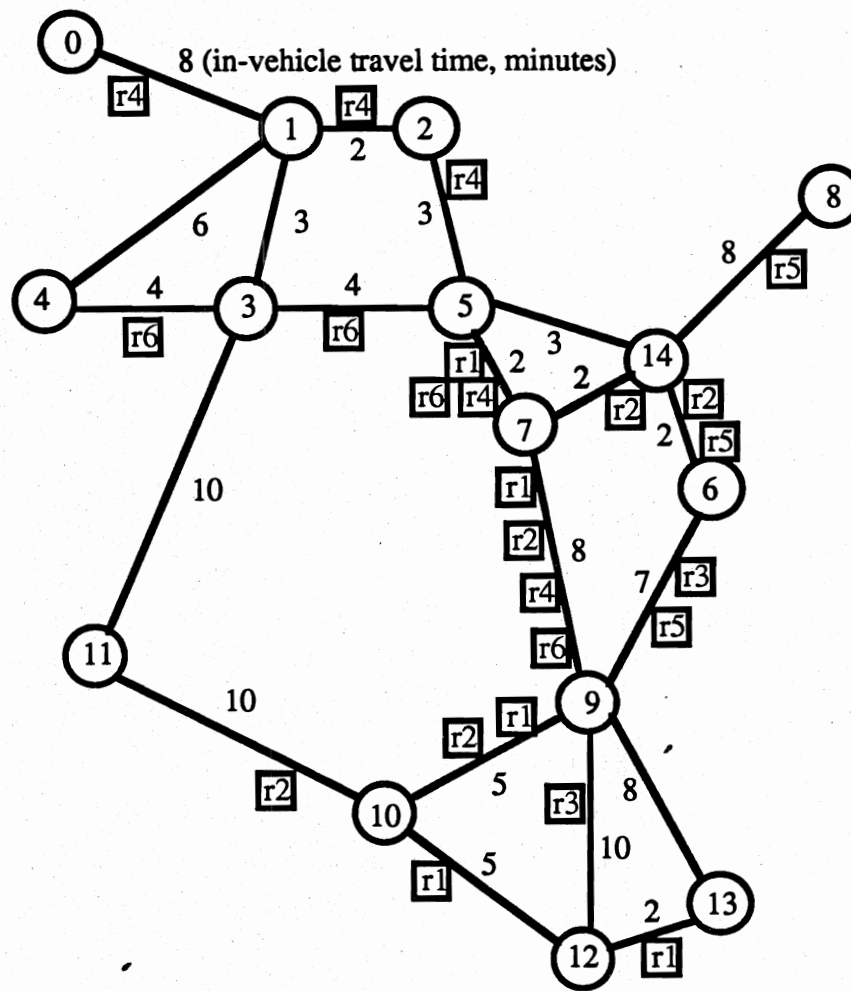
- MD Insertion
- Shortest Paths for Skeleton Layout
- *dsdirmin* = 50% and 70%

$\boxed{r1}$: links served by route r1

Route r1: 5-7-9-10-12-13
Route r2: 6-14-7-9-10-11
Route r3: 6-9-12
Route r4: 0-1-2-5-7-9
Route r5: 8-14-6-9
Route r6: 4-3-5-7-9

Figure 7.6 Route Layout Generated by RGP for First and Third Sets of Design Parameters
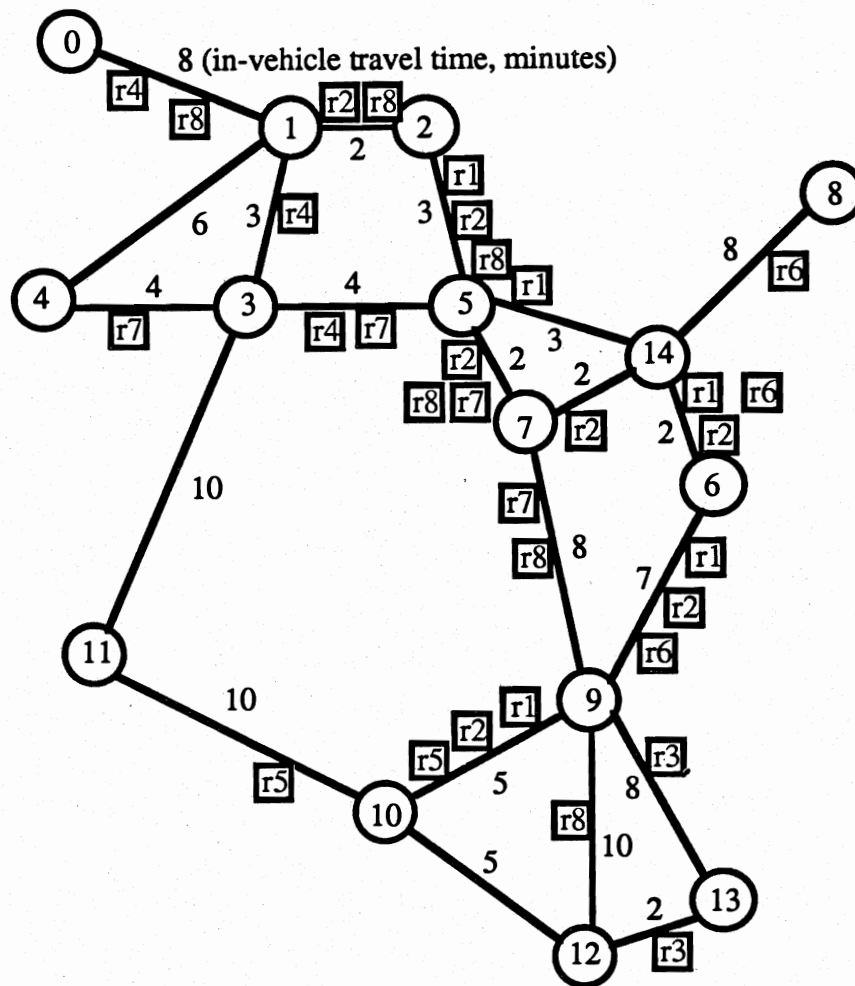
Figure 7.7 Route Layout Generated by RGP for Second
Set of Design Parameters

- MDMT Insertion
- Alternate Shortest Paths
  for Skeleton Layout
- *dsdirmin* = 50%

r1 : links served by route r1
Route r1: 2-5-14-6-9-10
Route r2: 1-2-5-7-14-6-9-10
Route r3: 9-13-12
Route r4: 0-1-3-5
Route r5: 9-10-11
Route r6: 8-14-6-9
Route r7: 4-3-5-7-9
Route r8: 0-1-2-5-7-9-12

Table 7.2 Comparison of Solutions for the Benchmark Network for Cases Using Fisrt Set of Design Parameters

Network Characteristics	RGP with Transit Center Concept		Baaj and Mahmassani's Solution	Mandl's Solution
	Coordinated	Uncoordinated		
% demand 0-transfer	82.59	82.59	78.61	69.94
% demand 1-transfer	17.41	17.41	21.39	29.93
% demand 2-transfer	0	0	0	0.13
% total demand unsatisfied	0	0	0	0
Total travel time (minutes)	225102	203936	205646	219094
Total in-vehicle-travel time	191826	170328	168077	177400
In-vehicle waiting time	20933	———	———	———
Total out-of-vehicle waiting time	19726	20058	20920	18194
Total transfer time (penalty)	13550	13550	16650	23500
Fleet size	87	84	89	99
Operation cost ($)	4043.14	3924.26	4163.46	4620.61
Fuel consumption (gallons)	346.8	336.6	357.12	396.33
First set of input design parameters: 50 % minimum total demand satisfied directly, MD node insertion strategy, and Shortest path heuristic				

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Table 7.3 Comparison of Solutions for the Benchmark Network for Cases Using Second Set of Design Parameters

Network Characteristics	RGP with Transit Center Concept		Baaj and Mahmassani's Solution	Mandl's Solution
	Coordinated	Uncoordinated		
% demand 0-transfer	87.73	87.73	79.96	69.94
% demand 1-transfer	12.27	12.27	20.04	29.93
% demand 2-transfer	0	0	0	0.13
% total demand unsatisfied	0	0	0	0
Total travel time (minutes)	221390	204028	209318	219094
Total in-vehicle travel time	187665	168023	166654	177400
In-vehicle waiting time	19574	——	——	——
Total out-of-vehicle waiting time	24175	26455	27064	18194
Total transfer time (penalty)	9550	9550	15600	23500
Fleet size	77	68	77	99
Operation cost ($)	3609.45	3150.39	3603.72	4620.61
Fuel consumption (gallons)	309.6	270.22	309.11	396.33
Second set of input design parameters: 50 % minimum total demand satisfied directly, MDMT node insertion strategy, and Alternate shortest path heuristic				

Table 7.4 Comparison of Solutions for the Benchmark Network for Cases Using Third Set of Design Parameters

Network Characteristics	RGP with Transit Center Concept		Baaj and Mahmassani's Solution	Mandl's Solution
	Coordinated	Uncoordinated		
% demand 0-transfer	82.59	82.59	80.99	69.94
% demand 1-transfer	17.41	17.41	19.01	29.93
% demand 2-transfer	0	0	0	0.13
% total demand unsatisfied	0	0	0	0
Total travel time (minutes)	225102	203936	217954	219094
Total in-vehicle travel time	191826	170328	180350	177400
In-vehicle waiting time	20933	———	———	———
Total out-of-vehicle waiting time	19726	20058	22804	18194
Total transfer time (penalty)	13550	13550	14800	23500
Fleet size	87	84	82	99
Operation cost ($)	4043.14	3924.26	3830.03	4620.61
Fuel consumption (gallons)	346.8	336.6	328.52	396.33
Third set of input design parameters: 70 % minimum total demand satisfied directly, MD node insertion strategy, and Shortest path heuristic				

more appropriate to use a lower transfer penalty for transfers completed under route coordination; the total transfer penalty for the coordinated networks would have then been lower than the results presented.

All the timed-transfer networks required smaller fleet sizes (87, 77, and 87 buses) than Mandl's network (99 buses). In comparison with Baaj and Mahmassani's solutions, the coordinated design required a smaller fleet size (87 vs. 89 buses) for the first case, the same fleet size (87 buses) for the second case, and a larger fleet size (87 vs. 82 buses) for the third case. The same patterns were observed for the operation cost and total fuel consumption. For the first case, the timed-transfer design required lower operation cost ($4043 vs. $4163) and fuel consumption (347 vs. 357 gallons) than Baaj and Mahmassani's design. For the second case, the operation cost and fuel consumption for the two designs are nearly the same. For the last case, the timed-transfer network required higher operation cost ($4043 vs. $3830) and fuel consumption (347 vs. 329 gallons) than Baaj and Mahmassani's design. Mandl's solution resulted in both the highest operation cost ($4620) and fuel consumption (396 gallons).

All the uncoordinated networks generated by the RGP using the transit center concept outperformed the solution network proposed by Mandl in all aspects except the total waiting time component. The required fleet size varied from 68% to 85% of that proposed by Mandl. The operation cost and fuel consumption savings ranged from 15% to 32%. The total travel times were lower by about 7% in all three cases; the in-vehicle travel times were 4% to 6% lower. The total out-of-vehicle waiting time for Mandl's network was lower by about 9% to 31% than those of the resulting networks because of the higher frequencies.

The RGP designs also outperformed Baaj and Mahmassani's solutions with the exception of the in-vehicle travel time for the first and second cases and the operator costs for the third case. The required fleet sizes for the RGP solutions were smaller in the first and second cases than Baaj and Mahmassani's solutions (84 vs. 89 and 68 vs. 77), but slightly higher in the third case (84 vs. 82). Similarly, the operation costs were lower in the first two cases ($3924 vs. $4163 and $3150 vs. $3604) and worse in the third case ($3924 vs. $3830). Following the same pattern, the fuel consumption was lower for the first two cases (337 vs. 357 and 270 vs. 309 gallons) and higher in the last case (337 vs. 329 gallons). The total travel time was at worst slightly lower than that of Baaj and Mahmassani (0.8%) and in the best case 6% lower. The total out-of-vehicle waiting times for all cases were better by about 2% to 12% than those of Baaj and Mahmassani's solutions. The in-vehicle travel times in the first two cases were slightly higher (approximately 1%) than in Baaj and Mahmassani's solutions, but 6% lower in the third case.

In summary, the networks generated around the transit center concept had better performance in terms of the levels of demand satisfaction for all study cases. The timed-transfer design reduced the total passenger out-of-vehicle waiting time in all cases compared to Baaj and Mahmassani's solution (19726 vs. 20920, 24175 vs. 27064, and 19726 vs. 22804 minutes), but required very high additional in-vehicle waiting time in all three cases (23749, 21011, and 11476 minutes, respectively) due to the route coordination. The uncoordinated networks generated with the transit center concept had solutions that outperformed the solutions proposed by Mandl and by Baaj and Mahmassani. Overall, in comparison with Mandl's solution, the best uncoordinated network satisfied 18% more passengers directly with approximately 32% fewer buses, lower operation cost, and less fuel consumption, and 7% less total travel time. In comparison with Baaj and Mahmassani's solutions, the best case satisfied 8% more passengers directly with 12% fewer buses, lower operation cost, and less fuel consumption and, 2.5% less total travel time.

The benchmark network used in this section was small and dense with only 15 nodes within a 33 minute shortest travel distance between the two furthest nodes and with a total demand of 15570 trips per day. With this relatively high demand density, all the passengers in this network were served with a high level of service and had high frequencies of service on all routes. It has been shown in this section that conventional uncoordinated, fixed-route and fixed-schedule bus service is suitable for this type of network. Coordination has less impact on networks with high frequency routes because it tends to increase in high in-vehicle time with limited opportunity for out-of-vehicle waiting time saving. Demand-responsive service is not particularly suitable for this type of system. As discussed by Baaj (1990), constraints on route length, route circuity, and route duplication may not affect the search in a small network such as Mandl's, but will tend to be more important in medium to large networks. As a result, conclusions obtained on the basis of this network may not necessarily be applicable to actual networks. Therefore, the design procedures and alternative design concepts in the solution framework should be tested in actual networks. In the next section, the tests of the proposed design procedures and alternative design concepts are performed with the data generated for the transit network of Austin, Texas.

TESTS ON THE AUSTIN TRANSIT NETWORK

In this section, the design procedures and alternative design concepts of the solution framework are tested with the data generated from the transit system of Austin, Texas. The network data for this application was discussed in Section 4.7.1, and includes the transit demand matrix, the network connectivity, and the lists of the shortest paths and k shortest paths for all the

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transit node pairs. Several user specified parameters for the execution of the numerical experiments on the Austin case are listed in Table 7.5. The experiments are performed with six combinations of minimum system coverage (*dsmin*) and directness (*dsdirmin*) levels to investigate the performance of the design procedures and alternative design concepts. Table 7.6 lists the six combinations of the two user desired minimum demand levels.

The computational experiments address the following four objectives:

1) Investigate the TCSP, described in Chapter 6. The sets of transit centers obtained for different combinations of desired minimum system coverage and directness levels and from different application strategies (one-pass vs. iterative process) are presented and compared in Section 7.3.1.

2) Test the RGP and NETAP and investigate the performance of fixed route designs for different combinations of minimum system coverage and directness levels. Route networks generated to satisfy a lower minimum system coverage level generally serve areas with high demand and leave spatially dispersed demand unsatisfied, whereas networks generated to provide greater demand coverage naturally serve more spatially dispersed demand. Therefore, alternative design concepts can be tested for different spatial distributions of demand by altering the minimum system coverage level. In addition, route networks generated by the RGP perform differently for alternative designs with different system directness levels. The effect of the system directness level are also examined. In Section 7.3.2, the performance of four alternative fixed route designs are investigated under different combinations of minimum demand levels. The alternative designs are: uncoordinated design with fixed vehicle size, uncoordinated design with variable vehicle sizes, coordinated design with fixed vehicle size, and coordinated design with variable vehicle sizes.

3) Investigate the effects of the proposed route splitting procedure on coordinated systems. This procedure is intended to improve the system effectiveness by splitting routes at transit centers and reducing the negative effect (transfer waiting time) of route coordination. Section 7.3.3 shows the results of the procedure and discusses their sensitivity to the value of the splitting indicator.

4) Investigate performance of the integrated bus system proposed in the solution framework. The integrated bus system serves high demand density areas with fixed route service and low demand density areas with demand responsive service. The intent is to examine the performance of the demand responsive service procedure. Results of the integrated bus system design tests are presented in Section 7.3.4.

Table 7.5 User Specified Parameters for Experiments on the Austin Network

Set of terminal nodes	none
Skeleton layout heuristic	shortest path
Node insertion strategy	maximum demand per minimum route length increase (MDML) heuristic
Number of initial skeletons	15 for *dsmin* = 40
25 for *dsmin* = 60	
40 for *dsmin* = 80	
Maximum operational frequency	20 buses/hour
Minimum allowable bus frequency	1 bus/hour
Maximum load factor	1.25 on routes with frequency more than 2 buses/hour
0.80 on routes with frequency less than 2 buses/hour	
Transfer penalty	5 minutes of equivalent in-vehicle travel time
Bus seating capacity	40 passengers for fixed bus size option
Available commercial vehicle sizes	15, 27, and 37 seats for variable bus size option
Fuel consumption coefficients	3, 6, and 9 miles per gallon for vehicles with 37, 27, and 15 seats, respective.
Operation cost coefficient, a	2.962
Operation cost coefficient, b	0.0078
Minimum separation travel time between two transit centers	15 minutes
Minimum demand covered by a transit center	150 passengers/hour
Waiting time value	$9/hour
In-vehicle travel time value	$3/hour

Tests of the TCSP

As described in Section 6.2, the TCSP may be applied in two different ways to identify sets of transit centers for a given system. The first application strategy consists of executing the procedure in a single pass (i.e. one iteration only). The second consists of executing the procedure iteratively until the set of transit centers converges. In Table 7.7, the results obtained for different combinations of application strategies and minimum system coverage and directness levels are reported. A total of twelve different sets of transit centers were generated by the TCSP for evaluation.

Table 7.6 Six Selected Combinations of Minimum System Coverage and Directness Levels

Minimum System Directness Level *dsdirmin* (%)	Minimum System Coverage Level *dsmin* (%)
40	80
40	98
60	80
60	98
80	80
80	98

The TCSP produced consistent solutions in the numerical experiments. The results show that six transit nodes, (2, 9, 19, 36, 78, 84), were identified as transit centers in all the study cases. Transit nodes 87 and 101 were identified as transit centers in eleven out of the twelve cases. Except for the combination of 40% minimum system directness and 80% minimum system coverage, the sets of transit centers identified by the TCSP were nearly the same with only two transit nodes, 42 and 87, alternating with each other in those cases. The number of iterations to reach convergence for each combination of desired demand levels is also shown in Table 7.7. In the worst case (40% minimum system directness and 80% of minimum system coverage), four runs were needed. For three out of six demand combinations, convergence to the same set of transit centers was obtained in only two iterations. For two demand combinations, only one transit center was different between the two sets generated by a single pass versus the convergent iterative process. Even in the worst case, only two transit centers were different.

Transit centers identified by the TCSP contained a downtown transit center, major shopping malls or centers in the city, and transit nodes serving major population clusters or communities in the suburban areas. Among the selected centers, node 2 is the major transit station in the downtown area; nodes 19 and 36 correspond to major activity centers, Northcross Mall and Highland Mall in the north; node 84 is at Westgate Mall, a major shopping center in the south. Node 9 is located at a commercial center surrounded by major residential areas in the far north of the city. Since nodes 42 and 87 are close to each other in the east of the city, each set of transit centers contains only one of these two nodes so as to meet the separation criterion. The total node demand criterion determines which of these two nodes should be selected. Nodes 57, 73, and 121 cover major residential areas and are located at major arterial intersections and shopping centers in the far south of the city.

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Table 7.7 Sets of Transit Centers Generated by TCSP for Different Combinations of Minimum System Coverage and Directness Levels & Terminating Strategies

Desired demand levels	Set of transit centers for one iteration	Set of transit centers after convergence	Iterations to reach convergence
dsdirmin = 40% *dsmin* = 80%	2, 9, 19, 36, 57, 78, 84, 87, 101, 121	2, 9, 19, 36, 57, 78, 84, 87	4
dsdirmin = 40% *dsmin* = 98%	2, 9, 19, 36, 42, 73, 78, 84, 101	2, 9, 19, 36, 73, 78, 84, 87, 101	3
dsdirmin = 60% *dsmin* = 80%	2, 9, 19, 36, 73, 78, 84, 87, 101	2, 9, 19, 36, 73, 78, 84, 87, 101	2
dsdirmin = 60% *dsmin* = 98%	2, 9, 19, 36, 42, 73, 78, 84, 101	2, 9, 19, 36, 73, 78, 84, 87, 101	3
dsdirmin = 80% *dsmin* = 80%	2, 9, 19, 36, 73, 78, 84, 87, 101	2, 9, 19, 36, 73, 78, 84, 87, 101	2
dsdirmin = 80% *dsmin* = 98%	2, 9, 19, 36, 42, 73, 78, 84, 101	2, 9, 19, 36, 42, 73, 78, 84, 101	2

Tests of the RGP and NETAP

In this section, the RGP and the NETAP were tested on the transit network data of Austin, Texas. Experiments were performed on the four types fixed-route, fixed-schedule service designs described in the solution framework: uncoordinated network with fixed vehicle size, uncoordinated network with variable vehicle sizes, coordinated network with fixed vehicle size, and coordinated network with variable vehicle sizes. These four design types were investigated under six selected combinations of minimum system coverage and directness levels to accomplish the second objective described in Section 7.3. The six combinations are the same ones used in the TCSP tests.

