DEVELOPMENT OF A GENERAL PURPOSE SIMULATION MODEL FOR EVALUATION AND SELECTION OF OPTIMAL DEMAND RESPONSIVE BUS SYSTEMS

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ABSTRACT

DEVELOPMENT OF A GENERAL PURPOSE SIMULATION MODEL FOR EVALUATION AND SELECTION OF OPTIMAL DEMAND RESPONSIVE BUS SYSTEMS

By

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As the number of applications of demand actuated public transit systems increases, it is essential that careful consideration be given to the evaluation and selection of operating policies. There exists a broad spectrum of policy variables within demand actuated systems, and without a generalized evaluation procedure, considerable inefficiencies can result from poor systems and operating strategies.

As a part of this research, a general purpose simulation model has been developed which can replicate the operations of various types of Demand Responsive Bus Systems on a single data base. This model produces and aggregates both user (wait time, ride time, travel time) and operator (bus utilization, vehicle productivity, vehicle hours of operation, driver hours required) statistics in a format compatible with techniques for the evaluation of alternative system. The research also explored the effect of several variables (demand density, bus pooling policy, street network configuration, service area) on the economic and service characteristics of demand responsive bus systems. Comparative tables and figures are developed and a systematic evaluation and selection process is demonstrated.

Tapan Kumar Datta

The selection criteria include user statistics such as ride time and waiting time and operator statistics such as total capital cost, operating hours and vehicle productivity. Since the selection of a system will necessitate a trade-off between service and operating costs, a technique for formalizing these decisions are presented along with results of an example application of the selection technique.

The simulation model developed in this research can replicate operations of various types of demand responsive bus systems under a many to one or one to many environments. The basic model is set up such that it can be changed to a many to few and/or many to many environment with minimal programming effort. The data produced by the model for a case study indicates that it can be used for any formal evaluation technique which quantifies community goals and policies reflected in user and operator characteristics.

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This Thesis is Dedicated

To My Beloved Wife Mira

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

A. INTRODUCTION

Mass transit was the most important mode of transportation until the early twentieth century when automobiles started influencing the life style of Americans. The personal mobility offered by the automobile increased sharply with the availability of personalized transport container and this brought about a revolution in the trip making characteristics of the people. The life style of the people changed as did the physical dimension of our cities.

The auto-highway system has evolved to the point where it now accounts for about 90 percent of the nations intercity travel. In many ways, it has shaped its own environment. However, with an increasing population in metropolitan areas, this environment is showing signs of trouble.

Traffic congestion, air and noise pollution, accidents, displacement of people, the unfilled needs of those people who do not drive, unfilled partially because of the decline in alternative forms of urban transportation--all of these are causing concern in the industry, in government, and among the people.

In addition, the nation's transportation "system" was not designed for integrated use by the various transport forms. The resulting interface problems are well-known today in terms of congestion, delay and inconvenience.

Existance of mass transportation system dates back to the horse and buggy era. Although some form of public transportation system has been present since this time, they are not well planned to form a balanced transportation system. In early years patronage of mass transportation was due to economic and technological reasons. The availability of a personalized transport container was limited by high cost and lack of technology. The increasing automobile popularity in the twentieth century, brought competition to mass transportation systems.

Public transportation in urban areas consisted of steel tracked street cars, trains, rubber wheeled trolley buses, and some motor buses in the late forties and early fifties. However, as auto volumes increased fixed track systems in the same right of way caused increasing problems. Provision of separate right of way was economically infeasible in most urban areas due to declining ridership. The result of this dilemma is evident today. Most metropolitan environments have eliminated fixed track carriers (street cars) and instead have multi-passenger automobiles or what we call buses.

This mode of public transportation (Bus) has more flexibility in terms of reaching to and from potential origins and destinations than the fixed tracked mass transit systems like the street cars. Buses can travel anywhere within an urban environment without additional expenses for facilities and right of way.

As bus systems replaced trolley lines, analysts and operators started to lay out the bus routes with the goal of providing as much coverage of the urban areas as possible. During the first few years, most systems were not only self-supporting but also profitable. However, the increasing usage of the automobile started to affect the bus ridership and most private enterprises faced regular losses in their operation.

This decline in mass transportation patronage has been recorded over the last decade. As a result, public transportation usage generally does not offset the operating costs of such systems. As the systems experience operating deficits, many privately owned systems either cease to operate entirely or sell their depleted operating systems to public agencies. Intermediate measures, such as service cuts, increased fares and public subsidies have all proved to be ineffective in either making public transportation systems operate at cost or to increase patronage.

Concern for these problems and their relation to other urban ills has resulted in a nationwide movement toward major changes and improvements in the transport of people and goods. The Federal government has defined an integrated and balanced transportation system as a national goal. Its achievement is a top priority item of the current Administration, and a wide range of efforts is moving forward.

Widest in scope and concept are system analyses attempting to define national and regional transport needs ranging up to fifty years into the future. These integrated planning efforts can be attributed to the Urban Mass Transportation Act of 1964. This act was amended in 1966 to include a new subsection which reads as follows:

"The Secretary shall, in consultation with the Secretary of Commerce, undertake a project to study and prepare a program of research, development, and demonstration of

> new systems of urban transportation that will carry people and goods within metropolitan areas speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning. The program shall (1) concern itself with all aspects of new systems of urban transportation for metropolitan areas of various sizes, including technological, financial, economic, government and social aspects; (2) take into account the most advanced available technologies and materials; and (3) provide national leadership to efforts of States, localities, private industry, universities, and foundations. The Secretary shall report his findings and recommendations to the President, for submission to the Congress, as rapidly as possible and in any event not later than eighteen months after the effective date of this submission.

In addition to the systems planning studies, a second level of effort is aimed at development of specific concepts, hardware and components. At the lower end of the spectrum are attempts to improve existing subsystems through innovation until long-term solutions can be provided.

As a result of this legislation, considerable attention has been focused on development and testing of innovative mass-transportation systems. Some of these systems consist of completely new hardware as well as software technology. Others consider innovation in system technology which utilizes basic existing "facilities" and modified "carrier". Demand-scheduled bus system (DSB), Dial-A-Bus (DAB), Dial-A-Ride (DAR), Demand Jitney (DJ), Computer aided routing system (CARS), etc., are some variety of methods being proposed by various agencies which utilizes basic highway facilities and consists of some modified version of existing mass-transportation vehicles.

The continuing decline in ridership can be attributed to several interdependent causes. Decentralization and affluence contributes to the ridership decline, as does the changing life style of Americans. Whatever may be the cause, it is evident from existing studies and research that public transportation services must be re-oriented towards todays transportation needs if this trend is to be reversed. It has become evident that a public transportation system will attract potential riders only when the service is such that it can supplement certain auto trips without causing major inconvenience or discomfort to the public.

The trip making behavior has been following a trend as shown in figure A-1, at least for the past decade. The number of person trips by mass transportation system has been decreasing slightly, but mass transit trips as a percent of total trips is decreasing rapidly as person trips by automobiles have increased (figure A-1). It may not be possible to reverse the trend of overall auto trips by introducing innovative systems. However, the rate of increase of auto trips can surely be slowed by using viable mass transportation system.

Prior to the discussion of the potential impact of demand responsive bus system, it is pertinent to define the potential market. A

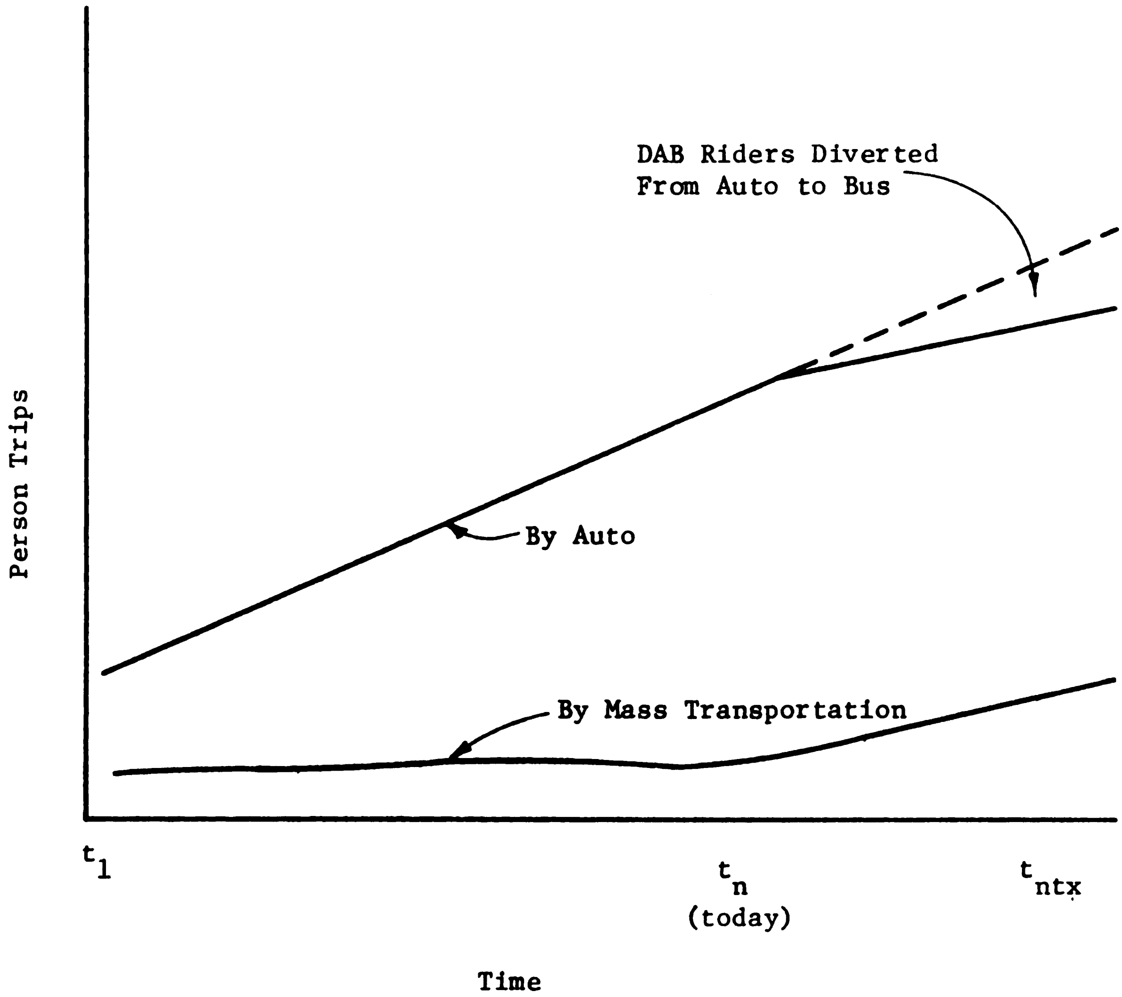

Figure A.1 Transportation Trends

person who does not have a car or does not have access to a car during a trip is defined as a captive rider. A person who uses an automobile, but may change to a public transportation system if and when a certain level of service is provided, is called a potential rider.

There are also generated riders, who would not have made a trip, but for the high level of service of a public transportation system.

Those three definitions can be illustrated in figure A-2. Say t_1 is the time of reference when auto travel started increasing and the total number of mass transit trips remained more or less constant as shown. Let t_n is the time reference when, by introduction of a higher level of in mass transportation service riders are attracted to mass transit.

't_{n+x}'is any point on the time scale occurring at a later date than 't_n'. M represents the captive rider. 'A_1' indicates the auto riders who are diverted from auto travel (the potential riders) and M_2 is equal to A_1. M_3 represents the new transit trips made who would not have made the trip unless the mass transit system provided a higher level of service (the generated rider).

General Concept of Demand Actuated Bus System

It was recognized that there are several ways of improving the service of a bus system. Studies were conducted to accomplish the objective of improving the level of service as early as the 1950's. The first concept used to provide better service was the express bus system. The next major improvement came when premium service was tested in demonstration programs in Peoria and Decatur, Illinois. The

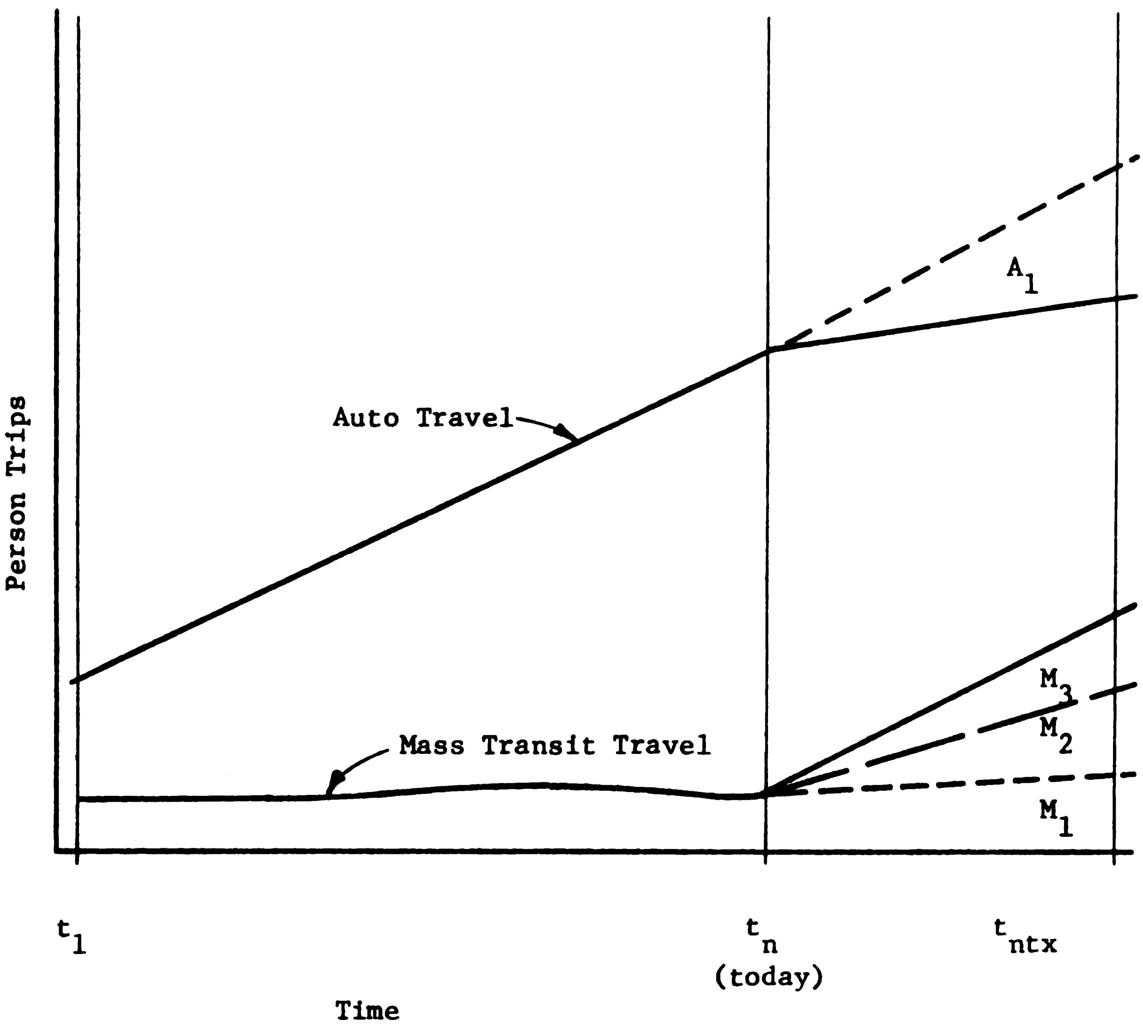

Figure A.2 Transportation Trends

concept of operating bus service without having fixed routes and fixed headway but responding to calls for door to door service came next. The flexibility in routing and scheduling of buses on demand is the basic underlying philosophy of these systems. However, under this acronym there are various alternative operational strategies available.

Depending on the operational alternatives and service options, it is possible to define a number of distinctly separable bus systems. These can be arranged in the order of level of service to form a hierarchy of bus systems.

Since passenger demand over space and time will determine route and schedule of these bus systems, the entire family of bus systems falling within this spectrum are classified as demand actuated.

It is important that we understand the relationship between the operational variables used to define this system, their respective service characteristics, which will determine their impact on potential and generated riders, and their cost. Only with this thorough understanding can we select the optimal system for any given environment.

The purpose of this research was to develop a generalized simulation model, which can replicate various operating strategies of Bus-Transit systems for various service options and provide necessary system performance data for system evaluation and selection.

B.1. DEMAND ACTUATED BUS SYSTEMS - AS DEFINED BY RESEARCHERS AND ANALYSTS

Considerable research activity has been pursued both funded by public and private agencies to investigate and determine the guide lines and feasibility of implementation of such demand responsive systems.

'Ford Motor Company is currently pursuing a program of company-funded research in urban transportation. This work is being carried on by the Transportation Research and Planning Office that is staffed by a multi-disciplinary team of researchers and engineers. The programs cover a wide variety of critical problem areas and place strong emphasis on the proper role of public transportation as well as the use of the personal vehicle. To make certain that these problems are relevant and useful, we work closely with transportation system operators and specific communities.

Typical of this approach is the work on dynamically dispatched public transportation conducted by Ford Motor Company'.[1]

Researchers at General Motors Tech Center were involved in defining and testing the same basic concept.

"It was the primary purpose of this study to provide information to aid in decisions regarding the merit of demand responsive transportation systems and the need for vehicles specifically designed for D-J transportation systems."[2]

[1] Incremental Implementation of Dial-A-Ride systems by Karl Guenther H.R.B. Special Report 124.

[2] Case Study of a Demand Responsive Transportation System by H.J. Bauer, H.R.B. Special Report 124.

Researchers at M.I.T. were forerunners in the field of DAB and were involved in utilizing simulation technique for evaluating the feasibility of such a system.

'"Dial-A-Bus", a public transportation system offering the desirable characteristics of automobile and taxi travel at a cost only slightly higher than conventional transit, provides door-to-door service with maximum waiting and travel time guarantees. The principal objectives here will be to review the results of research conducted at the M.I.T. for the U.M.T.A. and related to the feasibility of dial-a-bus systems.'[1]

The State of the Art of DAB indicates that researchers have one thing in common, the utilization of simulation techniques for the basic evaluation of systems they defined. It is noteworthy to look at the various definitions that have come from various researchers from the basic concept of demand-responsive bus systems.

1. "Before exploring the essential modeling questions, it is important to briefly describe the CARS system. CARS is an attempt to provide high quality mass-transportation service to complement the automobile as a major urban transportation mode. It offers door-to-door service using small multi- passenger vehicles. Someone using the system would phone his request into a control center consisting of a digital computer with peripheral communication equipment. The digital computer assigns vehicles to serve passengers and, at the appropriate time, causes a message to be sent to the vehicle informing the

[1] "Dial-A-Bus System Feasibility", by Daniel Roos, H.R.B. Special Report 124.

driver of his next stop. The vehicle travels the existing street network, generally carrying more than one passenger, and collecting and delivering passengers as instructed by the computer."[1]

2. "Here's how Dial-A-Ride works. The customer calls the dispatcher on the telephone and tells him where he wants to go and when he wants to be picked up. The dispatcher plans the most effective route for the requested time period, considering all other requests. He gives the call to the vehicle driver on the two-way radio. The driver, following a route sequence specified by the dispatcher, picks up each customer wherever he is and delivers him to his destination."[2]

3. "TELEBUS" is a hybrid form of public transit, incorporating the demand responsive characteristics of taxi systems, while accommodating multiple requests for service at one time. By being demand responsive, TELEBUS is able to reduce or eliminate completely the delay times associated with walking to and waiting for conventional public transit services.

The heart of this system lies in its ability to provide the convenience of limousine service on demand, to and from the user's home. This depends, in turn, on an effective dispatching system. In initial, smaller scale experiments which have been carried out to date, manual

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[1] Modeling the CARS System by J.D. Kennedy & N.H.M. Wilson - Paper presented to Ohio Transportation Research Forum - May 1969.

[2] Dial-A-Ride is here by Stephen D. Brumble - Paper presented in 1972 National Planning Conference of the American Society of Planning Officials.

dispatching has been used, similar to taxi dispatching. In larger scale, TELEBUS operations dispatching would be handled by a central computer.[1]

An overview of the above few examples of definitions indicate that though the terminology used by various researchers and analyst vary, the essential features of all such systems belong to demand actuated bus systems. The implementation studies of various demonstration projects reveal that even with varying levels of service in different projects the transit analysts tend to call them generally Dial-A-Bus or Dial-A-Ride.

The research activities performed to date for analysis and evaluation of applicability of various systems to different environments generally utilized simulation techniques.

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[1] Summary Report - Regina TELEBUS Study.

B.2. PUBLISHED PAPERS AND PROJECT REPORTS ON DAB SYSTEMS

It is important to realize the various interesting phenomena observed and experienced by the researchers, analyst, and operators of demand actuated bus systems.

This section summarizes the observations of the theoretical studies and papers relevant to the proposed research in the field of DAB.

Specific attention has been directed towards the work at Northwestern University, Westinghouse Brake Co., MIT, Ford Motor Company and GMRL. A critical review of the model assumptions, operations and reported results is made highlighting their differences, similarities and possible limitations.

Specific attention have been directed towards the following in reviewing the relevant state of the art.[1]

1. The proposed levels of service.

2. The selection of a vehicle for pick up and delivery of passengers.

3. The ability to handle groups of passengers with common origins and with or without common destinations.

4. The method of contact and the frequency of communication with individual vehicles.

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[1] Howson, L.L. & Heathington, R.W., "Algorithms for Routing and Scheduling in Demand Responsive Transportation Systems". H.R.B. Record 318. The model assumptions and operations are mostly adopted from this paper.

5. The method of describing the street network characteristics of the area to be served.

6. The dispatching policies.

7. The cost elements of DAB systems.

Level of Service

The Northwestern simulation package had 3 items included in the level of service--minimum and maximum pick up times and a maximum travel time. The minimum pick up time was automatically set at 1 minute. The maximum pick up time guaranteed the passenger that he would be picked up before a specified time limit has elapsed; the maximum pick up time was arbitrarily chosen to be 6 minutes. The maximum travel time was a linear function:

$$\text{Max. Travel Time} = \begin{cases} kn, & \text{for } n \leq n' \\ T + en, & \text{for } n > n' \end{cases}$$

where

n = the number of links between origin and destination (a link is 1 block long)

n' = a control parameter constant set equal to 10 links

k = a control parameter constant that equals 1 minute per link

T = a control parameter constant that equals 5 minutes

e = a control parameter constant that equals one-half minutes per link

The level of service as defined by these three constraints were guaranteed to each individual demand for service. In the analyses reported in this study, 100 percent of the demand was assured this level of service, and the operating and dispatching policies were thus constrained.

The Northwestern study[1] reported the sensitivity of wait, ride and total travel time for various levels of service. In this case, level of service have been used as "maximum pick up time" and "link travel time".

The WABCO guaranteed level of service used a single measure of time that includes the waiting time. This time varied from 2 to 6 times the automobile driving time. The automobile driving time was assumed to be based on 20 mph average speed plus a fixed value of 2 minutes. The WABCO simulation was not constrained so that each passenger was not guaranteed a "phone to destination" time. However, in the simulation runs, 95 percent of all passengers were served within the prescribed time.

The M.I.T. simulation work used a waiting time of 15 minutes and a linear function of the distance as a travel time constraint.

The M.I.T. study[2] reported the sensitivity of "vehicle requirements" for various levels (figure B.2.9). The level of service is defined as the ratio of total service time by Dial-A-Bus to total travel time by automobile.

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[1] Bruggeman, J.M., Heathington, R.W., "Sensitivity to Various Parameters of a Demand Scheduled Bus System Computer Simulation Model."

[2] Roos, Daniel, "Dial-A-Bus Feasibility", H.R.B. Special Report 124.

The GMRL model also used guaranteed pick up and delivery time as a measure of the level of service. This study simulated bus operations for 4 systems (A, B, C, D) on the basis of the level of service. The simulation results were related to trip diversions for various levels of fare (figure B.2.1.).

Ford Motor Co's[3] Transportation Research group investigated the sensitivity of "level of service" as functions of:

1. Service area (ref. fig. B.2.12)
2. Demand (ref. fig. B.2. 12)
3. Vehicle capcity (ref. fig. B.2.13)

where "level of service" is defined as the ratio of total travel time (from call to delivery) via Dial-A-Ride to the direct driving time. They also recognized that this definition does not account for the delays at either end of the auto trip, it tends to over estimate the actual ratio of door to door time. All of the above mentioned studies used time as the only variable in describing level of service. Some allowed weights for total travel time and waiting time whereas others did not differentiate between them.

Vehicle to Passenger Assignment Rules

The Northwestern University simulation program specifies a methodology for vehicle to passenger assignment. As a call for

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[1] Mason, F.J. and Mumford, J.R., "Computer Models for Designing Dial-A-Ride Systems". Automotive Engineering Congress, Detroit, Michigan, January 1972.

service is received, it scans the location and usage of all the vehicles that are currently operating in the system. The vehicle which is nearest (by distance) to the origin of the call is the first one considered for service. It is then checked to see if the new demand can be serviced without violating any of the passenger service criteria that have been established for passengers already in the bus or for those passengers that are scheduled to be picked up by this bus. If the nearest bus to the new call is not able to service due to violation of any commitment, then the next nearest bus is selected and is scanned to see if it can service the new demand. When all the buses in the system are found not to be able to meet the new demand, then a new bus is sent from the terminal to service the call. When a new bus is generated, it then is considered to be in the system and will be considered for any other incoming calls. Since the closest bus is always the first one to be considered as a possible server, there is really no guarantee that the vehicle to passenger assignment will be optimal.

The simulation model places a priority on the pick up of new demands at the earliest opportunity. When a passenger is assigned to a vehicle, the vehicle will pick up first before making any drops not directly on his existing route pattern.

In the Westinghouse Air Brake Co. simulation, a given vehicle makes a pick up or a delivery to serve the caller or the passenger with the highest priority. For the caller (the passenger that is to be picked up), a priority is assigned that has an arbitrary value of 110 minus his distance from the vehicle under consideration in grid units minus the callers origin to destination (O-D) distance in grid units.

A grid unit is a function of the grid density; for example, in an area of 25 square miles and a 20 by 20 grid, the grid unit would have a value of 0.25 miles. For those users already on the bus, the priority used was 100 minus the destination distance in grid units plus one unit for every five minutes of total wait time plus one unit extra for every 10 minutes of total wait time.[1] If a passenger has been waiting for 40 minutes, including the time that he spent on the vehicle, he is assigned a top priority. The WABCO model uses one additional vehicle designated to handle the longest trips and the longest wait times. This vehicle attempts to handle those callers who cannot receive service from the other vehicles in the system. A passenger waiting to be picked up will be given a priority relating to the largest value computed by adding his O-D distance in grid units to his waiting time measured by 1 unit for 3 minutes of wait, 1 unit for additional 2 minutes, and 1 unit for additional 1 minute of wait time. If this extra vehicle cannot keep up with the task of handling the callers with longer

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[1] Study of Evolutionary Urban Transportation. Westinghouse Air Brake Company, Volume 3, Appendix 4, Section 3.9, February 1968

waiting times, provision is made for other vehicles to assist by assigning a top priority to those waiting over 50 minutes.

In the M.I.T. CARS project, a vehicle is selected to serve a new demand depending on the criteria of waiting time of the new user, his travel time, his overall service time, link constraints, and the travel constraints of all current users. The link constraints are the specified time that a vehicle is due at a particular node in course of the tour of the bus. The travel constraints of all current users are waiting time, travel time, and total service time. The new user is assigned to a vehicle that can serve him without violating the travel constraints of those already traveling and who are scheduled to be served by the particular vehicle.

General Motors Research Laboratories simulation model assigns vehicle to passengers on the basis of an weighted function of:

A. Minimizing the increase in travel to those already on board.

B. Attempting to minimize the waiting time and travel time to the new demand.

C. Minimizing the deviation of the vehicle from a given path.

D. Reducing the number of buses in the system.

The weighted summation of the quantities relating to these criteria was used as the cost (in time) of providing service. A cost increase was considered if the new demand assigned to a bus under consideration had a scope for minimizing cost on a system wide basis.

The value used for the weights was arrived at, once the system performance levels were set, the necessary values for the weights to make the system cost the least to the user.

In formulating the vehicle to passenger assignment policy, some optimized the user travel characteristics whereas others looked at the entire system and attempted to optimize the system characteristics.

The Ability to Handle Groups of Passengers with Common Origins and With or Without Common Destinations

The Northwestern University's simulation package does not specifically handle multiple origins or destinations. If multiple origins or destinations need to be handled, they would have to be treated as separate and individual destinations. For example, if there were three people desiring to make a trip together from a common origin, this would be treated in the simulation model as three separate demand calls for service. Also, each destination would be treated separately. Thus, there would be three destinations used by the simulation model. Three people, perhaps of one family, desiring to have service to the same destination might be assigned to more than one vehicle to obtain the service.

The Westinghouse Air Brake Company (WABCO) report does not specify its method of handling multiple origins and destinations.

It would seem from their report that they also treat multiple origins and destinations in the same manner as the Northwestern University simulation package.

In the M.I.T. formulation of the problem, a demand may consist of more than one person and is referred to as a passenger group. For each passenger group there is a unique origin and destination. The possibility exists that more than one bus would be used to satisfy the demand for travel from this one origin, if the destinations were not coincident.

The GMRL model handles groups of passengers with a common origin and with or without a common destination. The passengers at the same origin are picked up by the same vehicle treating them as a single group. If they have the same destination, they are treated as one stop each for pick up and delivery, considering extra embarkation and disembarkation time depending on the number of passengers involved. If the passengers originating from one point have different destinations, the vehicle makes separate stops for unloading, like two different demands.

The Method of Contact and the Frequency of Communication with Individual Vehicles

The Northwestern University simulation package assumes continuous contact with all vehicles operating in the system. There was no proposal as to the methods of contacts as far as electronic equipment is concerned.

The WABCO model also assumed automatic vehicle monitoring. WABCO, having problems with the general purpose simulation program (GPSS), used a negative time feature to account for automatic vehicle monitoring. This study suggested the possibility of two way radio communications as a means of achieving this constant monitoring of the vehicle.

The M.I.T. Dial-A-Bus project considered two possibilities:

1. Continuous communication
2. Discrete communication

For continuous communication, the simulation model allows instant reassignment of demand. For the discrete communication system, intermediate reassignment is not possible since the precise location of the vehicle is only known when passengers are either picked up or delivered.

GMRL model allows communication on demand. New passengers can be assigned to vehicles and re-routed if vehicles could be located when desired. The GMRL approach seems most viable in terms of system costs and simulation of real world situations.

Method of Describing Various Network Patterns

The Northwestern University package used a simple, 1 mile square grid, This grid was in turn divided into 100 basic units that represent the intersections of blocks. Equal travel times were assumed on all links of the network.

The WABCO simulation also used a square grid. Their square grid ranged from a 1 mile by 1 mile square up to 5 mile by 5 mile area. However, the grid unit size varied from one tenth to one-quarter mile. Like the Northwestern simulation, the WABCO origin and destination points occur at grid intersections. The link travel time appeared to be uniform over the entire area.

The M.I.T. work of an earlier date was based on a rectilinear grid ranging from 1 mile by 1 mile to 3 mile by 3 mile area. The recent work discusses a network that is based on airline distances between points, using the reasoning that the specific street network under study is not pertinent to the grasp of the fundamental algorithm concepts.

The GMRL used a real network with one way links. The size of the GMRL study area is approximately 36 square miles. Because of the desire to be able to pick up a new demand within 5 or 10 minutes after a request for service is received and an average speed on the street network of 20 mph, it becomes apparent that 1 station or terminal located in the center of the city will not be sufficient. At a speed of 20 mph, it would require 0.21 hour or 12.6 minutes to travel to the corner of the area from the center. Therefore, there will be more than one terminal required if either the 5 or 10 minute pick up service guarantee is used.

The networks used in the various studies are either very simple like grid network, or very specific system like a case study. The airline distances were considered in one study. Thus, the importance of network configuration in the overall system performance

has not been tested. None of the studies reported the effect of variability in the network pattern. The assumption of only one way streets in a real world case study is possibly unrealistic.

Dispatching Logic

In the Northwestern simulation model, when all of the vehicles on the grid cannot service a demand call, then a new vehicle is dispatched from the terminal to service this demand. This vehicle will not be dispatched until after all of the other vehicles have been rejected.

The WABCO simulation designates a special vehicle that handles particular situations. When WABCO's 3 vehicles on the system can not service a given demand, then the special vehicle handles this individual demand. Each individual demand that cannot be serviced by the other vehicles is assigned a special waiting time measured by 1 unit for 3 minutes of wait, 1 unit for 2 minutes, and 1 unit for 1 minute of wait time. Once the extra vehicle is on its way to pick up a passenger and if there is a new demand located on the way to this origin, he will also be picked up. Essentially, the extra vehicle uses an algorithm that is designed to handle the longest trips and those waiting the longest.

In the CARS project a bus is dispatched when none of the other vehicles in the system can service the demand. When a demand call is recorded on the system, the vehicles which are currently operating are scanned to determine which vehicles can service the demand.

If none of the vehicles can serve the demand, due to violation of constraints of current users, then a new vehicle is dispatched from the station.

The GMRL model considers dispatching a new bus from the terminal when none of the buses currently in the area can service a new demand because of violation of user guarantees. In this case, a stored bus will be dispatched from the nearest terminal to the demand.

Cost Element of DAB Systems

The cost of DAB operation is the critical issue in the feasibility of such a system in any environment and almost all researches and analysts attempted to address this in various forms.

The Northwestern study looked at cost per passenger mile of travel time as a function of (ref. fig. B.2.10 and B.2.11)

A. maximum pick up time

B. link travel time

C. demand frequency

D. ratio of sides of service area

E. bus capacity

The bus operating characteristics have been converted to operating costs. The unit costs data used for evaluating system costs are as follows:

A. vehicle cost - $5,000 ammortized over 10 year period of 6% interest and based on usage of only 4 peak hours per day (1,000 hours per year).

B. driver-labor cost was set at $3.00 per hour per vehicle generated and came to $3.35 per simulated period which allowed for an average of 7 extra minutes required by the up and down operation.

Finally, a cost of 2.2 cents per vehicle minute of operation, which corresponded to 12 cents per vehicle mile was used to cover the cost of vehicle operation. Other costs like terminal facilities, taxes, licenses, administration, etc. were felt relatively constant and as such not considered in the system cost analysis. The Northwestern study presented sensitivity of user cost elements (wait, ride and total travel time) separately.

The M.I.T. study as presented by Roos (Dial-A-Bus feasibility, H.R.B. Special Report 124) did not attempt to convert either user or operator characteristics generated by simulation results to any dollar figure. His presentation dealt with operator cost element as vehicle productivity (no. of trips/vehicle/hour) as a function of (ref. fig. B.2.7.and .8)

A. demand density

B. service area

C. mean level of service

However, the entire work was performed on the basis of a single system strategy (Dial-A-Bus).

GMRL[1] (General Motors Research Laboratory) also conducted a system cost study in their case study area for Demand-Jitney System.

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[1] Bauer, H.J., "Case Study of a Demand Responsive Transportation System", H.R.B. Special Report 124.

Their definition of alternative systems pertain to variation of passenger wait time and ride time only. Costs were expressed as a function of both peak period demand and demand for specific hours, and were developed from the hourly distribution of estimated ridership. The GMRL simulation study used fare as one of the control variables to look at profit and loss. They have used wait time and ride time of the passengers as indices of level of service and all of their cost functions are presented for fixed levels of user characteristics (refer. figures B.2.2 to B.2.6).

TRPO (Transportation Research and Planning Office) of Ford Motor Company[1] did not attempt to convert the system parameters to dollar values. The approach used in this study was to identify and quantify the variables that would be used in an economic analysis, but not to affix prices to these variables.

All of the studies mentioned above treated cost (assumed dollar values) or cost elements as independent of demand parameters except the GMRL study which considered demand as a function of cost. This study also looked at the sensitivity of demand due to various fare structures.

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[1]Mason, F.J. and Mumford, J.R., paper presented at Automotive Engineering Congress, Detroit, Michigan, January 1972.

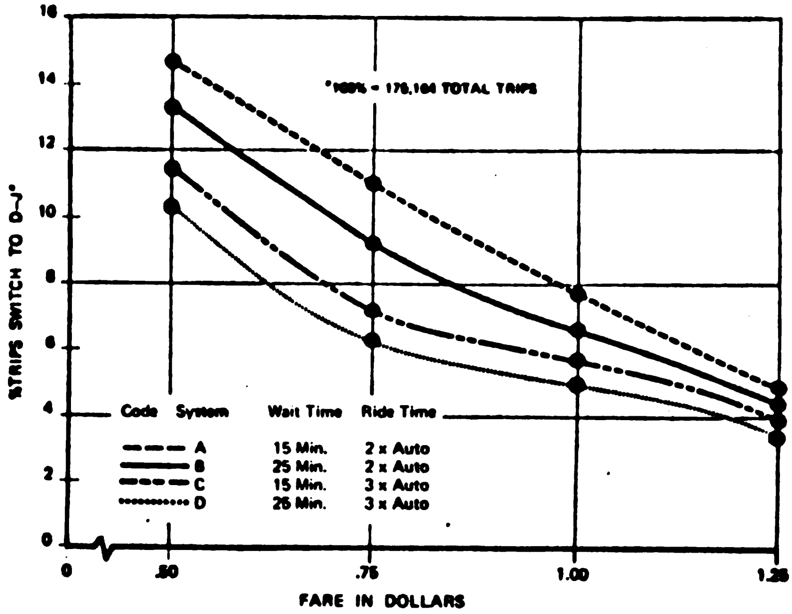


Figure 7. (Basic diversion to D-J based on fare.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation System", H.R.B. Special Report 124

Figure B.2.1. Basic Diversion to D-J Based on Fare

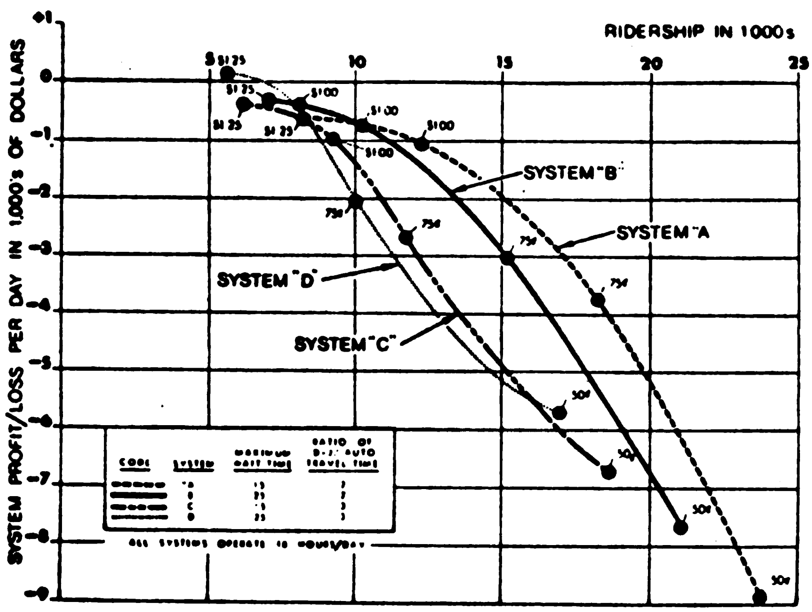


Figure 10. (Profit and loss versus ridership, fare-box revenue.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation System", H.R.B. Special Report 124

Figure B.2.2. Profit and Loss Versus Ridership, Fare Box Revenue

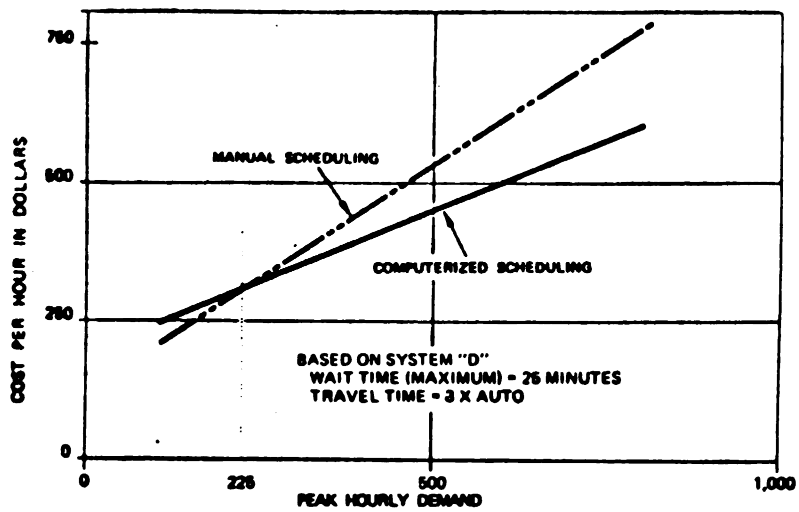


Figure 11. (Operating costs for manual versus computer assignment of vehicles.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation Systems", H.R.B. Special Report 124

Figure B.2.3. Operating Costs for Manual Versus Computer Assignment

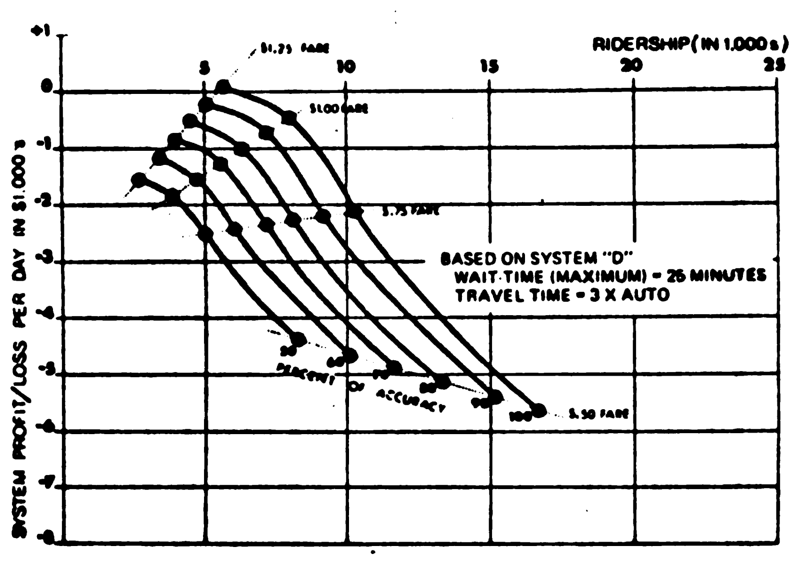


Figure 12. (Influence of accuracy of ridership estimate on profit.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation System", H.R.B. Special Report 124

Figure B.2.4. Influence of Accuracy of Ridership Estimate on Profit

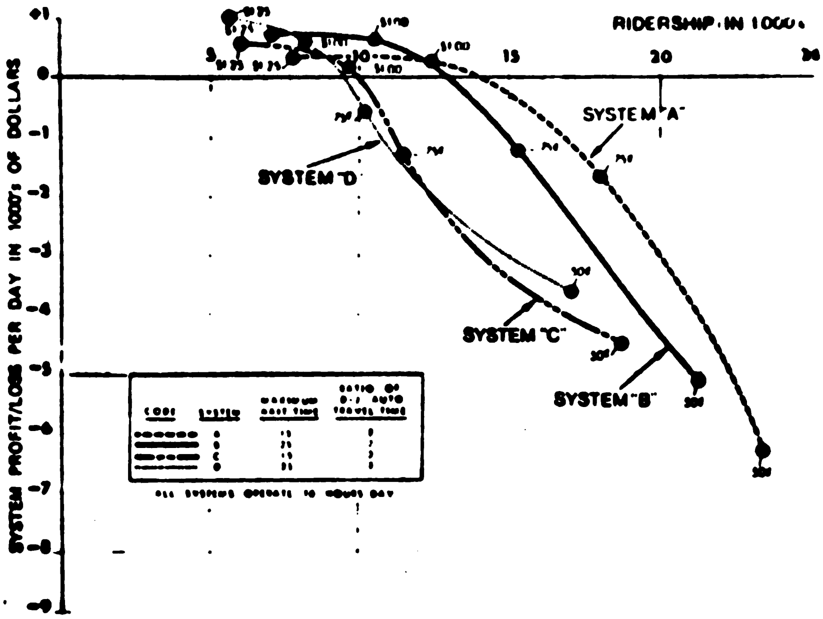


Figure 13. (Profit and loss versus ridership, two-thirds capital grant.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation Systems", H.R.B. Special Report 124

Figure B.2.5. P-L Versus Ridership, Two-Thirds Capital Grant

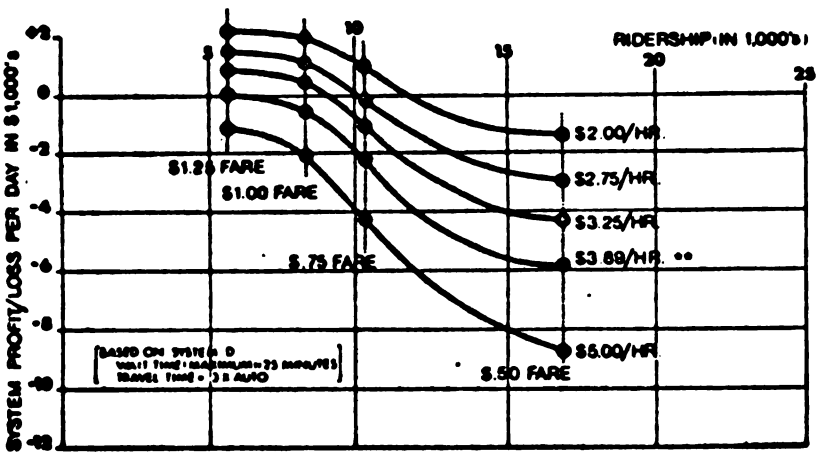
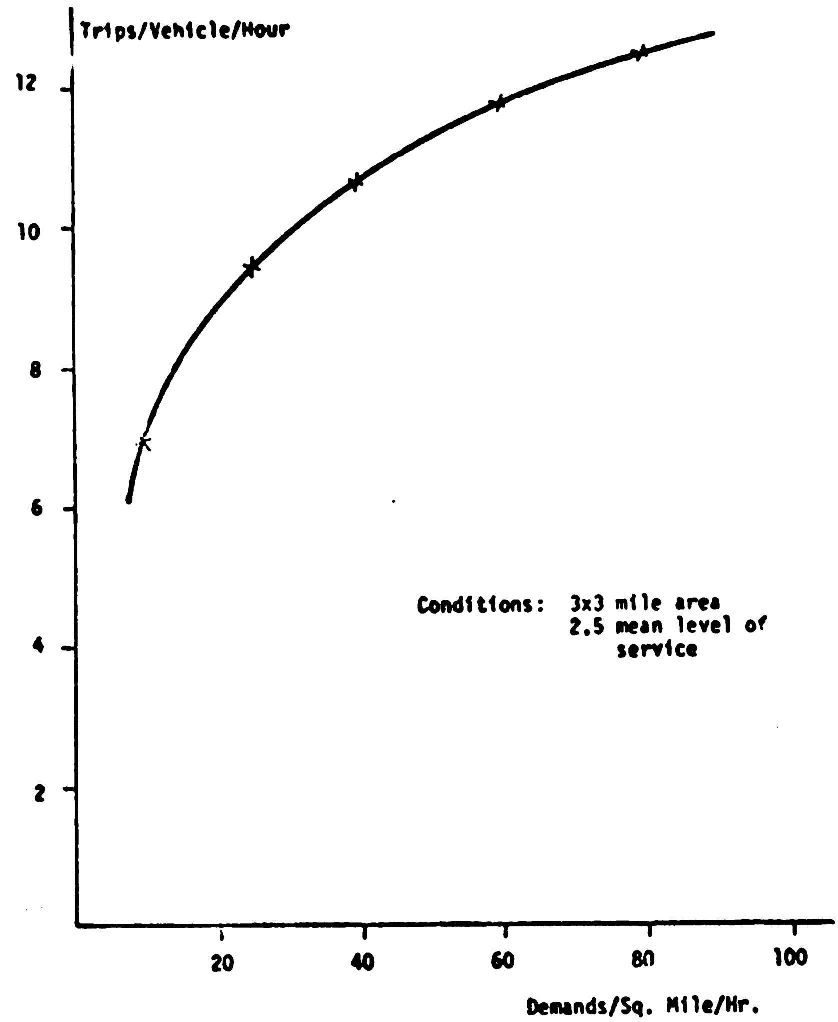


Figure 14. (Profit and loss versus ridership, effect of wage rate.)

From: H.J. Bauer, "Case Study of Demand Responsive Transportation System", H.R.B. Special Report 124

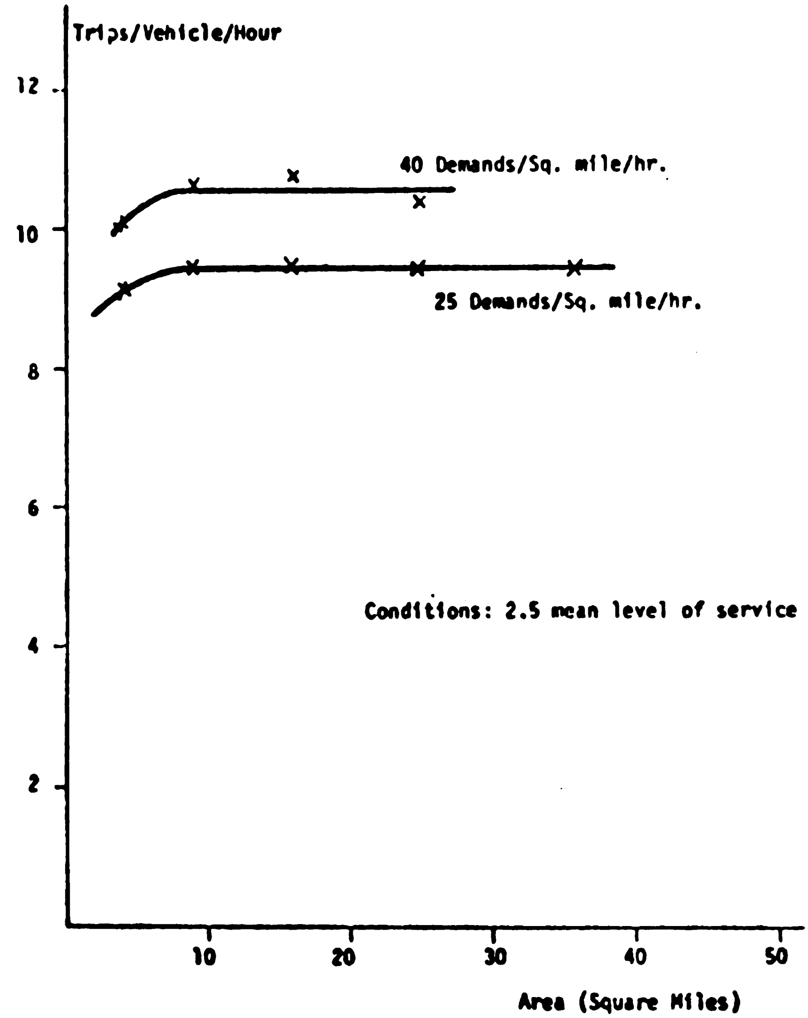
Figure B.2.6. P-L Versus Ridership, Effect of Wage Rate



(Figure 2. Effect of demand level on vehicle productivity.)

From: Daniel Roos, "Dial-A-Bus Feasibility", H.R.B. Special Report 124

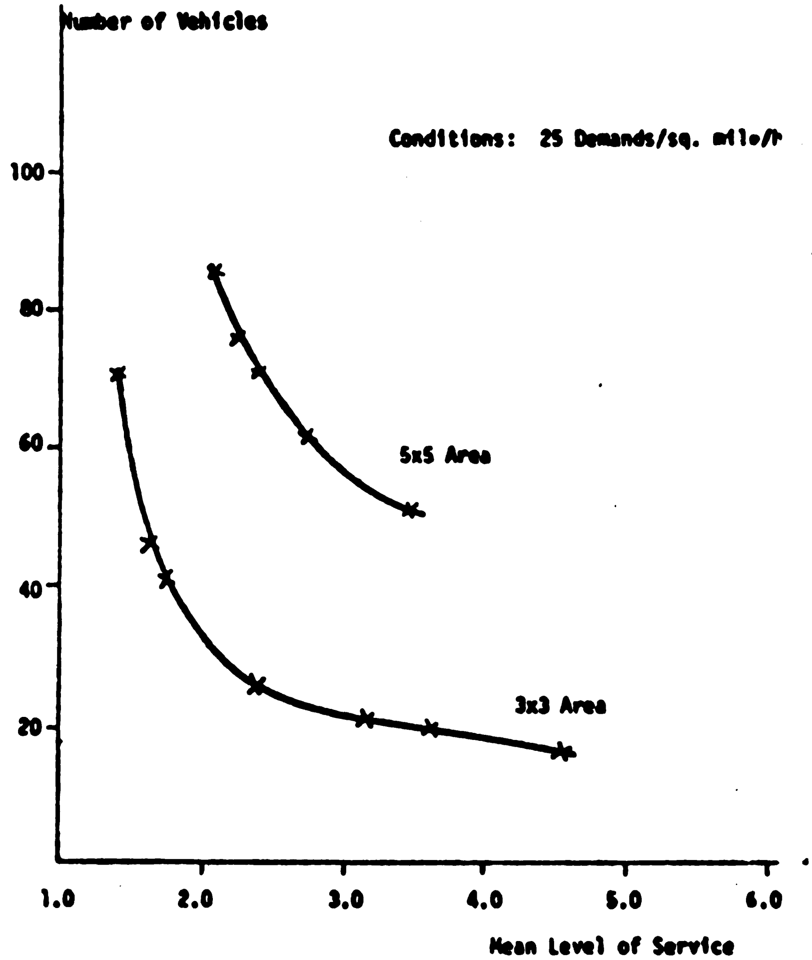
Figure B.2.7. Effect of Demand on Vehicle Productivity



(Figure 3. Effect of area size on vehicle productivity)

From: Daniel Roos, "Dial-A-Bus Feasibility", H.R.B. Special Report 124

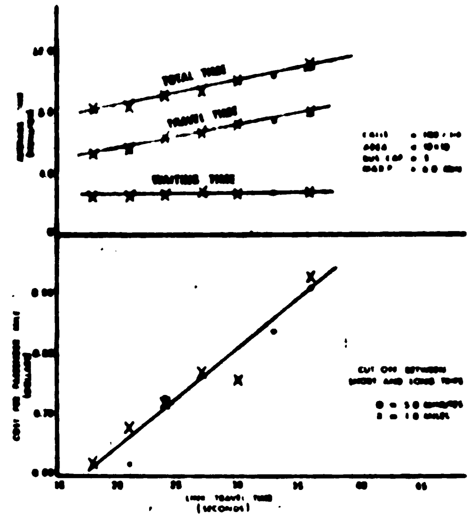
Figure B.2.8. Effect of Area Size on Vehicle Productivity



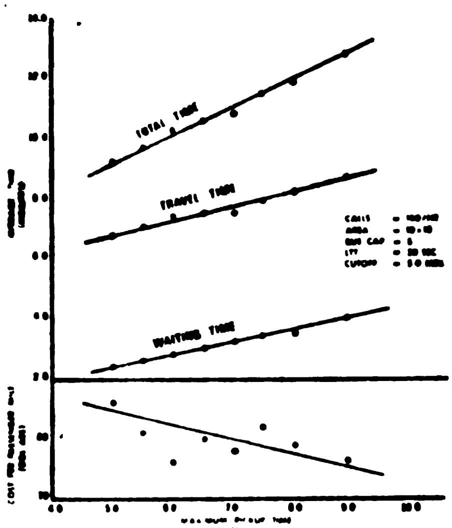
(Figure 4. Relationship between number of vehicles and level of service)

From: Daniel Roos, "Dial-A-Bus Feasibility", H.R.B. Special Report 124

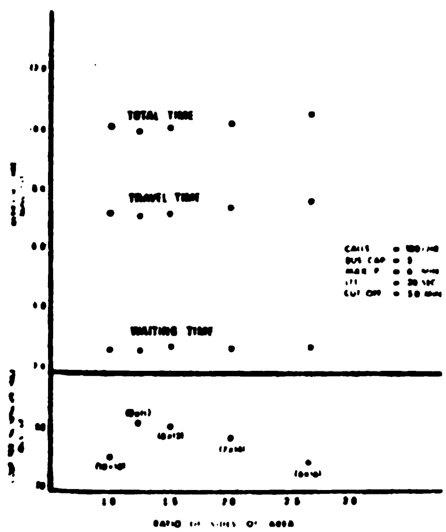
Figure B.2.9. Relationship Between Number of Vehicles and Level of Service



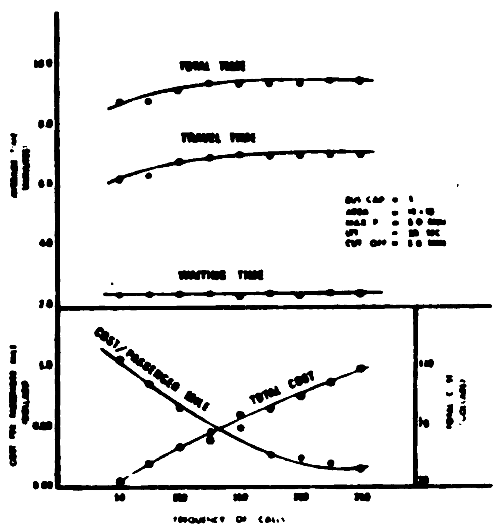
(Figure 1. Sensitivity to changes in link travel time.)



(Figure 2. Sensitivity to changes in maximum pickup time.)



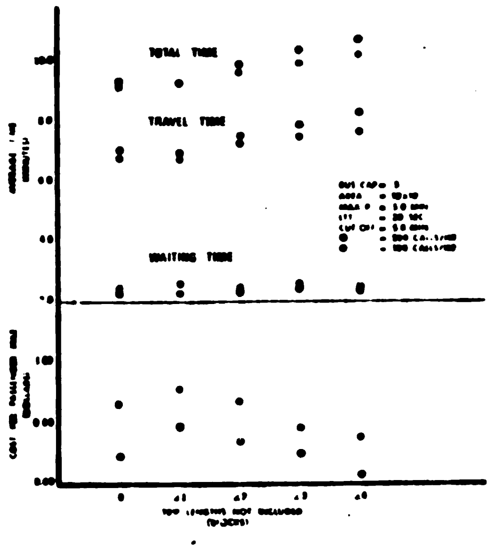
(Figure 3. Sensitivity to changes in shape of area.)



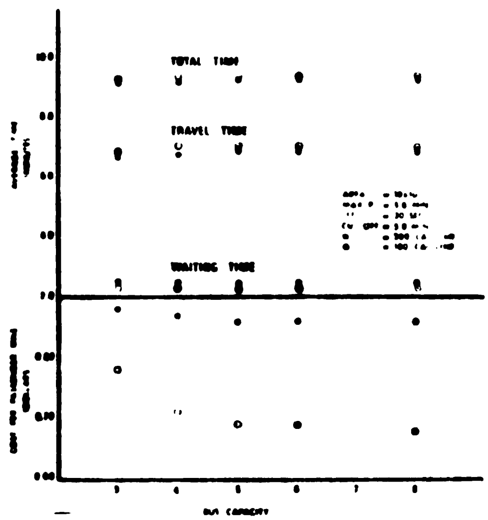
(Figure 4. Sensitivity to changes in demand.)