For each uncoordinated design, one RGP run and one NETAP run were required. The TCSP was first utilized to generate a set of transit centers for the coordinated design. In all the experiments, the set of transit centers was generated with a single pass of the TCSP, each of which required one RGP run and one NETAP run. Therefore, each coordinated design required two RGP, and two NETAP runs. Since six combinations of minimum system coverage and directness levels were tested, the two uncoordinated designs required 12 runs and the two coordinated designs required 24 runs, for a total of 36 RGP runs and 36 NETAP runs.

The numerical results were compared according to four catégories of performance measures: 1) demand satisfaction levels, 2) user travel costs, 3) operation costs, and 4) total system cost. Demand satisfaction levels used for the comparison are the percentages of demand satisfied directly, demand satisfied with one transfer, and total demand satisfied. User travel costs considered include total in-vehicle travel time, average passenger in-vehicle travel time, total out-of-vehicle waiting time, average passenger out-of-vehicle waiting time, total transfer penalty, and total travel time. Total fuel consumption and total operation cost are the operation costs performance measures used for the comparison. The total system cost components are the total user cost and total operation cost. In each of the following figures, the output variable of interest is plotted for the different levels of the user specified design parameters, namely the minimum system coverage at levels of 80 and 98% and minimum system directness at levels of 40, 60, and 80%. Values are shown for both coordinated networks and uncoordinated networks and in some cases for fixed and variable vehicle sizes.

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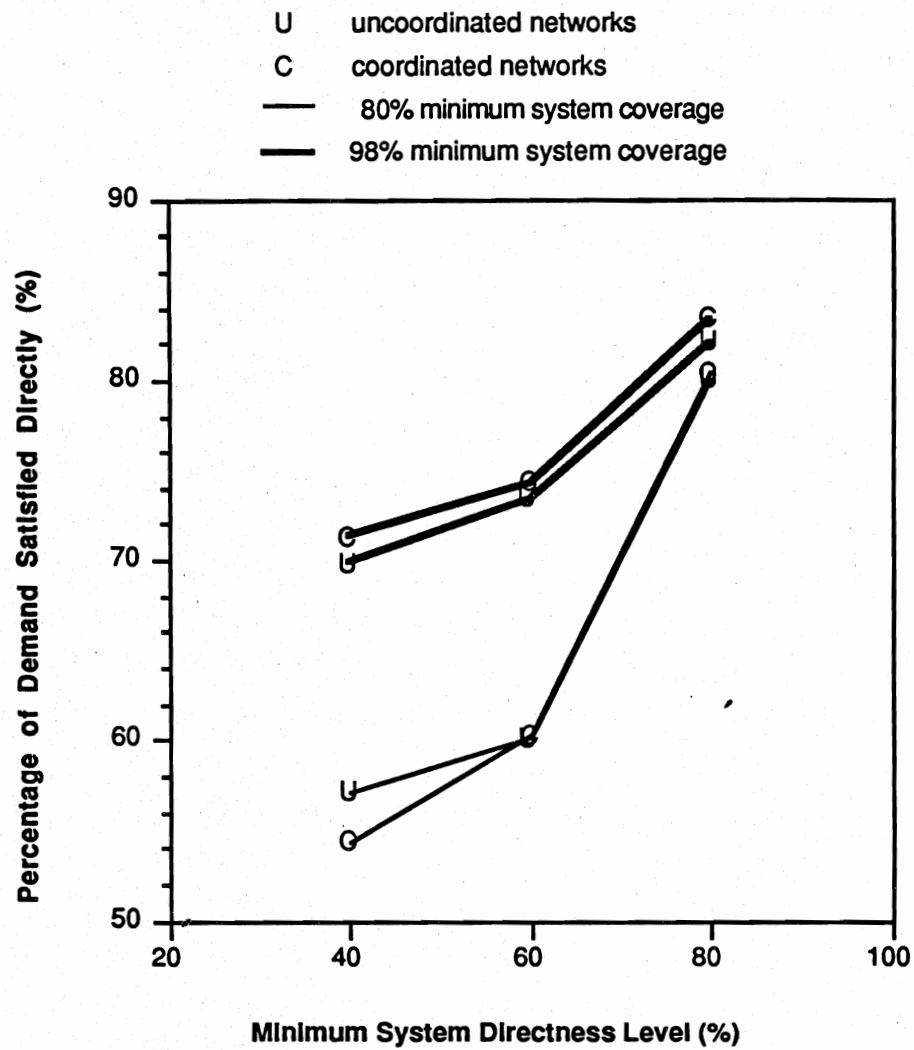
Figure 7.8 Percentage of Demand Satisfied Directly vs.
Minimum System Directness Level

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1) Demand Satisfaction Levels:

Percentage of Demand Satisfied Directly: Figure 7.8 shows the percentage of demand satisfied directly for the coordinated and uncoordinated network designs generated under the six combinations of minimum demand levels. With only one exception, the coordinated networks satisfied a slightly higher percentage of the demand directly (system directness level) than the uncoordinated networks. In the best case (*dsmin* = 98% and *dsdirmin* = 40%), 1.5% more passengers were satisfied directly. The coordinated networks satisfied more demand directly for all cases at the 98% level minimum system coverage level.

Percentage of Demand Satisfied with One Transfer : In contrast to the percentage of demand satisfied directly, the uncoordinated design had higher percentages of demand satisfied with one transfer with the exception of the case with *dsmin* = 80% and *dsdirmin* = 40%. The percentage of demand satisfied with one transfer for all networks is shown in Figure 7.9.

Percentage of Total Demand Satisfied: Figure 7.10 shows the percentage of total demand satisfied for all cases. With one exception, the uncoordinated design satisfied slightly higher percentages of total demand than the coordinated design. For cases at the 98% level of minimum system coverage, the differences between the coordinated and uncoordinated designs were within 1%. In the worst case (*dsmin* = 80% and *dsdirmin* = 80%), the difference was 2.5 %.

2) User Travel Costs:

Total and Average Passenger In-Vehicle Travel Time: When the coordination concept is applied, the total passenger in-vehicle travel time may increase because of the additional time (equal to a transfer time window) spent on board by continuing passengers at the transfer centers. On the other hand, the in-vehicle travel time of transferring passengers may decrease as they select the shortest downstream path among all the competing paths at the transfer points. Figures 7.11 and 7.12 show the total in-vehicle travel time for cases with minimum system coverage at levels of 80% and 98%, respectively. For all cases, the coordinated design required higher total in-vehicle travel time than the uncoordinated design. Since each network satisfied different amounts of the total demand, the comparison of in-vehicle travel time should be based on the average passenger in-vehicle travel time. As seen in Figures 7.13 and 7.14, the average in-vehicle time was within the range of 25 and 31 minutes for all networks. The differences in average in-vehicle time between the coordinated and uncoordinated designs ranged from 1.0 to 2.1 minutes. In all runs, the network design with variable vehicle sizes had slightly better average in-vehicle time than networks with fixed vehicle size.
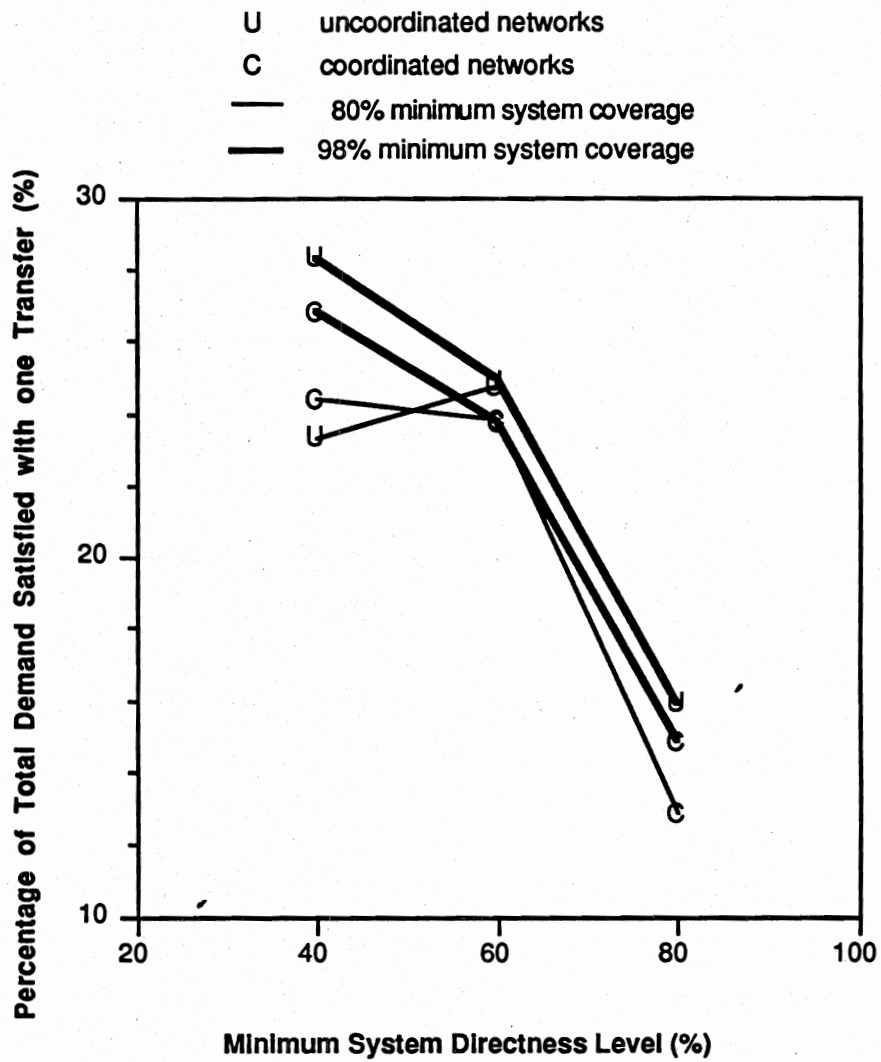
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U   uncoordinated networks

C   coordinated networks

————   80% minimum system coverage

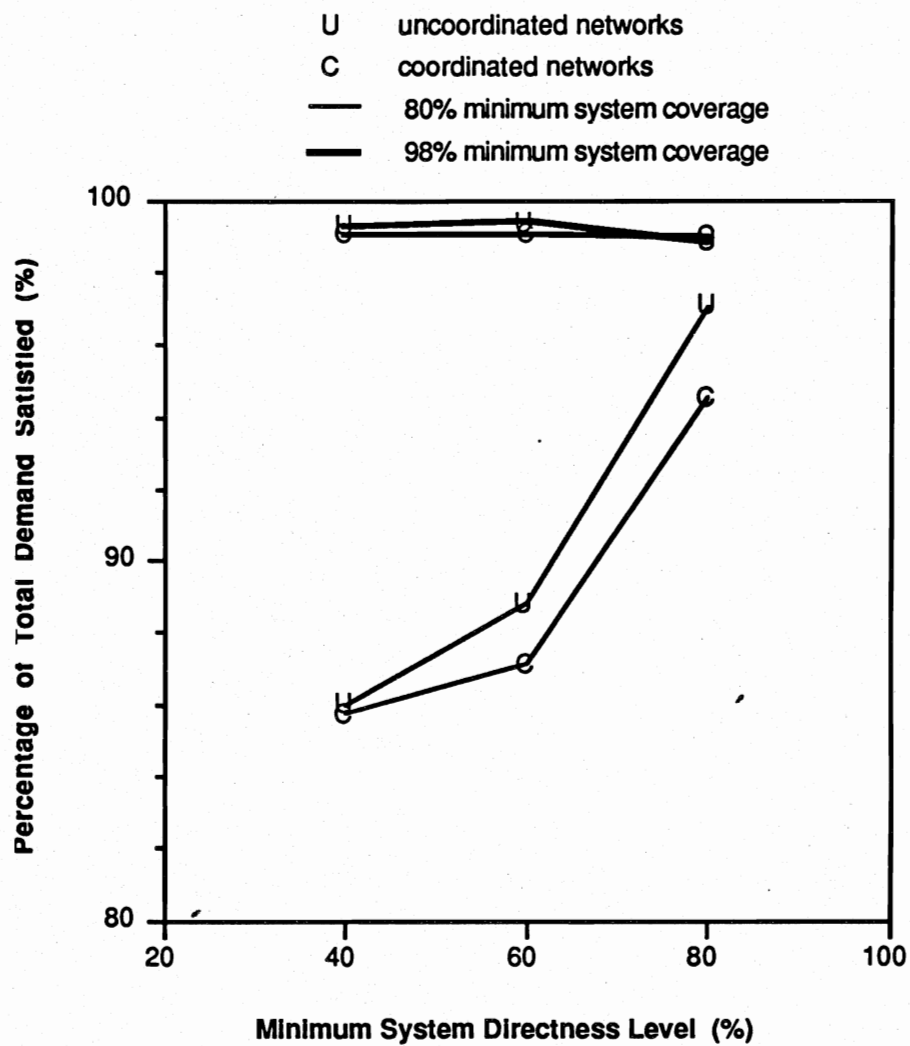━━━━   98% minimum system coverage

**Figure 7.9 Percentage of Demand Satisfied with One Transfer
vs. Minimum System Directness Level**

Figure 7.10 Percentage of Total Demand Satisfied vs. Minimum System Directness Level
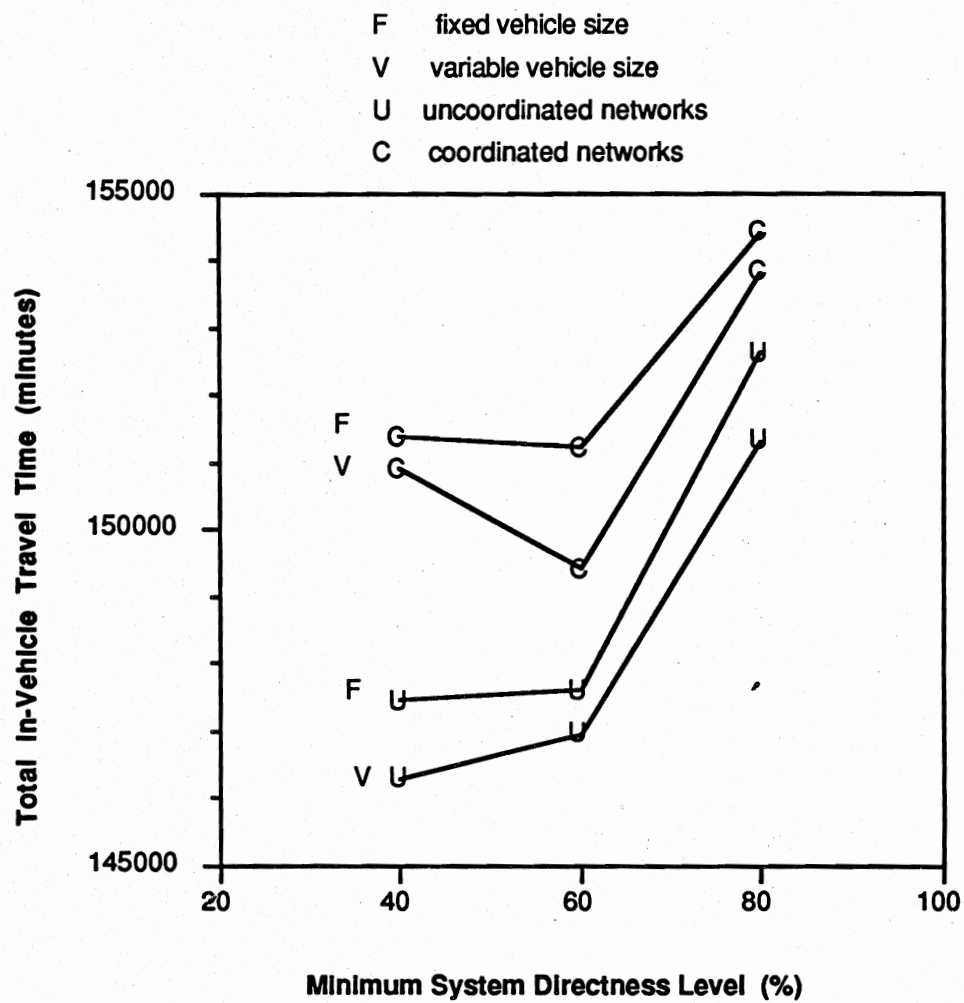
F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks

Figure 7.11 Total In-Vehicle Travel Time vs.   Minimum
System Directness Level for Minimum System
Coverage Level = 80%

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F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
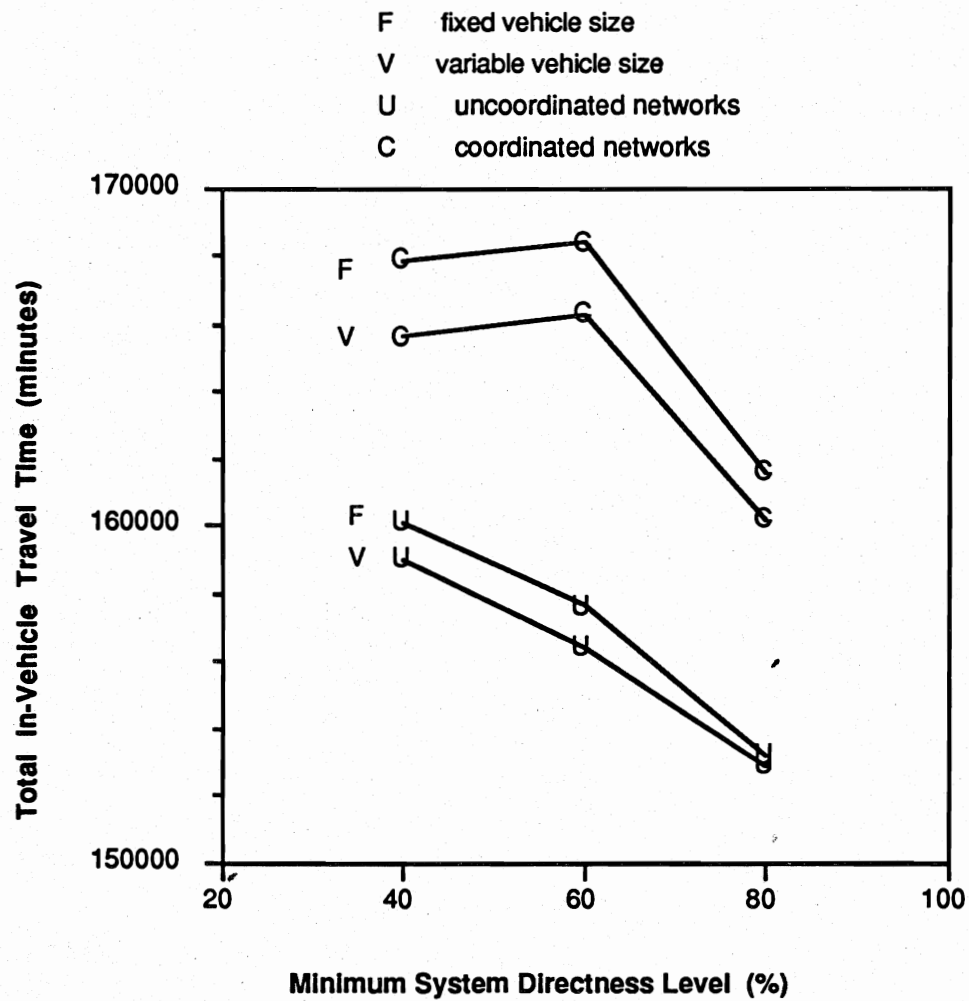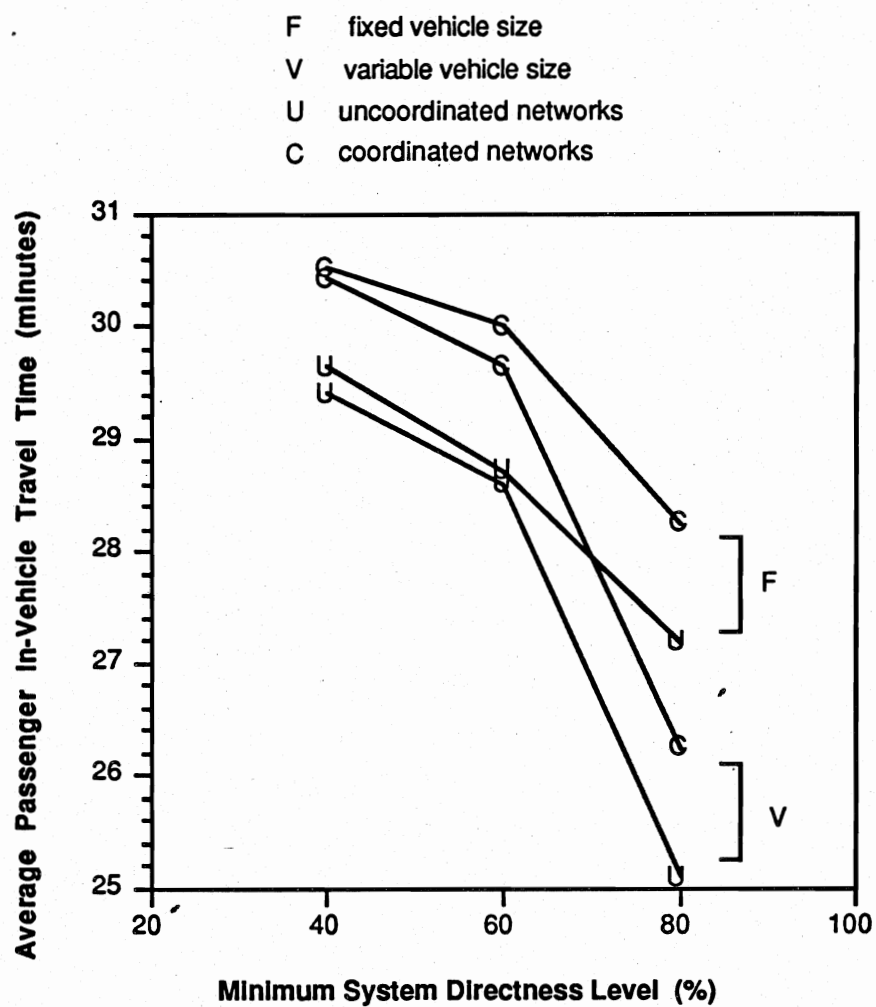C   coordinated networks

**Figure 7.12 Total In-Vehicle Travel Time vs. Minimum
System Directness Level for Minimum System
Coverage Level = 98%**

Total and Average Passenger Out-of-Vehicle Waiting Time: The total out-of-vehicle waiting times for cases with minimum system coverage of 80% and 98% are presented in Figures 7.15 and 7.16, respectively . In all cases, the coordinated design resulted in better (lower) total out-of-vehicle waiting time because the transfer waiting time was reduced by route coordination at transit centers. Coordinated Networks yielded higher total out-of-vehicle waiting time savings at the higher system coverage level. This was expected because a network providing greater coverage serves more spatially dispersed demand than a network that provides less coverage of the projected service area. Routes serving spatially dispersed demand generally require low service frequencies and involve more transfers from and to the low frequency routes. At coordinated operation centers, more out-of-vehicle waiting time can be saved for passengers transferring to a lower frequency route than for those transferring to a higher frequency route. Consequently, the coordinated design is more desirable for areas with spatially dispersed demand than for areas with high demand density.