From: Bruggemman, J.M. & Heathington, R.W., "Sensitivity to Various Parameters of a Demand Scheduled Bus System Computer Simulation Model," H.R.R. 251

Figure B.2.10 Sensitivity Data of Northwestern Study



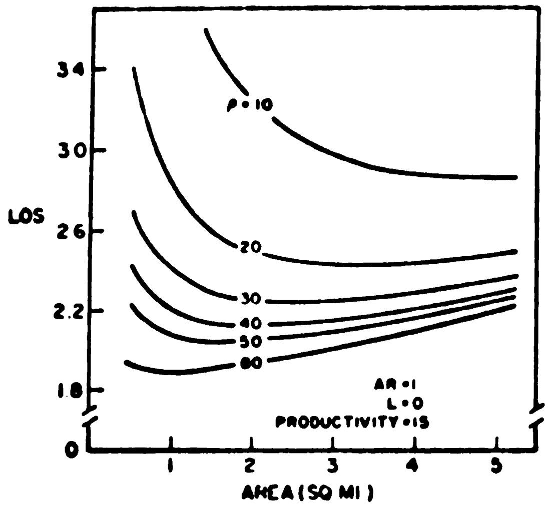
(Figure 6. Sensitivity to reduction in short trips.)



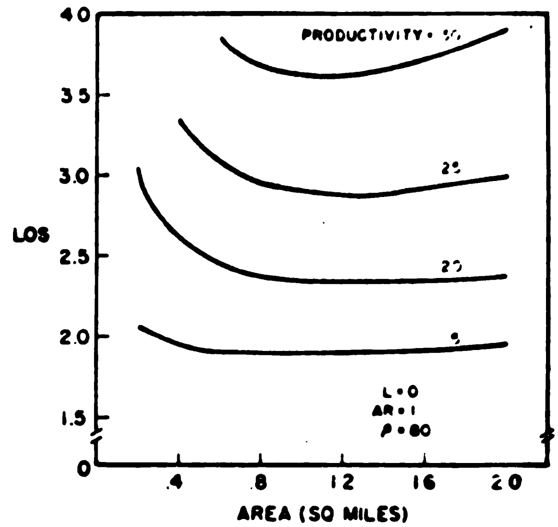
(Figure 5. Sensitivity to bus capacity.)

From: Bruggerman, J.M., Heathington, R.W., "Sensitivity to Various Parameters of a Demand Scheduled Bus System Computer Simulation Model", H.R.R. 251

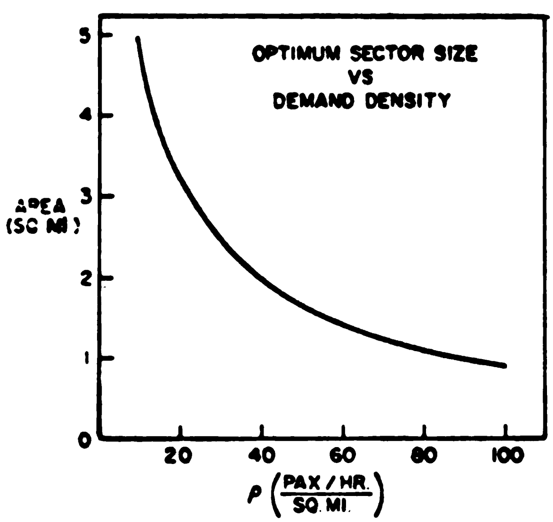
Figure B.2.11. Sensitivity Data of Northwestern Study



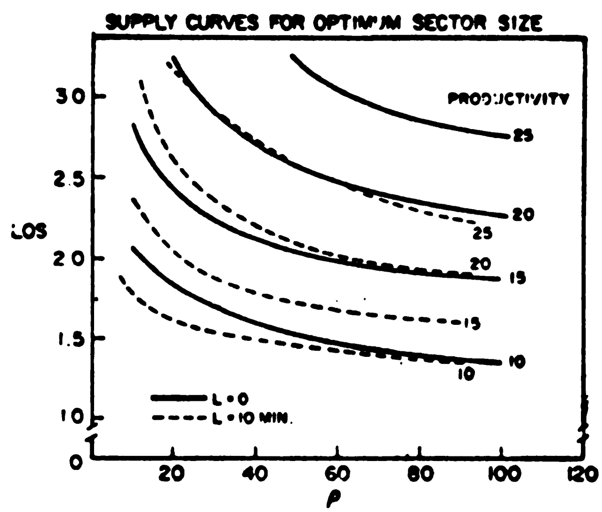
(Figure 5.3)



(Figure 5.4)



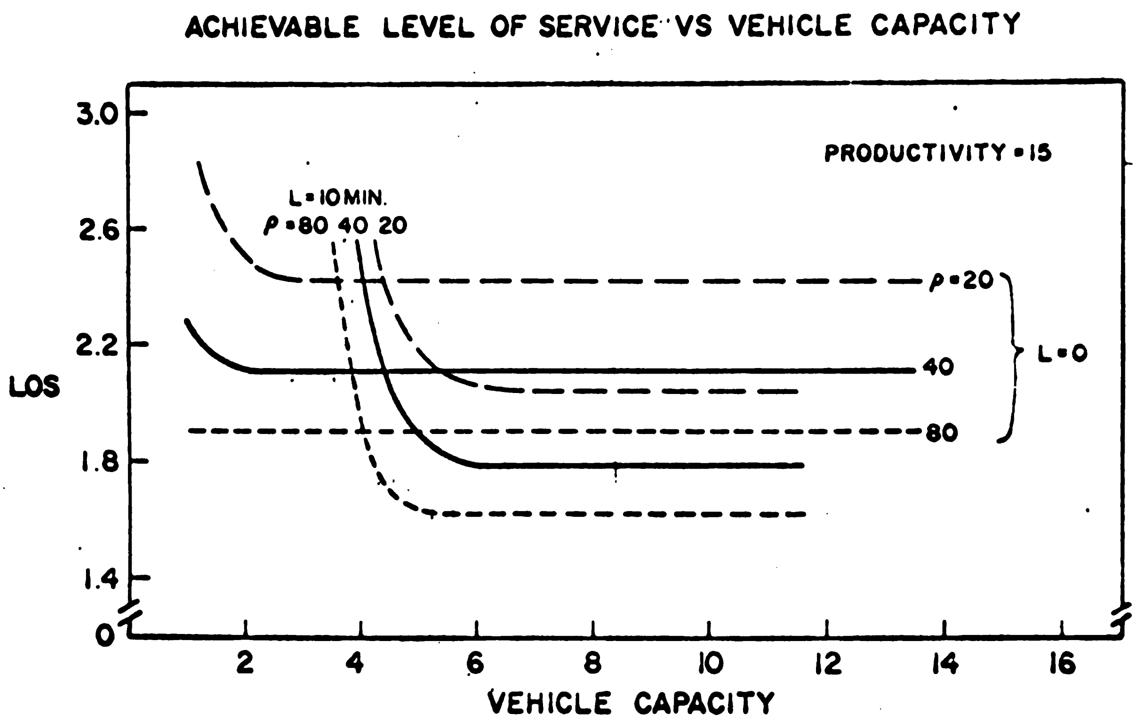
(Figure 5.5)



(Figure 5.6)

From: Mason, F.J. & Mumford, J.R., "Computer Models for Designing Dial-A-Ride Systems", Automotive Engineering Congress, Detroit Michigan, January 1972.

Figure B.2.12. Results of Ford Motor Company Study



(Figure 5.7)

From: Mason, F.J. & Mumford, J.R., "Computer Models for Designing Dial-A-Ride Systems", Automotive Engineering Congress, Detroit Michigan, January 1972.

Figure B.2.13. Results of Ford Motor Company Study

B.3. EXPERIENCES OF IMPLEMENTATION STUDIES OF DEMAND ACTUATED BUS SYSTEMS

Several demand responsive systems have been implemented across the country for study and experiment during the past few years. An attempt is made to consolidate the most important experiences of such test programs in this chapter which are most pertinent to the proposed research.

Vehicle Size and Type

The vehicle size used in the simulation of various demand scheduled bus systems varies from 30 to 20 seats. The Northwestern University's simulation model considered vehicle sizes with 3 to 8 seat capacities. WABCO model used 5 to 20 passenger capacity vehicles for simulation. The MIT CARS project considered 6 to 10 seats per bus. The GMRL simulation package did not use any capacity constraint; rather they were attempting to study the reasonable number of seats per bus necessary to provide various levels of service.

The vehicles used in the demonstration and experimental projects across the country also varied from 10 passenger vehicles to 53 passenger big coaches.

Table B.3.1 shows the various types of vehicles, types of service and implementing authorities associated with some of the experimental projects in the spectrum of demand actuated bus systems.

Various types and sizes of vehicles have been used to date for DAB systems across the country. However, they can be summarized in three basic categories:

1. Van type units with 10 to 12 seats.

2. Mini buses with 19 to 25 seats.

3. Standard buses with 40 to 53 seats.

The vehicle productivity data of the implemented systems tend to support small size buses with greater maneuverable capability rather than standard or large coaches.

Type of Service

The experience of DAB to date indicates that the type of service between experiments vary, though all of them can be defined as Demand Responsive Systems.

The Mansfield, Columbus and Emmen projects used a route deviation system though each varied in criteria.

Toronto started with many to one service and then added many to many service.

Ann Arbor and Reginia basically provided many to few service.

Columbia and Batavia provided many to many service with premium service during rush hours with subscription and predetermined rider demand.

The variety in service over time in each system seems to be based on the subjective analysis of the operators and the system designers in absence of any rigorous method for pre-evaluation of optimality of the type of service.

Service Area

The service area populations vary from 10,000 in Ann Arbor to 55,000 in Columbus.

The area coverage also varies from 1.34 square miles in Bay Ridges, Ontario to 6.5 square miles in Haddonfield, New Jersey.

Dispatching Techniques

The dispatching activities performed to date in all implementation projects are manual. The Mansfield project used the decision of the driver for dispatching, where as all other projects utilized a central control center and manual dispatchers.

Most systems concluded that the manual dispatching and voice communication are satisfactory. However, one of the major limitations of such dispatching and communication systems is the area coverage and population.

Nearly all the reports and studies concluded that manual dispatching, though not optimal, proved to be cost effective for the systems tested.

Batavia, New York, recently conducted a study on a digital communication system. It also concluded that digital communication becomes cost effective only when the system is sufficiently large to require more than 12 to 15 buses.

Fare Structure

There is considerable variability in the fare used and tested in different projects. These seem to depend on, local labor rates for drivers and dispatchers, the amount of subsidy and the basic goal of the project.

The fare varies from 20¢ in Columbus, Ohio to 50¢ in Haddonfield, New Jersey.

The simulation studies performed at M.I.T. and G.M. Research Tech. Center indicated that a fare of \$.50 to \$1.25 is required to cover all fixed and operating costs of a demand responsive system.

Ridership

The ridership in all the implemented projects increased during the study period. However, no quantitative estimate of future ridership for improved efficiency and service have been established to date.

Some DAB systems are extension of fixed route system whereas others are completely new. As such, the rate of increase of ridership in relation to improved service is hard to establish from the study reports. The G.M.R.L. simulation study of a real community predicted a significant ridership increase. The demand estimation for improved levels of service have not yet been fully explored by the researchers, though simulation provides a viable tool for ridership estimation.

Vehicle Productivity

Vehicle productivity has been defined by all as the number of passengers per hour, per vehicle and has been treated as the most important system performance measure.

However, this system attribute can be limited either by supply or by demand, or by both.

Since no standard level of service have been maintained by all the operating systems, it is hard to compare the various vehicle productivity figures presented by various studies and reports.

The factors which either singly or in combination affect the vehicle productivity as obtained from the studies and reports seem to include:

1. Type of Service: The M.I.T. researchers and the analysts at Ford Motor Company who were involved with at least six major DAR projects seem to favor route deviation service as having a greater potential for higher vehicle productivity over many to many service.
2. Service Requests: Vehicle productivity increases with the increase of prebooked or standing service requests. This provides for preplanning, and results in more efficient vehicle routings. The operator has a guaranteed ridership for which they can schedule buses before they receive any on-line calls for service.
3. Dispatching Efficiency: Efficient dispatching appears to increase productivity, since more passengers can be handled by the same vehicle with no or little extra time to the passengers.
4. Demand Density: Since no two systems have equal levels of service and passenger and trip characteristics, comparison of the effect of demand on bus utilization is not possible from the reports.

Cost of Ride

The cost per person trip is a function of the total operating and fixed costs and vehicle productivity. Thus, the local labor rates play a very important role in the cost of a ride.

The cost varies from project to project. Regina, Saskatchewan reported cost of $0.54 per ride and Haddonfield, New Jersey reported $1.75 per ride. The labor rates in the above two projects vary considerably, and the vehicle productivity of Regina is 3 times that of Haddonfield.

Cost Functions

There has been considerable effort expended in the past in relating the system attributes to dollar cost both in research and implementation.

A comprehensive study was done at M.I.T. on the "Dial-A-Ride" system in defining and establishing the cost functions. The cost of a typical DAR system was divided into four basic components:

1. Message handling
2. Message processing
3. Passenger transport
4. System support

The primary objective on the research was to "develop a set of predictive cost models for a Dial-A-Ride system."[1]

The following cost models were the product of the above research.

1. Message Handling:

   A. Customer (voice)

   $$\text{Cost per demand} = \frac{(\$2.\text{ to }\$2.5)(\text{Demand/Hr.})(\text{Operator Wage Rate})}{(\text{Operator Productivity})}$$

   B. Vehicle (voice):

   $$\text{Cost per demand} = \frac{(\$1.8\text{ to }\$2.1)(\text{Demand/Hr.})(\text{Output Operator Wage Rate})}{(\text{Output Operator Productivity})}$$

2. Message Processing:

   Cost per demand a function of system size x(2¢ to 20¢ per demand)

[1] Gary L. Urbanek - Cost Considerations for Dial-A-Ride. M.I.T. Systems Lab. publication, June 1971.

3. Passenger Transport:

   Cost per hour=($1.45 to $1.55) x (Driver's wage rate) + ($1.30 to $2.71) per vehicle per hour.

4. System Support:

   Cost=($.02 to $.05) x (total cost of the other functions)

Table B.3.1 Demand Actuated Bus Implementation Information

No.	Location of Experiment	Type of Service	Implementation	Passenger Capacity	Type & Make of Vehicle
1	Peoria & Decatur Illinois	Subscription, Fixed Schedule, Dynamic Route	Private Transit Co. in Conjunction with Univ.	45 Passengers	GM Coach
2	Flint, Michigan Maxi-cab	"	Public Authority with Promotion Agency	45 & 53 Passengers	GM Coach
3	Newcastle, PA	Fixed Route, Fixed Schedule. Changed Period for Experiment. Small Bus	Public Authority	19 Passengers	Mini Bus
4	Mansfield, Ohio	Variable Headway. Semi-Variable Route	Private Entrepeneur	12 Passengers	Econolines
5	Atlantic City, NJ	Fixed Route, Dynamic Schedule	Individual Owner	10 Passengers	Metro
6	Detroit Shopper's Chauffeur	Fixed Route, Fixed Schedule, Used as Special Feeder	Public Authority	53 Passengers	GM Coach
7	Haddonfield, NJ	Variable Route Variable Schedule-door to door pick up	Public Authority	17 Passengers	Specially Designed Vehicle
8	Ann Arbor, MI	Dial-A-Ride	Public Authority	12 Passengers	Econoline
9	Regina, Saskatchewan, Canada	Variable Route Variable Schedule-Door to Door Service	Public Authority	42 Passengers	

Table B.3.2. Demand Productivity Relationships of 7 Dial-A-Ride Projects

Name of Host City	Typical Weekend Ridership	Total Hours Of Operation Per Day	Service Area	Demand/Sq. Mile/Hr.	Vehicle Productivity
Ann Arbor, Michigan	214	12	1.36	13.11	7.65
Bay Ridges, Ontario	463	20	1.34	17.28	11.3
Batavia, New York	455	12	4.75	7.98	10.1
Columbia, Maryland	54	7.5	6.0	1.2	4.4
Columbus, Ohio	485	15.5	2.5	12.52	9.5
Haddonfield, New Jersey	333	24 hrs.	6.5	2.13	2.6
Regina, Saskatchewan	1200	16.75	2.75	26.05	15.0

B.4. CONCLUSIONS OF THE STATE OF THE ART

An overview of the state of the art indicates that there has been research, demonstration and implementation studies made on demand actuated bus systems throughout North America and abroad. These studies range from very simple application to sophisticated computer simulation studies. However, all of them are oriented towards the case study approach, and do not treat a family of Demand Actuated Bus systems on a single set of parameters. Thus, it is not possible to define a set of parameter values that would determine the applicability of the various systems. Though simulation has been used, most of the models developed are for a specific level of system constraints rather than a family of systems.

It is pertinent to briefly review at this stage the questions:

A. What do we know about DAB systems from the State of Art?

B. What are the aspects of DAB systems still unknown to date which require additional study?

The following conclusions can be made from the experience of DAB demonstration and implementation studies.

1. Several factors are apparently of great importance to the success of a DAB systems; with service area, service selection and dispatching strategies the most important.

2. DAB systems have not been self supporting or money making systems. Public subsidy is necessary to support a bus system with this higher level of service. Ridership increase due to implementation

of DAB systems compared to fixed route fixed headway systems is significant.

3. Public subsidy is not a guarantee for system success. This requires a competent system analyst and management and staff.

4. Significant operating economies can be achieved by using small coaches which increase the occupancy-capacity ratio.

5. Increased vehicle productivity (no. of passengers per hour per vehicle) is possible with DAB systems.

6. Off peak fare reductions policy results in redistribution of ridership--i.e., peak smoothing--but does not affect total ridership or revenue.

7. Ridership seems to have limited sensitivity to fares between 25¢ and 60¢.

8. Manual dispatching works fairly well for smaller service areas with few buses. For larger areas computer routing and dispatching is required.

9. Careful analysis of service area may allow a system to be efficiently operated under many to one or many to few environments.

10. For high density (riders) areas, fixed time fixed route systems work as well as any DAB system.

The following conclusions can be made from the research and development studies:

1. System simulation provides a tool for system evaluation and selection.

2. The concept of DAB systems is technically feasible.

3. Financially the systems cannot be self supporting.

4. Demand estimation analysis shall be a part of system study prior to implementation for selecting viable service criteria.

5. Heuristic Traveling Salesman algorithms works for optimal routing in most of the existing simulation models.

6. Computer dispatching is economical for large systems.

7. The limited sensitivity analysis presented in various studies and papers indicate sensitivity of system performance to waiting time, trip time, and link travel time for specific systems only.

8. Most simulation studies are for specific systems, with limited sensitivity analysis to performance as a function of levels of input parameters like, demand, link travel time, etc.. As such, no comparison can be made between various system alternatives.

The following questions regarding demand actuated bus system still remain unanswered:

A. Can a single simulation model replicate the operations of various types of demand actuated bus systems, which will generate system performance data for use in the alternative system evaluation and selection process?

B. 1. Do the variables used in demand estimation and economic feasibility tests (e.g. wait time, ride time, driver hours required for service, vehicle hours of operation, bus utilization, etc.) vary significantly with demand for various DAB systems? and;

2. Can the parametric information produced by a general purpose bus system models be used for any organized system selection procedure?

C. Do variations in system parameters such as service area, bus pooling and street configuration cause major changes in the value of the operating variables?

C. PROBLEM STATEMENT AND OBJECTIVE OF THE RESEARCH

The concept of publicly owned multi-passenger vehicles circulating through our residential areas, responding to telephone requests for picking up or delivering riders to and from their door step is certainly an attractive one. This enables the riders to enjoy personalized service without the cares of vehicle maintenance and storage.

However, the search of the literature indicates that insufficient information on the cost-effectiveness of various systems exist. The simulated studies to date, generally worked with specified levels of service options and particularly do not provide any means of evaluating various system alternatives. A generalized study approach demonstrating a viable system selection strategy of various discrete system alternatives for a wide range of demand is needed for decision makers for optimal system selection.

The objective of this research was to develop such procedure which can be used to determine a set of parameters which provide necessary information to define the cost-effective regime for demand actuated bus system alternatives.

To accomplish this objective the research included the following:

1. Development of system definitions of several discrete DAB systems.

2. Development of a generalized model, which will simulate the operation of all systems on a common data base.

3. Determination of system attribute functions for each system as a function of:

a) ridership levels

b) roadway network configuration

c) pooling policy

d) service area

4. Demonstration of a method for constructing cost functions for evaluation of alternative system strategies.

The research was limited to "many to one" and "one to many" environments. However, the simulation model has been designed such that with minimal change, it can be used to simulate "many to few" or "many to many" environments.

The basic objective of this research was to develop a decision making tool (generalized simulation model) which can be used to establish trade-off functions to determine the bounds of demand and user characteristics for different systems. If system attributes under various demand conditions are reduced to cost functions, it is expected that the viability of the various system alternatives will change with the demand. Figure C.1 indicates a hypothetical situation where cost limits the use of various system alternatives for increased level of ridership demand. Evaluations of this nature requires a system performance data and a general purpose simulation model which can replicate various operational alternatives and service options provides such information.

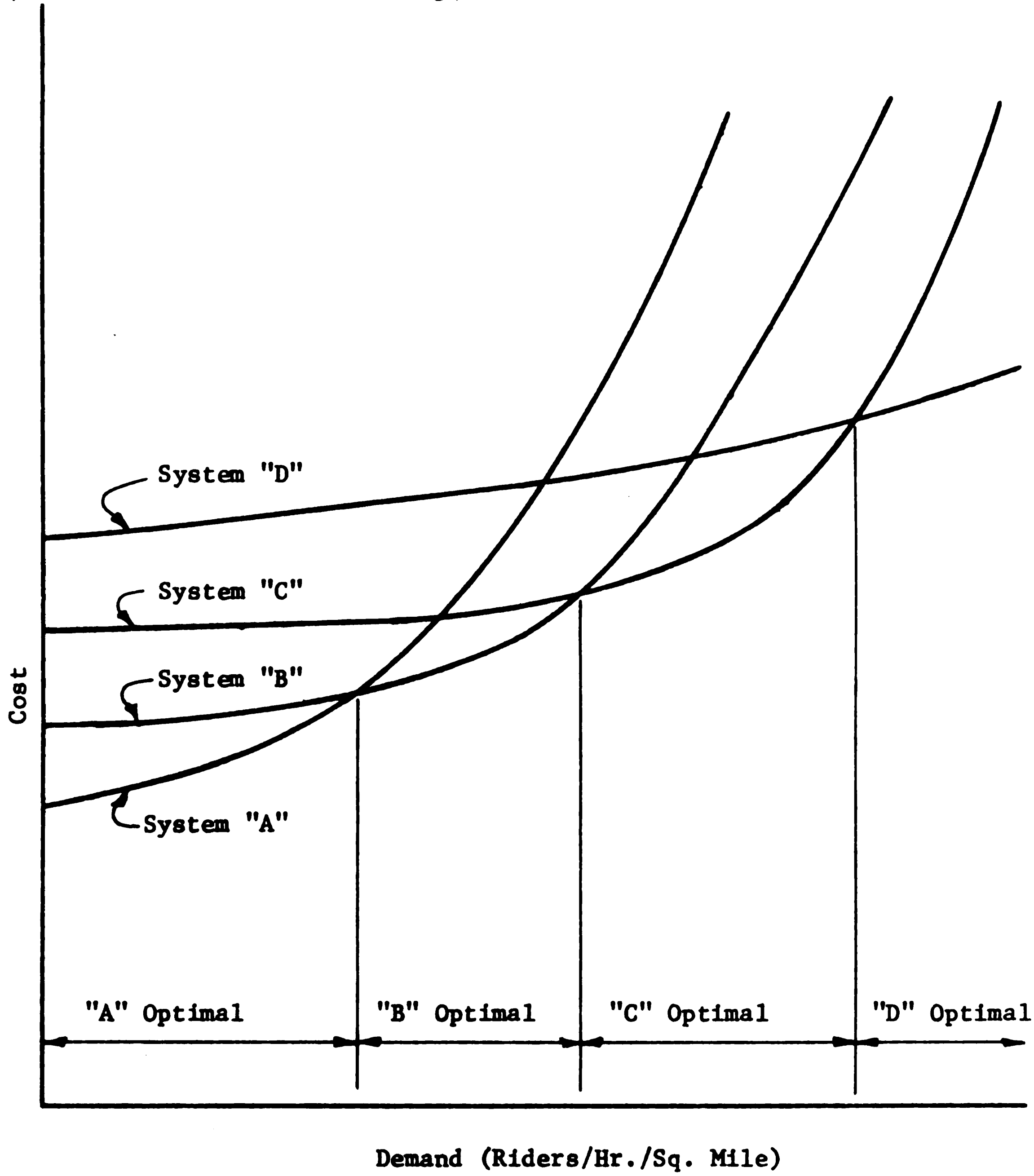


Figure C.1 Optimal Regions for DAB Systems Alternatives

D. METHODOLOGY

D.1 SYSTEMS DEFINITION

To initiate the study, it was necessary to define the characteristics of the various systems to be tested and evaluated.

Table D.1.1 is a list of public transportation systems which belong to the family of Demand Actuated Bus Systems. The dispatching criteria to meet the specified requirements of system performance parameters are also shown in the table. A brief description of the operating characteristics of some of the systems under investigation are as follows:

1. Fixed headway - fixed route bus system. This system is based on multiple passenger vehicles traveling on pre-determined routes at pre-scheduled headways for passenger pick up and delivery. The route and headways for such operations are pre-determined from past demand experiences. This type of system now exists in most urban areas.

2. Variable headway - fixed route bus system. This system is based on the concept of riders being able to register their demand by calling the central dispatcher. The dispatcher notes the location and time of such demands, and depending on the dispatching criteria, vehicles are sent out for servicing such demand.

There can be defined a host of bus systems under this category on the basis of the dispatching logic. The routes of systems under this category are also fixed (pre-determined) though headways are determined from the demand register.

Table D.1.1 Performance Criteria Levels in the Hierarchy of DAB Systems

System No.	Dispatch Logic	Response to Demand	Priority of Pick-up	Priority of delivery	Route
1	Predetermined (fixed) route and fixed head-way (general purpose)	Non responsive	Constant for all position	Function of position on route	Fixed
2	Variable headway fixed route	Semi responsive to fixed node	Constant for each position	Function of position on route	Fixed
3	Fixed headway variable route to fixed nodes	Semi responsive to fixed points	Function of posi-tion rela-tive to other details	Function of demand posi-tion	Traveling salesman
4	Fixed headway variable route to address	Semi responsive to address	Function of position relative to other calls	Function of demand position	Traveling salesman
5	Variable route variable headway (non-dynamic) to fixed nodes	Responsive to fixed points	Guaranteed within specified interval	Function of demand position	Traveling salesman
6	Variable route variable headway (non-dynamic) door-to-door	Fully responsive to address	Guaranteed within specified time	Function of demand position	Traveling salesman
7	Variable route variable headway (dynamic)	Fully responsive to address	Guaranteed within specified time	Guaranteed within specified time	Traveling salemsan
8	Taxi type	Fully responsive to address	First	First	Minimum path

3. Fixed headway - variable route. This system is based on the premise that a bus is dispatched to service riders in any area on a fixed schedule. An optimal routing technique is necessary for system operation. To increase the efficiency in computing the optimal routing strategies, high speed digital computers are necessary.

In this system the riders call the central dispatcher to register their demand. The locations of the demands are then analyzed for optimal routing for a given set of buses and pre-determined headways. The task performed at the dispatch center is the determination of optimal routes of vehicles and assignment of passengers to vehicles.

4. Variable headway - variable route (non-dynamic). This system is based on the concept that riders call the dispatching center and register the demand. The demands are recorded and analyzed according to their time of calls and spatial locations for determining the optimal routes according to the dispatching criteria.

The dispatching criteria can be functionally related to costs and level of service to the users. To accomplish this, the total demand and socio-economic characteristics of the users, must be known. Thus, the determination of headways does not pose a great problem and in most cases depends on the environment where the system is operating. However, the problem of selecting routes requires an optimal routing algorithm as in case 3.

The methodology employed in this study was to develop a simulation model which can simulate each of these systems under various environmental (socio-economic characteristics - Demand) conditions to produce system performance data necessary to provide data for selection of alternative bus systems.

D.2.a. SIMULATION

The basic tool for this research is a simulation model developed as a part of the study to generate system performance and cost functions. The simulation model is flexible enough to replicate all the systems as defined here with various levels of operational alternatives.

Characteristics of Simulation

The variability and probabilistic nature of the variables involved in demand actuated transportation problems has made analytical solutions complex. Past transportation system studies and evaluations have tended to approach the problems by making simplifying assumptions or by testing only one system under given conditions.

The evaluation process involved in this system simulation approach provides a viable alternative for determining the trade-off functions between cost and benefit parameters over a wide range of alternative policy questions.

The simulation technique adopted in this study allows generation of rider demand from random numbers for any type of probability distribution. The time and location of passenger demands are independent random variables and as such utilization of random generators in the simulation provides an effective and realistic means of replication of real world situations.

Simulation Model

The simulation model was developed with the capability of replicating the operations of bus systems under various system strategies, and collecting the data required for statistical summaries of system performance parameters (refer Appendix II for flow charts).

The model is initiated by generating strings of demands (collection and distribution) for each specific area of operation. There is no limit with regard to the size of an area. For larger areas, the model can handle sectoring or splitting of the entire area in segments, and can operate the simulated bus systems concurrently in each segment.

The model assumes a central pool of buses from which vehicles are dispatched to any sector on demand.