Similar conclusions can be reached on the basis of the average passenger out-of-vehicle waiting time as shown in Figures 7.17 and 7.18. The savings in average out-of-vehicle waiting time for the coordinated design ranged from 0.1 to 1.4 minutes at the 80% system coverage level and from 0.8 to 1.9 minutes at the 98% coverage level. These savings increased as the minimum system directness level increased from 40% to 60%, but decreased as the level further increased from 60% to 80%. At the 40% level, a smaller percentage of routes in the resulting network was set to low frequencies; thus a smaller saving of passenger out-of-vehicle waiting time was achieved than for cases at the 60% level. However, at the 80% level, fewer passengers transferred, yielding smaller total passenger out-of-vehicle waiting time saving.

The use of variable vehicle sizes had meaningful impacts on the out-of-vehicle waiting time reduction. From the results in Figures 7.17 and 7.18, the average passenger out-of-vehicle waiting time saved with the variable vehicle size option ranged from 7 to 11 minutes. This saving resulted mainly from higher service frequencies used with the smaller vehicle sizes.

Total Transfer Penalty: Figure 7.19 shows the total transfer penalty for all the networks (each transfer was considered equivalent to 5 minutes of in-vehicle time). The pattern is similar to the percentage of total demand satisfied with one transfer shown in Figure 7.9 The uncoordinated design resulted in a higher total transfer penalty than the coordinated design except at the 80% level of demand coverage and 40% demand satisfied directly.

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F fixed vehicle size
V variable vehicle size
U uncoordinated networks
C coordinated networks

Figure 7.13 Average Passenger In-Vehicle Travel Time vs. Minimum System Directness Level for Minimum System Coverage Level = 80%

F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks
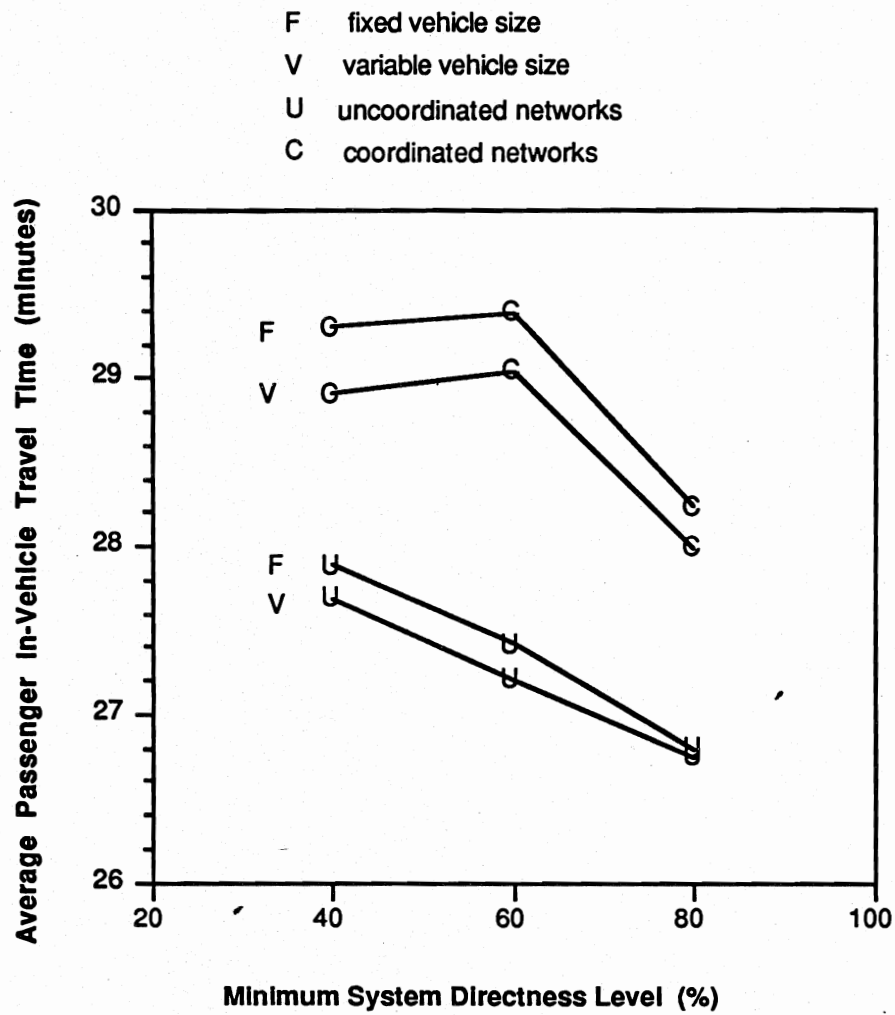
Figure 7.14 Average Passenger In-Vehicle Travel Time vs. Minimum System Directness Level for Minimum System Coverage Level = 98%

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F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks

Figure 7.15 Total Out-of-Vehicle Waiting Time vs. Minimum
System Directness Level for Minimum System
Coverage Level = 80%

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F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
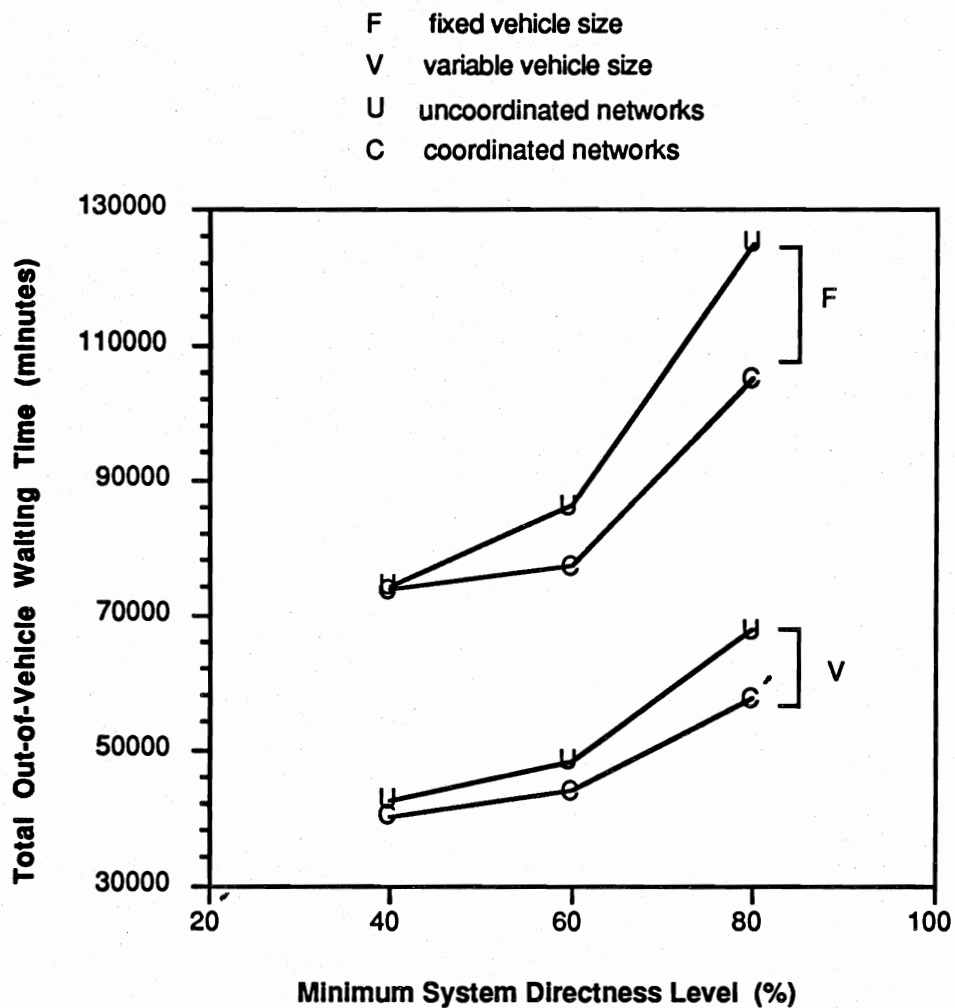C   coordinated networks

Figure 7.16 Total Out-of-Vehicle Waiting Time vs. Minimum
System Directness Level for Minimum System
Coverage Level = 98%

137

F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks

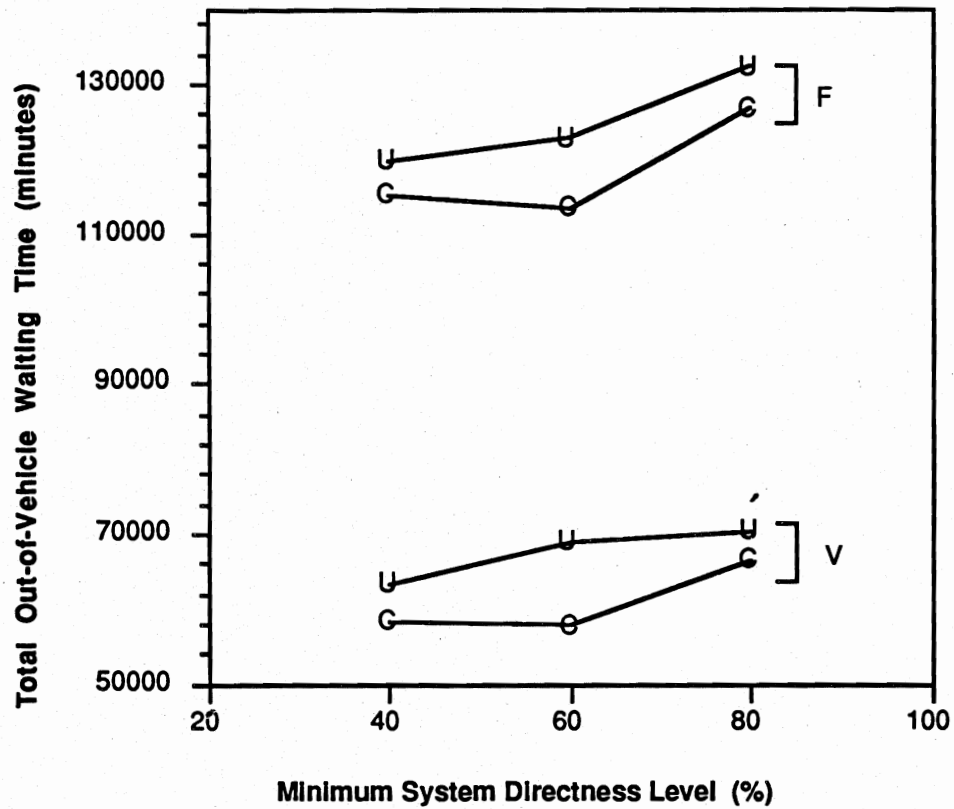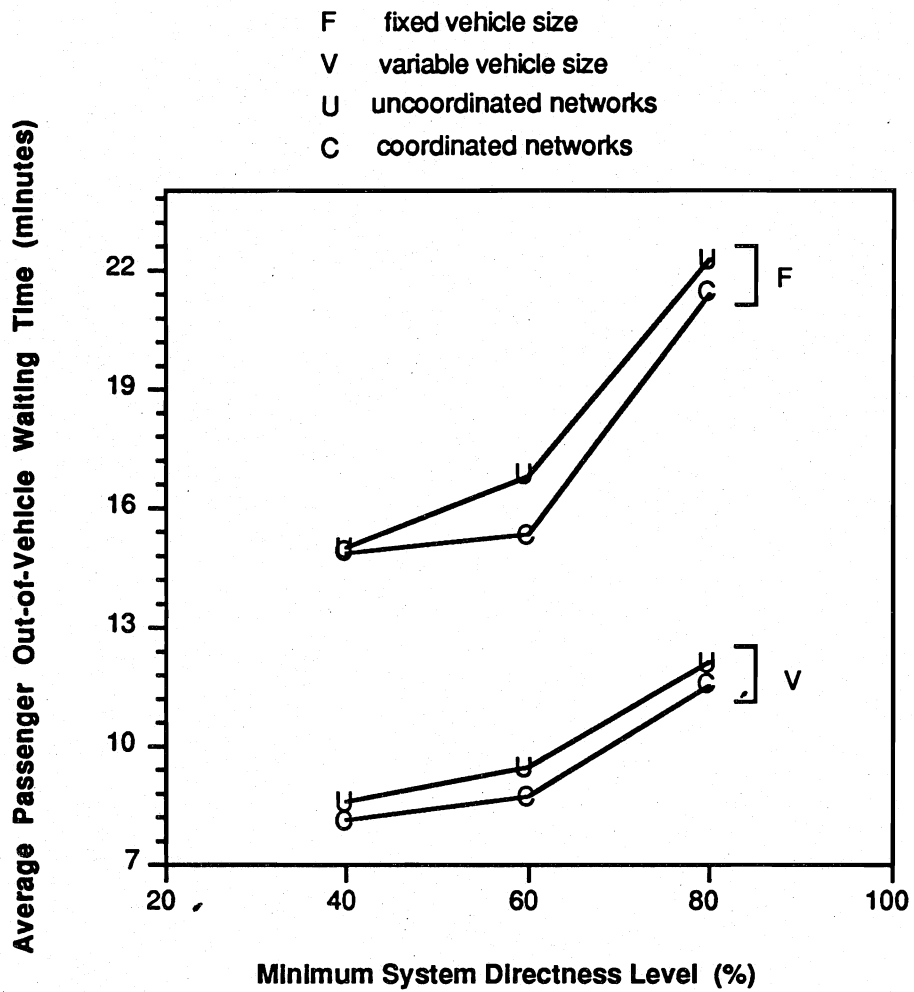Figure 7.17 Average Passenger Out-of-Vehicle Wiating Time vs.
Minimum System Directness Level for Minimum
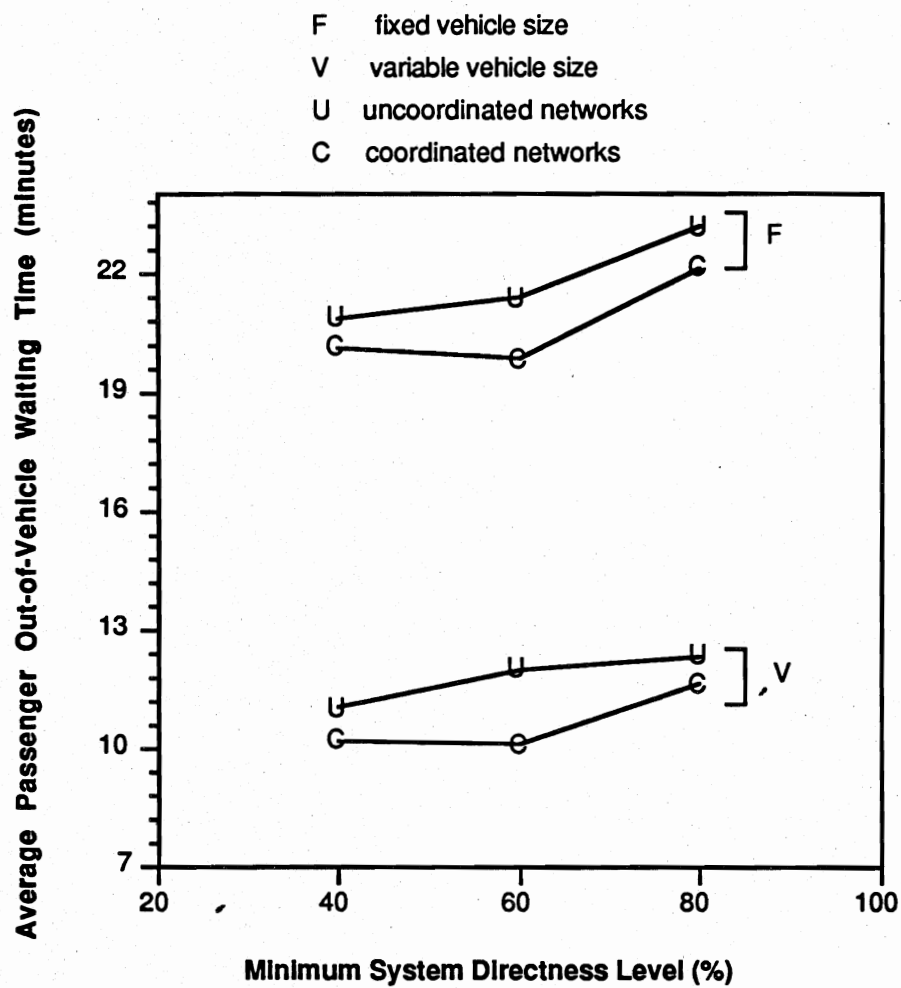System Coverage Level = 80%

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Figure 7.18 Average Passenger Out-of-Vehicle Waiting Time vs.
Minimum System Directness Level for Minimum
System Coverage Level = 98%

Total Travel Time: Total travel time is the sum of the in-vehicle travel time, out-of-vehicle waiting time, and transfer penalty. Figure 7.20 shows the total travel time for all study cases. With one exception, the uncoordinated design had lower total travel time at the 98% minimum system coverage level. At the 80% coverage level, the uncoordinated design had better total travel time at the 40% minimum system directness level, but worse at both the 60% and 80% directness levels. This was because the uncoordinated networks at 60% and 80% directness levels actually satisfied higher total demand than the coordinated networks. The designs with variable vehicle sizes had much lower total travel time because of their lower total out-of-vehicle waiting time. The reductions of total travel time due to the variable vehicle size option ranged from 15% to 21%.

3) Operation Costs:

Total Fuel Consumption: Figures 7.21 and 7.22 show that the differences in total fuel consumption between the uncoordinated and coordinated designs (at the 98% minimum system coverage level) were rather small and less than 4%. At the 80% coverage level, the uncoordinated design was better for minimum system directness levels of 40% and 60%, but worse at the 80% level. Compared with the fixed vehicle size option, the network design with variable vehicle sizes had much better total fuel consumption. In the best case, the fuel consumption saving with the variable vehicle size option reached 30%. In the worst case, the saving still reached 11%.

Total Operation Cost: The total operation cost is obtained using Equation 5.5.4, a function of vehicle size and total vehicle miles. This cost function accounts for all types of expenses, which include costs for ownership, labor, fuel, and maintenance. Figure 7.23 shows that the total operation cost trends were similar to the total fuel consumption trends for the coordinated networks. Smaller vehicle sizes were obtained for designs with variable vehicle sizes, and thus much higher total vehicle miles were required. In the cost function, the operation cost has a linear relationship with the total vehicle miles. As a result, networks with variable vehicle sizes required much higher total operation cost than those with a fixed vehicle size. In the worst case, the increase in total operation cost reached 76%. Note that vehicle size for each bus route is obtained by minimizing the total system cost, consisting of the operation cost and user cost. Although the operation cost is much higher for networks with variable vehicle sizes, the waiting cost is reduced significantly. Therefore, the total system cost is lower than designs with fixed bus size (as presented next).

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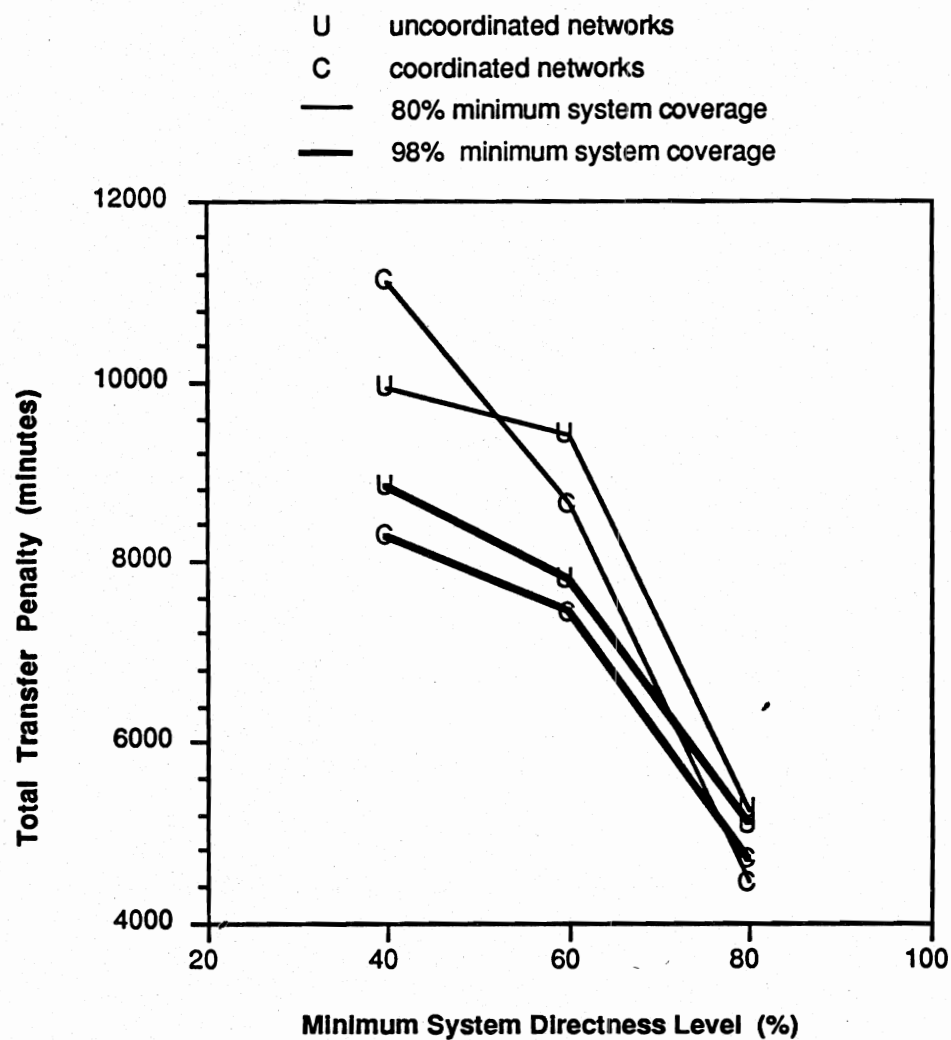
Figure 7.19 Total Transfer Penalty vs. Minimum System Directness Level
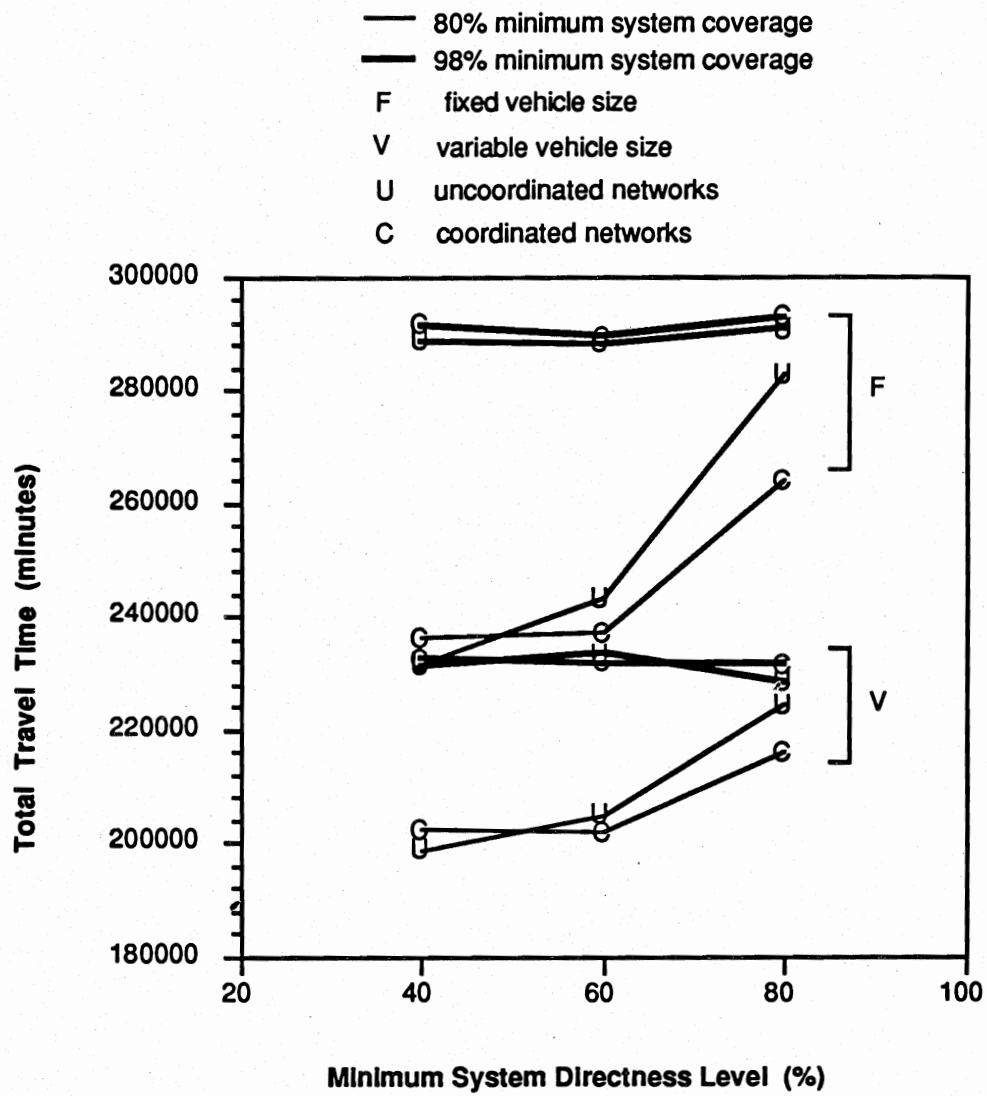
Figure 7.20 Total Travel Time vs. Minimum System Directness Level

F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks

**Figure 7.21 Total Fuel Consumption vs. Minimum System
                Directness Level for System Coverage Level =
                80%**

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F   fixed vehicle size
V   variable vehicle size
U   uncoordinated networks
C   coordinated networks
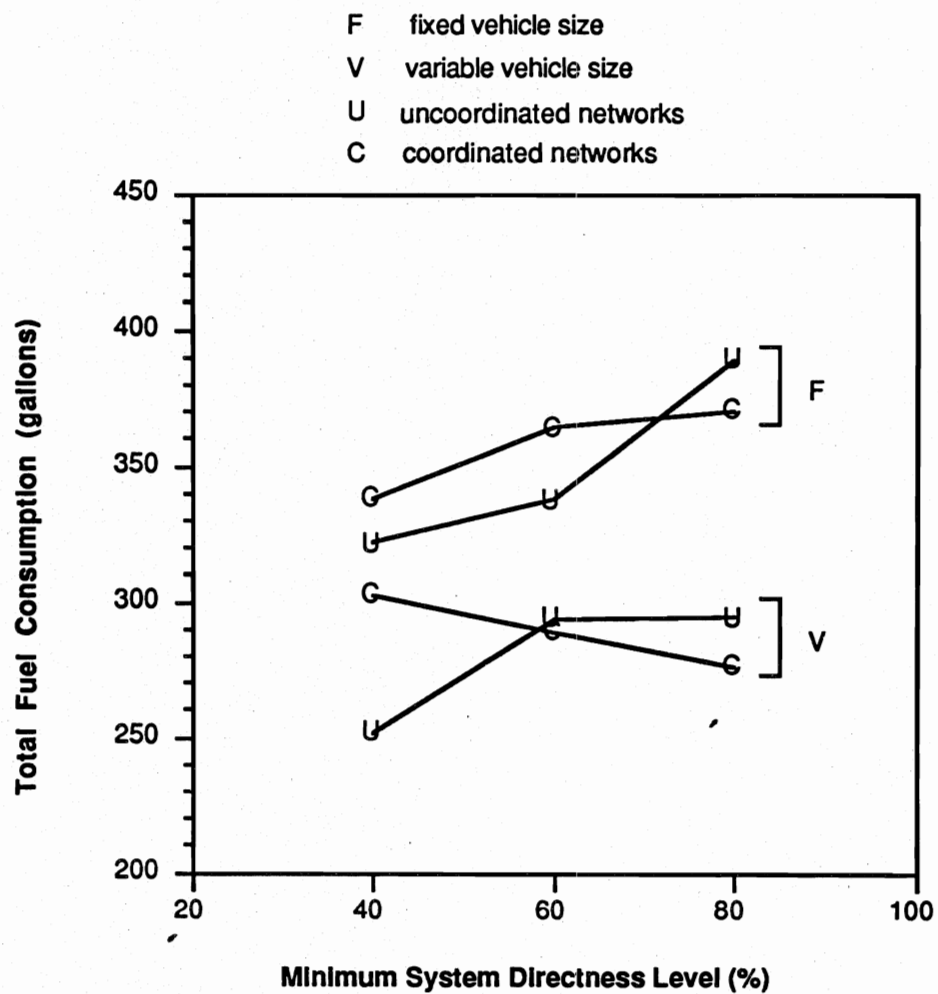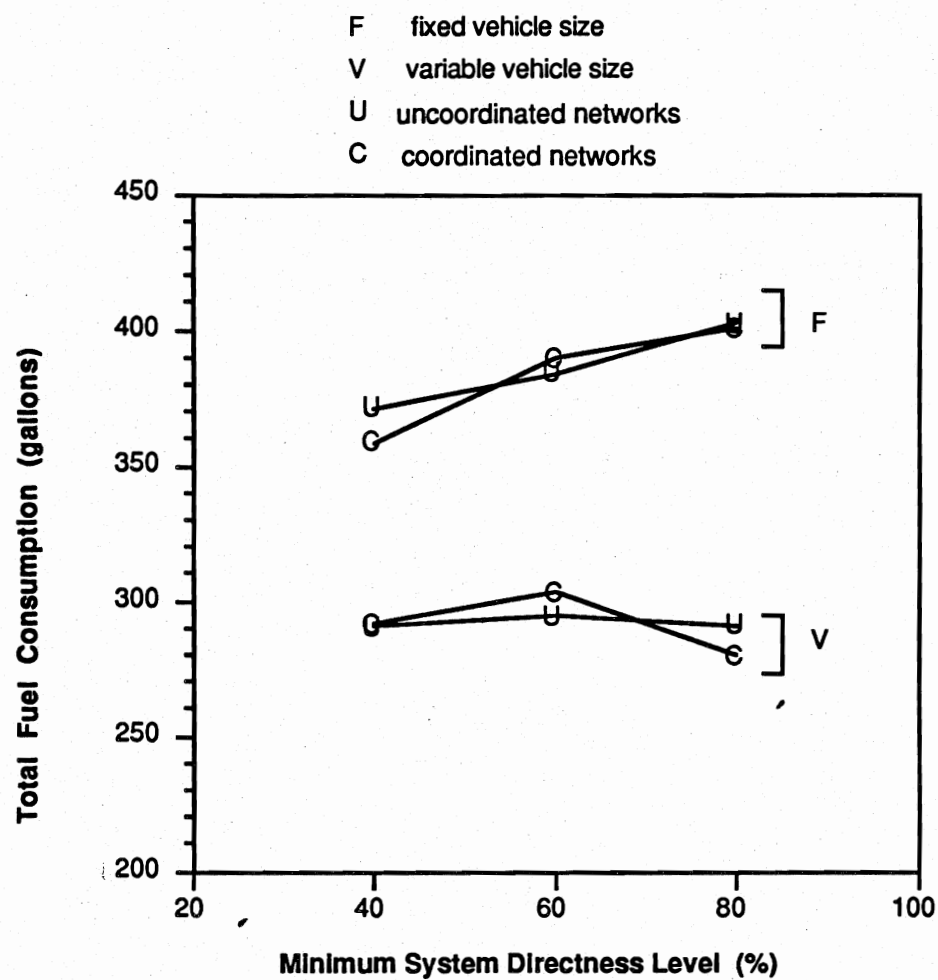

Figure 7.22 Total Fuel Consumption vs. Minimum System
              Directness Level for Minimum System Coverage
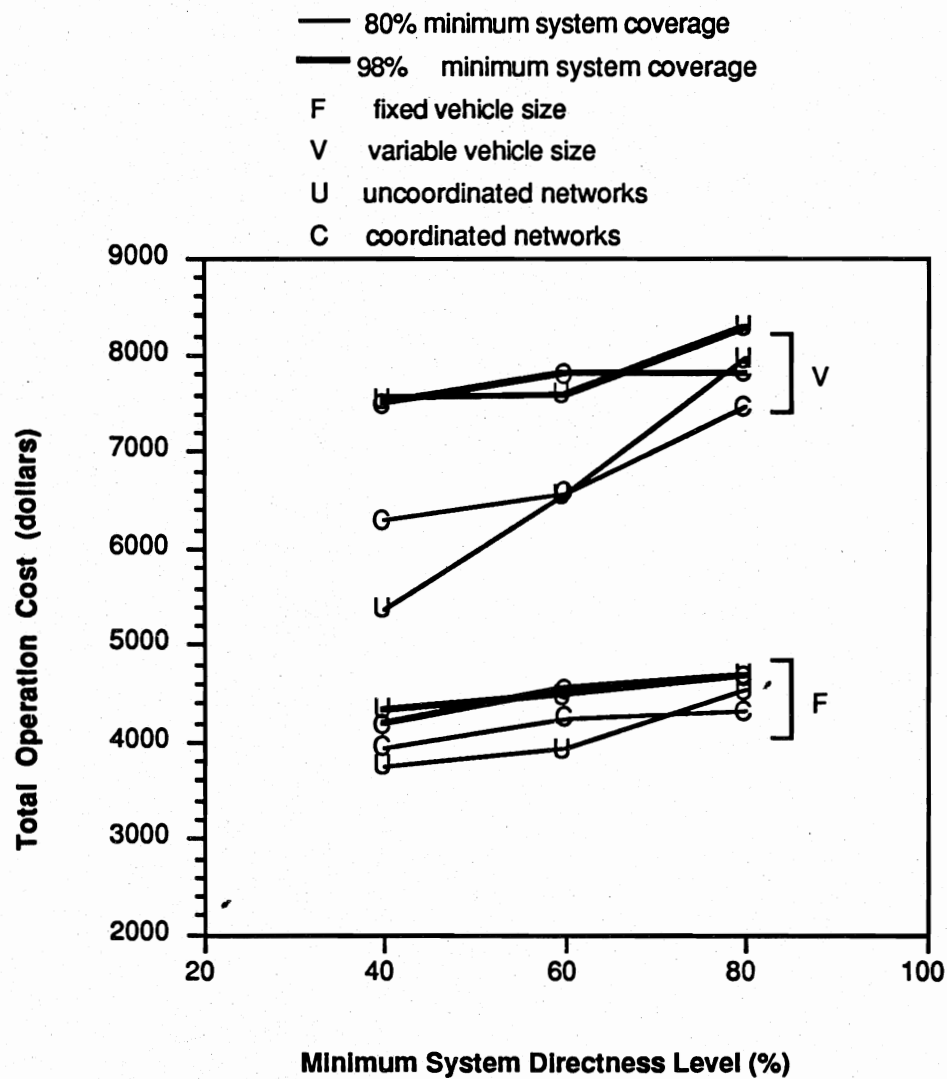   Level = 98%

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Figure 7.23 Total Operation Cost vs. Minimum System Directness Level

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4) Total System Cost:

Figure 7.24 shows that lower total system costs were obtained with the coordinated design except for the two cases with the lowest minimum system coverage (40%) and directness levels (80%). The reductions of total system cost ranged from a few point percentage to 10%. The results also show that the system cost for variable vehicle size designs was 13% to 17% lower than fixed vehicle size designs.

Computational Study of the Route Splitting Procedure for Coordinated Networks

The past section addressed the performance of the RGP and NETAP for different fixed-route, fixed-schedule service concepts. In the following sections, two modification procedures are illustrated: route splitting at transit centers and demand responsive service. This section focuses on the route splitting procedure, intended to improve the effectiveness of the transit system by splitting unbalanced segments of a route at a transit center so that the route segment with lower maximum link flow can be operated with a lower frequency of service. Consequently, operator costs are reduced and higher system utilization can be achieved. However, the route splitting modification will result in more transfers. This procedure splits routes only at transit centers so that the waiting time for passengers who are forced to transfer due to route splitting is reduced through route schedule coordination.

In the previous section, twelve sets of coordinated routes were generated. The route splitting procedure is tested here on one of the resulting coordinated networks with fixed vehicle size and values of the minimum system directness and coverage levels of 60% and 98%. The splitting ratio was defined in Section 6.3.2 as the ratio of the product of the peak load point count on the proposed two new routes obtained by splitting a route to the square of the peak load point count on the existing route. The splitting ratio ranges from 0 to 1. A route with a lower splitting ratio tends to be more amenable to splitting. The sensitivity of the acceptable splitting ratio is investigated for ratios of 0.2, 0.4, 0.5, 0.6, 0.7, and 0.8. A ratio of zero implies no splitting and therefore leaves the network unchanged.

Table 7.8 shows the numerical results of the route splitting procedure for different acceptable splitting ratios. For cases with acceptable splitting ratios up to 0.4, the impacts of the procedure were not dramatic. In this ratio range, the procedure split only 5 routes and resulted in the same required fleet size and slight savings in operation cost and fuel consumption. The percentage of total demand satisfied directly decreased slightly (from 74.31 to 73.13%) and the percentage of total demand satisfied decreased by only 0.03%. Similarly, the total out-of-vehicle
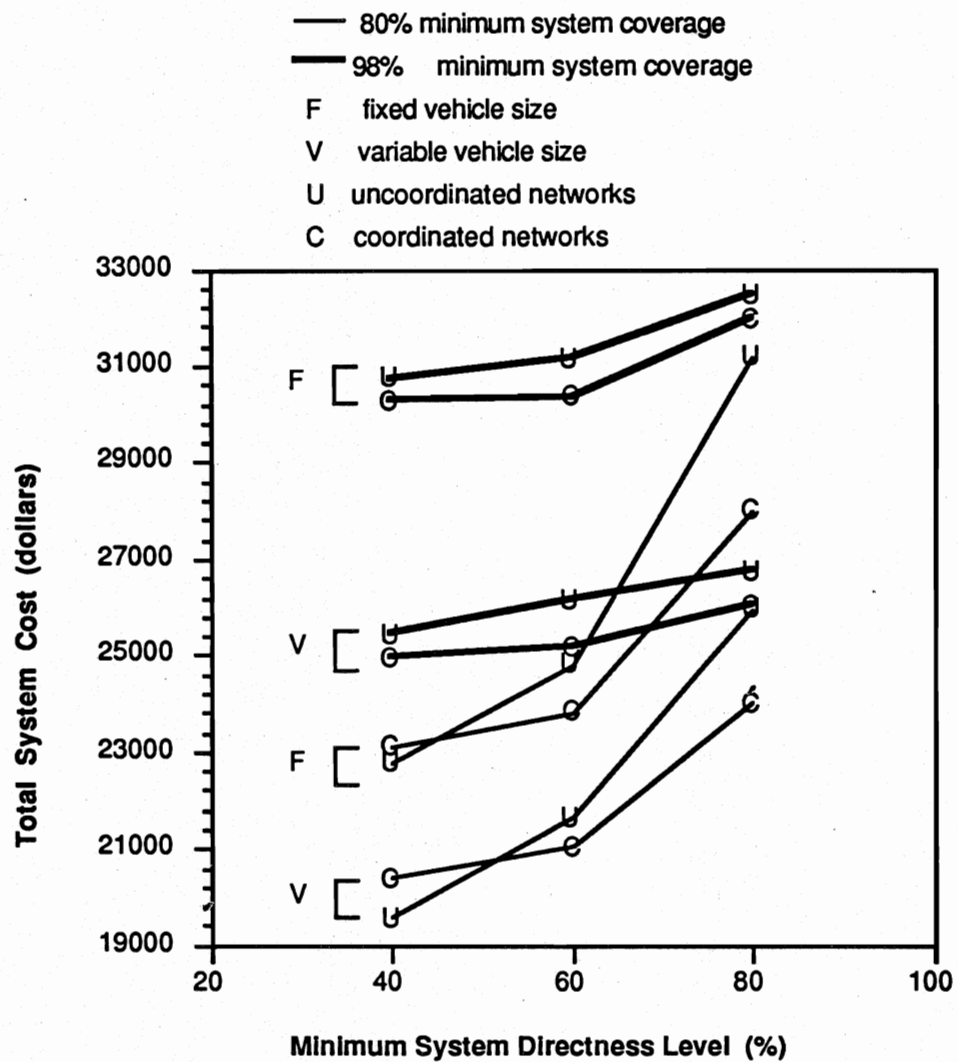
146

Figure 7.24 Total System Cost vs. Minimum System Directness

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waiting time increased only 0.6% and the total in-vehicle travel time decreased only 0.3%. Significant impacts were detected for cases with acceptable splitting ratios greater than 0.4. The percentage of total demand satisfied directly decreased from 73.13%, to 68.08%, and to 64.70% as the splitting ratio increased from 0.4, to 0.6, and to 0.8. Correspondingly, the number of routes split increased from 5 to 15 and to 22. The total out-of-vehicle waiting time initially worsened rapidly (approximately 7%) then improved slightly (less than 0.1%) for two reasons: 1) slightly higher frequencies were set on some of the routes; and 2) some new routes had the same frequencies as the existing routes; thus each new transferring passenger required a waiting time of only one half of the transfer time window. The total in-vehicle travel time decreased from 167681 to 165469 and to 164744 minutes. The required fleet size dropped from 97 to 95, and then to 94 buses. Following the same pattern, the operation cost decreased from $4506 to $4423, and to $4403; fuel consumption dropped from 389 to 379, and to 378 gallons. The results indicate that the operation cost can be reduced only up to a certain value of the acceptable splitting ratio. For a higher ratio, the new routes require the same frequencies of service as the original routes; and thus no further improvement can be achieved by route splitting.

Figure 7.25 shows each component of user travel time vs. different acceptable splitting ratios. The total passenger travel time, which is the sum of the in-vehicle travel time, out-of-vehicle waiting time, transfer penalty, is worse for higher splitting ratios. The total travel time changes most for splitting ratios between 0.4 and 0.6. Figure 7.26 shows each component of system cost vs. the acceptable splitting ratio. The total system cost increased as the acceptable splitting ratio increased. Similar pattern as the total passenger travel time was detected.