For fixed route systems, the routes of bus operation must be specified. For variable route systems, the shortest path will be formed and used by the model.

The simulation program develops internally a point to point travel distance matrix from the given size of the area under investigation and density of demand generation points. The distance matrix is then converted to a travel time matrix for given speed. The speed of travel can either be used as an average speed or as a function of other parameters.

The simulation model consists of two separate but interconnected programs. The first program handles the systems which are operated on the basis of separate distribution and collection. And the second program handles the alternative operational procedure of concurrent collection and distribution.

The computer models have a block data part which specifies the values of the parameters, number of sectors to be serviced, fixed headways, dispatch logic, vehicle capacity, and number of buses. This part is the same for both the programs. The next part of the model is the main program which does the initializing of the various parameters, calls all different subroutines in sequence and executes demand. The execution is event ordered and the output statistics (waiting time, riding time, total travel time, etc.) are accumulated.

Subroutine

The "generate" subroutine generates rider demands on the basis of input, average arrival rate and type of demand function. The door to door or node to node travel distances are formed from the given dimensions of an area of service and the criteria set in the system operation.

The "BS Pool" subroutine performs the function of servicing the demands using the number of buses assigned to it by the block data. When a bus completes its tour it is returned to the pool and at this time, the subroutine "BSSTAT" is called to execute the summary statistics. Besides this summary, statistical output is printed for the individual bus tour at the completion of its tour.

The "STATIS" subroutine (also referred to as DSTAT, CSTAT AND QUTSTS) calculates pertinent statistical information on passenger wait, ride and total travel time. The subroutine prints out the information at the end of the simulation period.

The functions SMEAN, HIGH, NOVER and the subroutine SORT are used by the subroutine STATIS (DSAT, CSTAT) in the calculation of passenger statistics.

BSSTC (BSSTAT) subroutine performs the same function as the STATIS subroutine, except it calculates pertinent statistics for each bus in the bus pool.

The "RDList" subroutine is used to read into the system all information to be used by the program in modeling. This includes the "Time-Travel" matrix and the demand string. The demand string is separated in two manners: First, by sector and secondly, whether the demand is for distribution or collection. For convenience, the "RDList" subroutine prints out all data by sector and by demand type before any simulation takes place.

The "DList" subroutine, chooses which sector to execute next. The sector with a demand string to be executed that has the lowest absolute clock time associated with it is chosen. "SLICE" (also referred to as SLICE 2) slices the distribution demands on the basis of capacity and headways into buses and the dispatch logic of the system into executable sub lists. It also calculates the absolute clock time that bus will be required in a particular sector.

"C" List" performs the same operation as "D" List" on the collection demands.

Subroutine "DISTR" produces the best tour on route, to minimize passenger travel time of the string of executable demands by "SLICE". Should there be demands of the sub-string to be executed after the best tour has been constructed the "DISTR" subroutine, returns them to their respective lists.

"CLICT" performs the same operation as "DISTR" on the collection demands.

"TTIME" is used by "DISTR" and "CLICT" to construct a miniature Time-Travel matrix.

Routing Module

The algorithm is an heuristic solution of the classical "traveling salesman problem" under many to one or one to many environments. This module computes the optimal routes for given demand and their location.

In the evaluation of policy questions regarding service options, fleet size, vehicle capacity, etc., different variations of the program can be constructed by setting pertinent input parameters.

Service Options - Since there are the possible triggers in the dispatch logic, the fixed headway operation can be achieved by setting the demand parameter high enough to trigger a vehicle dispatch on the basis of predetermined headway. The variable headway operation can be achieved by setting the time parameter high.

The concurrent or separate collection and distribution operation can be achieved by specifying the input data.

The simulation model requires the following inputs:

Fleet size - The number of vehicles available in the bus pool must be specified in the input data. The simulation program is set up to use vehicles from the top of the list. Thus a high number of buses used in any system simulation can answer questions regarding optimal fleet sizes.

Vehicle capacity - The capacity of vehicles used in the simulation is also an input parameter and must be specified. This capacity is treated as a constraint in making the decision of vehicle to passenger service.

Activity Center - The zone number for identification of activity center is also an input parameter. Thus changing the location of an activity center for various trip purposes is possible.

Demand - The mean arrival rate for the area under study must be an input. The generation subroutine computes the rider demand on the basis of the pre-assigned probability distribution and random numbers. The frequency of collection and distribution demand is also computed according to the probability function and its parameters. Thus, the generation of rider demand is completely random (poisson's or any other probability distribution) and is computed for any specified length of time in the model.

The demand locations are identified as points in the model, and as such can be specific bus stops or individual homes.

Sector size and number of blocks - The program generates possible demand points (door steps or nodes) from specified length and breadth of each sector and the number of blocks in each direction. A travel distance matrix and finally a point to point travel time matrix is generated for given speed of travel or speed function.

Delay - The delay at any stop for a bus is a function of the number of passengers involved and whether they are loading or unloading. The model includes separate delay functions for evaluation of travel time. For a given bus stop the delay is computed on the basis of the number of passengers entering and leaving at that location. This function is set up as a default option in the absence of specific input.

Dispatch logic - The dispatching criteria are input to the model. Dispatching logic may signify a certain type of bus system as outlined in Table D.1.1.

The model requires specific inputs regarding minimum number of passenger demand to warrant dispatching a bus or maximum headway of buses if the specified demand is not registered. These, of course, have to be pre-determined in the system definition part of any problem.

Service Constraints

The maximum tolerable waiting time for a passenger is also an input to this model. This parameter signifies to some extent the level of service provided to the riders. It also is used to define the limit at which potential riders switch to other means of transportation.

The Assumptions and Operation of the Simulation Model

1. Demand is considered as call for service and can consist of either single or multiple passenger.

2. Number of passenger in a demand is generated from given probability function with assigned probabilities for 1 passenger, 2 passengers, etc.

3. The available buses in the "Bus Pool" are serially numbered and the simulation model always searches for lowest numbered buses for use, and will not call for a new bus (though available from the system constraints) as long as there is a bus in the "Bus Pool" which have been used before. Thus, maximum utilization of each bus is accomplished for given number of buses.

4. The travel times between all possible generation points are determined from the computed distances and given average travel speed or speed function. The simulation results presented here are based on average travel speed of 20 miles per hour. However, the model can handle individual speed functions for specified links of travel.

Model Operation

1. The "Generate" subroutine generates passenger demands (collection and distribution) with necessary identification information like origin zone no., distination zone no., number of passengers in each demand, absolute clock time of generation, etc.

2. The passenger demand is then separated by sectors and arranged in increasing order of generation time.

3. The model then looks at the demand lists of each sector at specified interval of time (5 sec., 10 sec., 15 sec., 20 sec., 30 sec., etc.) and tests with the maximum headway constraint and dispatch logic. If none of the above two dispatch trigger is satisfied, the model moves to the next increment of time and tests again to investigate whether or not dispatch criteria is met. This operation is done concurrently in all sectors with incrementing the time clock.

As soon a dispatch criteria is satisfied, a bus is dispatched with selected demand list into the specific sector for service.

4. The "Bus Pool" subroutine receives message for bus dispatching and searches for a bus with the lowest serial number and sends it to the warranted destinations.

5. The time of bus dispatch is noted and a time clock is advanced in each bus to keep record of tour time. This time clock considers point to point travel time from the generated travel time matrix and also accumulates embarkation and disembarkation times at each service point. This data is also accumulated to generate bus tour time, percent of time buses in use, number of distribution and collection passengers served.

6. Another module keeps track of individual passenger generation time, time when picked up by a bus, length (time) of travel, time of reaching at destinations, etc. Accumulates waiting times, riding times, total travel times, etc. This module summarizes passenger service data after each bus tour and also compiles summary statistics. The summary statistics also segregates passenger service information hour by hour basis.

Outout of the Simulation Model

The output of the model consists of the following system performance parameters:

1. User Statistics - The simulation of system is performed by the model and all pertinent statistics of the riders are accumulated.

The waiting time at the point of demand, riding time, and total travel time are accumulated by the model and printed for each bus trip. The origin and destination of the riders, their time of generation, waiting time, riding time and total travel time are printed for each bus trip and also for each segment of the service area (refer to Appendix I).

The summary statistics tables consist of "wait time", "ride time" and "total travel time". Wait time is the time difference between the absolute clock time of rider demand generation (time of demand request in the real world situation) and the time when the rider is picked up by a bus. If any passenger has to skip a bus due to capacity constraints, the time of wait until the next bus picks the rider up is also added to the wait time.

Individual wait time of riders are accumulated to determine the distribution of waiting time.

Ride time is the time difference between a rider boarding time and drop off time. This time includes bus running time and embarkation and disembarkation delay on route.

Total travel time is the time from the demand generation to the end of the demand service. Thus, total travel time = wait time + ride time.

These tables are printed for specified time segments and for all sectors (refer to Appen. I). The mean, maximum and frequency over a specified limit is accumulated and printed for all of the above summary statistics. This enables the analyst to take a closer look at the system attributes.

2. Bus Statistics - The bus occupancy, the trip time and the bus utilization are accumulated for the entire simulation period. The first set of output consists of a table for each vehicle indicating each tour, the number of passengers collected, distributed and total tour time.

The summary statistics for the buses consist of one table for each time segment indicating the number of tours performed by each bus, number of passengers collected and distributed, total tour time, mean tour time and bus utilization.

Bus utilization is the percent of time a bus was on the road within the entire period of simulation.

Vehicle productivity is the average number of passengers serviced per vehicle per unit time.

D.2.b. THE TEST SYSTEM

The service area tested in this research composed of 3 sectors with a common activity center. Each sector is one mile square and contains 225 passenger generation points. The roadway pattern assumed to be grid with a radial road in each sector (figure D.Z.b.1).

The variable route systems assumes access to each generation points through the grid network. The fixed route systems follow the route shown in figure D.2.b.1. It is important to mention here, that the fixed route plan used in this study provides a higher level of area coverage than what can be found in real urban environment. The buses follow this fixed pattern for all of their tours and make a total of 20 fixed stops to pick up or drop off passengers. The generated riders are assumed to walk to their nearest stops for service. The walking time is included in the waiting time of the individual passengers.

The passengers are generated at each of the 225 generation points/sector using a random generator. The distribution of passenger arrivals at each point is considered to be poisson, with the mean value being one of the variable tested. The probability of generating a collection demand is used as 0.5. Where the collection demand represents the riders who need to be picked up at their point of generation and dropped off at the activity center. The distribution demands are the passengers who are picked up at the activity center and dropped off at the various destination points within each sector.

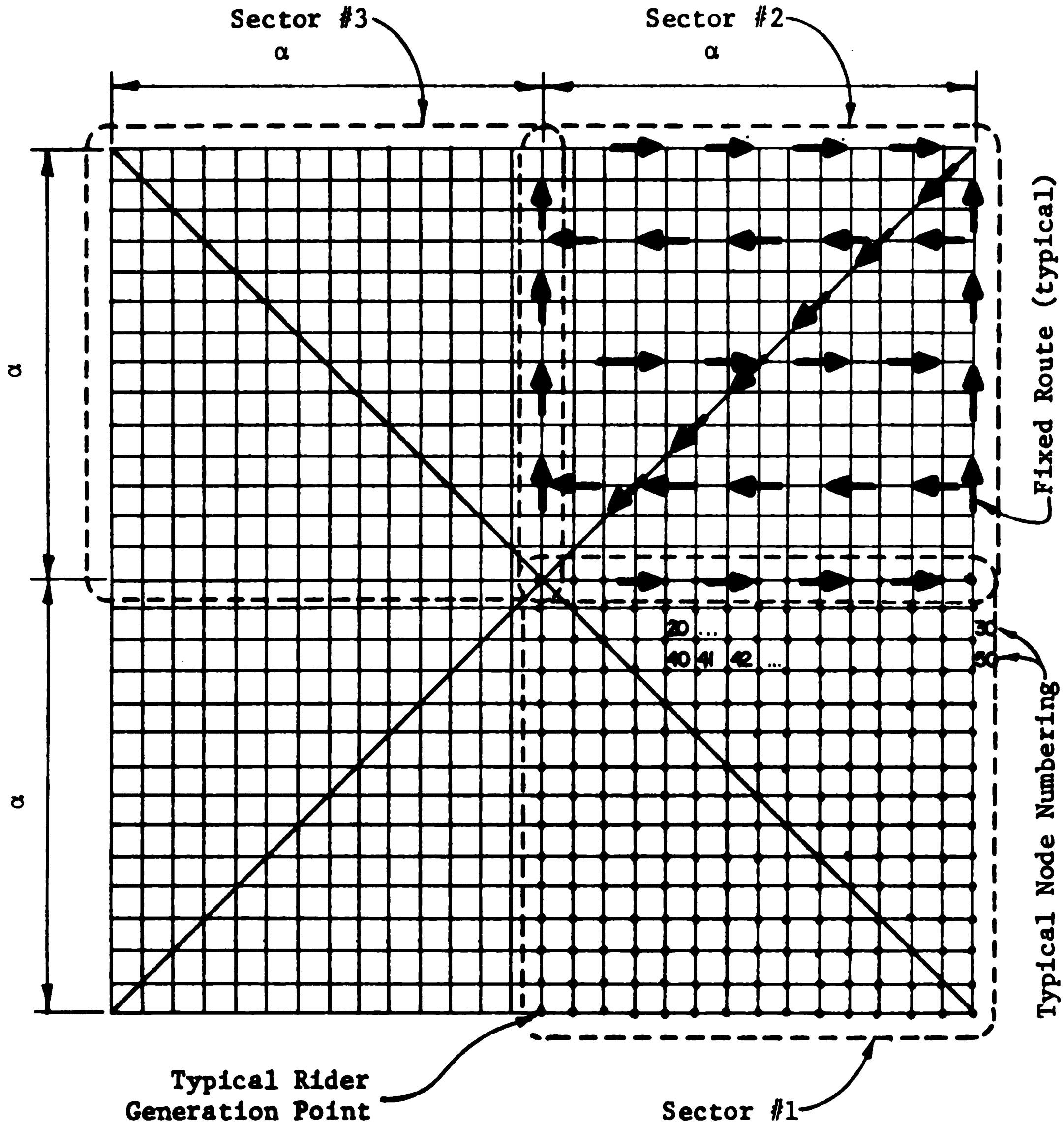


Figure D.2.b.1 Basic Network Configurations

Prior to an analysis of the differences in system performance characteristics produced by the models, validation of the model results is essential. To test this, a comparison was made between the model results over a range of demand densities and actual field experiences, as shown in figure D.2.b.2. As expected, the existing systems perform better than fixed time - fixed route systems considered in the study but not as good as an optimally routed Demand Actuated System. This figure also indicates that the advantages of demand actuation decreases with increasing demand as would be expected.

The results of this study were also compared to the results of the M.I.T. study[1]. There are several differences in the basic conditions assumed in the two studies. The service area in the M.I.T. study was 9 square miles compared to total of 3 square miles for the study. A network expansion coefficient of 1.8 was used to convert the service area of this study into an area of 3.24 square miles per sector.

The mean level of service of the M.I.T. study was set at 2.5. In this study, level of service is an output and thus not controllable. The resultant figure (LOS = 2.26) represents a better service.

Figure D.2.b.3. illustrates the results of one of the most important measures of system performance, system productivity, as a function of demand. Productivity, expressed in trips per hour per

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[1] Roos, Daniel, "Dial-A-Bus Feasibility", H.R.B. Special Report 124.

vehicle, will dictate the economics of the operation. Since the simulation used in this study is non-dynamic, operating expenses will be less even though the service level was higher than that resulting from the M.I.T. study. Some further observations can be made from this comparison:

1. The current simulation is more efficient when measured by vehicle productivity.

2. The increase in productivity of both systems levels off at a demand of 60-80/sq. mile.

3. The non-dynamic simulation in this study produces higher productivity than the dynamic system since the bus waits until a certain number of demands are registered. This eliminates operation during those periods of low demand. Thus, the high values of the productivity from the current study is quite reasonable. However, wait time in a dynamic system is always lower than in the non-dynamic operation.

The differences in productivity for equal levels of demand can be attributed to this difference in operational strategy. The points considered are not sufficient to conclude that the current productivity function will remain higher at all levels of demand.

Table D.2.b.1 Simulated Data for Variable Route-Variable Headway Systems

System Attributes	Demand/hr./sector						
	10	20	30	40	60	80	100
Mean Total Travel Time by Bus	15.59	16.62	14.9	13.94	15.46	15.24	17.33
Mean Ride Time By Bus	6.7	7.67	7.75	7.69	7.96	8.56	9.92
Delay Due To Embarkation And Disembarkation	0.5	0.67	1.05	1.19	1.06	1.26	1.92
A-p. Travel Time By Auto	6.2	7.0	6.70	6.50	6.90	7.30	8.0
Level of Service = $\frac{\text{TTT by Bus}}{\text{TT by Auto}}$	2.51	2.4	2.22	2.15	2.26	2.1	2.17
Vehicle Productivity	11.7	19.33	21.08	20.9	27.24	27.7	26.9

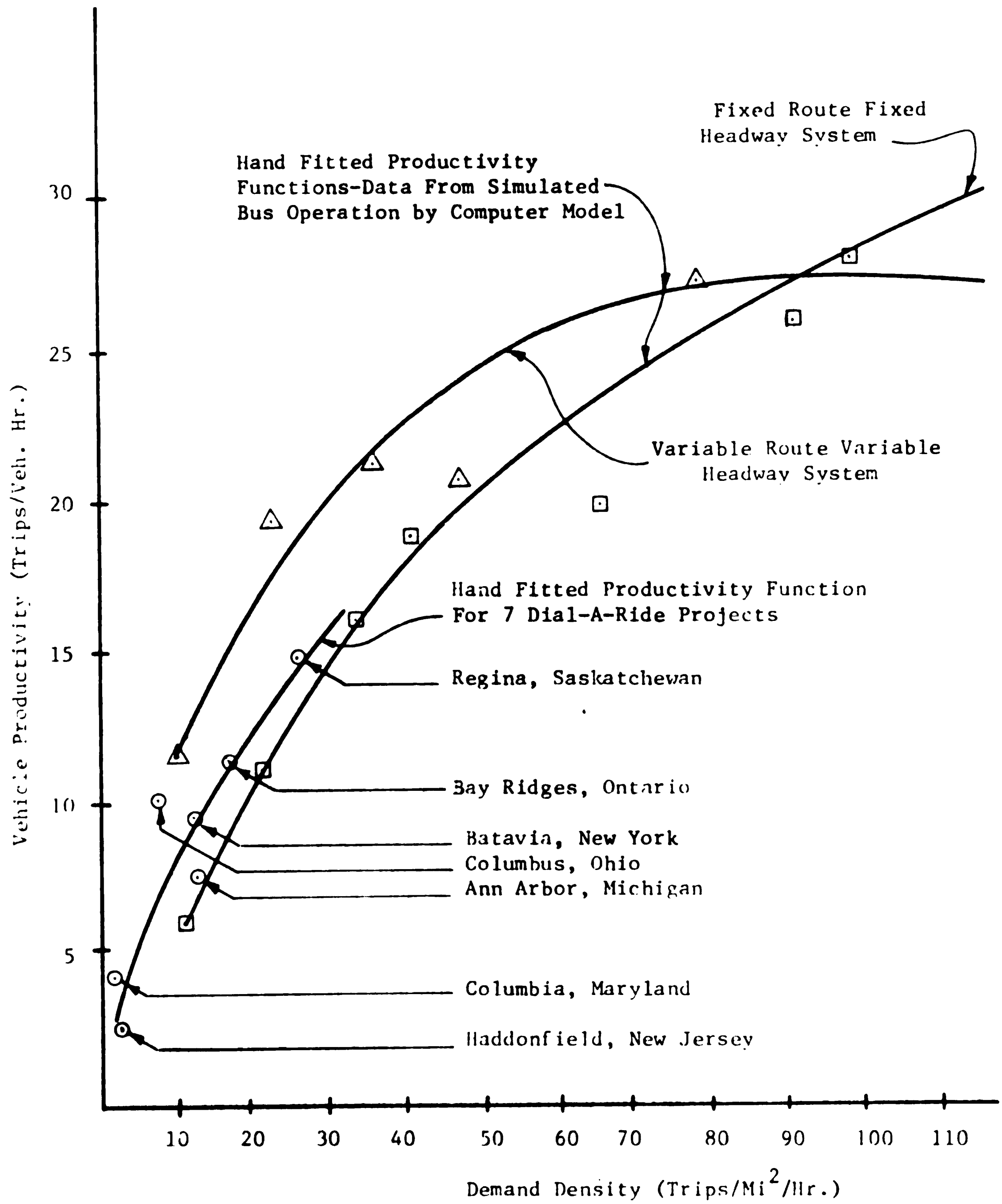


Figure D.2.b.2. Comparison of Simulated Productivity with Operating Systems

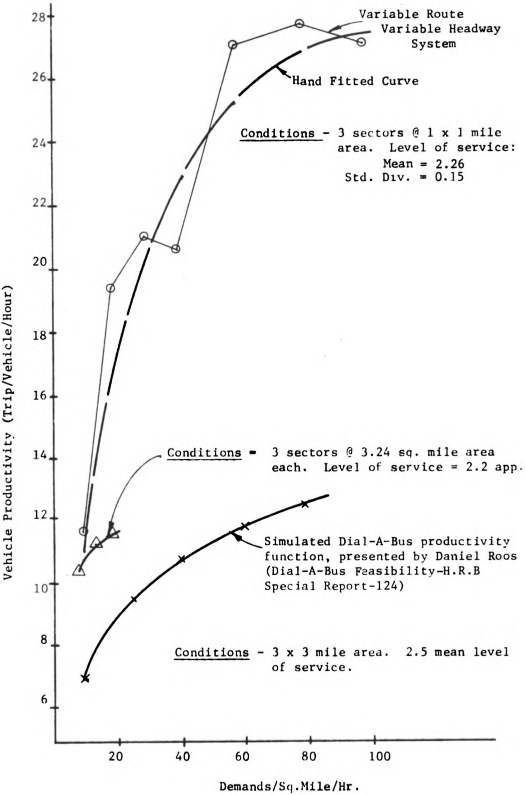


Figure D.2.b.3. Comparison of Simulated Results and M.I.T. Study

E. RESULTS

E.1. SYSTEM PERFORMANCE CHARACTERISTICS

Each of the four systems identified in the previous section were used as the basis for simulation on a fixed data set representing three hours of operation at each of several levels of demand. The demand levels tested in the analysis were: 10, 20, 30, 40, 60, 80 and 100 demands per hour, per sector.

Summary statistics, both user and operator, were collected and compared as a method of establishing system performance. These statistics (refer Tables E.1.1. to E.1.4.) include waiting time, riding time, number of vehicles required and vehicle productivity.

In Figure E.1.1 the average wait time per passenger is plotted against the demand per hour/sector for each system. The variable headway-variable route system provides the lowest wait time for a demand level below 75 per hour per sector. Beyond this level, the fixed route variable headway has the lowest waiting time, although the variable headway variable route system is quite close. At demand levels beyond 60/hr./sector the fixed route fixed headway system has almost the same wait time characteristics as that of the variable route variable headway system. The variable route fixed headway system is clearly not comparable as it results in a much higher waiting time than any other system.

Figure E.1.2 illustrates the ride time characteristics of each system. The variable route variable headway system can reduce riding time in the network for all levels of demand tested. Both the fixed route systems yielded very high ride time, as one might expect.

Table E.1.1 System Performance Data - Fixed Route Fixed Headway

SYSTEM: Fixed Route Fixed Headway
OPERATION STRATEGY: Concurrent collection and Distribution

SYSTEM ATTRIBUTES	Demand/Hr/Sector						
	10	20	30	40	60	80	100
No. of Sectors	3	3	3	3	3	3	3
Total Area (sq. miles)	3	3	3	3	3	3	3
Simulation Period (hrs)	3	3	3	3	3	3	3
Network Configuration	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Dispatch Logic (No. of pex)	35	40	40	40	40	40	40
Headway (mins)	15	15	15	15	10	10	10
Total Passengers Served*	91	198	318	374	613	827	1168
Total No. of Buses Reqd.	8	9	9	9	13	14	15
Mean Waiting Time (mins)	10.98	9.84	9.86	10.34	7.6	7.42	7.77
Mean Ride Time	16.8	18.00	18.50	19.31	18.98	19.56	20.17
Mean Total Travel Time	27.78	27.84	28.36	26.95	26.58	26.98	27.94
Total Driver Hrs. Reqd.	30	32	34	34	50	52	55
Vehicle Productivity	6	11.04	16.13	18.64	19.77	25.65	34.25
Mean Bus Utilization	51%	56%	58%	59%	62%	62%	62%
Total Vehicle Hrs. of Operation	15.29	17.92	19.72	20.06	31.0	32.24	34.1

*Total number of passengers for 3 hours of simulation.

Table E.1.2. System Performance Data - Fixed Route Variable Headway

SYSTEM: FIXED ROUTE VARIABLE HEADWAY
OPERATION STRATEGY: CONCURRENT COLLECTION AND DISTRIBUTION

SYSTEM ATTRIBUTES	Demand/Hr/Sector						
	10	20	30	40	60	80	100
No. of Sectors	3	3	3	3	3	3	3
Total Area (sq. miles)	3	3	3	3	3	3	3
Simulation Period (hrs)	3	3	3	3	3	3	3
Network Configuration	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Disptach Logic (No. of pax)	3	5	5	5	5	5	5
Headway (mins)	15	15	15	15	10	10	10
Total Passengers Served *	91	199	320	388	628	845	1079
Total No. of Buses Reqd.	9	11	12	14	19	25	30
Mean Waiting Time (mins)	8.6	8.74	8.68	7.49	5.4	5.65	4.26
Mean Ride Time (mins)	14.68	18.18	17.96	18.75	18.5	17.89	17.67
Mean Total Travel Time (mins)	23.28	26.92	26.64	26.24	23.9	23.54	21.93
Total Driver Hrs. Reqd.	30	36	42	49	74	91	122
Vehicle Productivity (no. of pax/hr/veh)	4.8	5.5	7.6	7.9	8.5	9.3	9.63
Mean Bus Utilization	63%	54%	58%	56%	62%	63%	61%
Total Vehicle Hrs. of Operation	18.98	19.44	24.36	27.44	45.88	57.33	68.35

*Total number of passengers for 3 hours of simulation.

Table E.1.3 System Performance Data - Variable Route Fixed Headway

SYSTEM: Variable Route Fixed Headway
OPERATION STRATEGY: Concurrent Collection & Distribution

SYSTEM ATTRIBUTES	Demand/Hr./Sector						
	10	20	30	40	60	80	100
No. of Sectors	3	3	3	3	3	3	3
Total Area (sq. Miles)	3	3	3	3	3	3	3
Simulation Period (hrs)	33	3	3	3	3	3	3
Network Configuration	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Dispatch Logic (no. of pax)	35	20	20	20	40	40	40
Headway (mins.)	15	15	15	15	10	10	10
Total Passengers Served *	91	208	309	459	684	867	1101
Total No. of Buses Reqd.	4	6	6	6	9	9	10
Mean Waiting Time (mins.)	12.23	12.87	13.41	13.48	11.52	13.2	16.02
Mean Ride Time (mins.)	8.17	8.02	9.38	10.89	12.48	13.13	13.63
Mean Total Travel Time (mins.)	20.4	20.89	22.79	24.37	24.00	26.34	29.65
Total Drive Hours Reqd.	14	20	21	23	33	34	40
Vehicle Productivity (no. of pax/hr./veh.)	14.4	25.36	31.98	37.65	38.38	43.22	45.88
Mean Bus Utilization	45%	41%	46%	53%	54%	59%	66%
Total Vehicle Hours of Operation	6.31	8.2	9.66	12.19	17.82	20.06	24

*Total number of passengers for 3 hours of simulation.

Table E.1.4 System Performance Data - Variable Route Variable Headway

SYSTEM: Variable Route Variable Headway
OPERATION STRATEGY: Concurrent Collection & Distribution

SYSTEM ATTRIBUTES	Demand/Hr./Sector						
	10	20	30	40	60	80	100
No. of Sectors	3	3	3	3	3	3	3
Total Area (sq. miles)	3	3	3	3	3	3	3
Network Configuration	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Dispatch Logic (no. of pax)	3	5	5	5	5	5	5
Headway (mins.)	15	15	15	15	10	10	10
Total Passengers Served *	91	214	324	432	717	893	1115
Total No. of Buses Reqd.	5	9	9	11	15	15	15
Mean Wait Time (mins.)	8.89	8.95	7.15	6.25	7.5	6.68	7.41
Mean Ride Time (mins.)	6.7	7.67	7.75	7.69	7.96	8.56	9.92
Mean Total Travel Time (mins.)	15.59	16.62	14.9	13.94	15.46	15.24	17.33
Total Driver Hours of Operation Reqd.	15	27	29	39	47	52	60
Vehicle Productivity No. of pax/hr./veh.	11.7	19.33	21.08	20.9	27.24	27.7	26.9
Mean Bus Utilization	52%	41%	53%	53%	56%	62%	69%
Total Vehicle Hours of Operation	7.76	11.07	15.37	20.67	26.32	32.24	41.4

*Total number of passengers for 3 hours of simulation.

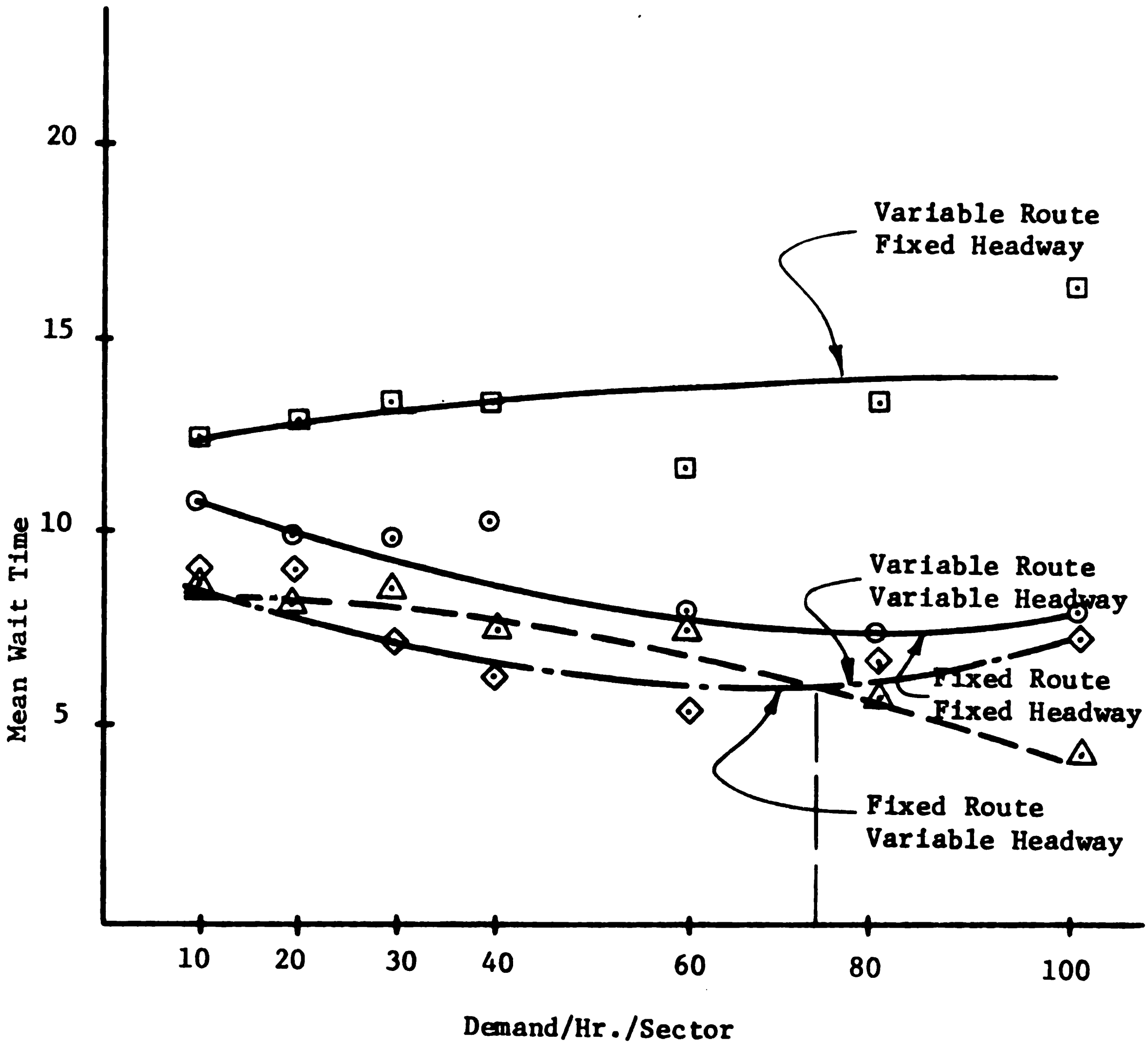
There is no single system that provides the optimal value of each characteristics at all demand levels. However, if the two recorded times are added to obtain total travel time the variable route variable headway system yields the lowest total travel time at all tested levels of demand.

Figure E.1.4 shows that the variable route fixed headway operation yields the highest vehicle productivity for all levels of demand. The variable route variable headway system produces a higher productivity than either fixed route system for demand levels below 80 per hour. Beyond this point the fixed route fixed headway system shows higher productivity.

Figure E.1.3 shows the total number of buses required for each system investigated in this study. Since this measure is inversely related to productivity the variable route fixed headway system has the lowest vehicle requirement for all levels of demand. A similar result is shown if we look at the "Driver Hours" requirement for each system as shown in Figure E.1.5. . Again, the "variable route fixed headway" operation results in the lowest driver hour requirements for all levels of demand. The variable headway operation has a driver requirement lower than the fixed route fixed headway system in the low demand levels, but becomes nearly coincident with the fixed route fixed headway system for higher demands.

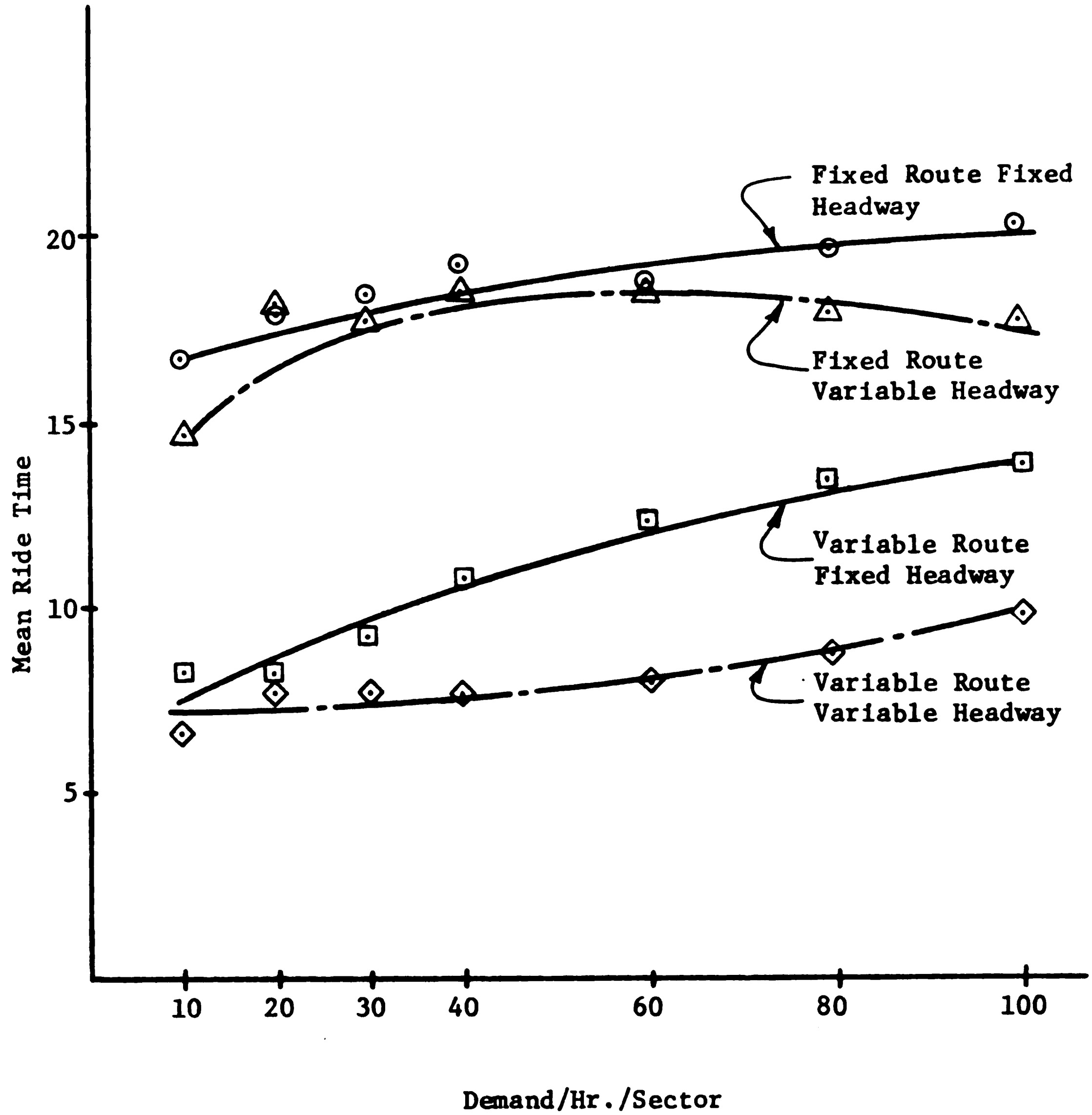
A final statistical measure "vehicle hours of operation" is plotted for various demand levels in figure E.1.6. The variable route fixed headway operation produces the lowest vehicle hours of operation among the systems. The variable route variable headway operation has a lower vehicle hour requirement than fixed time fixed route system up to the demand of 65/hr./sector.

These curves cross at a different demand level than in the driver hour statistic because the variable route variable headway system is a more efficient system when measured by bus utilization. Therefore, there are fewer idle hours for the bus driver while waiting for their run to start.



Total Area of Operation = 3 Square Miles

Figure E.1.1 Systems Performance Functions - Wait Time



Total Area of Operation = 3 Square Mile

Figure E.1.2 Systems Performance Functions - Ride Time

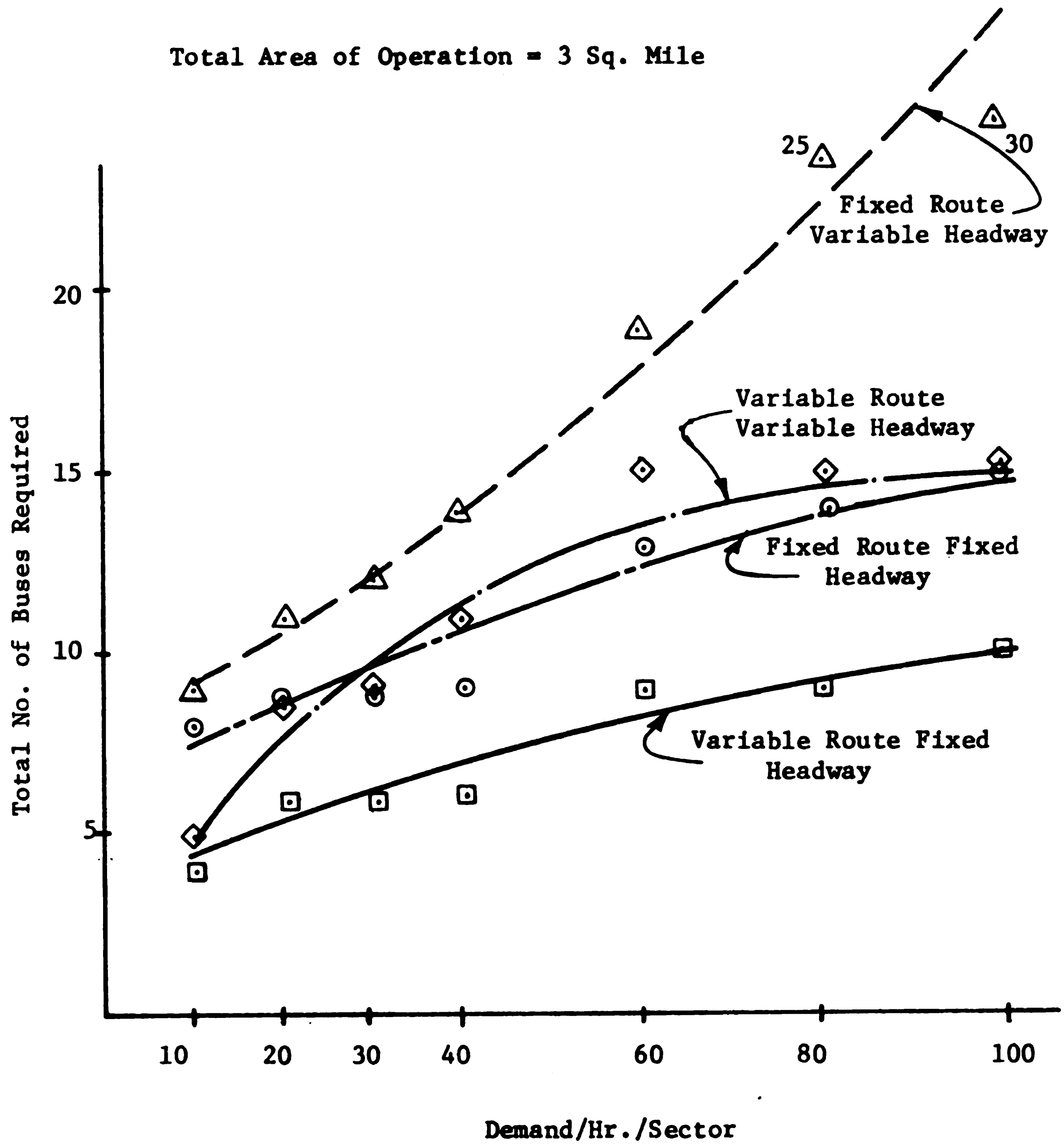


Figure E.1.3 Systems Performance Functions - Bus Requirements

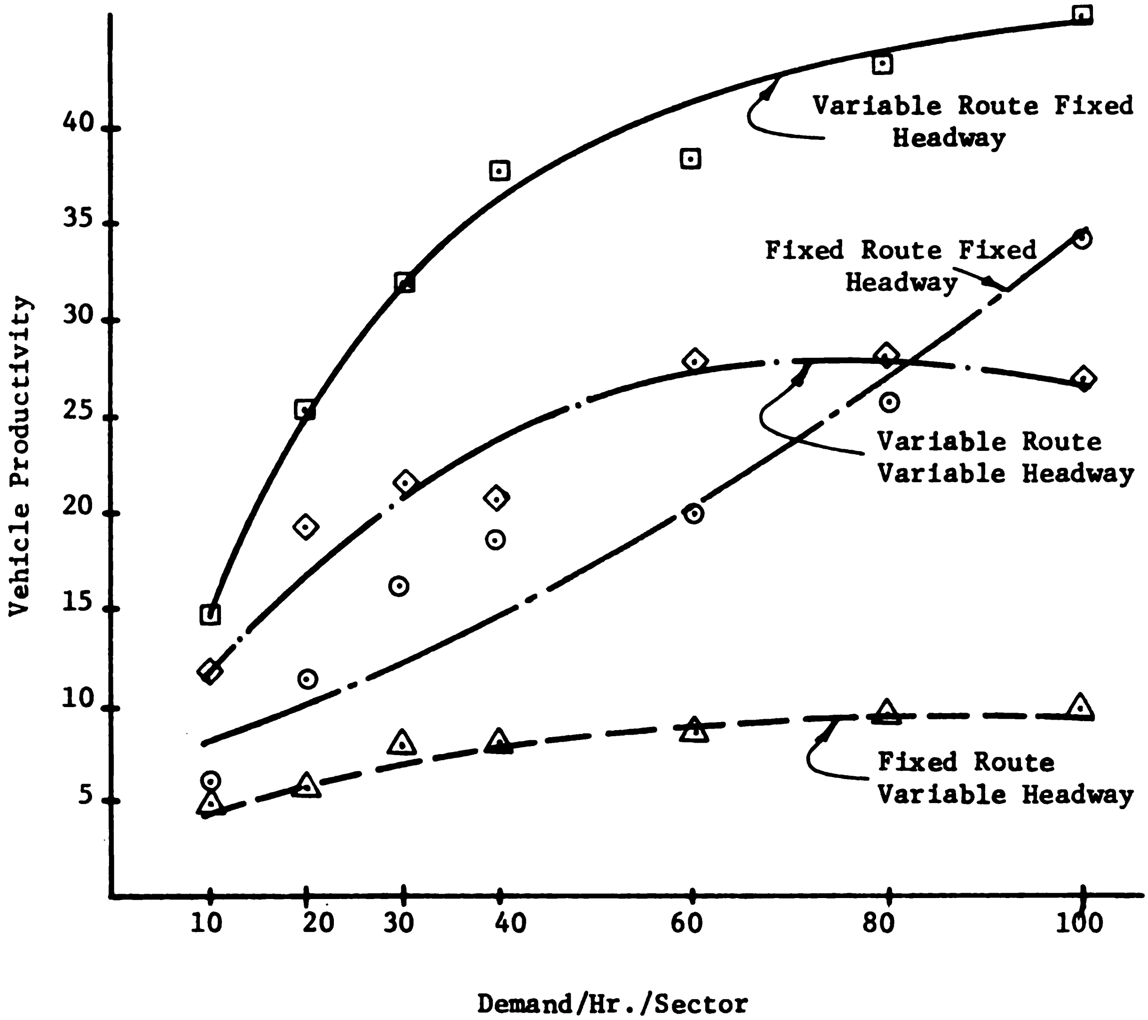
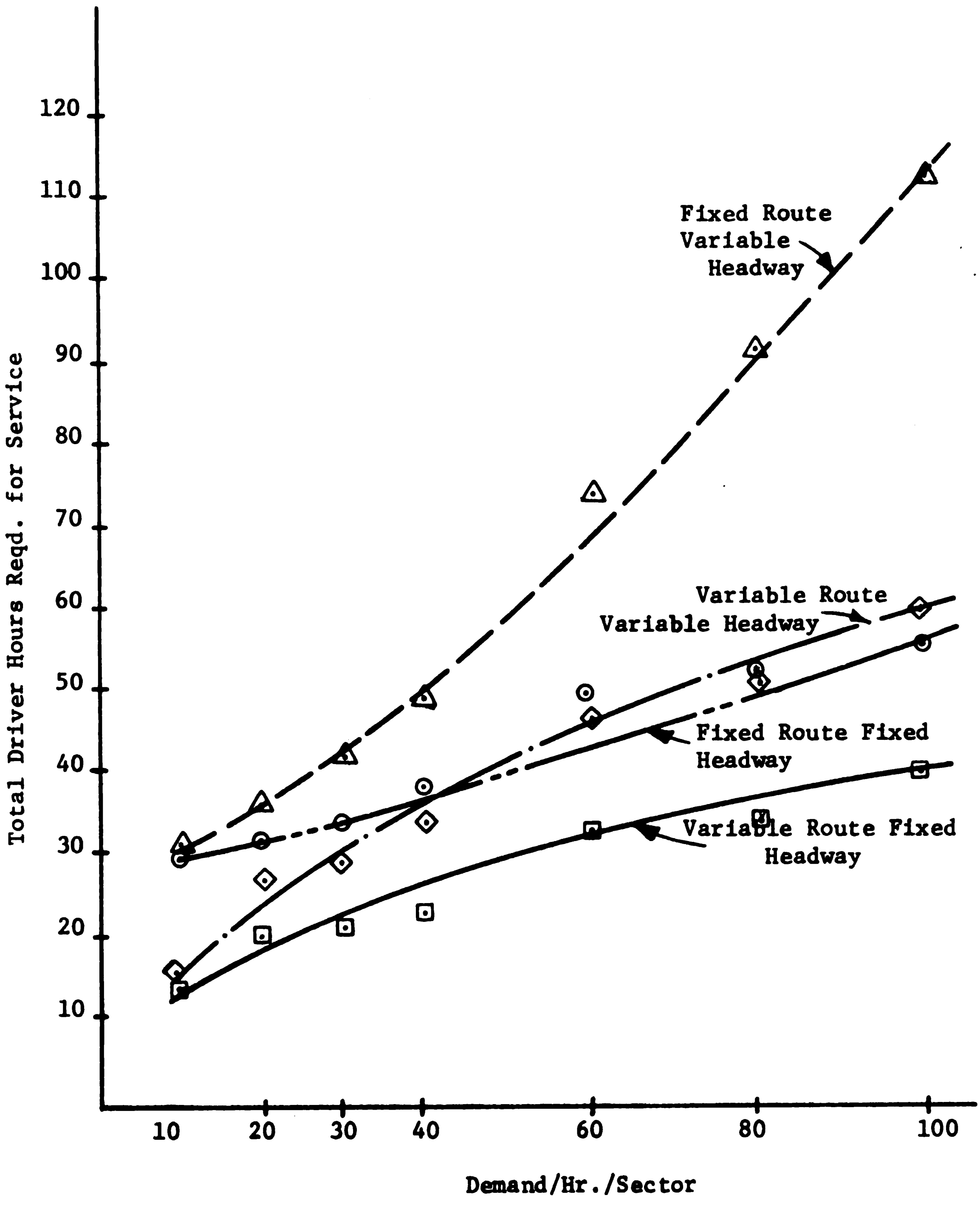
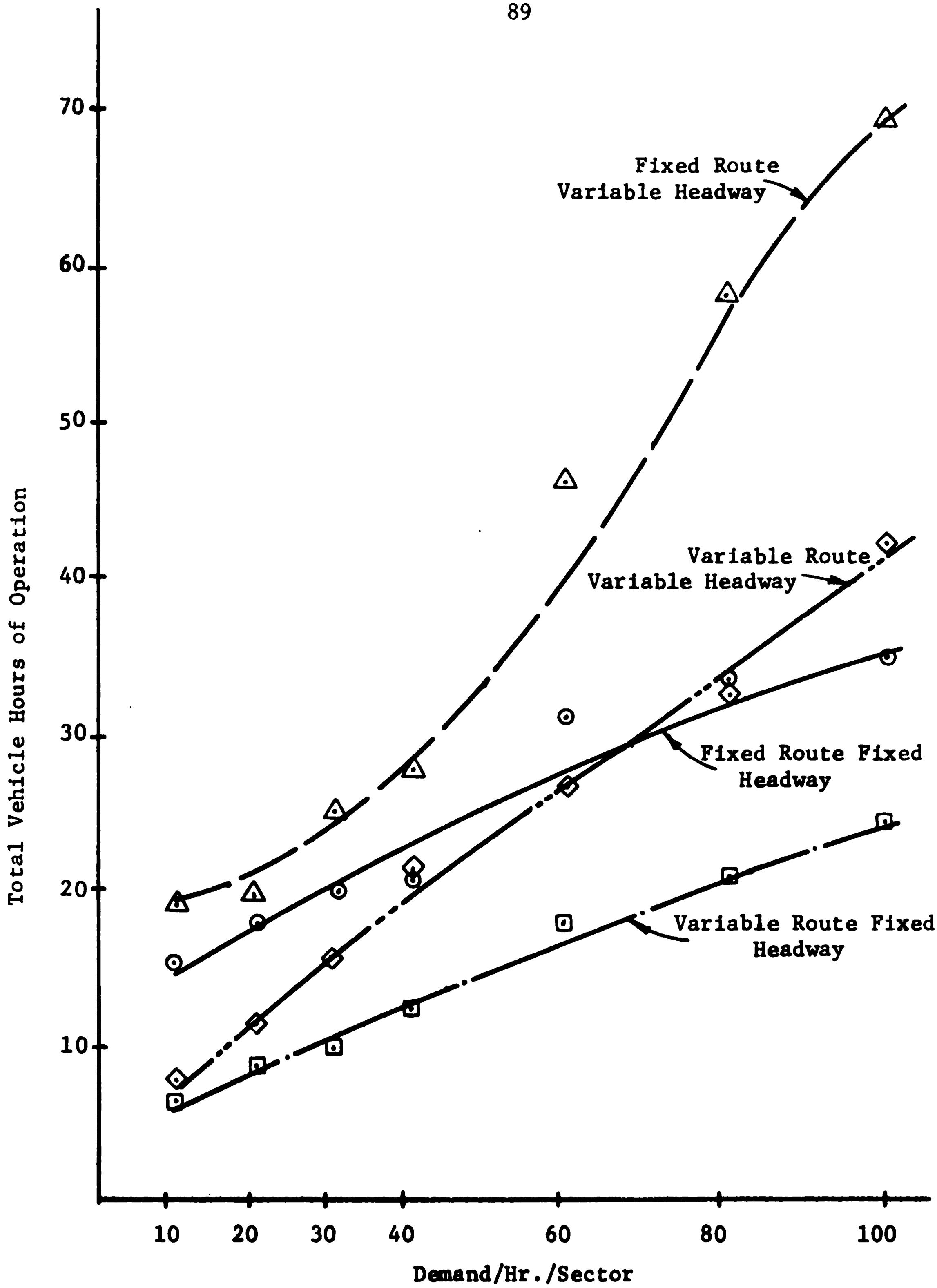


Figure E.1.4 Systems Performance Functions - Vehicle Productivity



Total Area of Operation ≐ 3 Sq. Mile

Figure E.1.5. System Performance Functions - Driver Hours Required



Total Area of Operation = 3 Sq. Mile

Figure E.1.6 Systems Performance Functions - Total Vehicle Hours of Operation

E.2. SYSTEM EVALUATION AND SELECTION

The primary objective of this study was to develop a comprehensive model which can generate data to assist in the selection of demand actuated bus system alternatives. If one were to make the very simple assumption that demand, service, and operating costs are all non-elastic, then the curves shown in the preceding section would suffice.

The bus manager attempting to operate a bus system for profit could survey the demand and select the system with the lowest product of vehicle operating time multiplied by his cost per hour and the capital cost of required buses amoritized over their life span. The cost of this bus service could then be compared with a feasible fare and a decision made.

Similarly, if it were appropriate to consider public transportation as a public service, a specified level of service as measured by waiting time and ride time statistic could be established, and the system that meets these criteria for the projected demand selected. The appropriation required for the service could be determined from the bus statistics, and a decision reached by the appropriate body.

There is sufficient evidence, however, to reject this assumption of a non-elastic market. The structure of existing trip generation and modal split models used in transportation planning include a dependent relationship between demand, service and cost.

Thus, the problem is not that simple, even if the data are known.

From the preceding graphs, it is obvious a trade-off must be made between the user's performance characteristics (wait time, ride time, total travel time) and the transit operating charcteristics (number of buses, vehicle hours of operation, vehicle productivity, bus utilization). The use of constant unit cost figures for each of these characteristics is unrealistic, as they vary with location and in many cases are quite subjective.

The value of these system attributes depends largely on the goals and policies of the community for which the transit system is being planned. In economic analysis, where the trade-off between intangible and tangible costs need to be established, it is common practice to use a value scale for both items. This value scale varies depending on the goals of the environment and is often referred to as a utility scale with system alternatives selected on the basis of their score, or utility function.

Whether the simple benefit-cost analysis or the more complex utility analysis is preferred by the analyst, there are two common factors in all evaluation techniques:

1. A scaling factor representing the "value" of an incremental change in each of the significant measures of performance (Vi).

2. A quantitative representation of the change in the magnitude (Xi).

The evaluation models can combine these factors in an additive, multiplicative, or exponential manner. They can be linear or non-linear, independent or interdependent and time independent or time dependent.

This modeling represents an entire area of study and is beyond the scope of this paper. However, for the purpose of demonstrating the applicability of these model outputs to the evaluation process, a simple, additive, linear type model is assumed. The scaling factors (Vi) are also assumed, but variations in these values are tested to demonstrate user-oriented, operator-oriented, and system-oriented assumptions.

The model structure used is:

Utility (U_j) = f (system performance data, policies)

$$U_j = V_1 x_1 + V_2 x_2 + V_3 x_3 + \ldots + V_n x_n$$

Where x_i = The score of a selected system performance parameter

V_i = Value coefficient selected in accordance with the goals and policies

The following variables have been selected to demonstrate the applicability of the methodology of utility cost functions for system alternatives in the selection procedure.

X1 = Mean wait time/passenger

X2 = Mean ride time/passenger

X3 = Driver hours required for service

X4 = Total vehicle hours of operation

V1 = Value coefficient for mean wait time

V2 = Value coefficient for mean ride time

V3 = Value coefficient for driver hours required for service

V4 = Value coefficient for vehicle hours

Since these parameters all become increasingly undesirable with increasing scores, this model defines the disutility or utility cost ($U_j = V_1x_1 + V_2x_2 + V_3x_3 + V_4x_4$) of each system.

Selection of high value coefficients for variables x_1 and x_2 (i.e. mean wait and ride time) will result in the selection of a service oriented operation where passenger service criteria are quite stringent and the non-monetary benefits of mass transportation given high weights compared to the monetary costs of operation.

High value coefficients for variable x_3 and x_4 (i.e. driver hours required and vehicle hours of operation) will lead to the selection of low cost operation with greater emphasis on tangible costs than user benefits.

The methodology presented here does not suggest any specific values for these coefficients, but merely demonstrates a procedure which could be used in evaluating alternative systems.

Figure E.2.1 shows the utility cost plotted against demand density for all four systems where the utility coefficients are all equal to 1.0 or there is no bias between user values and operator values.

At a very low demand density (10/hr) the variable route-variable headway operation results in the lowest utility cost. As the demand increases, variable route fixed headway operation results in the lowest cost system for demand in excess of(20/hr). The fixed route fixed headway operation which results in a high cost at low demand approaches the variable route variable headway system at approximately (100/hr) demand.

It appears that for low demand situations characteristics of Columbia, Maryland or Haddonfield, New Jersey, the variable route variable headway system should be selected if the user and the operators characteristics are considered to be equally important.

Figure E.2.2 indicates the utility cost function for value coefficients V_1 and V_2 equal to 1, and V_3 and V_4 equal to 3.0. This might be representative of a system with a limited subsidy. In this case, some increase in user costs would be accepted in return for lower operating costs.

As a result of this change in the weighting functions, the total user time increased from 15.6 to 20.4 minutes at a demand level of 10/hr, while vehicle hours of operation was reduced by 18.6% from 7.76 to 6.31 hours. We are equating this 5 minutes of extra travel time to 1.2 hours reduction in bus hours.