Experiments with the Integrated Bus System Design

At very high demand satisfaction levels (approaching 100%), the set of routes generated by the RGP contains many low ridership routes. These routes are operationally uneconomical and result in ineffective resource allocation. This section investigates the integrated bus system design concept which uses fixed-route, fixed-schedule service (FRS) for the transit demand that can be served effectively and demand responsive service (DRS) for the remaining unsatisfied demand. In the integrated system design procedure, low ridership routes are first discontinued and the resulting network is then evaluated by the NETAP to identify the unsatisfied demand. Low ridership routes are identified as those with associated load factor below an acceptable level. After the unsatisfied demand is identified, the demand responsive service procedure is applied. The experiments were performed for both uncoordinated and coordinated networks generated in Section 7.3.2 using the 60% minimum system directness level and the 98% minimum system

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Table 7.8 Comparisons of Network Characteristics for Route Splitting at Transit Centers under Different Splitting Ratios

| Network Characteristics	Acceptable Splitting Ratio						
	0	0.2	0.4	0.5	0.6	0.7	0.8
% demand 0-transfer	74.31	74.17	73.13	71.06	68.08	66.36	64.7
% demand 1-transfer	23.72	23.82	24.65	26.49	27.80	29.18	29.94
% demand 2-transfer	1.00	1.04	1.21	1.45	3.11	3.11	4.36
% total demand satisfied	99.03	99.03	99.00	99.00	99.00	99.00	99.00
% total demand unsatisfied	0.97	0.97	1.00	1.00	1.00	1.00	1.00
Total in-vehicle travel time (minutes)	168391	168346	167681	165718	165469	165367	164744
Total out-of-vehicle waiting time	113503	113733	114240	118764	120926	121666	122127
Total transfer penalty	7440	7490	7830	8500	9840	10440	11180
Fleet size	97	97	97	94	95	95	94
Number of routes	49	50	54	59	64	66	71
Operation cost ($)	4539.33	4518.19	4506.72	4393.71	4423.37	4431.76	4403.32
Fuel consumption (gallons)	389.36	387.55	386.56	376.87	379.41	380.13	377.69
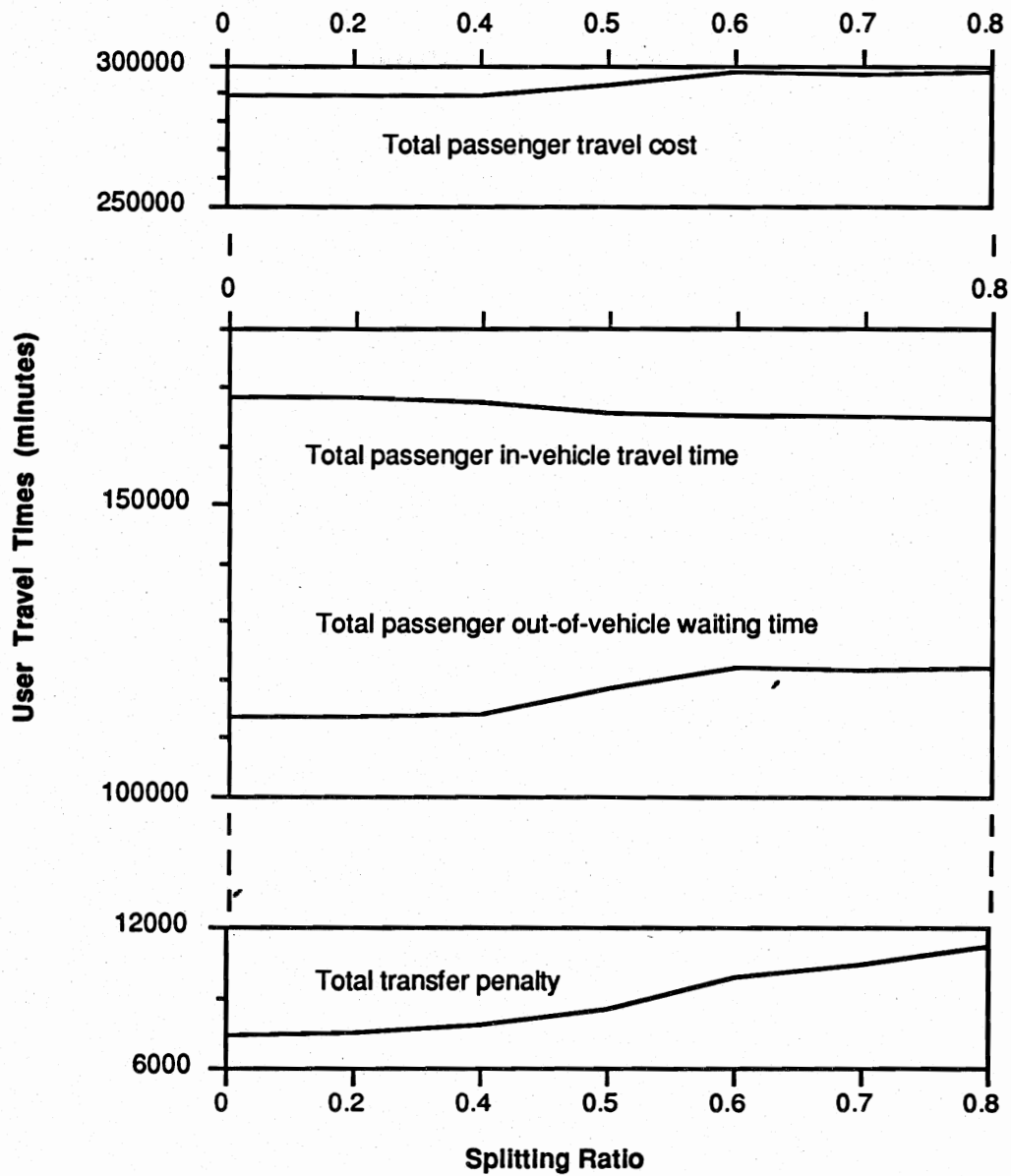
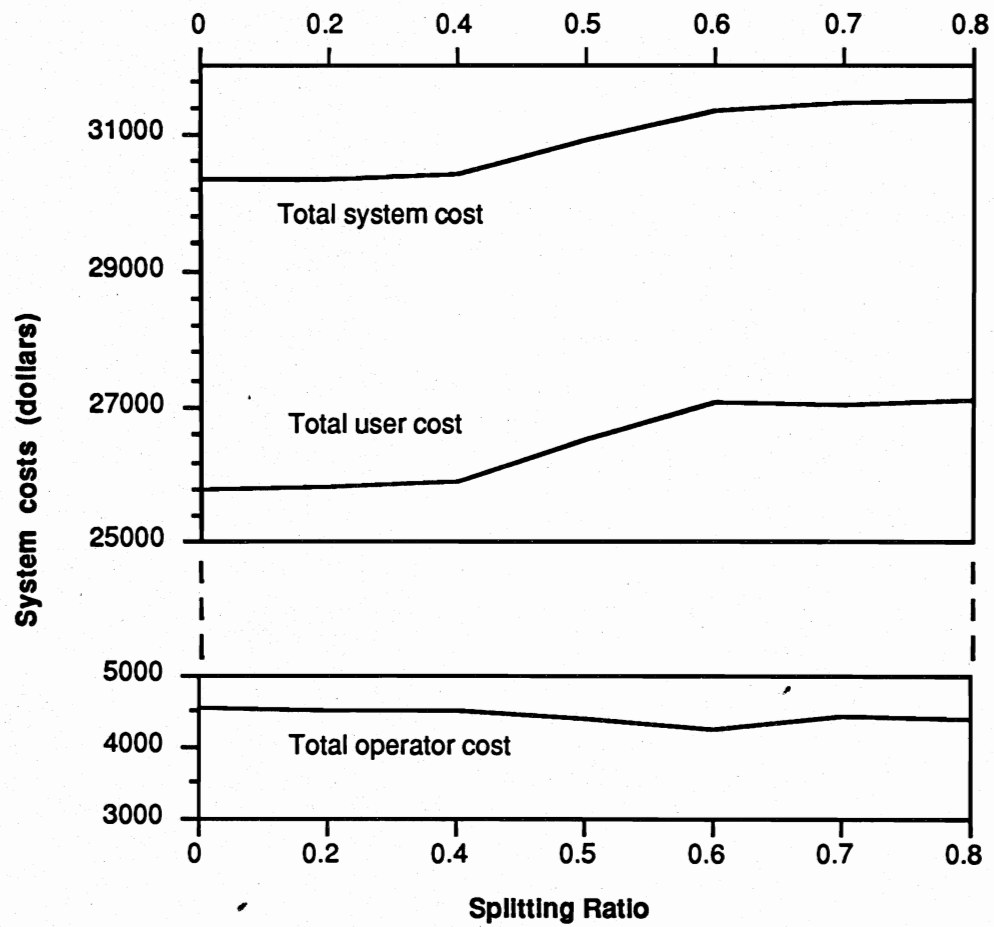**Figure 7.25 User Travel Times vs. Splitting Ratio**

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Figure 7.26 System Costs vs. Splitting Ratio

coverage level. Each network was tested using two load factor levels (0.4 and 0.8) as cut-off points for route discontinuation. The performance of the initial networks, the networks after discontinuing all low ridership routes but before applying the demand responsive service, and the final integrated networks are reported and compared hereafter .

In Table 7.9, the results of the uncoordinated network are presented. In the initial uncoordinated network, 10 out of 50 routes had a load factor less than 0.4, and 23 routes had a load factor less than 0.8. Discontinuation of low ridership routes resulted in lower required fleet size , operation cost, and fuel consumption. In the case with minimum acceptable load factor (LF_{min}) of 0.4, the required fleet size was 92% of that in the initial solution, and the operation cost and fuel consumption both decreased by 8% . In the case with LF_{min} = 0.8, the required fleet size was 86% of that in the initial solution, and the operation cost and fuel consumption both decreased by 13%. The impacts on the demand satisfaction levels caused by the route discontinuation were significant. Compared to the initial solution, the percentage of demand satisfied directly decreased by 4.1% for the case with LF_{min} = 0.4, and 11.1% for the case with LF_{min} = 0.8. As a result, the number of transfers increased by 1.1% and 4.3%, respectively. Correspondingly, the percentage of total demand satisfied decreased by 2.9% and 6.6%; the unsatisfied demand increased from 0.6% to 3.6% and 7.2%.

After applying the demand responsive service procedure to the unsatisfied demand, the integrated system satisfied much more demand with only a slight increase in operation cost. For the cases with the minimum acceptable load factor equal to 0.4 and 0.8, the percentage of total demand satisfied directly increased 0.59% (from 69.33% to 69.92%) and 1.31% (from 62.31% to 63.62%), respectively, compared to the network before the DRS procedure. Correspondingly, the percentage of total demand satisfied increased 0.56% (from 96.95% to 97.51%) and 4.63% (from 92.81% to 97.44%); the unsatisfied demand decreased from 3.6% to 2.5% and from 7.2% to 2.6%. Also in comparison with the network before the DRS procedure, the FRS portion had a slightly larger fleet size (no change for LF_{min} = 0.4 and one bus increase for LF_{min} = 0.8), and less than a 1% increase in operation cost and fuel consumption. The 0.4 case required 5 buses (15 seats) for the demand responsive service. Twelve DRS buses were needed for the case with LF_{min} = 0.8. The results show that the total in-vehicle travel time and out-of-vehicle waiting time were lower in all modified networks than in the initial network. However, this does not imply that the modified networks performed better in terms of the above performance measures since each network satisfied different levels of demand. Furthermore, the in-vehicle travel time and out-of-vehicle waiting time for passengers using the demand responsive service were neither measured

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Table 7.9 Network Characteristics for Integrated Bus Systems with Uncoordinated Route Operations

Network characteristics		Fixed route and set schedule systems			Integrated systems	
		Initial solution	$LF_{min}=0.4$	$LF_{min}=0.8$	$LF_{min}=0.4$	$LF_{min}=0.8$
FRS	% demand 0-transfer	73.44	69.33	62.31	69.92	63.62
	% demand 1-transfer	24.9	26.07	29.25	26.35	31.15
	% demand 2-transfer	1.02	1.04	1.24	1.24	2.66
	% total demand satisfied	99.38	96.95	92.81	97.51	97.44
	% total demand unsatisfied	0.62	3.56	7.19	2.49	2.56
	Total in-vehicle-travel time	157632	155688	151034	156364	156937
	Total out-of-vehicle waiting time	122765	116616	101670	117056	102008
	Total transfer penalty	7800	8140	9180	8200	9590
	Fleet size	96	89	83	89	84
	Number of routes	50	40	27	40	27
	Operation cost	4480.74	4128.13	3881.22	4137.65	3912.41
	Fuel consumption	384.34	354.09	332.91	354.91	335.59
DRS	Fleet size	0	0	0	5	12
	Number of routes	0	0	0	5	12
	Total number of DRS trips	0	0	0	62	296

in the procedure nor added to the in-vehicle travel time and out-of-vehicle waiting time shown in the table. The average passenger in-vehicle travel time and out-of-vehicle waiting time are expected to be higher in the integrated system because the demand responsive service generally has more circuitous routes and generates more transfers than the fixed route and set schedule service.

Table 7.10 shows the results of the coordinated network. The coordinated network after discontinuing low ridership routes followed the same pattern as the uncoordinated network and had better fleet size, operation cost, and fuel consumption. The number of routes decreased from 49 initially to 36 and 28 for the cases with LF_{min} = 0.4 and LF_{min} = 0.8, respectively. Correspondingly, the fleet size decreased rapidly from 97 to 88 and then slowly to 87 buses. The operation cost and fuel consumption followed the same pattern as the fleet size and both had a 9.6% reduction for LF_{min} = 0.4 and a 10.6% reduction for LF_{min} = 0.8. Differences in the operation cost (including fleet size, and fuel consumption) between the two load factor cases were insignificant because of the frequency setting procedure in the coordinated design. Since the service frequencies for all coordinated routes need to be set to the same or multiple integer values, the operation cost is affected by the frequency setting procedure. Thus, the operation cost in the coordinated design case may not change as much as in the uncoordinated design case. The demand satisfaction levels were worse in the coordinated networks after the route discontinuation was applied. The percentage of total demand satisfied directly for LF_{min} = 0.4 and 0.8 decreased by 3.9% and 8.2%, respectively. The percentage of total demand satisfied decreased by 2.0% and 6.1%; the percentage of total unsatisfied demand increased from 1% to 3% and 7% for the two minimum acceptable load factors.

In comparison with the networks before the DRS procedure, the integrated coordinated system obtained better demand satisfaction levels with no increase in fleet size for the FRS portion. The results show that the integrated system satisfied higher percentages of total demand directly (0.44% more for the case with LF_{min} = 0.4 and 1.17% more for the case with LF_{min} = 0.8). The percentages of total demand satisfied were increased by 0.93% and 4.04% for the above two cases. The percentages of total unsatisfied demand for the above two cases were lower (2.04% vs. 2.97% and 3.01% vs. 7.05%). Four buses were required to operate the demand responsive service for LF_{min} = 0.4; 11 buses were needed for the case with LF_{min} = 0.8. Similar to the uncoordinated networks, the modified coordinated networks had lower total in-vehicle travel time and total out-of-vehicle waiting time. However, when comparing these two performance measures, the factors described for the uncoordinated case need to be considered here as well.

Table 7.10 Network Characteristics for Integrated Bus Systems with Coordinated Route Operations

Network characteristics		Fixed route and set schedule systems			Integrated systems	
		Initial solution	$LF_{min}=0.4$	$LF_{min}=0.8$	$LF_{min}=0.4$	$LF_{min}=0.8$
FRS	% demand 0-transfer	74.31	70.44	66.15	70.89	67.32
	% demand 1-transfer	23.72	25.55	26.31	25.97	28.56
	% demand 2-transfer	1.00	1.04	0.48	1.11	1.11
	% total demand satisfied	99.03	97.03	92.95	97.96	96.99
	% total demand unsatisfied	0.97	2.97	7.05	2.04	3.01
	Total in-vehicle-travel time	168391	167083	160977	167978	165014
	Total out-of-vehicle waiting time	113503	108669	95440	109074	97348
	Total transfer penalty	7440	7990	7890	8010	8070
	Fleet size	97	88	87	88	87
	Number of routes	49	36	28	36	28
	Operation cost	4539.33	4103.02	4058.83	4103.02	4058.83
	Fuel consumption	389.36	351.94	348.15	351.94	348.15
DRS	Fleet size	0	0	0	4	11
	Number of routes	0	0	0	4	11
	Total number of DRS trips	0	0	0	54	236

Summary of Tests on the Austin Transit Network

The previous sections of this chapter focused on the tests of the design procedures and alternative design concepts in the solution framework. These tests were conducted with data generated from the transit system of Austin, Texas. The TCSP was tested under two application strategies and six selected combinations of minimum system coverage and directness levels. Twelve sets of transit centers were generated in the TCSP tests. Thirty-six RGP runs and an equal number of NETAP runs were executed to investigate the performance of design alternatives with and without route coordination and variable vehicle sizes. The same six combinations of minimum system coverage and directness levels were used as in the test of the TCSP. The route splitting procedure for improving the effectiveness of coordinated networks was tested. The sensitivity of the procedure to the acceptable splitting ratio was investigated. Finally, the integrated bus system concept was tested on a coordinated network and uncoordinated network. This included the test of the demand responsive service procedure. Analysis of the test results leads to the following conclusions:

1) The TCSP generates robust solutions for cases using different application strategies and different combinations of minimum system coverage and directness levels.

2) The coordinated design results in lower total out-of-vehicle waiting time and total system cost. Since the coordinated design incurs in-vehicle waiting time for non-transferring passengers at transit centers, the in-vehicle travel time and total passenger travel time are higher. Neither the coordinated design nor the uncoordinated design appear to consistently outperform the others in terms of the fleet size, total operation cost, or fuel consumption. With respect to out-of-vehicle waiting time, the coordinated service concept is more suitable for designs that satisfy high minimum system coverage levels. The coordinated service concept may not be particularly advantageous for designs that satisfy high system directness levels since only limited waiting time savings can be achieved with such a design.

3) The network design with the variable vehicle size option has much better total out-of-vehicle waiting time, total travel time, total system cost and fuel consumption, and slightly better in-vehicle travel time. However, using the variable vehicle size option requires much higher total operation cost.

4) The route splitting procedure for the coordinated network improves network effectiveness and results in lower fleet size, operation cost and fuel consumption. In addition, the procedure reduces in-vehicle travel time. However, route splitting causes more passengers to transfer and thus reduces the percentage of total demand satisfied directly and increases the total waiting time. Sensitivity analysis of the acceptable splitting ratio shows that the impacts of the

splitting become significant as the ratio reaches a certain value (0.4 in the study case). Improvements in system effectiveness appear to be obtainable only for ratios up to a certain value (0.6 in the study case).

5) The integrated bus system results in lower fleet size, operation cost and fuel consumption. However, the negative impacts on the demand satisfaction levels are significant. Operators should investigate the trade-offs so as to obtain a more effective transit system with acceptable reductions in levels of service.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study is to develop and test computer-based procedures which incorporate alternative service concepts into the design of bus transit route networks. This work complements and extends the initial solution approach to the bus transit network design problem presented by Baaj and Mahmassani (1991), which was limited to the design of conventional fixed-route, fixed-schedule, fixed vehicle size, and uncoordinated bus transit systems. Conventional service is generally suitable for areas with high and dense transit demand. For areas with medium, low, or spatially dispersed demand patterns of the type prevailing in most U.S. urban areas, alternative service concepts including coordinated systems, variable vehicle sizes, and demand responsive service have been used to a limited degree with generally positive results. The focus of this study is the development of a bus transit design model which incorporates the above service concepts.

In the next section, the principal features of the design procedures are reviewed, followed by a summary of conclusions from the computational tests. Section 8.2 presents a brief discussion of possible directions for further research.

SUMMARY AND CONCLUSION

The bus transit network design problem addressed in this report is to construct a set of bus routes and determine the associated service frequencies and vehicle sizes. Several sources of complexity were recognized by Baaj (1990) including difficulty of formulating the problem; non-linearity and non-convexity of the mathematical formulation; inherent combinatorial complexity of the problem; multi-objective nature of the problem; and spatial layout of routes for solving such a bus network design problem. These inherent complexities preclude finding a unique optimal solution using optimization formulations. This study is an attempt to find good and efficient solutions to the bus transit network design problem via AI search heuristic approaches.

Previous approaches to the transit network design were either OR heuristic approaches with limited applicability, or practical guidelines and ad hoc procedures reflecting important current practice, but not sufficient on their own. The shortcomings of previous approaches include failure to address the inherent multi-objective nature of the transit network design problem, limited responsiveness to the demand pattern in the route layout, failure to incorporate alternative design concepts, and failure to consider service planning guidelines and professional judgment of transit planners. The solution approach, which has evolved from Baaj and Mahmassani's algorithm, includes the following major features: 1) an AI search heuristic for transit route generation and

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improvement, 2) a transit network evaluation model to compute a variety of system performance measures, and 3) systematic use of context-specific knowledge to guide the search technique. Alternative design concepts and features oriented towards the kind of land use and transit demand pattern found in most U.S. cities are incorporated to provide transit planners with additional service design dimensions. Additional system performance measures are computed to provide useful information to operators so that trade-offs between conflict objectives can be clearly addressed.

The solution approach consists of four algorithmic procedures. The route generation procedure (RGP) constructs sets of bus routes for designs with or without the transit center concept. The network evaluation procedure (NETAP) determines route service frequencies and vehicle sizes and evaluates transit systems for both coordinated and uncoordinated designs. The transit center selection procedure (TCSP) identifies candidate sets of transit centers when the network is to be configured around the transit center concept. The network improvement procedures (NIP) applies modifications to the set of routes generated by the RGP to improve performance from the user's or operator's perspective.

Numerical experiments were performed to test the solution approach on a benchmark problem . The results showed that networks generated by the RGP'around the transit center concept outperformed the solutions of Mandl's and Baaj and Mahmassani's algorithm. Numerical experiments on data for the transit system of Austin, Texas, were also performed to test the design procedures and investigate the performance of alternative designs. The TCSP was tested based on two application strategies and six selected combinations of demand satisfaction levels. The tests indicated that the TCSP generated consistent results in all study cases. Transit centers generated from the TCSP were either major activity centers or transit nodes within major communities in the suburban areas. The RGP and NETAP were tested using four design alternatives under six combinations of demand satisfaction levels. The tests compared the performance of coordinated vs. uncoordinated networks. The tests also investigated the performance of networks with the variable vehicle sizes vs. fixed vehicle size. The numerical results showed that 1) the coordinated design resulted in better demand satisfaction levels, total out-of-vehicle waiting time, and total system cost, but worse total in-vehicle travel time and total travel time because additional in-vehicle waiting time was generated by the route coordination, 2) designs with variable vehicle sizes greatly reduced the total system cost, fuel consumption, and out-of-vehicle waiting time, but increased the operation cost. Two possible NIP modifications were tested. The procedure that splits routes at transit centers reduced the required operational resources, but the levels of demand satisfaction were decreased. The demand responsive

service procedure resulted in significant savings of operating resources and much lower reductions in the levels of demand satisfaction compared to outright route discontinuation.

The principal unique features of this work, which define its contribution, are:

1) A computer-based route generation procedure which is superior to other route generation algorithms by incorporating the transit center concept to provide good transfer opportunities at transit centers and fast and direct service between transit centers.

2) A transit network analysis procedure with the following important features:

    i) It incorporates a trip assignment procedure which assigns trips for both uncoordinated and coordinated networks. This enables the evaluation and design of timed-transfer bus system designs.

    ii) It computes system performance measures reflecting service quality, user costs, and operator costs.

    iii) It can be used as a sensitivity analysis tool for system performance measures and a variety of variables and parameters such as route configuration, route frequency, bus seating capacity, transfer penalty, maximum allowable route load factor, timed-transfer window, waiting time value, in-vehicle travel time value, and operation cost coefficients.

3) A vehicle sizing procedure which provides the transit operator with an additional choice dimension to design the service configuration to better meet user needs and desired service level.

4) A transit center selection procedure which identifies suitable transit centers to support the implementation of timed-transfer design and demand responsive service.

5) A computer-based procedure to identify suitable service areas and the corresponding transit center for the provision of demand responsive service. The procedure enables the design of an integrated bus system that serves high density demand with fixed-route and fixed-schedule service and low density demand with demand responsive service.

FUTURE RESEARCH

In the present version, the route generation procedure is a long range planning tool which generates a new set of routes for a given projected service area. For the route generation procedure to support short or medium range planning, it needs to be capable of modifying or replacing a subset of routes of the existing transit system. This is extremely important because any transit planning tool intended to be used in practice should offer this capability.

The ability to display the results graphically is extremely important to any network design problem. As shown in the output for the RGP and NETAP, the set of routes was presented in the

form of a list of transit nodes, which cannot give transit planners an instant picture of route layouts. It would be extremely useful if the transit planner could delineate the resulting route network and develop a 'feel' for the performance of the route design, by means of the graphic display ability. In addition, network descriptors computed by the NETAP could be made explicit using graphic display technology so that transit operators would quickly notice the sensitivity of the resulting solutions to different user input parameters.

The solution approach requires further testing on different transit networks and their corresponding transit demand matrices. The solution approach provides alternative design features that are applicable to different demand levels and spatial distributions. Therefore, it would be extremely valuable to perform systematic tests of alternative service design concepts under different demand patterns to ascertain the conditions that determine their success.

Lastly, incorporating other service choice dimensions which could improve the performance of bus transit systems will make the solution approach more versatile. One example is express bus service that serves two terminal nodes non-stop or with limited stops. In addition, application of the solution approach in other urban transportation network problems should be investigated, especially in integrated bus and rail systems. The integrated bus and rail system is a common combination in urban transit systems. Urban rail systems usually serve as trunk or main lines interconnecting the various transit centers. They usually have fewer routes than bus networks, higher service frequencies, larger passenger capacities, and more transferring activity among routes. They are essentially the same as the express bus service with higher vehicle seating capacity and more reliable service schedules. Therefore, with some minor modifications, the solution approach would be applicable in this context.

Appendix A Node Selection and Insertion Strategies

Four different node selection and insertion strategies are considered:

a) 1-Link, Maximum Demand Insertion (MD)

b) 1-Link, Maximum Demand per Minimum Time Insertion (MDMT)

c) 1-Link, Maximum Demand per Minimum Route Length Increase Insertion MDML)

d) 1-Link, Maximum Demand per Minimum Cost Insertion (MDMC)

Each of these strategies is discussed in turn hereinafter.

1-Link. Maximum Demand Insertion (MD)

Step I) (Generation of Feasible Insertion Nodes). For a given route r_0 under expansion, find the set of feasible insertion nodes. If this set is empty, terminate the route expansion, otherwise proceed to Step 2.

Step 2) (Node Selection and Insertion). Select node i whose DDS_i is the maximum and insert it in r_0 (call the new route r_1). DDS_i is the increase in the network's total demand satisfied directly as a result of inserting node i in route r_0 (considering only the yet unsatisfied node pairs).

Step 3) (Termination Test). If the new route r_1 is feasible, (i.e. both r_1's capacity and length are acceptable) then set $r_0 = r_1$ and return to Step 1. Otherwise, terminate the route expansion process and return r_0.

1-Link. Maximum Demand per Minimum Time Insertion (MDMT)

Same as MD heuristic, but replace Step 2 by the following:

Step 2) (Selection and Insertion). Select node i whose $\{DDS/DT_{inv}\}_i$ is a maximum and insert it. DDS is as defined in the MD heuristic while DT_{inv} is the corresponding increase in the total in-vehicle travel time.

1-Link. Maximum Demand per Minimum Route Length Increase Insertion (MDML)

Same as MD heuristic, but replace Step 2 by the following:

Step 2) (Selection and Insertion). Select node i whose $\{DDS/DT_{r_0}\}_i$ is a maximum and insert it. DDS is as defined in the MD heuristic while DT_{r_0} is the corresponding increase in route r_0's length (i.e. the difference in the round trip times of r_0 and r_1).

1-Link. Maximum Demand per Minimum Cost Insertion (MDMC)

Same as MD heuristic, but replace Step 2 by the following:

Step 2) (Selection and Insertion). Select node i whose $\{DDS / [c_1(DT_{inv}) + c_2(DT_{r_0})]_i\}$ is a maximum and insert it. DDS is as defined in the MD heuristic while DT_{inv} and DT_{r_0} are as defined in the MDMT and MDML heuristics, respectively. c_1 and c_2 are constants that express different tradeoffs between the proxies of the user and operator costs. Currently, they are chosen in such a way that both user and operator cost are weighted equally.

Appendix B Node Location List and Network Connectivity List

B1 Listing of Node Location

Node	Location
0	Pflugerville Elementary
1	2nd at Congress
2	6th at Congress
3	11th at Colorado
4	Guadelupe at 15th
5	Guadelupe at 24th
6	Guadelupe at 45th
7	Lamar at Koenig
8	N. Lamar Transit Center
9	Mearns Meadow at Rutland
10	San Jacinto at 11th
11	Rosewood at Chicon
12	Oak Springs at Airport
13	Lott at Prock
14	2nd at Brazos
15	Brazos at 6th
16	Rio Grande at MLK
17	Lamar at 38th
18	Burnet at Koenig
19	Northcross at Foster
20	MLK at Chicon
21	7th at Colorado
22	7th at I-35
23	7th at Chicon
24	7th at Pleasant Valley
25	Riverside at Montopolis
26	Guadelupe at MLK
27	Speedway at 38th
28	Woodrow at Koenig
29	Anderson at Woodrow
30	12th at Chicon
31	12th at Airport
32	E. 12th at Springdale
33	U.S. 183 at Technicenter (ACC)
34	Trinity at MLK
35	45th at Duval
36	Highland Mall
37	Georgian at Rundberg
38	Braker at Bluff Bend
39	Braker at Dessau
40	Oltorf at Burton
41	E. 5th at Pleasant Valley
42	Airport at Springdale
43	MLK at Springdale
44	Manor at Rogge
45	Berkman at Briarcliff
46	Cameron at St. Johns
47	W. 12th at West Lynn
48	Enfield at Exposition
49	Rockmoor at Windsor

Node	Location
50	35th at Pecos
51	Laguna Gloria
52	S. 1st at Barton Springs
53	S. 1st at Oltorf
54	S. lst at Ben White
55	S. 1st at Emerald Wood
56	William Cannon at S. 1st
57	William Cannon at Woodhue
58	26th at San Jacinto
59	26th at Lafayette
60	38 1/2 at Cherrywood
61	Hancock Center
62	Red River at MLK
63	Colorado at 2nd
64	Lamar at Barton Springs
65	Manchaca at Lamar
66	Manchaca at Ben White
67	Cannon League at Matthews
68	Congress at Oltorf
69	Congress at Ben White
70	Sheraton at Congress
71	Fort Clark at Battle Bend
72	William Cannon at Congress
73	Bluff Springs at William Cannon
74	San Jacinto at MLK
75	Monroe at Congress
76	St. Edwards at Eastside
77	Oltorf at Parker
78	Woodward at Parker
79	Red River at 26th
80	51st at Airport
81	Barton Springs at Bouldin
82	S. 5th at Oltorf
83	Banister at Ben White
84	Westgate Mall
85	Nueces at MLK
86	E. 2nd at Chicon
87	Lyons at Springdale
88	Gardner at Lotus
89	Gardner at Levander
90	E. 6th at I-35
91	MLK at Airport
92	FM 969 at Craigwood
93	Travis St. School
94	24th at Rio Grande
95	Windsor at Harris
96	35th at Jefferson
97	Hancock at Bull Creek
98	Northland at Balcones
99	Village Center at Far West

Node	Location
100	Robert Mueller Airport
101	Manor at Loyola
102	Crystalbrook at Loyola
103	RBJ Center
104	38 1/2 at I-3 5
105	29th at Guadelupe
106	35th at Exposition

107	29th at Guadelupe	165	Steck at Rockwood
108	5th at Congress	166	Spicewood Springs at Mesa
109	Spicewood Springs at Wood Hollow	167	Mesa at Jollyville
110	Wood Hollow at Far West	168	11th at Brazos
111	Far West at Mesa	169	Stassney at Palo Blanco
112	Ohlen at U.S. 183	170	MLK at Congress
113	Parkfield at Peyton Gin	171	Guadelupe at 8th
114	Lamar at Rundberg	172	1st at Lamar
115	Centre Creek at Rutherford	173	Lake Creek at U.S. 183
116	I-35 at Holly	174	Spicewood Springs at Shopping Center
117	Riverside at Pleasant Valley	175	Lavaca at 11th
118	Texas 71 at Presidential	176	Lavaca at 6th
119	Bergstrom AFB (Ave F at lst)		
120	Burton at Riverside		
121	Pleasant Valley at William Cannon		
122	Ben White at Pack Saddle Pass		
123	Barton Creek Square		
124	Robert E. Lee at Barton Springs		
125	Barton Skyway at Oakhaven		
126	Zilker Park		
127	Wallingwood at Spyglass		
128	Bee Cave at Walsh Tarlton		
129	Oltorf at Lamar		
130	Advanced Micro Devices (Oltorf at AMD Drive)		
131	Airport at Manor		
132	Montopolis at Delmonte		
133	ACC Riverside Campus		
134	VA Clinic		
135	Leander (Park and Ride)		
136	Latta at Convict Hill		
137	William Cannon at Brodie		
138	William Cannon at Westgate		
139	William Cannon at Manchaca		
140	Lamar at 5th		
141	15th at Red River		
142	Cameron at Corona		
143	Loyola at Colony Park		
144	Loyola at Wentworth		
145	Siskin at Westgate		
146	St. Johns at I-35		
147	Rutherford at Cameron		
148	Ridge Point at Interparke		
149	Parkfield at Kramer		
150	Bittern Hollow at Braker		
151	Wells Branch at Tandem		
152	Wells Branch at Thermal		

Node	Location
153	Parmer at Lamar
154	Riverside at Congress
155	Quail Valley at Rutland
156	Braker at Metric
157	Lamplight Village at Parmer
158	Metric at Parmer
159	Roxanna
160	Manasas at Shiloh
161	Balcones Woods Shopping Center
162	Arboretum Shopping Center
163	IBM East
164	Burnet at US 183

B2 Network Connectivity List

```
(setf *CONNECTIVITY-LIST* '
  '((0 ((37 49.0) (38 42.0) (115 58.1) (146 56.7) (147 57.05) (148 63.35) (153 30.45)))
   (1 ((14 0.35) (52 0.75) (63 0.35) (87 17.5) (108 1.25) (116 4.25) (154 2.45)(172 4.65)))
   (2 ((3 2.75) (15 0.4)(21 0.75) (22 2.95) (108 0.4) (168 2.9) (176 0.8)))
   (3 ((2 2.75)(21 1.35) (168 0.85) (171 1.25) (175 0.35)))
   (4 ((10 3.4) (16 2.3)(26 1.45) (34 3.5) (47 5.25) (74 3.5) (85 2.15)(141 3.75) (170 2.4) (171 2.5) (175 1.8)))
   (5 ((26 2.15) (34 4.9) (85 2.7) (94 1.15) (105 2.7)))
   (6 ((7 5.65) (17 4.7) (27 4.65) (28 9.05) (35 2.85) (97 9.65) (105 6.1)))
   (7 ((6 5.65) (8 9.65) (28 2.5) (29 10.5) (35 9.1) (36 5.9) (146 10.15)))
   (8 ((7 9.65) (28 10.05) (29 3.5) (36 9.0) (37 7.0) (38 21.0) (112 5.6)(113 8.1) (114 8.95) (115 13.0) (146
       7.2) (147 11.25) (148 13.9)))
   (9 ((38 12.9) (113 4.2) (114 2.45) (149 9.0) (153 13.6) (155 7.5)))
   (10 ((11 7.05) (14 3.4) (15 2.0) (22 3.5) (30 6.95) (34 3.2) (74 2.15)(86 6.9) (90 3.5) (103 6.55) (104 10.5)
        (116 7.2) (141 2.35) (168 0.4)(171 2.95)))
   (11 ((10 7.05) (12 7.35) (23 2.65) (24 6.0) (30 1.4) (42 9.15) (87 7.9)(90 6.15)))
   (12 ((11 7.35) (13 7.5) (24 7.0) (31 1.45) (32 3.4) (42 2.85) (87 4.9)))
   (13 ((12 7.5) (32 6.55) (42 7.8)))
   (14 ((1 0.35) (10 3.4) (15 1.2) (22 3.85) (34 6.65) (90 3.4) (103 7.5)(108 1.35) (172 5.05)))
   (15 ((2 0.4) (14 1.2) (22 2.85) (103 8.6) (108 0.7) (168 1.8)))
   (16 ((4 2.3) (85 0.4) (94 1.9) (95 5.7) (175 4.15)))
   (17 ((6 4.7) (18 10.7) (27 3.3) (28 9.75) (95 8.75) (96 2.95) (97 10.5)(105 4.75)))
   (18 ((17 10.7) (19 11.15) (28 2.85) (97 7.8) (98 4.6)))
   (19 ((18 11.15) (29 5.95) (97 16.85) (98 12.6) (109 4.25) (112 9.55)(164 9.4) (165 3.95)))
   (20 ((30 2.1) (59 1.75) (62 3.6) (91 5.6) (131 6.15)))
   (21 ((2 0.75) (3 1.35) (22 2.95) (63 1.8) (140 3.95) (171 0.8)))
   (22 ((10 3.5) (14 3.85) (15 2.85) (21 2.95) (23 4.0) (30 5.7) (34 5.6)(62 4.8) (90 0.4) (104 10.5) (141 3.95)
        (168 3.45)))
   (23 ((11 2.65) (24 4.7) (41 4.4) (86 1.7) (90 4.4)))
   (24 ((12 7.0) (41 1.2) (42 7.35) (87 4.55) (89 7.2) (132 11.2)))
   (25 ((11 6.0) (40 12.05) (117 12.1) (118 16.1) (130 12.15) (132 7.9)(133 6.35) (134 3.95))) (26 ((4 1.45) (5
       2.15) (85 0.75) (170 1.1)))
   (27 ((6 4.65) (17 3.3) (35 4.5) (58 4.4) (61 4.4) (104 4.8) (105 4.25)(170 7.2)))
   (28 ((6 9.05) (7 2.5) (8 10.05) (17 9.75) (18 2.85) (29 8.05) (36 7.45)(97 5.25)))
   (29 ((7 10.5) (8 3.5) (19 5.95) (28 8.05) (36 10.0) (112 6.7)(164 8.55)))
   (30 ((10 6.95) (11 1.4) (20 2.1) (22 5.7) (31 6.9)(141 4.4)))
   (31 ((12 1.45) (30 6.9) (32 4.75) (91 2.25) (100 4.9)))
   (32 ((12 3.4) (13 6.55) (31 4.75) (33 14.3) (42 4.2) (43 3.6) (92 9.2) (100 6.3)))
   (33 ((32 14.3) (43 7.9) (88 7.2) (92 4.7) (101 12.25) (102 11.05)(148 21.35)))
   (34 ((5 4.9) (14 6.65) (22 5.6) (58 3.6) (62 0.7) (74 0.35)))
   (35 ((6 2.85) (7 9.1) (27 4.5) (36 13.0) (58 6.05) (61 3.7) (80 4.2)(104 3.15)))
   (36 ((7 5.9) (8 9.0) (29 10.0) (35 13.0) (37 23.45) (45 11.2) (46 8.4)(80 2.3) (142 7.7) (146 9.8) (148 18.9)))
   (37 ((8 7.0) (36 23.45) (38 12.65) (39 14.0) (114 1.55) (115 14.65)(146 11.9) (147 11.9) (148 18.2) (0
       49.0)))
   (38 ((8 21.0) (9 12.9) (37 12.65) (39 3.65) (114 12.05) (115 19.6)(146 18.9) (147 15.25) (148 17.5) (149
       8.75) (153 14.0) (0 42.0)))
   (39 ((37 14.0) (38 3.65) (115 14.0) (147 15.6) (148 16.1) (153 20.65)))
   (40 ((25 12.05) (77 1.15) (117 5.5) (120 3.7) (130 6.7)))
   (41 ((23 4.4) (24 1.2) (86 4.8) (87 5.25) (103 7.35) (117 8.1) (120 9.45)(132 8.75)))
   (42 ((11 9.15) (12 2.85) (13 7.8) (24 7.35) (32 4.2) (87 1.75) (88 8.25)(89 7.0) (132 8.6)))
   (43 ((32 3.6) (33 7.9) (44 8.55) (91 7.35) (92 5.95) (100 6.5) (101 8.75)(102 12.95)))
   (44 ((43 8.55) (45 7.5) (100 10.35) (101 4.95)))
   (45 ((36 11.2) (44 7.5) (46 5.65) (101 10.65) (142 4.6) (148 10.5)))
   (46 ((36 8.4) (45 5.65) (101 15.4) (115 6.65) (142 5.95) (146 5.8)(147 4.5) (148 10.15)))
   (47 ((4 5.25) (48 7.0) (95 4.2) (107 7.55) (108 8.4) (126 8.75) (140 5.1)(171 6.15) (175 30.95) (176 7.6)))
   (48 ((47 7.0) (49 6.65) (95 6.15) (96 11.55) (106 9.15) (107 2.9)))
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   (50 ((49 7.85) (51 10.15) (97 13.3) (98 10.5) (106 1.45)))
```