At the other extreme, figure E.2.3 represents a case in which the user characteristics are weighted very heavily. This might be characteristics of a highly subsidized service for a model city neighborhood, in which service is the important factor to be considered. The operating characteristics of the variable route variable headway system are far superior to any other system at all

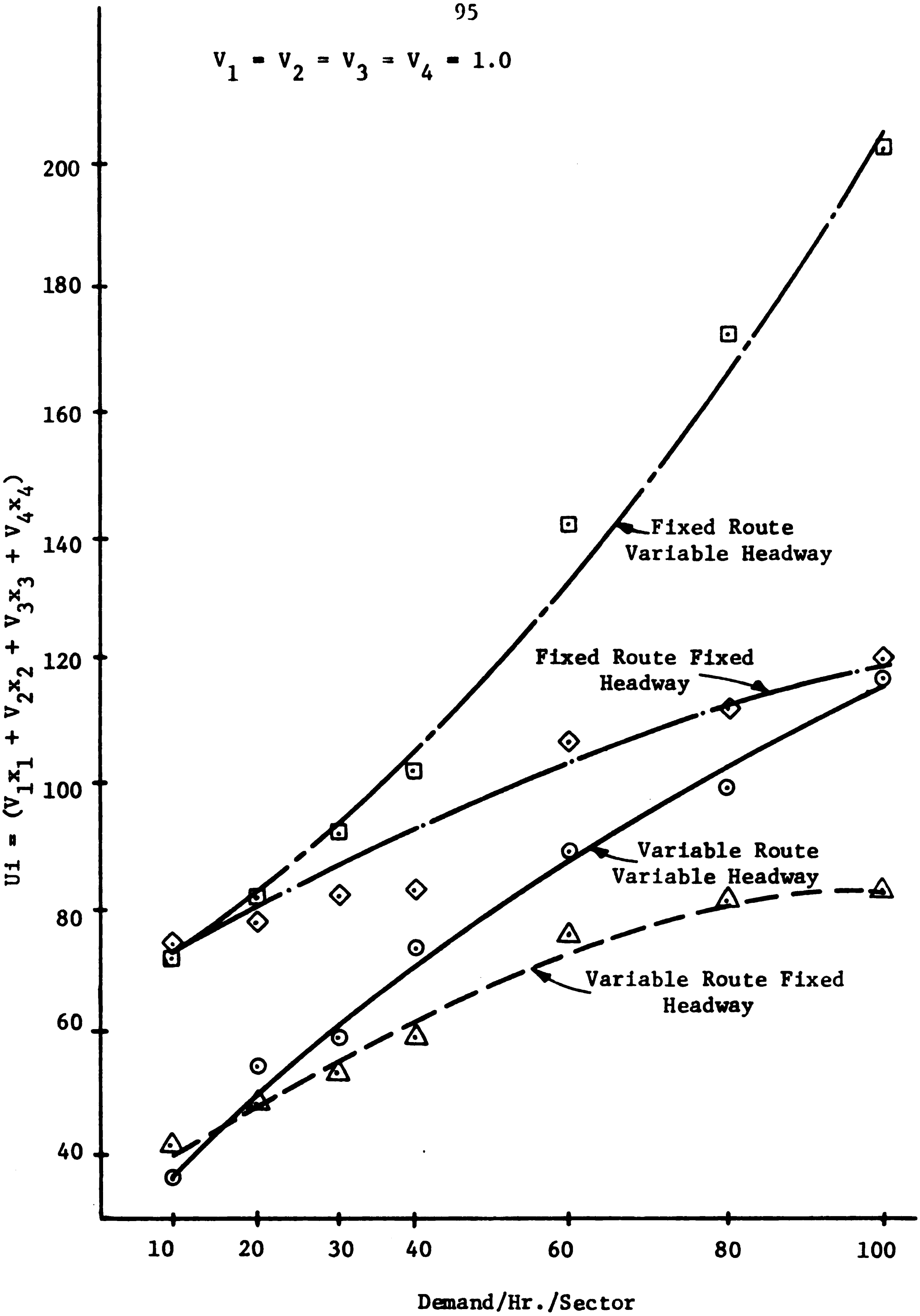


Figure E.2.1 Utility Cost Functions

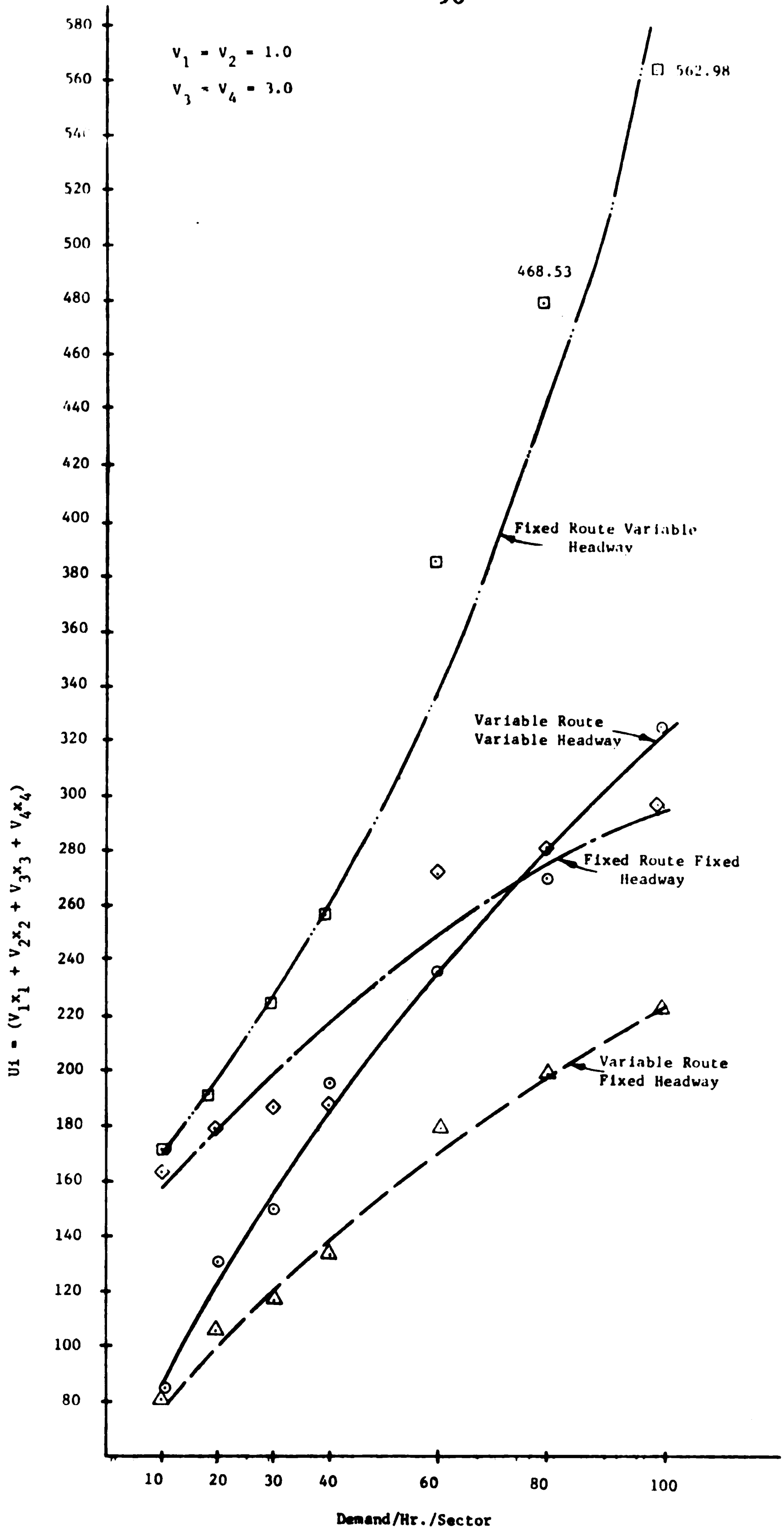


Figure E.2.2. Utility Cost Functions

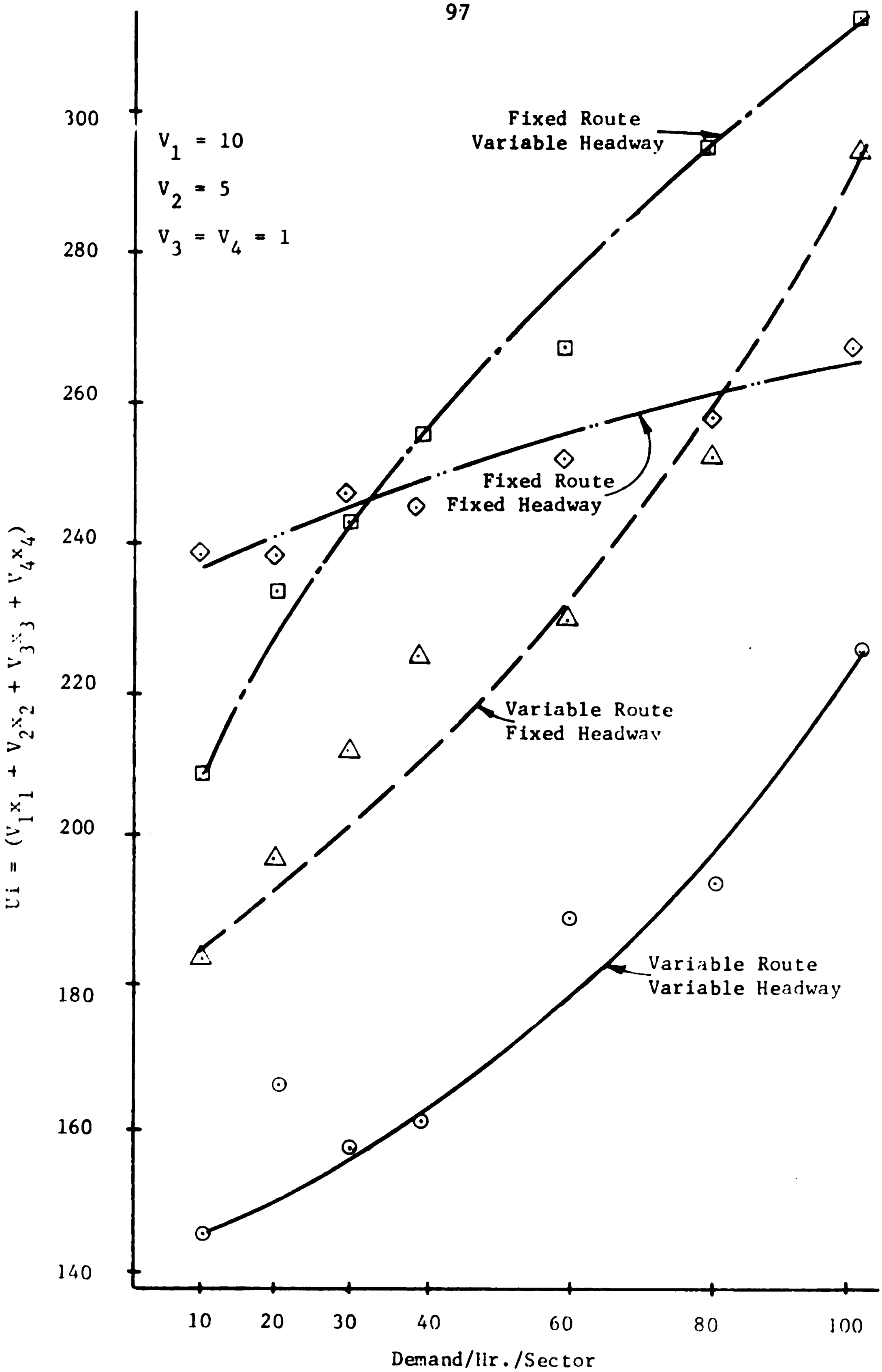


Figure E.2.3. Utility Cost Functions

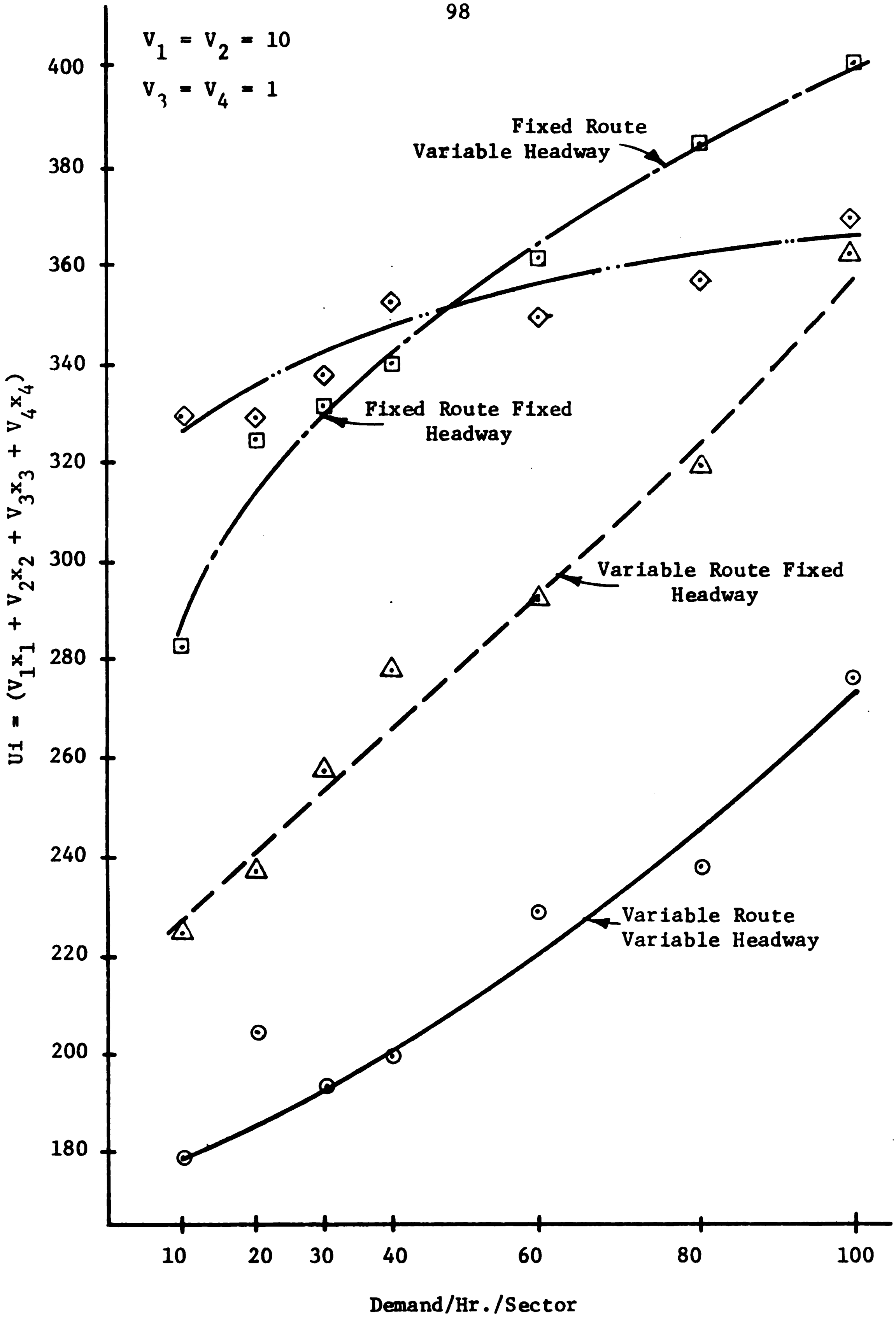


Figure E.2.4. Utility Cost Functions

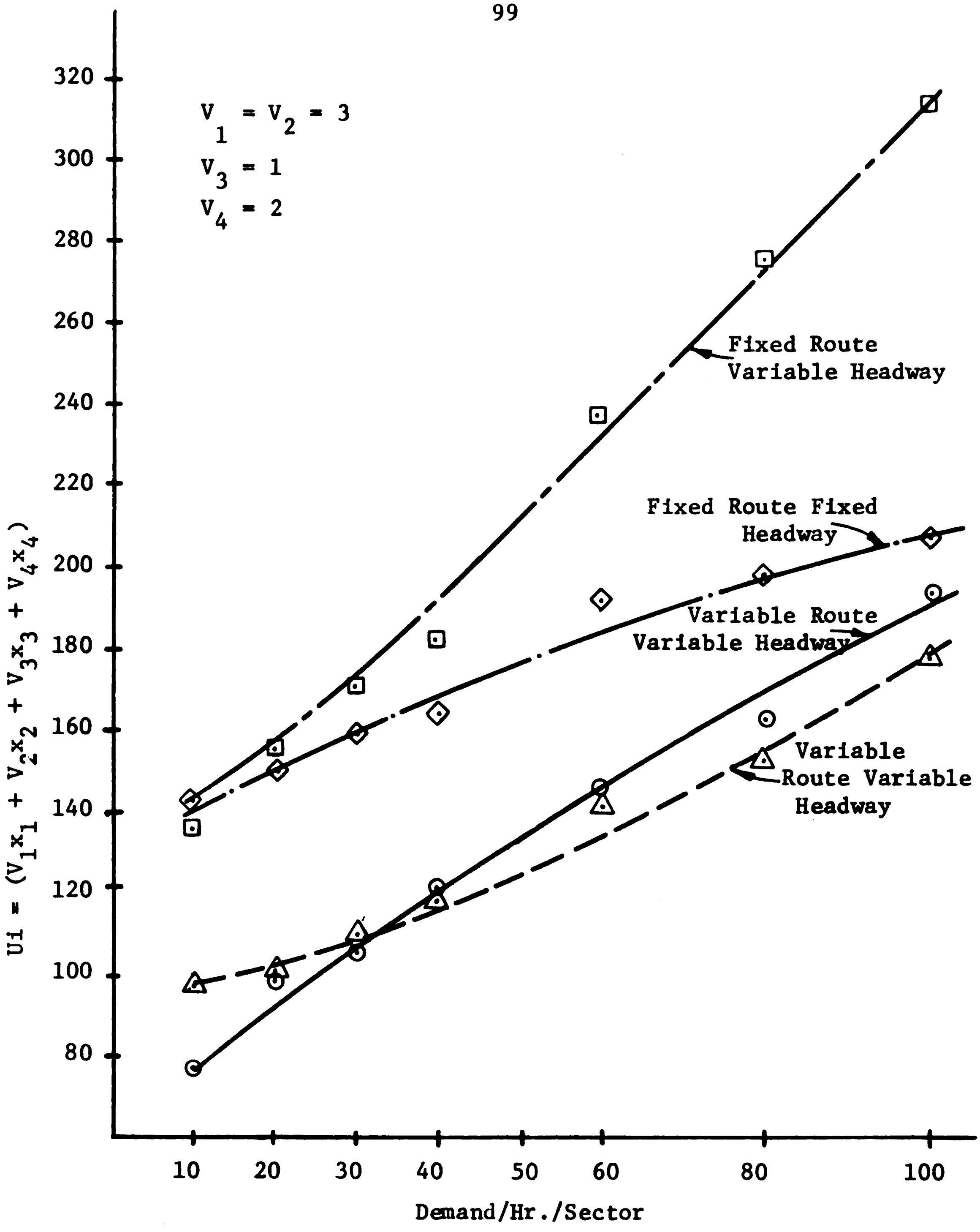


Figure E.2.5. Utility Cost Functions

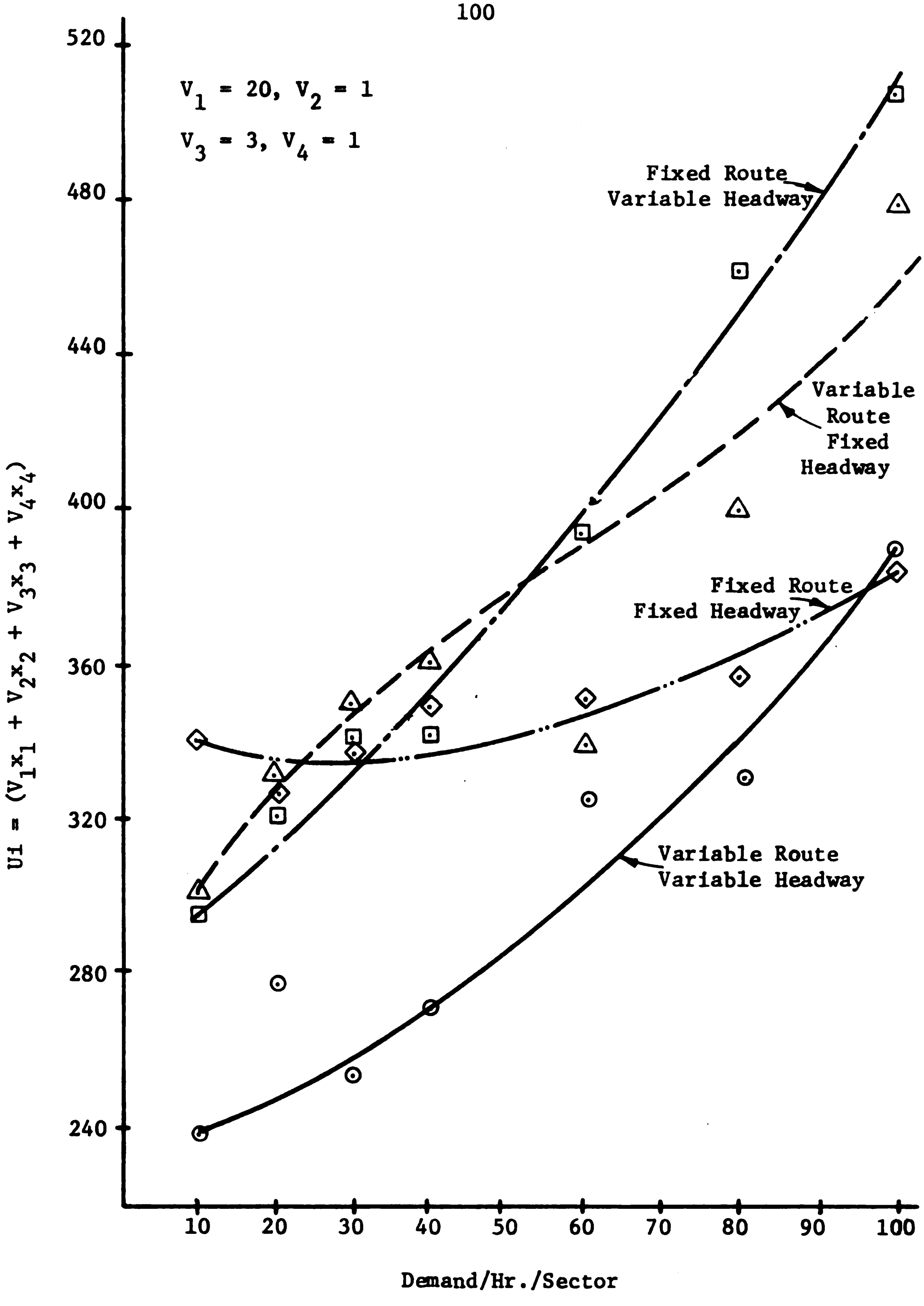


Figure E.2.6. Utility Cost Functions

levels of demand. Comparing this operation with the normal operation (fixed route-fixed headway) at a demand level of 100/hr., savings in total travel time is 51% with a penalty of 17% in operating hours.

In addition to system selection policies, the analyst is also faced with the task of recommending operating policies. In this study variations in system characteristics and utility costs as they are implemented by different bus pooling policies, vehicle to sector assignment policies, sector size and network accessability factors and variations in demand over-time, were also investigated and results are presented in the subsequent sections.

The demand for bus transit ridership in any area varies with time, it is extremely important that such variations in demand be considered in the system selection process. As it was shown previously, the demand at which any system becomes "better" than other systems depends on the value coefficients. Thus, different systems can be optimal at different times during a typical day's bus operation. To demonstrate the effect of changes in operating system alternatives, a hypothetical passenger demand distribution (figure E.2.7.) has been assumed. Using the same decision variables; wait time, ride time, vehicle hours of operation and driver hours required and the value coefficient as in figure E.2.2.: $V_1 = V_2 = 1.0$;

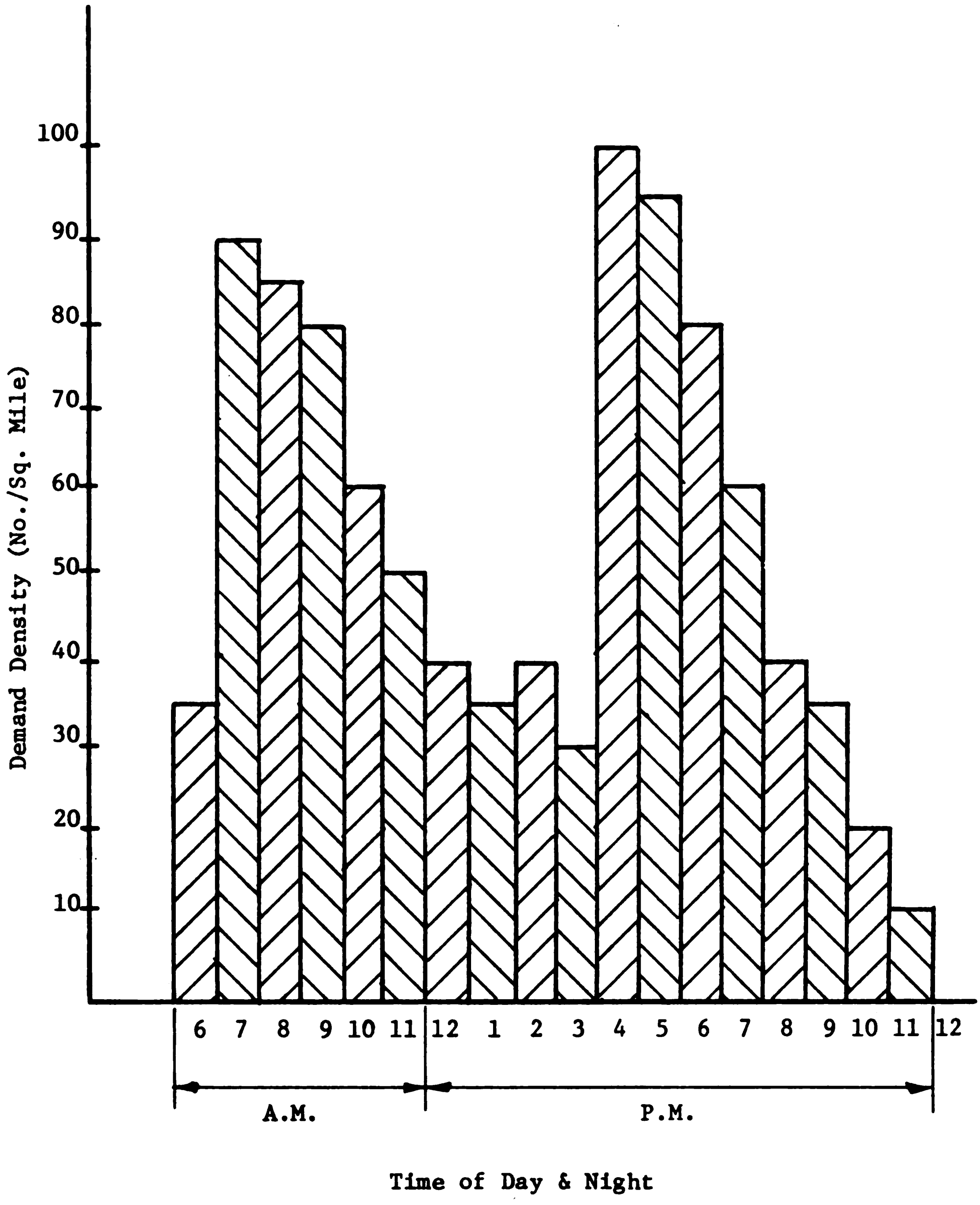


Figure E.2.7. Typical Distribution of Rider Demand

Table E.2.1. Utility Costs of Alternative Systems

Time of Day	Demand Rate (Nos./Sq. Mile)	Utility Cost of System: Variable Route Variable Headway (non-dynamic)	Utility Cost of System: Fixed Route Fixed Headway
6-7 AM	35	* 170	208
7-8 AM	90	298	* 282
8-9 AM	85	284	* 275
9-10 AM	80	276	* 272
10-11 AM	60	* 232	248
11-12 Noon	50	* 210	233
12-1 PM	40	* 182	217
1-2 PM	35	* 170	208
2-3 PM	40	* 182	217
3-4 PM	30	* 155	198
4-5 PM	100	318	* 292
5-6 PM	95	308	* 282
6-7 PM	80	376	* 272
7-8 PM	60	* 232	248
8-9 PM	40	* 182	217
9-10 PM	35	* 170	208
10-11 PM	20	* 121	178
11-12 PM	10	* 83	163

$V_3 = V_4 = 3.0$ and plotting the utility cost versus demand density, the utility costs of two alternative systems (variable route-variable headway and fixed route-fixed headway) for hourly variations in demand were constructed. Then, reading the cost functions from these curves, Table E.2.1. was developed which shows the time, demand and utility cost of the two alternative systems. The cost entries preceeded by an asterik indicate the optimal system for that hour. With this information, 3 different alternative operating strategies were compared.

1. Variable route variable headway operation for entire period.
2. Fixed route fixed headway operation for entire period.
3. Combination of the above two systems to achieve minimum total cost.

Table E.2.2. Costs of Various Operating Policies

Operating Policy	Total System Cost	% Inefficient
A. Single System - Variable Route Variable Headway	3849	3
B. Single System - Fixed Route Fixed Headway	4218	12
C. Mixed System - Combination of two	3754	

This example only serves to illustrate how the results of this study might be used. It is important to point out that the difference in cost saving or magnitude of system efficiency can be quite significant in some cases. This depends on the value coefficients selected for evaluation purposes (which really reflect the goals and policies of the community) and the magnitude of the variations in demand.

Other policies, like bus pooling, sector selection, guaranteed pick-up time, dispatching logic and level-of-service provided will also influence these numbers. The approach used in this study provides the tools necessary to assess each of these and bring a little more rationale in the system selection process.

E.3. POOLING POLICY

Since the bus utilization factor for the highest numbered bus assigned in all of the previous examples is low, it is possible that serving several sectors from a single bus pool may be more efficient. To test this hypothesis, the variable route variable headway simulation model was executed for multiple sector assignment.

Three separate policies; single sector, double sector and triple sector were tested for a range of demands to determine the effect on bus utilization as well as the other user and operator characteristics. The results are indicated in tables E.3.1., E.3.2 and E.3.3. and shown in figures E.3.1. through E.3.4.

As shown in figures E.3.1. and E.3.2., there is little difference in the user statistics of mean wait time and mean ride time as expected. The dispatch logic was not altered and thus the effect on the user should be minimal.