(51 ((50 10.15) (97 14.35) (98 12.6)))
(52 ((1 0.75) (53 6.3) (63 2.95) (75 8.6) (81 2.5) (154 1.4) (171 5.6)(176 3.85)))
(53 ((52 6.3) (54 6.2) (68 1.95) (75 4.55) (81 7.35) (82 1.7)))
(54 ((53 6.2) (55 5.3) (69 6.0) (70 5.25) (76 8.4) (82 7.35) (83 3.25)))
(55 ((54 5.3) (56 6.1) (57 10.15) (66 9.3) (69 7.35) (70 6.5) (83 7.35)(84 11.4) (138 15.75) (139 12.6) (169 12.95)))
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(58 ((27 4.4) (34 3.6) (35 6.05) (60 4.9) (61 6.85) (74 4.85) (79 2.6)(104 6.85)))
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(62 ((20 3.6) (22 4.8) (34 0.7) (59 5.3) (79 3.15) (104 7.35) (141 1.6)))
(63 ((1 0.35) (21 1.8) (52 2.95) (64 7.0) (86 7.25) (108 1.5) (140 4.9)(172 4.35) (176 1.9)))
(64 ((63 7.0) (81 1.5) (124 4.6) (129 6.95) (172 2.8)))
(65 ((66 6.45) (84 8.75) (122 8.4) (123 14.9) (125 1.75) (129 4.4)(135 30.8) (137 19.25) (138 20.3)))
(66 ((55 9.3) (56 15.4) (65 6.45) (72 14.2) (83 3.25) (84 3.5) (122 1.0)(139 13.85)))
(67 ((56 7.7) (57 3.35) (139 0.5) (145 8.95) (160 4.2)))
(68 ((53 1.95) (69 6.25) (75 3.35) (76 2.8) (77 5.5) (78 10.0)))
(69 ((54 6.0) (55 7.35) (68 6.25) (70 3.05) (71 10.85) (72 17.0)(73 15.6) (76 11.9) (78 10.3)))
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(84 ((54 11.4) (56 18.55) (65 8.75) (66 3.5) (83 7.85) (122 1.75)(123 15.75) (135 24.85) (137 15.4) (138 11.0) (139 11.9)))
(85 ((4 2.15) (5 2.7) (16 0.4) (26 0.75) (94 2.35) (105 4.55)(175 3.85)))
(86 ((10 6.9) (14 6.15) (23 1.7) (41 4.8) (63 7.25) (90 5.25) (103 6.2)(116 5.45) (117 11.9)))
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(90 ((10 3.5) (11 6.15) (14 3.4) (15 1.9) (22 0.4) (23 4.4) (34 3.15)(86 5.25) (103 7.0) (116 3.15) (141 3.85)))
(91 ((20 5.6) (31 2.25) (43 7.35) (100 3.15) (131 1.45)))
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(93 ((92 14.3) (102 14.0) (143 14.0)))
(94 ((5 1.15) (16 1.9) (85 2.35) (95 4.25) (105 2.85)))
(95 ((16 5.7) (17 8.75) (47 4.2) (48 6.15) (94 4.25) (96 9.0) (105 7.7)(106 9.45)))
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(99 ((96 17.15) (97 10.15) (98 5.6) (110 0.85) (111 6.35)))
(100 ((31 4.9) (32 6.3) (43 6.5) (44 10.35) (91 3.15) (131 4.65)))
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   (141 8.7) (142 8.25)))
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(107 ((47 7.55) (48 2.9) (126 7.2) (127 7.7) (140 8.25) (176 11.05)))
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(111 ((99 6.35) (109 10.65) (110 7.2)))
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(113 ((8 8.1) (9 4.2) (112 2.95) (114 6.1) (155 7.2)))
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   58.1)))
(116 ((10 4.25) (14 4.4) (77 10.15) (78 13.85) (86 5.45) (90 3.15)(103 2.8) (120 7.8)))
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(118 ((25 16.1) (78 28.0) (119 5.2) (132 15.05)))
(119 ((118 5.2)))
(120 ((40 3.7) (41 9.45) (75 9.45) (76 13.65) (77 5.7) (116 7.8)(117 2.75) (154 9.45)))
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(124 ((64 4.6) (125 10.2) (126 1.1)))
(125 ((65 1.75) (124 10.2)))
(126 ((47 8.75) (107 7.2) (124 1.1) (127 3.5) (128 14.3) (140 8.75)(172 8.75)))
(127 ((122 18.2) (123 12.6) (126 3.5) (127 7.7) (128 8.25) (137 28.0)(138 27.85)))
(128 ((123 6.55) (126 14.3) (127 8.25)))
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(130 ((25 12.15) (40 6.7) (117 9.45) (133 12.25)))
(131 ((20 6.15) (59 4.55) (60 3.15) (80 10.1) (91 1.45) (100 4.65)(142 11.4)))
(132 ((24 11.2) (25 7.9) (41 8.75) (42 8.6) (87 8.05) (89 3.5)(118 15.05) (133 10.5)))
(133 ((25 6.35) (77 15.75) (117 8.05) (130 12.25) (132 10.5)))
(134 ((25 3.95) (78 13.65)))
(135 ((65 30.8) (84 24.85) (122 26.15) (123 29.05) (136 15.4) (137 17.5)(172 47.5)))
(136 ((135 15.4) (137 12.5) (145 12.6)))
(137 ((65 19.25) (84 15.4) (122 15.95) (123 19.95) (127 28.0) (135 17.5)(136 12.5) (138 5.3) (145 8.75)))
(138 ((55 15.75) (65 20.3) (84 11.0) (123 21.0) (127 27.85) (137 5.3)(139 3.1) (145 7.1) (160 7.0)))
(139 ((55 12.6) (57 2.4) (66 13.85) (67 0.5) (70 17.5) (83 13.65)(84 11.9) (138 3.1) (145 8.4) (160 12.4)))
(140 ((47 5.1) (63 4.55) (107 8.25) (108 3.6) (126 8.75) (171 3.85)(172 1.4) (176 3.2)))
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(142 ((36 7.7) (45 4.6) (46 5.95) (60 10.5) (61 8.4) (80 2.45) (104 8.25) (131 11.4) (146 10.5) (148 13.3)))
(143 ((92 9.8) (93 14.0) (102 3.35) (144 9.05)))
(144 ((143 9.05)))
(145 ((67 8.95) (136 12.6) (137 8.75) (138 7.1) (139 8.4) (159 10.15)(160 6.65)))
(146 ((7 10.15) (8 7.2) (36 9.8) (37 11.9) (38 18.9) (46 5.8) (101 18.2)(115 11.2) (142 10.5) (147 9.1) (148
   10.85) (153 29.25) (0 56.7)))
(147 ((8 11.25) (37 11.9) (38 15.25) (39 15.6) (46 4.5) (115 2.15)(146 9.1) (148 9.8) (153 30.1) (0 57.05)))
(148 ((8 13.9) (33 21.35) (36 18.9) (37 18.2) (38 17.5) (39 16.1)(43 10.5) (45 10.5) (46 10.15) (92 19.25)
   (101 9.65) (102 14.0)(115 15.4) (142 13.3) (146 10.85) (147 9.8) (153 35.7) (0 63.35)))
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   (151 17.15) (152 10.5) (158 4.55)(0 30.45)))
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(160 ((67 4.2) (138 7.0) (139 12.4) (145 6.65) (159 11.9)))
(161 ((162 5.5) (163 11.55) (164 14.7) (167 9.8) (174 11.05)))
(162 ((161 5.5) (163 11.9) (164 10.15) (167 4.9) (174 17.5)))
(163 ((149 9.1) (155 8.4) (156 5.25) (157 14.0) (161 11.55) (162 11.9)(164 13.1) (167 13.3)))
(164 ((19 9.4) (29 8.55) (112 4.4) (155 8.75) (156 11.2) (161 14.7)(162 10.15) (163 13.1) (165 5.6) (167
    6.3)))
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(168 ((2 2.9) (3 0.85) (10 0.4) (22 3.45)))
(169 ((55 12.95) (70 12.25) (71 8.4) (73 9.1) (78 12.9) (121 6.95)))
(170 ((4 2.4) (26 1.1) (27 7.2) (74 0.75) (141 2.45)))
(171 ((3 1.25) (4 2.5) (21 0.8) (47 6.15) (52 4.9) (140 3.85) (175 1.6)(176 1.15)))
(172 ((1 4.65) (14 5.05) (63 4.35) (64 2.8) (126 8.75) (135 47.3)(140 1.4)))
(173 ((174 12.6)))
(174 ((161 11.05) (162 17.5) (173 12.6)))
(175 ((3 0.35) (4 1.8) (16 4.15) (47 5.9) (85 3.85) (170 3.15)))
(176 ((2 0.8) (47 7.6) (52 4.25) (63 1.9) (107 11.05) (108 1.05)(140 3.2) (171 1.15) (175 1.9)))))

Appendix C Tsygalnitzky's Algorithm and Input Data

C1 Tsygalnitzky's Algorithm

```
;;;DECLARATION:

(defvar *number-of-nodes*)
(defvar *demand-matrix*)
(defvar *data-list*)
(defvar *output-data-file*)

;;; REEXPRESS-1:

(defun reexpress-1 (node1 node2)
 (read (make-string-input-stream
     (format nil "~a~a~a~a" 'pair- node1 '- node2))))

;;; REEXPRESS-2:

(defun reexpress-2 (node)
 (read (make-string-input-stream (format nil "~a~a" 'node- node))))

;;; MATRIX:

(defun matrix ()
 (setf *print-array* t)
 (print `(What is the number of nodes in the network?))
 (setf *number-of-nodes* (read))
 (array-initialize (setf *demand-matrix*
             (make-array `(, *number-of-nodes*, *number-of-nodes*))) 0.0)
 (open-output-file)
 (print (apply '+ (mapcar #'(lambda (e)
             (let (( m (apply '+ (cadr e))))
               (print `(,(car e), m) *output-data-file*) m))
             *data-list*)) *output-data-file*)
 (mapcar #' (lambda (e) (od-matrix e)) *data-list*)
 (do ((i 0 (+ i 1)))
  ((= i *number-of-nodes*))
 (do ((j 0 (+ j 1)))
    (( = j *number-of-nodes*))
  (let* (( m (aref *demand-matrix* i j))
      (n (round m)))
    (setf (aref *demand-matrix* i j) n))))
 (print *demand-matrix* *output-data-file*)
 (close *output-data-file*))


;;; OPEN-OUTPUT-FILE:

(defun open-output-file ()
 (setf *output-data-file* (open "cm:hd:shih:matrix-output.text"
             :direction : output
                  :if-exists : append
                  :if-does-not-exist : create)))
```

```
;;; OD-MATRIX:

(defun od-matrix (unchecked-route)
  (let ((route (modify-for-zero-initial-boarding (car unchecked-route)
          (cadr unchecked-route)(caddr unchecked-route))))
    (assign-values (car route) (cadr route) (caddr route))
  (do ((i (car route) (cdr i)))
      ((null (cdr i)))
    (setf (get (reexpress-1 (car i)(cadr i)) 'volume)
        (get (reexpress-2 (car i)) 'boarding)))
  (do* ((j (cdar route)(cdr j))
        (k (set-difference (car route) j)(set-difference (car route) j)))
       ((null j))
    (let ((factor (* (/ (get (reexpress-2 (car j)) 'alighting)
                (apply '+ (mapcar #'(lambda (e) (get (reexpress-1 e (car j))
                        'volume)) k))) 1.0)))
      (mapcar #'(lambda (e) (setf (get (reexpress-1 e (car j)) 'demand)
              (* 0.5 factor (get (reexpress-1 e (car j)) 'volume)))) k)
      (mapcar #'(lambda (e)
            (setf (get (reexpress-1 e (cadr j)) 'volume)
                (- (get (reexpress-1 e (car j)) 'volume)
                  (get (reexpress-1 e (car j)) 'demand)))) k)))
  (do ((i (car route) (cdr i)))
      ((null (cdr i)))
    (do ((j (cdr i)(cdr j)))
        ((null j))
      (let* ((m (reexpress-1 (car i)(car j)))
            (n (get m 'demand)))
        (setf (aref *demand-matrix* (car i)(car j))
            (+ (aref *demand-matrix* (car i)(car j)) n))
        (setf (aref *demand-matrix* (car j)(car i))
            (+ (aref *demand-matrix* (car j) (car i)) n))
        (print `(demand of ,m = ,n) *output-data-file*))))))

;;; MODIFY-FOR-ZERO-INITIAL-BOARDING:

(defun modify-for-zero-initial-boarding (node-list boarding-list alighting-list)
  (cond ((zerop (car boarding-list))
        (modify-for-zero-initial-boarding
        (cdr node-list)(cdr boarding-list)(cdr alighting-list)))
        (t (list node-list boarding-list alighting-list))))

;;; ASSIGN-VALUES:

(defun assign-values (node-list boarding-list alighting-list)
  (cond ((null node-list))
        (t (setf (get (reexpress-2 (car node-list)) 'boarding)(car boarding-list))
          (setf (get (reexpress-2 (car node-list)) 'alighting)(car alighting-list))
          (assign-values (cdr node-list)(cdr boarding-list)
                (cdr alighting-list)))))
```

C2 Boarding and Alighting Data List

```
(setf *data-list*
    (((73 72 71 70 69 68 1 2 3 4 5 6 7 8 9) (23 9 9 21 52 49 33 44 26 55 61 19 22 19 0) (0 1 1 2 5 16
        29 39 30 12 42 65 50 56 94))
    ((9 8 7 6 5 4 3 2 1 68 69 70 71 72 73) (91 50 47 58 37 15 38 48 37 19 5 4 4 3 0) (0 20 23 16 51
        51 31 47 33 56 60 22 11 11 24))
    ((13 12 11 10 1 52 53 54 55 56 57) (26 29 25 24 16 11 12 7 4 7 0) (0 4 11 32 25 4 11 20 16 16
        22))
    ((57 56 55 54 53 52 1 10 11 12 13) (15 17 15 18 11 11 22 21 11 6 0) (0 1 2 5 10 10 24 26 20 28
        22))
    ((89 88 87 41 86 63 21 3 16 17 18 19) (6 10 48 74 39 11 23 22 16 15 8 0) (0 4 3 15 31 29 47 43
        12 15 22 50))
    ((19 18 17 16 3 21 63 86 41 87 88 89) (49 25 14 9 16 25 23 15 11 12 11 0) (0 10 14 15 21 24
        15 20 32 25 20 17))
    ((25 24 23 22 90 10 20 91 43 92 93) (38 23 10 22 27 12 9 5 0 0 0) (0 16 10 9 29 27 15 23 11 2
        5))
    ((93 92 43 91 20 10 15 22 23 24 25) (10 9 6 9 14 29 27 9 12 18 0) (0 1 3 3 4 18 20 9 15 25 43))
    ((119 118 25 117 116 1 2 26 5 27 6 28 29 19) (13 19 20 14 4 16 19 13 11 4 4 4 3 0) (0 2 4 11
        12 7 14 16 12 12 10 12 12 19))
    ((19 29 28 6 27 5 26 2 1 116 117 25 118 119) (18 11 11 11 13 11 18 20 8 8 9 3 1 0) (0 2 4 5 4
        11 15 17 13 6 16 21 17 10))
    ((1 2 10 30 31 32 33) (13 21 14 6 3 3 0) (0 0 2 11 15 16 16))
    ((33 32 31 30 10 2 1) (16 15 13 9 2 0 0) (0 2 3 9 19 17 5))
    ((73 121 78 120 1 2 34 35 36 8 37 38 39) (93 62 44 27 21 25 15 11 15 8 3 1 0) (0 20 36 30 30
        49 38 19 31 32 22 13 4))
    ((39 38 37 8 36 35 34 2 1 120 78 121 73) (5 15 25 29 31 22 53 75 59 47 43 27 0) (0 0 2 11 17
        11 20 37 26 38 67 93 109))
    ((40 41 42 43 44 45 46 36 8 19) (56 39 23 25 32 30 23 13 2 0) (0 24 30 19 18 23 32 42 26 31))
    ((19 8 36 46 45 44 43 42 41 40) (31 23 22 16 10 8 8 12 13 0) (0 5 10 13 17 18 14 12 20 34))
    ((1 2 3 47 48 49 50 51) (6 7 5 1 1 1 0 0) (0 0 2 6 6 3 2 1))
    ((51 50 49 48 47 3 2 1) (1 3 4 7 7 2 0 0) (0 0 1 1 1 6 9 6))
    ((78 77 76 75 63 15 10 34 58 59 60 61) (5 4 4 2 2 3 1 1 2 1 1 0) (0 1 1 1 1 5 6 1 1 1 3 5))
    ((61 60 59 58 34 10 21 63 75 76 77 78) (6 4 1 1 3 5 3 1 2 1 1 0) (0 2 2 2 2 2 2 1 1 5 5 5))
    ((2 64 65 66 67) (66 14 21 36 0) (0 20 22 27 67))
    ((67 66 65 64 2) (37 12 12 19 0) (0 17 10 9 44))
    ((84 83 82 81 1 2 62 79 61 80 36) (29 25 17 2 22 25 7 9 7 3 0) (0 6 10 10 4 21 25 8 13 15 36))
    ((36 80 61 79 62 2 1 81 82 83 84) (75 27 22 15 35 28 3 9 8 8 0) (0 10 12 17 21 54 41 4 20 25
        28))
    ((99 98 97 96 95 94 16 15 63 124 125) (7 3 4 4 3 2 3 2 1 2 0) (0 0 0 1 1 2 3 8 8 2 4))
    ((125 124 63 21 16 94 95 96 97 98 99) (5 5 8 8 2 1 1 1 0 1 0) (0 2 3 3 2 2 2 3 3 4 6))
    ((1 15 62 59 100 101 102) (10 16 9 7 18 15 0) (0 2 5 6 8 27 26))
    ((102 101 100 59 62 15 1) (29 25 9 8 9 6 0) (0 12 16 9 11 23 17))
    ((78 69 54 83 66 122 123 128 127 126 52 2 74) (13 5 3 2 2 8 11 5 2 2 2 3 0) (0 2 2 2 3 4 7 7 1 1
        3 13 14))
    ((74 2 52 126 127 128 123 122 66 83 54 69 78) (18 17 2 0 1 5 4 3 4 2 2 2 0) (0 1 3 3 2 6 14 10 2
        2 3 4 10))
    ((65 129 68 40 130) (5 6 5 2 0) (0 0 3 8 6))
    ((130 40 68 129 65) (6 9 4 1 0) (0 0 4 7 8))
    ((103 86 59 104 105 17 106 107 108) (24 17 5 4 5 6 12 23 0) (0 26 14 6 4 6 5 6 29))
    ((108 107 106 17 105 104 59 86 103) (26 8 12 16 11 5 8 16 0) (0 24 14 10 13 9 7 12 13))
    ((19 109 110 111) (5 1 3 0) (0 1 3 6))
    ((111 110 109 19) (3 1 1 0) (0 1 0 4))
    ((19 112 113 114 115) (30 15 12 12 0) (0 8 10 23 28))
    ((115 114 113 112 19) (21 19 11 10 0) (0 8 13 14 26))
```

((36 80 131 42 132 133 134) (10 3 4 2 1 1 0) (0 2 3 5 4 3 4))
((134 133 132 42 131 80 36) (3 3 4 4 3 1 0) (0 0 1 3 4 3 9))
((135 136 137 138 139 72 73) (9 8 7 7 8 4 0) (0 1 4 5 4 7 20))
((73 72 139 138 137 136 135) (23 10 5 5 3 1 0) (0 3 8 8 8 8 12))
((145 138 84 65 64 140 21 10 141 142 45 101 143 144) (10 18 16 7 5 9 15 10 7 12 12 5 1 0) (0
    1 4 6 6 5 16 14 3 10 19 20 14 11))
((144 143 101 45 142 141 10 15 140 64 65 84 138 145) (14 13 20 20 9 6 12 8 4 5 7 5 2 0) (0 4
    4 9 11 8 15 14 4 4 8 15 16 12))
((36 146 46 147 148) (22 8 5 3 0) (0 7 13 11 7))
((148 147 46 146 36) (3 7 6 2 0) (0 0 3 4 11))
((8 114 149 150) (9 2 1 0) (0 5 4 2))
((150 149 114 8) (2 3 4 0) (0 0 1 7))
((151 152 153 9 8 5 2 154) (0 1 3 4 2 0 0 0) (0 0 0 0 2 3 3 2))
((154 2 5 8 9 153 152 151) (3 6 4 3 2 0 1 0) (0 0 0 2 7 6 1 2))
((8 114 155 156 157 158) (46 12 3 4 3 0) (0 10 15 18 16 9))
((158 157 156 155 114 8) (1 5 9 6 2 0) (0 0 1 1 5 16))
((159 160 67) (12 3 0) (0 3 12))
((67 160 159) (14 1 0) (0 3 11))
((161 162 163 164 19) (6 1 2 2 0) (0 0 0 1 10))
((19 164 163 162 161) (19 2 1 1 0) (0 4 7 6 6))
((19 165 166 167) (14 4 4 0) (0 3 10 9))
((167 166 165 19) (6 4 2 0) (0 2 0 10))
((58 74 168 2 1 169 121 73) (1 1 3 3 0 0 0 0) (0 0 0 0 0 3 3 2))
((73 121 169 1 2 168 74 58) (3 2 1 0 0 0 0 0) (0 0 0 1 2 1 1 1))
((145 2 170 114 155 156 157 158) (3 4 2 0 0 0 0 0) (0 0 1 2 1 1 1 1))
((158 157 156 155 114 170 2 154) (1 2 2 4 3 0 0 0) (0 0 0 0 1 2 5 5))
((74 171 172 135) (1 0 0 0) (0 0 0 2))
((135 172 171 74) (3 0 0 0) (0 0 1 2))
((78 8) (6 0) (0 6)) ((8 78) (4 0) (0 4))
((154 175 5 17 162 174 173 176) (20 30 26 4 3 2 1 0) (0 0 1 6 16 26 34))
((176 173 174 162 17 5 175 154) (37 23 12 6 1 1 0 0) (0 1 2 3 6 24 25 21))
((52 176 62 0) (3 5 2 0) (0 0 0 10))
((0 62 176 52) (13 0 0 0) (0 2 6 4))
((84 145 137) (0 0 0) (0 0 0))
((137 145 84) (8 0 0) (0 4 4)))

Appendix D Shortest Path Algorithm and K-Shortest Path Algorithm

D1 Shortest Path Algorithm

```
;;; DECLARATIONS :

(defvar *node-list*)
(defvar *open-list*)
(defvar *closed-list*)
(defvar *connectivity-list*)
(defvar *output-data-file*)

;;; ALL-SHORTEST-PATHS :

(defun all-shortest-paths ()
  (let* ((number-of-nodes (length *connectivity-list*))
         (*node-list* (generate-list number-of-nodes)))
    (open-output-file)
    (do* ((list-of-nodes *node-list* (cdr list-of-nodes))
          (node (car list-of-nodes)(car list-of-nodes)))
        ((null list-of-nodes) (close *output-data-file*))
      (shortest-paths (reexpress-2 node)))))

;;; OPEN-OUTPUT-FILE :

(defun open-output-file ()
  (setf *output-data-file*
    (open "cm:hd:shih:shortest-paths-output.text"
                :direction :output
                :if-exists :append
                :if-does-not-exist :create)))

;;; SHORTEST-PATHS :

(defun shortest-paths (node)
  (let ((*open-list* (remove (reexpress-1 node) *node-list*)))
    (mapcar #' (lambda (e)
          (setf (get e 'length) 1e6)) *node-list*)
    (let ((i (reexpress-1 node)))
      (setf (get i 'length) 0.0)
      (setf *closed-list* (list node)))
    (generate-all-paths node)))

;;; GENERATE-LIST :

(defun generate-list (number-of-nodes)
  (do ((i 0 (+ i 1))
       (j ()))
      ((= i number-of-nodes) j)
    (setf j (append j (list (reexpress-1 i))))))

;;; GENERATE-ALL-PATHS :

(defun generate-all-paths (node)
  (let* ((x (car *closed-list*))
```

```
          (y (get-all-open-edges x))
          (z (get (reexpress-1 x) 'length)))
     (mapcar #'(lambda (e)
          (let* ((m (get e 'length))
                (n (+ z (get-time x (reexpress-2 e)))))
               (cond ((> m n)(setf (get e 'length) n)
                        (setf (get e 'predecessor) (reexpress-1 x)))
                    (t ())))) y)
     (let ((a (next-node-to-close)))
       (setf *closed-list* (cons (reexpress-2 a) *closed-list*))
       (setf *open-list* (remove a *open-list*))
       (cond ((null *open-list*) (print-all-paths (reexpress-1 node)))
            (t (generate-all-paths node))))))))
```

;;; GET-ALL-OPEN-EDGES :

```
(defun get-all-open-edges (node)
  (let* ((x (cadr (assoc node *connectivity-list*)))
        (y (mapcar #' (lambda (e) (reexpress-1 (car e))) x)))
    (intersection y *open-list*)))
```

;;; GET-TIME :

```
(defun get-time (node1 node2)
  (cadr (assoc node2 (cadr (assoc node1 *connectivity-list*)))))
```

;;; NEXT-NODE-TO-CLOSE :

```
(defun next-node-to-close ()
  (caar (sort (mapcar #' (lambda (e)
                (list e (get e 'length))) *open-list*)
          #' < :key 'cadr)))
```

;;; PRINT-ALL-PATHS :

```
(defun print-all-paths (node)
  (setf x (remove node *node-list*))
   (do* ((i x (cdr i))
        (j (car i)(car i)))
      ((null i))
     (cond
       ((> (reexpress-2 j) (reexpress-2 node))
        (list-path node j j (get j 'length)(list (reexpress-2 j))))
       (t ()))))
```

;;; LIST-PATH :

```
(defun list-path (node1 node2 node3 path-length answer-list)
  (let ((x (get node3 'predecessor))
       (a (reexpress-2 node1))
       (b (reexpress-2 node2))
       (c (/ (round (* 10.0 path-length)) 10.0))
       (d (cons (reexpress-2 node1) answer-list)))
    (cond ((equal x node1)
         (format *output-data-file* "~%          (~a ~a ~a ~a)" a b c d))
```

```lisp
      (t (list-path node1 node2 x path-length
              (cons (reexpress-2 x) answer-list))))))
```

;;; REEXPRESS-1 :

```lisp
(defun reexpress-1 (node)
  (read (make-string-input-stream
      (format nil "~a~a" 'node- node))))
```

;;; REEXPRESS-2 :

```lisp
(defun reexpress-2 (node)
  (read (make-string-input-stream node 5)))
```

;;; Require *CONNECTIVITY-LIST* as input

D2 k-Shortest Path Algorithm

```
;;; DECLARATIONS :

(defvar *number-of-nodes*)
(defvar *number-of-paths*)
(defvar *list-of-nodes*)
(defvar *node-list*)
(defvar *open-list*)
(defvar *connectivity-list*)
(defvar *output-data-file*)
(defvar *reduced-list*)
(defvar *selected-list*)

;;; ALL-K-SHORTEST-PATHS :

(defun all-k-shortest-paths (k)
  (let* ((*number-of-nodes* (length *connectivity-list*))
         (*number-of-paths* k)
         (*list-of-nodes* (generate-list1)))
    (open-output-file)
    (do* ((x *list-of-nodes* (cdr x))
          (node (car x)(car x)))
         ((null x) (close *output-data-file*))
      (k-shortest-paths (reexpress-3 node)))))

;;; OPEN-OUTPUT-FILE :

(defun open-output-file ()
  (setf *output-data-file*
    (open "cm:hd:shih:k-shortest-paths.text"
                 :direction :output
                 :if-exists :append
                 :if-does-not-exist :create)))

;;; START :

(defun start ()
  (open-output-file)
  (do* ((i *selected-list* (cdr i))
        (j (car i)(car i))
        (k (car j)(car j))
        (m (cadr j)(cadr j)))
       ((null i) (close *output-data-file*))
    (setf *reduced-list* m)
    (k-shortest-paths k)))


;;; K-SHORTEST-PATHS :

(defun k-shortest-paths (node)
  (setf *number-of-paths* 6)
  (setf *number-of-nodes* 177)
  (setf *list-of-nodes* (generate-list1))
  (let* ((*open-list* (generate-list2))
```

```
            (*node-list* *open-list*))
      (setf *list-of-nodes* (remove (reexpress-1 node) *list-of-nodes*))
      (mapcar #' (lambda (e)
            (setf *node-list*
                (remove e *node-list*)))
                  (get (reexpress-1 node) 'node-names))
      (mapcar #' (lambda (e)
            (setf (get e 'length) 90)) *open-list*)
      (let ((x (reexpress-2 node 1)))
        (setf (get x 'predecessor) x)
        (setf (get x 'length) 0.0)
        (generate-all-k-paths node))))

;;; GENERATE-LIST1 :

(defun generate-list1 ()
  (do ((i 0 (+ i 1))
       (j 0))
      ((= i *number-of-nodes*) j)
    (setf j (append j (list (reexpress-1 i))))))

;;; GENERATE-LIST2 :

(defun generate-list2 ()
  (do ((i 0 (+ i 1))
       (j 0))
      ((= i *number-of-nodes*) j)
    (let ((x (make-node-names i)))
      (setf j (append j x)))))

;;; MAKE-NODE-NAMES :

(defun make-node-names (node)
  (do ((i 1 (+ i 1))
       (j 0))
      ((= i (+ *number-of-paths* 1))
       (let ((x (reexpress-1 node)))
         (setf (get x 'node1) node)
         (setf (get x 'node-names) j) j))
    (let ((y (reexpress-2 node i)))
      (setf (get y 'node1) node)
      (setf (get y 'node2) i)
      (setf j (append j (list y))))))

;;; GENERATE-ALL-K-PATHS :

(defun generate-all-k-paths (node)
  (let* ((i (next-node-to-close))
         (j (get i 'length))
         (k (get i 'node1))
         (m (get-neighboring-nodes k))
         (n (open-adjacent-nodes m)))
    (mapcar #' (lambda (e)
          (adjust-costs-predecessors
            e (+ j (get-time k (get (car e) 'node1))) i))
```

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```
   n)
  (setf *open-list* (remove i *open-list*))
  (cond ((null *open-list*)
     (assign-all-k-paths (reexpress-2 node 1))
     (list-two-paths node))
    (t (generate-all-k-paths node)))))

;;; NEXT-NODE-TO-CLOSE :

(defun next-node-to-close ()
 (caar (sort (mapcar #' (lambda (e)
           (list e (get e 'length))) *open-list*)
    #'< :key 'cadr)))

;;; GET-NEIGHBORING-NODES :

(defun get-neighboring-nodes (node)
 (let ((x (cadr (assoc node *connectivity-list*))))
  (mapcar #' (lambda (e)
        (reexpress-1 (car e))) x)))

;;; OPEN-ADJACENT-NODES :

(defun open-adjacent-nodes (list-of-nodes)
 (remove-if #'null (mapcar #' (lambda (e)
           (intersection (get e 'node-names)
                 *open-list*))
       list-of-nodes)))

;;; ADJUST-COSTS-PREDECESSORS :

(defun adjust-costs-predecessors (list-of-nodes c p)
 (cond ((> (get (car (last list-of-nodes)) 'length))
    (let* ((x (remove-if-not #' (lambda (e)
           (> (get e 'length) c))
         list-of-nodes))
      (y (reverse x))
      (z (car x)))
     (switch-costs-predecessors y)
     (setf (get z 'length) c)
     (setf (get z 'predecessor) p)))
   (t ()))

;;; SWITCH-COSTS-PREDECESSORS :

(defun switch-costs-predecessors (list-of-nodes)
 (cond ((null (cdr list-of-nodes)) ())
    (t (let ((x (get (cadr list-of-nodes) 'length))
        (y (get (cadr list-of-nodes) 'predecessor)))
     (setf (get (car list-of-nodes) 'length) x)
     (setf (get (car list-of-nodes) 'predecessor) y))
    (switch-costs-predecessors (cdr list-of-nodes)))))

;;; GET-TIME :
```

```lisp
(defun get-time (node1 node2)
  (cadr (assoc node2 (cadr (assoc node1 *connectivity-list*)))))
```

;;; ASSIGN-ALL-K-PATHS :

```lisp
(defun assign-all-k-paths (node)
  (do* ((i *node-list* (cdr i))
        (j (car i)(car i)))
       ((null i))
    (assign-k-path node j j (get j 'length)(list (get j 'node1)))))
```

;;; ASSIGN-K-PATH :

```lisp
(defun assign-k-path (n1 n2 n3 path-length path-list)
  (let ((x (get n3 'predecessor)))
    (cond ((= path-length 90)
           (setf (get (reexpress-1 (get n2 'node1)) 'path-condition)
                 'no-path))
          ((equal x n1)
           (setf (get n2 'path-length)(/ (round (* 10.0 path-length)) 10.0))
           (setf (get n2 'path-list) (cons (get n1 'node1) path-list)))
          (t (assign-k-path n1 n2 x path-length
                (cons (get x 'node1) path-list))))))
```

;;; LIST-TWO-PATHS :

```lisp
(defun list-two-paths (node)
  (do* ((i *list-of-nodes* (cdr i))
        (j (car i)(car i)))
       ((null i))
    (cond ((not (member (reexpress-3 j) *reduced-list*)))
          (t (determine-two-paths node j)))))
```

;;; DETERMINE-TWO-PATHS :

```lisp
(defun determine-two-paths (n1 n2)
  (let* ((x (get n2 'path-condition))
         (y (get n2 'node-names))
         (shortest-path (car y)))
    (cond ((equal x 'no-path)(print (list n1 (get n2 'node1)())))
          (t (find-two-paths
               n1 n2 (cdr y)
               (get shortest-path 'path-length)
               (get shortest-path 'path-list))))))
```

;;; FIND-TWO-PATHS :

```lisp
(defun find-two-paths (n1 n2 list-of-paths a b)
  (let* ((x (car list-of-paths))
         (y (get x 'path-length))
         (z (get x 'path-list)))
    (cond ((null list-of-paths)
           (print (list n1 (get n2 'node1)(list a b)())
```

```
                *output-data-file*))
        ((and (<= y (* 1.50 a))
            (not (cyclical? z))
            (different-links? z b))
        (print (list n1 (get n2 'node1)(list a b)(list y z))
                *output-data-file*))
        (t (find-two-paths n1 n2 (cdr list-of-paths) a b)))))
```

;;; CYCLICAL? :

```
(defun cyclical? (list-of-nodes)
  (cond ((= (length list-of-nodes)
        (length (remove-duplicates list-of-nodes))) ())
      (t t)))
```

;;; DIFFERENT-LINKS? :

```
(defun different-links? (next-shortest-path shortest-path)
  (cond ((<= (common-links next-shortest-path shortest-path 0)
        (* 0.5 (- (length next-shortest-path) 1))) t)
      (t ())))
```

;;; COMMON-LINKS :

```
(defun common-links (list1 list2 number-of-common-links)
  (cond ((null (cdr list1)) number-of-common-links)
      ((and (member (car list1) list2)
          (member (car list1) list2))
        (common-links (cdr list1) list2 (+ number-of-common-links 1)))
      (t (common-links (cdr list1) list2 number-of-common-links))))
```

;;; REEXPRESS-1 :

```
(defun reexpress-1 (node)
  (read (make-string-input-stream
      (format nil "~a~a" 'node- node))))
```

;;; REEXPRESS-2 :

```
(defun reexpress-2 (node1 node2)
  (read (make-string-input-stream
      (format nil "~a~a~a~a" 'node- node1 '- node2))))
```

;;; REEXPRESS-3 :

```
(defun reexpress-3 (node)
  (read (make-string-input-stream node 5)))
```

;;; *SELECTED-LIST* Example:

```
(setf *selected-list* '((34 (35 33 32))
            (8 (12 9))(14 (19 12))(123 (122 128))(78 (75 79))
            (54 (53 55))(72 (71 73))(82 (81 89))(103 (87 124)))))
```

;;; Require *CONNECTIVITY-LIST* as input.

REFERENCES

Abkowitz, M., Josef, R., Tozzi, J., and Driscoll (1987), "Operational Feasibility of Timed Transfer in Transit Systems," Journal of Transportation Engineering, Vol. 113, No.2, p 168-177, ASCE.

American Public Transit Association, (1991), Transit Fact Book, Washington, DC, 1991.

Baaj, M. H. (1990), The Transit Network Design Problem: An AI-Based Approach, Ph.D. thesis, Department of Civil Engineering, University of Texas, Austin, Texas.

Baaj, M. H. and Mahmassani, H. S. (1990), "TRUST: A Lisp Program for the Analysis of Transit Route Configuration," Transportation Research Record 1283, Transportation Research Board, Washington, D.C., p 125-135.

Baaj, M. H. and Mahmassani, H. S. (1991), "An AI-Based Approach for Transit Route System Planning and Design," Journal of Advanced Transportation Vol. 25, No. 2, p 187-210.

Baaj, M. H. and Mahmassani, H. S. (1992), "Artificial Intelligence-Based System Representation and Search Procedures for Transit Route Network Design," Transportation Research Record 1358, Transportation Research Board, Washington, D.C., p 67-70.

Bakker, J. J., Calkin, J., and Sylvester, S. (1988), "Multi-Centered Timed-Transfer System for Capital Metro, Austin, Texas," Transportation Research Record 1202, Transportation Research Board, Washington, D.C., p 22-28.

Bly, P. H. and Oldfield, R. H. (1986), "Competition Between Minibuses and Regular Bus Service," " Journal of Transport Economics and Policy 20 (1), p 47-68.

Bowman, L. A. and Turnquist, M. A. (1981), "Service Frequency, Schedule Reliability and Passenger Wait Times at Transit Stops," Transportation Research, Vol. 15A, No. 6, p 465-471.

Ceder, R. B. and Wilson, N. H. (1986), "Bus Network Design," Transportation Research, Vol. 20B, No. 4, p 331-344.

Cervero, R. (1986), Suburban Gridlock, Rutgers, Center for Urban Policy Research, The State University of New Jersey, New Brunswick, N.J..

Chang, S. K. (1990), Analytic Optimization of Bus Systems in Heterogeneous Environment, Ph.D. thesis, Department of Civil Engineering, University of Maryland, College Park, Maryland.

Chang, S. K. and Schonfeld, P. M. (1991), "Integration of Fixed- and Flexible-Route Bus System," Transportation Research Record 1308, Transportation Research Board, Washington, D.C., p 51-57.

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Daganzo, C. F., Hendrickson, C. T., and Wilson, N. H. M. (1977), " An Approximate Analytic Model of Many-to-One Demand Responsive Transportation Systems," Proc. 7th Int. Symp. on Transportation and Traffic Theory, Kyoto, Japan, p 743-772.

Dial R. B. (1967), "Transit Pathfinder Algorithm," Highway Research Record 205, p 67 - 85.

Dijkstra, E. W. (1959), "A Note on Two Problems in Connection with Graphs," Numerische Mathematik, Vol. 1, p 269-271.

Dubois, D., Bell, G., and Llibre, M. (1979), "A Set of Methods in Transportation Network Synthesis and Analysis," Journal of Operations Research Society 30, p 797-808.

Florian M. and Speiss H. (1983), "On Two Mode Choice/Assignment Models," Transportation Science 17, p 32-47.

Furth, P. G. and Wilson, N. H. M. (1981), "Setting Frequencies on Bus Routes: Theory and Practice," Transportation Research Record 818, Transportation Research Board, Washington, D.C., p 1-7.

Glaister, S. (1985), "Competition on an Urban Bus Route," Journal of Transport Economics and Policy 19 (1), p 65-81.

Glaister, S. (1986), "Bus deregulation, Competition and Vehicle Size," Journal of Transport Economics and Policy 20 (2), p 217-244.

Gwilliam, K. M., Nash C. A., and Mackie P. J. (1985), "Deregulating the Bus Industry in Britain-The Case Against," Transport Rev. 5 (2), p 105-132.

Han A. F. and Wilson N. H. M. (1982), "The Allocation of Buses in Heavily Utilized Networks with Overlapping Routes," Transportation Research, Vol. 16B, No. 3, p221-232.

Hasselstrom, D. (1981), Public Transportation Planning -- A Mathematical Programming Approach, Ph.D. thesis, Department of Business Administration, University of Gothenburg, Sweden.

Herman, B. and Ardekani, S. (1984), "Characterizing Traffic Conditions in Urban Areas," Transportation Science Vol. 18, No. 2, p101-140.

Israeli, Y. and Ceder, A. (1991), "Transit Network Design," Presented at the 70th Annual Meeting of Transportation Research Board, Washington, D.C..

Jansson, J. O. (1980), "A Simple Bus Line Model for Optimization of Service Frequency and Bus Size," Journal of Transport Economics and Policy 14 (1), p 53-80.

Lampkin, W. and Saalmans, P. D. (1967), "The Design of Routes, Service Frequencies and Schedules for a Municipal Bus Undertaking: A Case Study,". Operation Research Quarterly 18, p 375-397.

Larson, R. C. and Odoni, A. R. (1981), Urban Operations Research, Prentice-Hall Inc., Englewood Cliffs, New Jersey.

LeBlanc, L. J. (1988), "Transit System Network Design," Transportation Research B, Vol. 22B, No. 5, p 383-390.

Liu, Y. H. (1994), An Approach for the Characterization and Classification of Bus Transit Network Structure, Master Thesis, Department of Civil Engineering, University of Texas, Austin, Texas.

Mandl, C. E. (1979), "Evaluation and Optimization of Urban Public Transportation Networks," Presented at the 3rd European Congress on Operations Research, Amsterdam, Netherlands.

Mohring, H. (1972), "Optimization and Scale Economies in Urban Bus Transportation," American Economic Review .

Mohring, H. (1983), "Minibuses in Urban Transportation," Journal of Urban Economics 14, p293-317.

NCHRP Synthesis of Highway Practice 69 (1980), Bus Route and Schedule Planning Guidelines, Transportation Research Board, National Research Council, Washington, D.C..

Newman, D. A., Bebendorf, M., and McNally, J. (1983), Timed-Transfer: An Evaluation of its Structure. Performance and Cost, Urban Mass Transportation Administration, U.S. DOT, Washington, D.C..

Newell, C. E. (1979), "Some Issues Related to the Optimal Design of Bus Routes," Transportation Science 13, p 20-35

Oldfield, R. H. and Bly, P. H. (1988), "An Analytic Investigation of Optimal Bus Size," Transportation Research B, Vol. 22B, No. 5, p 319-337.

Osuna, E. E. and Newell, G. F. (1972), "Control Strategies for an Idealized Public Transportation System," Transportation Science 6, p. 57-72.

Rapp M. H., Mattenberger P., Piguet S., and Robert-Grandpierre A. (1976) "Interactive Graphic System for Transit Route Optimization," Transportation Research Record 619, p 27-33.

Rea, J. C. (1971), "Designing Urban Transit Systems: An Approach to the Rout-Technology Selection Problem," PB 204881, University of Washington, Seattle, WA.

Schneider, J. and Smith, S. (1981), "Redesigning Urban Transit Systems: A Transit-Center-Based Approach," Transportation Research Record 798, Transportation Research Board, Washington, D.C., p 56-65.

Shier D. R. (1979), "On Algorithms for Finding the K Shortest Paths in a Network," Networks, Vol. 9, p 195 - 214.

184

Shih, M. C. and Mahmassani, H. S. (1994), "A Vehicle Sizing Model for Bus Transit Systems," presented at the 73th Annual Meeting of the Transportation Research Board, Washington, D.C..

Silman, L. A., Barzily, Z., and Passy, U. (1974), "Planning the Route System for Urban Buses," Computers and Operations Research 1, p 201-211.

Simon, J. and Furth, P. G. (1985), "Generating a Bus Route O-D Matrix from On-Off Data," Journal of Transportation Engineering, Vol. III, No. 6, p 583-593.

Speiss, H. and Florian, M. (1989), "Optimal Strategies: A New Assignment Model for Transit Networks," Transportation Research B, Vol. 23, No. 2, p 83-102.

Taylor-Harris, A. and Stone, T. J. (1980) "Transit Center: A Means of Improving Transit Services," Transportation Research Record 760, p 39-42.

Tri-County M.T.D. (1982), "Planning, Implementation and Evaluation of a Timed-Transfer System in Portland, Oregon's Suburban Westside," Tri-County Metropolitan Transportation District of Oregon, Portland, Oregon.

Tsygalnitzky, S. (1979), Simplified Methods of Transportation Planning, Master Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Van Nes, R., Hamerslag, R., and Immer, B. H. (1988), "The Design of Public Transport Networks," Transportation Research Record 1202, Transportation Research Board, Washington, D.C., p 74-83.

Walters, A. A. (1979), "The Benefit of Minibuses," Journal of Transport Economics and Policy 14 (3), p 320-334.

Walters, A. A. (1982), "Externalities in Urban Buses," Journal of Urban Economics 11, p 60-72.

Wilson, N. H. M.(1982), "Bus Service Planning; Current Practice and New Approaches," Working Paper, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Wilson, N. H. M. and Gonzalez S. L. (1982), "Methods for Service Design," Transportation Research Record 862, Transportation Research Board, Washington, D.C., p 74-83.