The single sector assignment policy consistently requires higher driver hours and vehicle hours of operation for all levels of demand as shown in figures E.3.3. and E.3.4.. These performance indicators, which are most directly related to operator costs, illustrate that multiple sector assignment is definitely a better pooling strategy than fixed vehicle to sector assignment.

The impact of a multiple sector pooling policy can best be illustrated in the context of the utility analysis. The combination of $V_1 = V_2 = 1$; $V_3 = V_4 = 3$ used in the previous analysis was used for this purpose and is shown in figure E.3.5.

Table E.3.1. System Performance Data - Pooling Policy

SYSTEM: Variable Route Variable Headway
OP.RATION STRATEGY: Concurrent Collect & Distribution

SYSTEM ATTRIBUTES	1 Sector Served from 1 Bus Pool					
	Demand/Hr./Sector					
	20	30	40	60	80	100
Area/Sector (sq. miles)	1	1	1	1	1	1
Avg. Waiting Time per Passenger	8.53	7.6	6.54	5.92	5.12	5.07
Avg. Ride Time per Passenger	6.45	6.86	7.85	6.96	7.5	7.53
Total Travel Time (exp.)	14.98	14.46	14.39	12.88	12.62	12.6
Total Pass. * Served/Sector	84	119	147	223	295	364
Max. No. of Buses Reqd./ Sector (avg. for multi sector strategy)	3	4	4	7	8	9
Avg. Driver Hours of Operation/ Sector	10	13	15	22	28	32
Avg. Vehicle Hours of Oper-ation/Sector	4.1	6.1	7.25	9.15	11.32	14.53
Vehicle Productivity	20.5	19.5	20.28	24.37	26.06	25.05

*Total number of passengers for 3 hours of simulation.

Table E.3.2. System Performance Data - Pooling Policy

<u>SYSTEM</u>: Variable Route Variable Headway
<u>OPERATION STRATEGY</u>: Concurrent Collect and Distribution

System Attributes	2 Sectors Served From 1 Bus Pool Demand/Hr./Sector					
	20	30	40	60	80	100
Area/sector (sq. Miles)	1	1	1	1	1	1
Avg. waiting time per passenger	9.45	7.92	6.4	6.15	5.36	5.21
Avg. ride time per passenger	7.63	7.06	7.59	7.5	7.63	7.6
Total travel time (expected)	17.08	14.98	13.99	13.65	12.99	12.82
Total passengers* served/sector	75	109	156	229	293	353
Max. no. of buses required/sector (avg. for multi sector strategy)	3	3	4.5	7	8.5	8.8
Avg. driver hours of operation/ sector	8.5	11	14.5	28	28	30
Avg. veh. hours of operation/sector	4.15	5.82	7.21	8.93	11.12	14.23
Vehicle productivity	18.06	18.72	21.63	25.65	26.1	24.81

*Total number of passengers for 3 hours of simulation.

Table E.3.3. System Performance Data - Pooling Policy

SYSTEM: Variable Route Variable Headway
OPERATION STRATEGY: Concurrent Collect & Distribution

SYSTEM ATTRIBUTES	3 Sectors Served from 1 Bus Pool					
	Demand/Hr./Sector					
	20	30	40	60	80	100
Area/Sector (sq. miles)	1	1	1	1	1	1
Avg. Waiting Time per Passenger	8.95	7.15	6.25	7.5	6.68	7.41
Avg. Ride Time per Passenger	7.67	7.75	7.69	7.96	8.56	9.92
Total Travel Time (exp.)	16.62	14.9	13.94	15.46	15.24	17.33
Total Pass. * Served/Sector	71	108	144	239	298	372
Max. No. of Buses Reqd./ Sector (avg. for multi sector strategy)	3	3	3.7	5	5	5
Avg. Driver Hours of Operation/ Sector	9	9.7	13	15.6	17.3	20
Avg. Vehicle Hours of Operation/ Sector	3.69	5.12	6.89	8.77	10.75	13.8
Vehicle Productivity	19.24	21.09	20.9	27.25	27.72	26.96

*Total number of passengers for 3 hours of simulation.

Table E.3.4. Utility Cost Data

SYSTEMS: Variable Route Variable Headway

For $V_1 = V_2 = 1$, $V_3 = V_4 = 3$

Demand Level	$Ui = V_1x_1 + V_2x_2 + V_3x_3 + V_4x_4$		
	No. of Sectors Served by 1 Bus Pool		
	1	2	3
20/hr./sector	57.28	55.03	54.60
30/hr./sector	71.76	65.44	60.06
40/hr./sector	81.14	79.12	73.61

NOTE: X_1 = Mean Wait Time

X_2 = Mean Ride Time

X_3 = Average Driver Hours Required/Sector

X_4 = Average Vehicle Hours of Operation/Sector

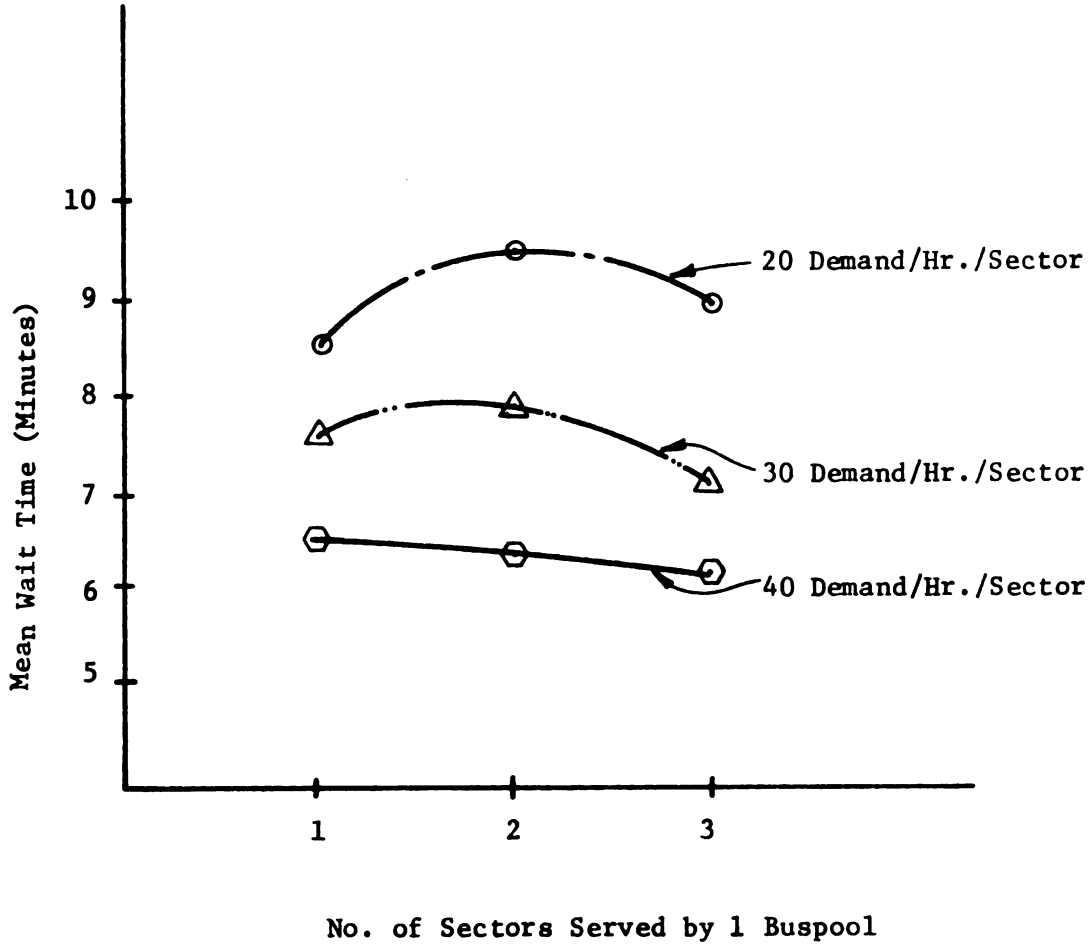


Figure E.3.1. Pooling Policy Data-Waiting Time

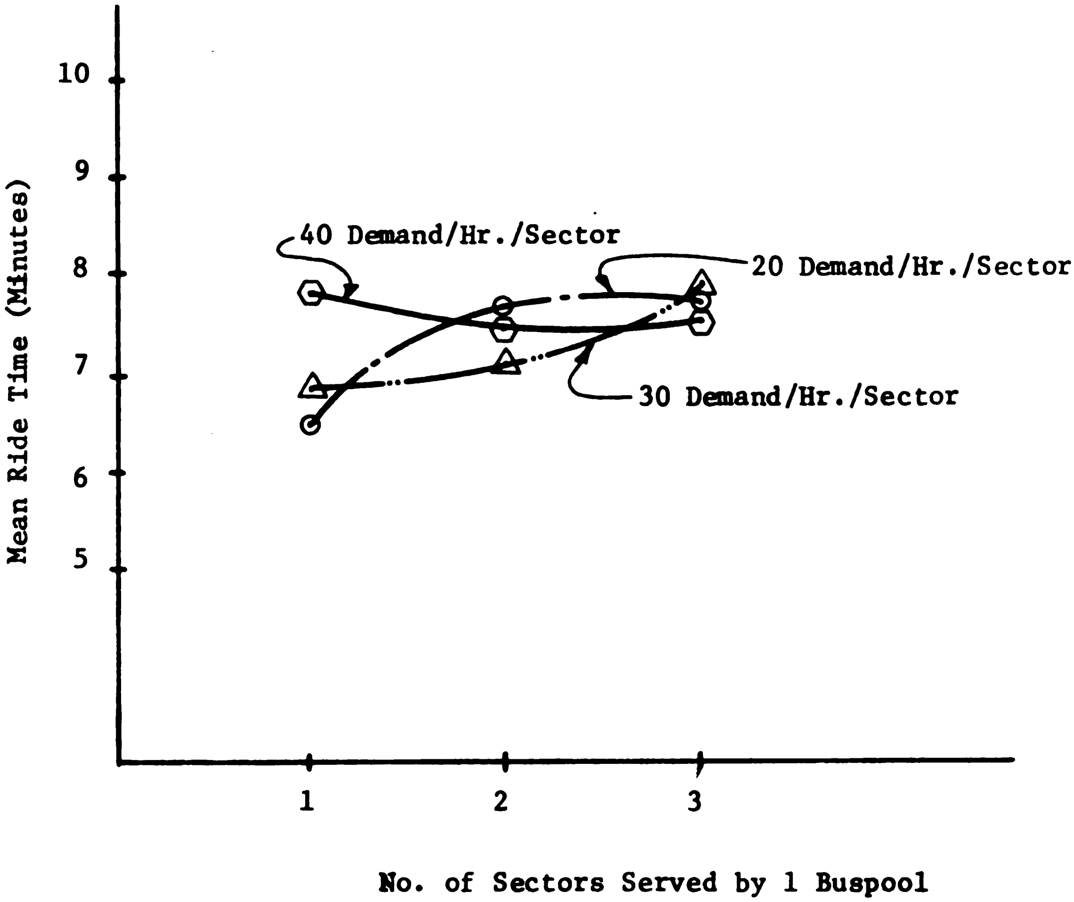


Figure E.3.2. Pooling Policy Data-Mean Ride Time

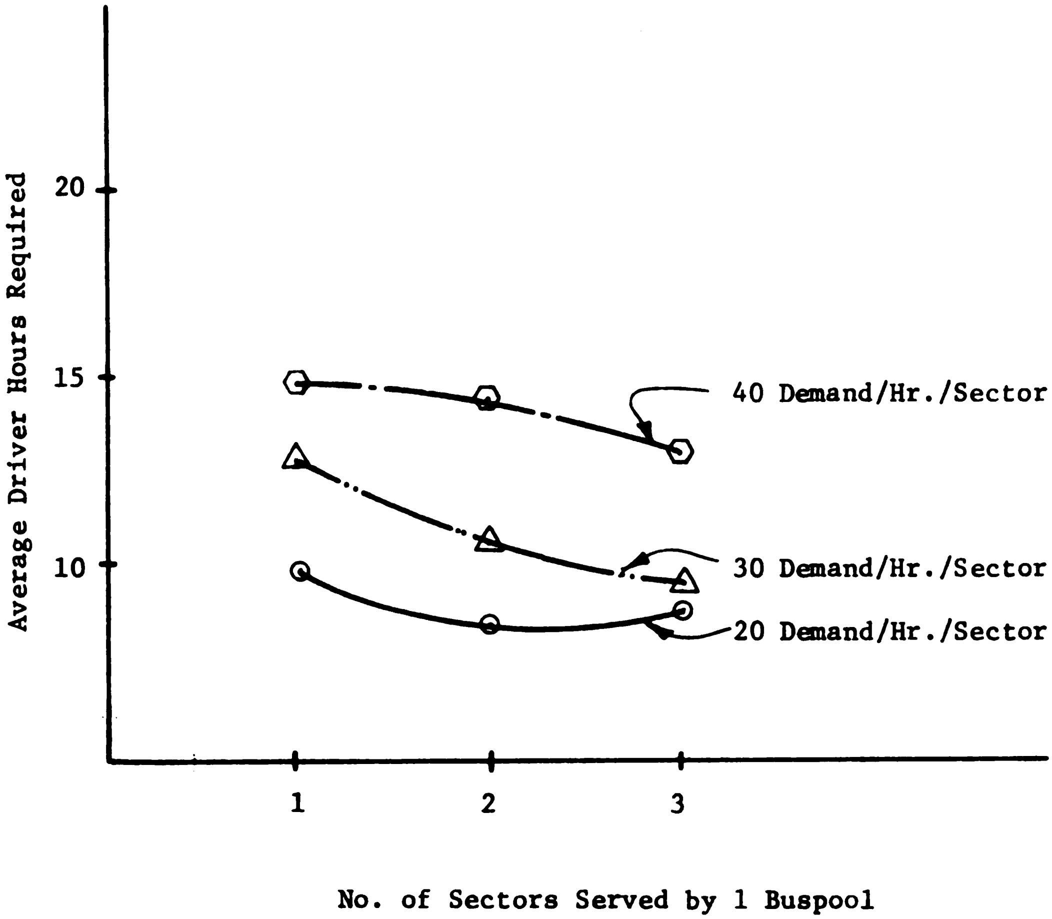


Figure E.3.3. Pooling Policy Data-Driver Hour Requirements

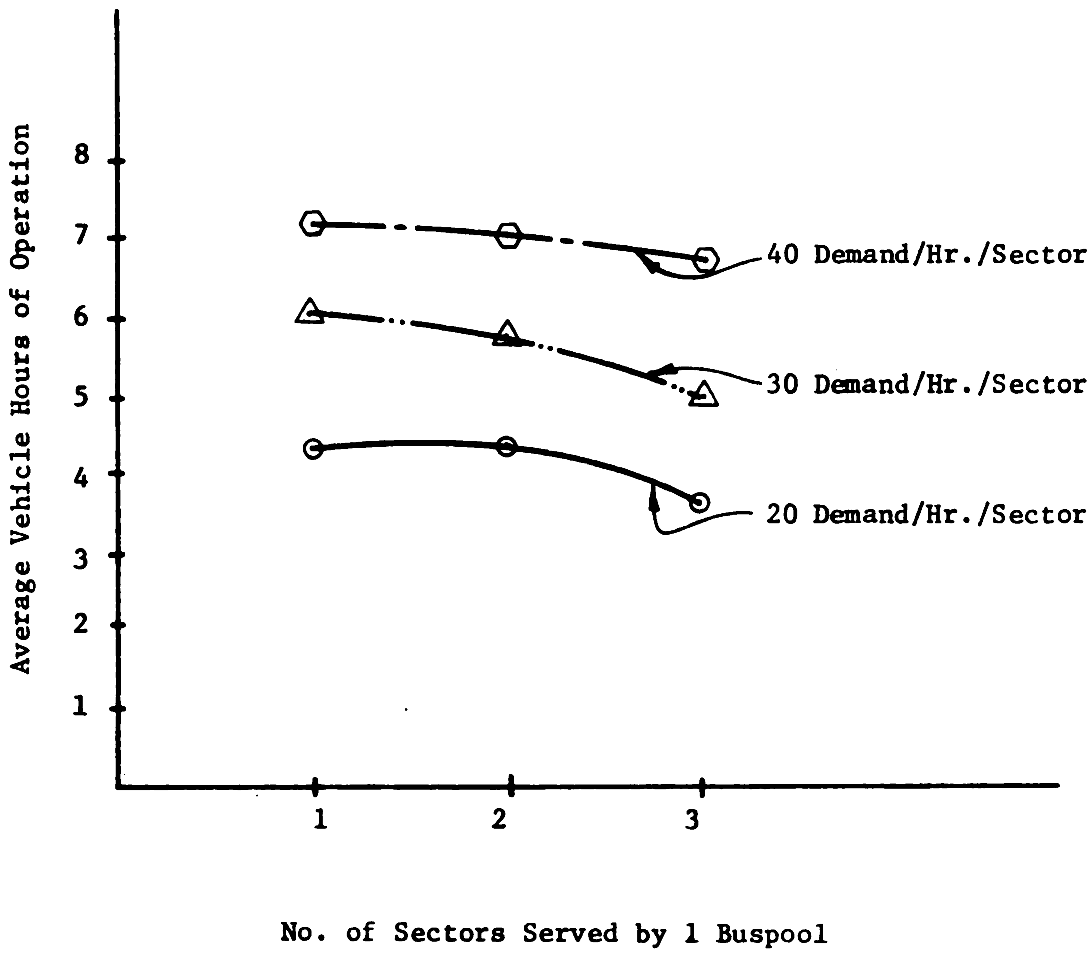
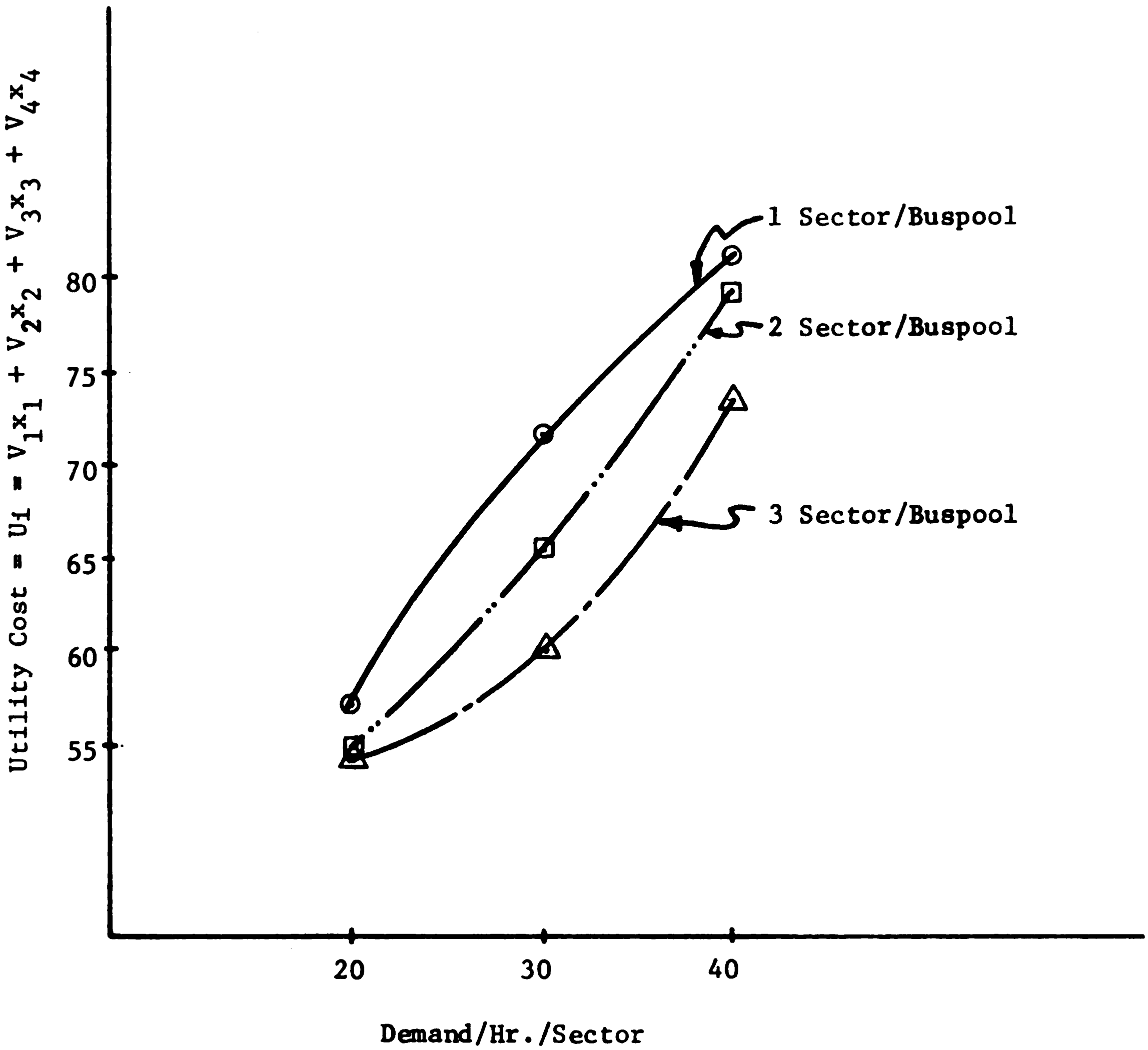


Figure E.3.4. Pooling Policy Data-Vehicle Hour Requirements



SYSTEM: Variable Route Variable Headway

$V_1 = V_2 = 1, V_3 = V_4 = 3$

Figure E.3.5. Utility Cost Functions for Pooling Policy

The discussed utility cost of multiple sector assignments would alter the demand level at which the variable headway-variable route system becomes "optimal" as defined in the previous section. Thus, the operating policy should be investigated concurrently with the system selection policies to determine the most suitable solution to a particular demand for public transportation.

E.4. EFFECT OF VARIOUS NETWORK CONFIGURATIONS

This study, as well as all other studies found in the literature, were conducted on a single network. The basic simulated bus operation considered 3 sectors each 1 mile x 1 mile area with a grid pattern of roadway network. The comparison of all system attributes has been made on this single network configuration. In applying the results to real-life, it is highly unlikely that a perfect grid type street network will exist. Therefore, a test was conducted to determine how a change in network configuration affects these system attributes.

The simulation model used in this study converts the street network to a point to point travel time matrix prior to executing the simulation. In the examples reported in this study, this was accomplished by assigning a travel time in accordance with the differences in 'X' and 'Y' coordinates of any two generation points.

A variation in real world roadway network configurations can be introduced into the travel distance matrix and ultimately to the travel time matrix by varying the relationship between coordinate distance and real distance. A network configuration factor "α" was used to introduce the variability of a real world network pattern. This factor can be considered as a measure of direct access between any two points in the sector. The perfect grid system is represented by an 'α' factor of 1.0.

To test the affect of variability of network pattern this 'α' factor was varied from .6 to 1.0 in increments of .2. Higher values

values of 'α' were not tested since grid network represents a higher route mileage characteristics than most real world networks. Six levels of demand (20, 30, 40, 60, 80 and 100) hr./sector were tested for variable route-variable headway and fixed route-fixed headway systems. The system performance parameters are shown in tables E.4.1. through E.4.3.

To illustrate the effect of 'α' on the system selection process, the same set of utility values used in the pooling section was selected. The simulated bus operation in this case was also performed for 3 sectors served by a single bus pool. The computed utility costs are shown in table E.4.4. and figure E.4.1. for both variable route-variable headway and fixed route-fixed headway systems.

The intersection points of variable route-variable headway and fixed route-fixed headway systems vary depending on the system configuration coefficients. For $\alpha = .6$ the variable route-variable headway system is optimal at demand levels lower than 45/hr./sector whereas for $\alpha = 1.0$ this system is optimal to 86 demands/hr./sector. For higher values of 'α' the crossing point moves to higher demand levels as shown by the circles on this figure.

This illustrates the expected operating characteristics. As the ability to move directly from all origins to all destinations decreases, the advantages of optimally routed systems also decrease. This is particularly true of a utility cost weighted in favor of the operator, as the vehicle miles and driver hours requirement to provide for a constant demand will increase with the circuitness of the street network.

Table E.4.1. System Performance Data for Network Configuration

Network Configuration: α = .6
No. of Sectors = 3

SYSTEM: Variable Route Variable Headway						
SYSTEM ATTRIBUTES	Demand/Hr./Sector					
	20	30	40	60	80	100
Mean Wait Time	8.21	6.03	5.02	5.52	6.13	6.02
Mean Ride Time	5.15	5.08	5.04	5.81	5.75	5.86
Driver Hours Reqd. (total)	15	21	33	38	44	51
Vehicle Hours of Operation	8.09	9.47	17.56	22.1	26.3	31.8

SYSTEM: Fixed Route Fixed Headway						
SYSTEM ATTRIBUTES	Demand/Hr./Sector					
	20	30	40	60	80	100
Mean Wait Time	9.41	9.57	9.15	8.89	8.83	8.36
Mean Ride Time	11.21	11.98	12.63	14.51	15.3	16.21
Driver Hours Reqd. (total)	21	22	22	28	33	39
Vehicle Hours of Operation	12.25	13.34	12.99	28.32	20.45	22.32

Table E.4.2. System Performance Data for Network Configuration

NETWORK CONFIGURATIONS: α = .8
No. of Sectors = 3

SYSTEM: Variable Route Variable Headway						
SYSTEM	Demand/Hr./Sector					
ATTRIBUTES	20	30	40	60	80	100
Mean Wait Time	7.6	7.25	6.42	7.5	6.4	7.18
Mean Ride Time	6.12	7.86	7.41	7.96	8.31	9.22
Driver Hours Reqd. (total)	24	26	31	42	48	56
Vehicle Hours of Operation	10.8	12.32	15.1	24.3	28.1	36.2

SYSTEM: Fixed Route Fixed Headway						
SYSTEM	Demand/Hr./Sector					
ATTRIBUTES	20	30	40	60	80	100
Mean Wait Time	9.32	10.08	9.78	9.32	7.21	7.45
Mean Ride Time	14.45	14.87	16.05	16.65	17.82	18.1
Driver Hours Reqd. (total)	23	31	33	37	42	49
Vehicle Hours of Operation	15.78	16.11	17.37	22.86	24.51	28.8

Table E.4.3. System Performance Data for Network Configuration

NETWORK CONFIGURATIONS: $\alpha = 1.0$
No. of Sectors = 3

SYSTEM: Variable Route Variable Headway						
SYSTEM ATTRIBUTES	Demand/Hr./Sector					
	20	30	40	60	80	100
Mean Wait Time	8.95	7.15	6.25	7.5	6.68	7.41
Mean Ride Time	7.67	7.75	7.69	7.96	8.56	9.92
Driver Hours Reqd. (total)	27	29	39	47	52	60
Vehicle Hours of Operation	11.07	15.36	20.67	26.31	32.25	41.13

SYSTEM: Fixed Route Fixed Headway						
SYSTEM ATTRIBUTES	Demand/Hr./Sector					
	20	30	40	60	80	100
Mean Wait Time	9.84	9.86	10.34	7.6	7.42	7.77
Mean Ride Time	18	18.5	19.31	18.98	19.56	20.17
Driver Hours Reqd. (total)	32	34	34	50	52	55
Vehicle Hours of Operation	17.91	19.71	20.07	31	32.25	34.2

Table E.4.4. Utility Cost Data

No. of Sectors = 3 (1 mile x 1 mile each)
$V_1 = V_2 = 1,\ V_2 = V_3 = 3$

SYSTEM: Variable Route Variable Headway						
	$Ui = V_1 x_1 + V_2 x_2 + V_3 x_3 + V_4 x_4$					
Network	Demand/hr/sector					
Configuration	20	30	40	60	80	100
.6	82.63	102.52	161.74	191.63	222.78	260.28
.8	118.12	130.07	152.13	214.36	243.01	293.00
1.0	130.83	147.98	192.95	235.39	267.99	320.72

SYSTEM Fixed route Fixed headway						
	$Ui = V_1 x_1 + V_2 x_2 + V_3 x_3 + V_4 x_4$					
Network	Demand/hr/sector					
Configuration	20	30	40	60	80	100
.6	120.37	127.57	126.75	192.36	184.48	208.53
.8	140.11	166.28	176.94	205.55	244.56	258.95
1.0	177.57	189.49	191.86	269.58	279.73	295.54

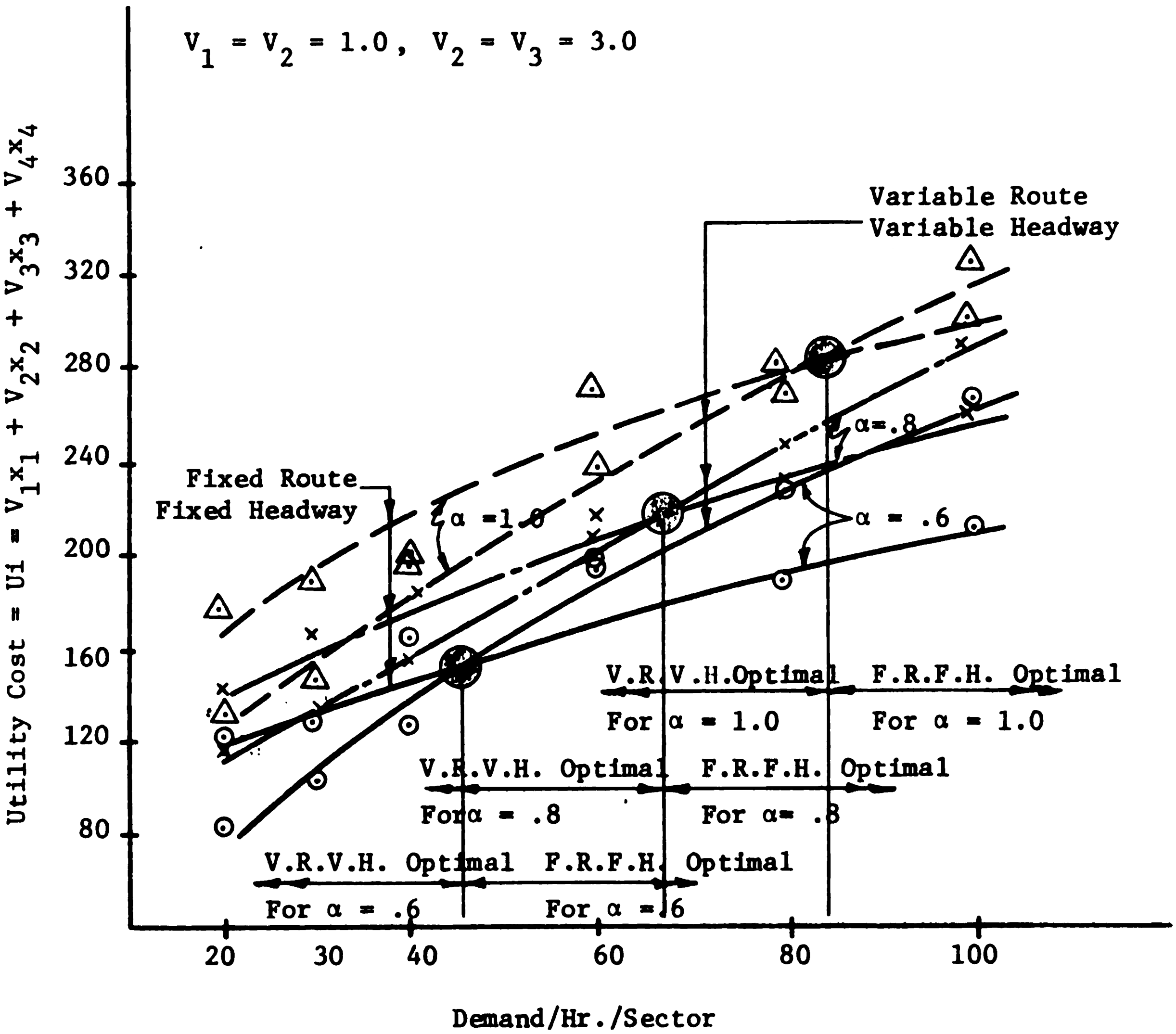


Figure E.4.1. Effect of Network Configuration on Cost

E.5. EFFECT OF SIZE OF SERVICE AREA

The size of the sector being served may also be an important consideration in the evaluation and selection of demand actuated bus systems. Thus, a 'λ' factor was used as a constant multiplier to expand the linear dimensions of the study area. The 'λ' factor was varied from 1.0 to 1.8 in increments of 0.2. Essentially, it changed the point to point travel distance since the number of roadways (both ways) per sector was kept constant. The following discrete service areas were simulated to study their effect on the system attributes.

a. $\lambda = 1$, 3 sectors - total area 3 square miles (base case)

b. $\lambda = 1.2$, 3 sectors - total area 4.32 square miles

c. $\lambda = 1.4$, 3 sectors - total area 5.88 square miles

d. $\lambda = 1.6$, 3 sectors - total area 7.68 square miles

e. $\lambda = 1.8$, 3 sectors - total area 9.72 square miles

Each of the service areas' bus operation was simulated for six levels of demand (20, 30, 40, 60, 80 and 100/hr./sector) and for variable route-variable headway and fixed route-fixed headway systems. The results of these simulated bus operations are shown in tables E.5.1. through E.5.5.

To relate these results to the preceding sections, the same set of values were used to construct utility cost curves.

These utility values are shown in tables E.5.6 and plotted in figure E.5.1. With the exception of the base case, the point of intersection of variable route-variable headway and fixed route-fixed headway system does not appear to vary with the size of the service area. It is believable that other system constraints like a maximum waiting time of 30 minutes and a maximum total travel time of 45 minutes which were held constant through this test may have influenced the results. These limits were established as an upper value at which customers would remain on the system. These constraints probably resulted in loosing some passengers in the fixed route-fixed headway system. Furthermore, the increase in service area for the same level of demand/hr./sector actually results in reduction in the demand density as the demands are generated on a per sector basis.

An investigation of the system performance data indicates that the percent increase in vehicle hours of operation and driver hour requirements are less than the percent increase in area for very limited change in user attributes. However, the present study did not cover the range of service areas to allow any definitive conclusion regarding selection of service area for optimal operation.

Table E.5.1. System Performance Data

1 mile x 1 mile sector

No of Sectors = 3

Total Service Area = 3 sq. miles

SYSTEM: Variable Route Variable Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	8.95	7.15	6.25	7.5	6.68	7.41
Mean Ride Time	7.67	7.75	7.69	7.96	8.56	9.92
Driver hours reqd. (total)	27	29	39	47	52	60
Vehicle hours of operation	11.07	15.26	20.67	26.31	32.25	41.13

SYSTEM: Fixed Route Fixed Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	9.84	9.86	10.34	7.6	7.42	7.77
Mean Ride Time	18	18.5	19.31	18.98	19.56	20.17
Driver hours reqd. (total)	32	34	34	50	52	55
Vehicle hours of operation	17.91	19.71	20.07	31	32.25	34.2

Table E.5.2. System Performance Data

1.2 mile x 1.2 mile sector

No. of Sectors = 3

Total Service Area = 4.32 sq. miles

SYSTEM: Variable Route Variable Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	10.71	7.92	7.09	8.65	8.12	7.96
Mean Ride Time	8.38	8.75	8.57	9.12	8.97	9.43
Driver hours reqd. (total)	26	39	49	56	62	68
Vehicle hours of operation	14.18	21.31	30.66	35.83	38.2	42.8

SYSTEM: Fixed Route Fixed Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	9.98	10.09	10.44	9.83	9.64	9.48
Mean Ride Time	21.6	21.79	22.66	22.31	22.46	23.41
Driver hours reqd. (total)	32	34	38	51	54	56
Vehicle hours of operation	22.03	19.72	24.5	32.31	33.4	36.1

Table E.5.3. System Performance Data

1.4 mile x 1.4 mile sector

No. of Sectors = 3

Total Service Area = 5.88 sq. miles

SYSTEM: Variable Route Variable Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	11.15	8.67	7.66	8.23	8.34	8.69
Mean Ride Time	10.04	10.2	10.05	9.98	10.42	10.34
Driver hours reqd. (total)	27	43	55	63	68	74
Vehicle hours of operation	15.86	24.35	35	38.3	44.12	48.4

SYSTEM: Fixed Route Fixed Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	10.66	10.26	10.88	10.83	10.76	10.86
Mean Ride Time	25.1	25.01	22.73	23.48	22.98	23.67
Driver hours reqd. (total)	41	43	43	56	58	61
Vehicle hours of operation	24.91	26.93	28.12	34.16	37.18	38.12

Table E.5.4. System Performance Data

1.6 mile x 1.6 mile/sector

No. of Sectors = 3

Total Service Area = 7.68 sq. miles

SYSTEM: Variable Route Variable Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	11.95	9.32	8.13	8.53	8.76	9.12
Mean Ride Time	13.4	11.08	11.36	10.95	10.91	10.76
Driver hours reqd. (total)	34	46	58	69	74	79
Vehicle hours of operation	18.21	28.2	39.6	44.3	49.1	56.12

SYSTEM: Fixed Route Fixed Headway						
System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	10.87	10.61	11.63	10.98	10.83	11.21
Mean Ride Time	28.45	28.2	29.5	29.68	29.74	29.85
Driver hours reqd. (total)	41	43	47	58	62	65
Vehicle hours of operation	25.26	30.41	31.76	36.21	40.2	42.1

Table E.5.5 System Performance Data

1.8 mile x 1.8 mile/sector

No. of Sectors = 3

Total Service Area = 9.72 sq miles

SYSTEM: Variable Route Variable Headway

System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	12.32	10.06	8.96	9.32	9.78	9.83
Mean Ride Time	14.03	12.6	12.62	12.68	13.13	14.1
Driver hours reqd. (total)	38	50	62	72	78	83
Vehicle hours of operation	20.23	31.3	43.32	46.8	54.6	62.6

SYSTEM: Fixed Route Fixed Headway

System Attributes	Demand/Hr/Sector					
	20	30	40	60	80	100
Mean Wait Time	11.36	11.17	11.73	12.16	12.58	11.97
Mean Ride Time	32.37	31.65	33.08	32.64	31.86	32.56
Driver hours reqd. (total)	47	52	52	61	65	69
Vehicle hours of operation	32.22	34.97	35.35	39.43	43.6	46.4

Table E.5.6 Utility Cost Data for Service Area

No. of Sectors = 3
$V_1 = V_2 = 1$ $V_2 = V_4 = 3$

SYSTEM: Variable Route Variable Headway

Service Area	$Ui = V_1 x_1 + V_2 x_2 + V_3 x_3 + V_4 x_4$					
	Demand/hr/sector					
	20	30	40	60	80	100
3.0	130.83	147.88	192.95	235.39	267.99	320.72
4.32	139.63	197.60	254.64	293.26	317.69	349.79
5.88	149.77	220.92	287.71	322.11	355.12	386.23
7.68	182.55	243.00	312.29	359.38	388.97	425.24
9.72	201.04	266.56	337.54	401.80	420.71	460.73

SYSTEM Fixed route Fixed headway

Service Area	$Ui = V_1 x_1 + V_2 x_2 + V_3 x_3 + V_4 x_4$					
	Demand/hr/sector					
	20	30	40	60	80	100
3.0	177.57	189.49	191.86	269.58	279.73	295.54
4.32	193.67	193.04	220.6	281.77	294.3	309.19
5.88	233.49	245.06	246.06	304.79	319.28	331.89
7.68	238.1	259.04	277.41	323.29	347.17	362.36
9.72	281.39	306.86	306.86	346.09	370.24	390.73

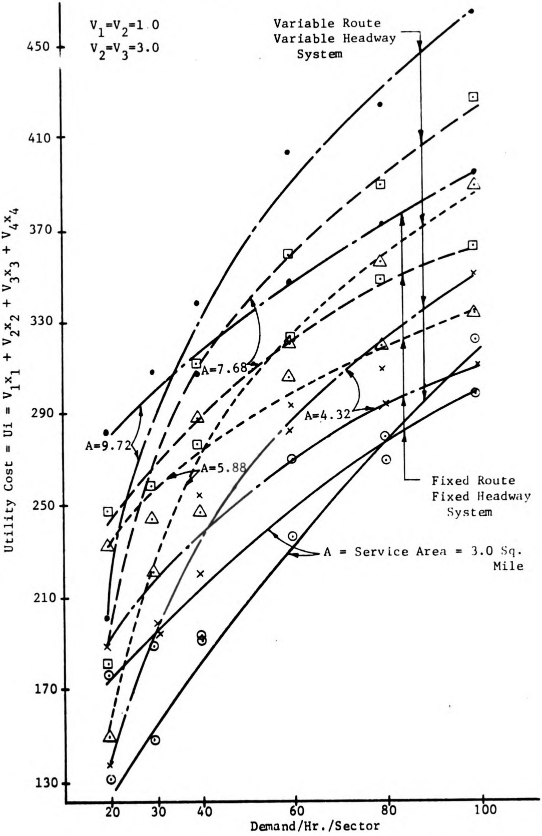


Figure E.5.1. Utility Cost Function for Variable Demand Levels

F. CONCLUSIONS

Conclusions of the State of the Art

An overview of the state of the art indicates that there has been research, demonstration and implementation studies made on demand actuated bus systems throughout North America and abroad. These studies range from very simple demonstration project to sophisticated computer simulation studies. However, all of them are oriented towards the case study approach, and do not treat a family of Demand Actuated Bus Systems on a single set of parameters. Thus, it is not possible to define a set of parameter values that would determine the applicability of the various systems. Though simulation has been used, most of the models developed are for a specific level of system constraints rather than a family of systems.

The following conclusions can be made from the experience of DAB demonstration and implementation studies.

1. Several factors are apparently of great importance to the success of a DAB systems; with service area, service selection and dispatching strategies the most important.

2. Public subsidy is necessary in most cases to support a DAB system.

3. Public subsidy is not a guarantee for system success. This requires a competent system analyst and management and staff.

4. Significant operating economies can be achieved by using small coaches which increase the occupancy-capacity ratio.

5. Increased vehicle productivity (no. of passengers per hour per vehicle) is possible with DAB systems.

6. Ridership increase due to implementation of DAB systems compared to fixed route-fixed headway systems is significant.

7. Off peak fare reductions policy results in redistribution of ridership--i.e. peak smoothing--but does not affect total ridership or revenue.

8. Ridership seems to have limited sensitivity to fares between 25¢ and 60¢.

9. Manual dispatching works fairly well for smaller service areas with few buses. For larger areas computer routing and dispatching is required.

10. Careful analysis of service area may allow a system to be efficiently operated under many to one or many to few environments.

11. For high density (riders) areas, fixed time fixed route systems work as well as any DAB system.

The following conclusions can be made from the research and development studies:

1. System simulation provides a tool for system evaluation and selection.

2. The concept of DAB systems is technically feasible.

3. Financially the systems cannot be self supporting.

4. Demand estimation analysis shall be a part of system study prior to implementation for selecting viable service criteria.

5. Heuristic Traveling Salesman algorithms work for optimal routing in most of the existing simulation models.

6. Computer dispatching is economical for large systems.

7. The limited sensitivity analysis presented in various studies and papers indicate sensitivity of system performance to waiting time, trip time, and link travel time for specific systems only.

8. The other simulation studies have tested certain variables; demand, level of service, etc. and found significant differences in the user and performance characteristics, but they have not compared alternative systems on a single base.

Conclusions of this Study

The general purpose simulation model developed as a part of this research can replicate operations of alternative systems within the spectrum of demand actuated bus systems. The accumulation and production of the statistical data by the model provide an excellent base for the system evaluation and selection process.

The analysis regarding the effect of variable demand condition on system performance parameters (both user and operator) indicates that significant gains in system attributes can be attained by changing operating policies for varying demand levels. This study also reaffirms the hypothesis that the selection of a system without a comparative evaluation of alternatives may result in significant inefficiencies.

The utility cost analysis as presented in this study provides a means for evaluating system alternatives for selection of optimal operating policies. This method can use both tangible and intangible cost parameters in the perspective of specific goals of the community.

The analysis of the effect of fixed vehicle to sector assignment, as opposed to multi-sector service from a single bus pool, indicated significant differences in some cost parameters. It can be concluded that multi-sector operation by a central bus pool provides cost savings in most cases.

The system cost parameters indicated significant sensitivity to network patterns. Thus, it appears that a method of classifying street patterns must be developed before general conclusions regarding system selection can be made.

The attempt to determine the effect of service area on the system attributes was inconclusive.

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BIBLIOGRAPHY

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APPENDIX I

```
DISPATCH LOGIC =    5           HEADWAY =   15. MIN.

CAPACITY =    35          NUMBER OF BUSSES =    30

ACTIVITY CENTER:   1           ALPHA =   1.4
```

```
***********************************************************************

CYCLE NUMBER    1

DISTRICT NUMBER    1

SIMULATION PERIOD =    3.0 HOURS

DEMANDS PER HOUR =  20.0

TIME OF START =    0.0 HOURS

PERCENT COLLECTION DEMANDS = 50.000 %

***********************************************************************

  IOUT = 2
```

SEQ	CODE	ZONE	NPAX	TIME
1	-1	28.	2.	-0.989
2	1	202.	1.	3.111
3	1	108.	1.	4.118
4	1	87.	2.	6.694
5	1	185.	1.	11.330
6	-1	210.	2.	-12.383
7	-1	77.	1.	-13.774
8	-1	44.	1.	-14.038
9	1	137.	1.	20.155
10	1	17.	1.	21.364
11	-1	140.	1.	-29.803
12	-1	222.	2.	-30.590
13	1	165.	1.	31.046
14	1	210.	1.	31.369
15	-1	175.	1.	-33.529
16	1	16.	1.	34.296
17	1	221.	2.	37.502
18	-1	173.	1.	-38.043
19	1	25.	1.	39.145
20	1	209.	1.	41.894
21	-1	81.	1.	-43.517
22	-1	43.	1.	-46.665
23	-1	105.	1.	-50.637
24	-1	98.	2.	-54.301
25	-1	124.	1.	-60.476
26	1	145.	1.	64.690
27	1	102.	2.	71.598

SEGMENT NUMBER 2 TIME FROM 60.00MIN. TO 119.99 MIN.

BUS #	NUMBER TOURS	NUMBER PASS. DISTRB	NUMBER PASS. COLLCT	TOTAL PASS. SERVED	TOTAL TOUR TIME	MEAN TOUR TIME	BUS UTILI-ZATION
1	2	6	4	10	51.01	25.50	0.85
2	2	4	4	8	48.26	24.13	0.80
3	3	9	3	12	48.83	16.28	0.81
4	3	4	5	9	43.30	14.43	0.72
5	2	4	6	10	47.09	23.54	0.78
6	2	3	10	13	50.37	25.19	0.84
7	1	1	3	4	23.00	23.00	0.38
8	0	0	0	0	0.0	0.0	0.0

PASSENGER "WAIT-TIME" STATISTICS,

SEGMENTING IS DONE EVERY 60 MINUTES BASED ON GEN.-TIME

	SECTOR #1			SECTOR #2			SECTOR #3		
SEG. #	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.
1	10.37	30.82	7	13.05	27.17	9	14.41	30.12	12
2	9.59	23.53	6	13.53	31.39	12	13.72	28.35	6
3	7.43	24.25	3	9.85	16.79	3	8.45	30.10	4
4	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0

PASSENGER "RIDE-TIME" STATISTICS,
SEGMENTING IS DONE EVERY 60 MINUTES BASED ON GEN.-TIME

	SECTOR #1			SECTOR #2			SECTOR #3		
SEG. #	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.
1	12.55	20.42	10	10.95	17.82	3	10.50	21.22	8
2	8.84	18.17	3	10.05	17.68	5	9.09	17.29	4
3	9.39	17.16	3	9.11	20.55	2	9.92	18.13	4
4	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0

PASSENGER =TOT.-TRAV.-TIME" STATISTICS,
SEGMENTING IS DONE EVERY 60 MINUTES BASED ON GEN.-TIME

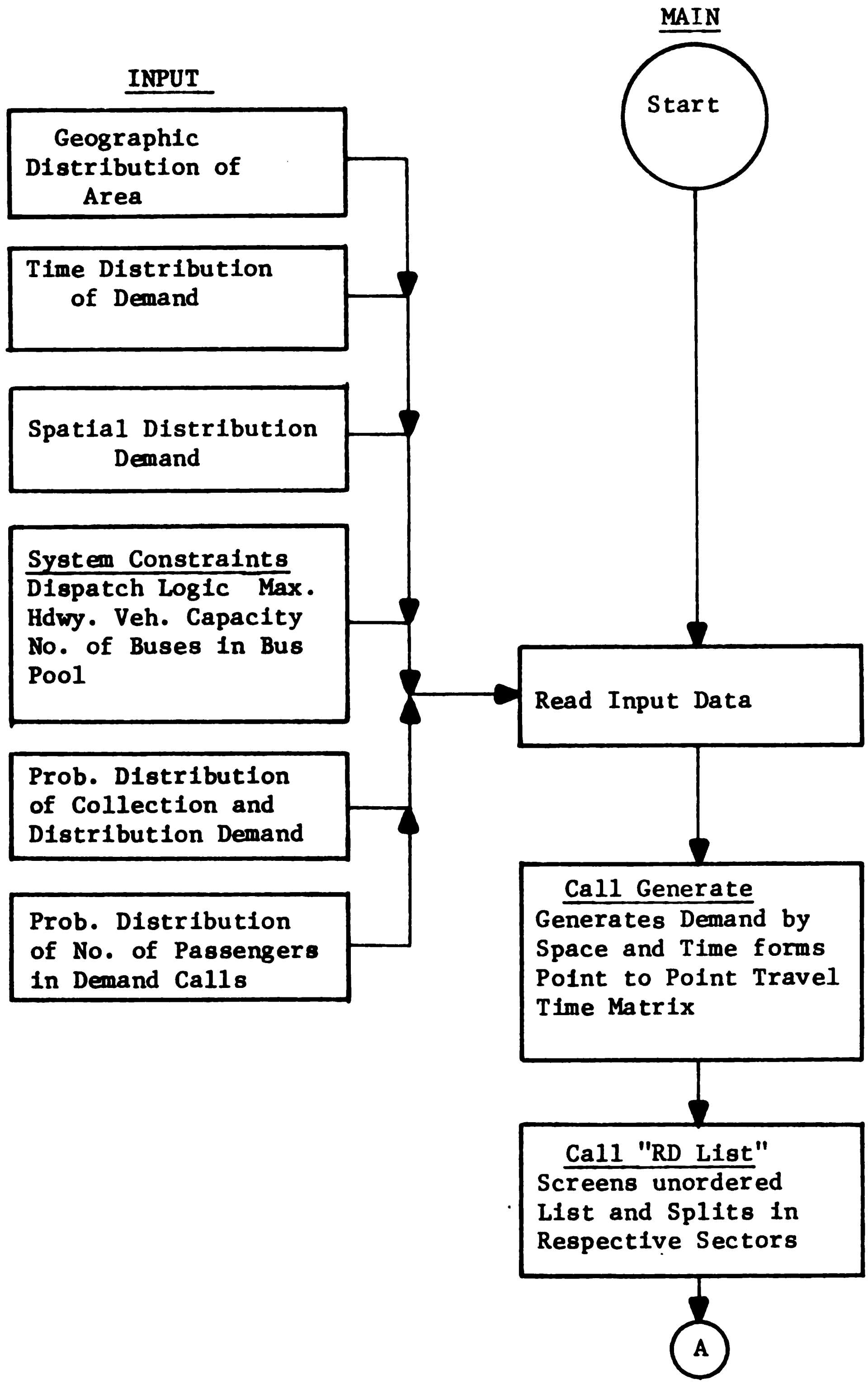
	SECTOR #1			SECTOR #2			SECTOR #3		
SEG. #	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.	MEAN	MAX.	OVER 15 MIN.
1	22.92	34.16	23	24.00	35.26	19	24.91	36.51	22
2	18.43	29.58	14	23.59	34.27	23	22.81	36.09	14
3	16.32	32.88	16	18.96	25.92	16	18.37	35.85	17
4	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0

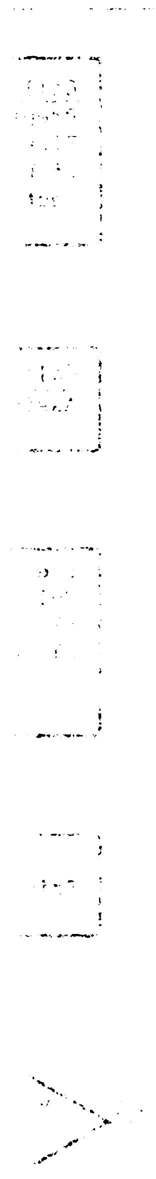
BUS NUMBER 1 EXECUTED 8 TOURS INVOLVING 37 PASSENGERS
TOTAL TIME IN USE = 163.98 MINUTES

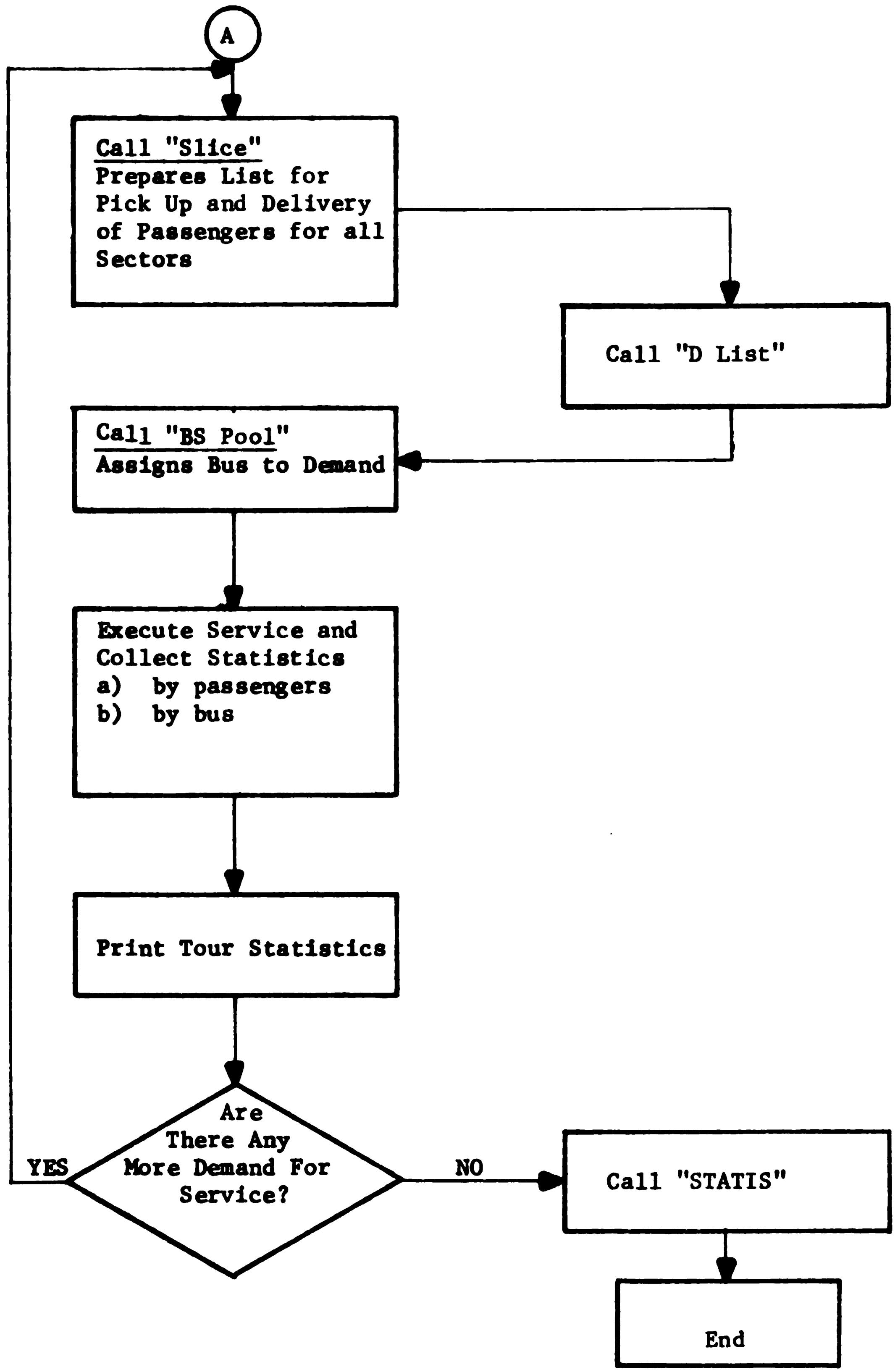
TOUR NUMBER	# PASS. DISTRB.	# PASS. COLLCT.	TOTAL TOUR TIME
1	0	5	19.24
2	2	3	19.54
3	1	3	20.25
4	4	1	20.89
5	1	3	21.41
6	0	5	20.04
7	3	2	21.81
8	3	1	20.80

APPENDIX II

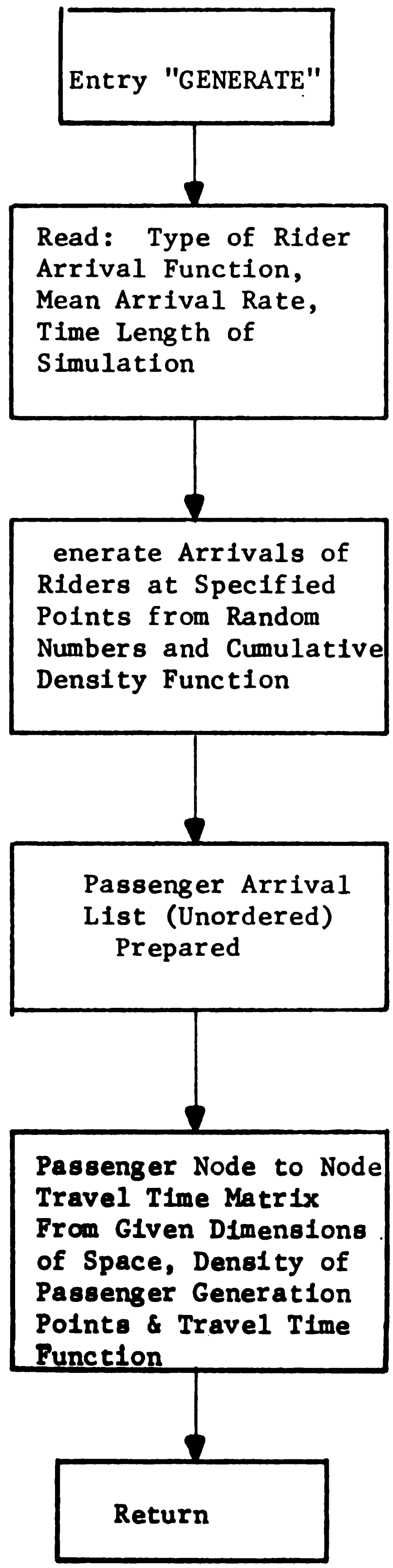
(Flow Charts)


MAIN
INPUT
Start
Geographic Distribution of Area
Time Distribution of Demand
Spatial Distribution Demand
System Constraints
Dispatch Logic Max. Hdwy. Veh. Capacity No. of Buses in Bus Pool
Prob. Distribution of Collection and Distribution Demand
Prob. Distribution of No. of Passengers in Demand Calls
Read Input Data
Call Generate
Generates Demand by Space and Time forms Point to Point Travel Time Matrix
Call "RD List"
Screens unordered List and Splits in Respective Sectors
A

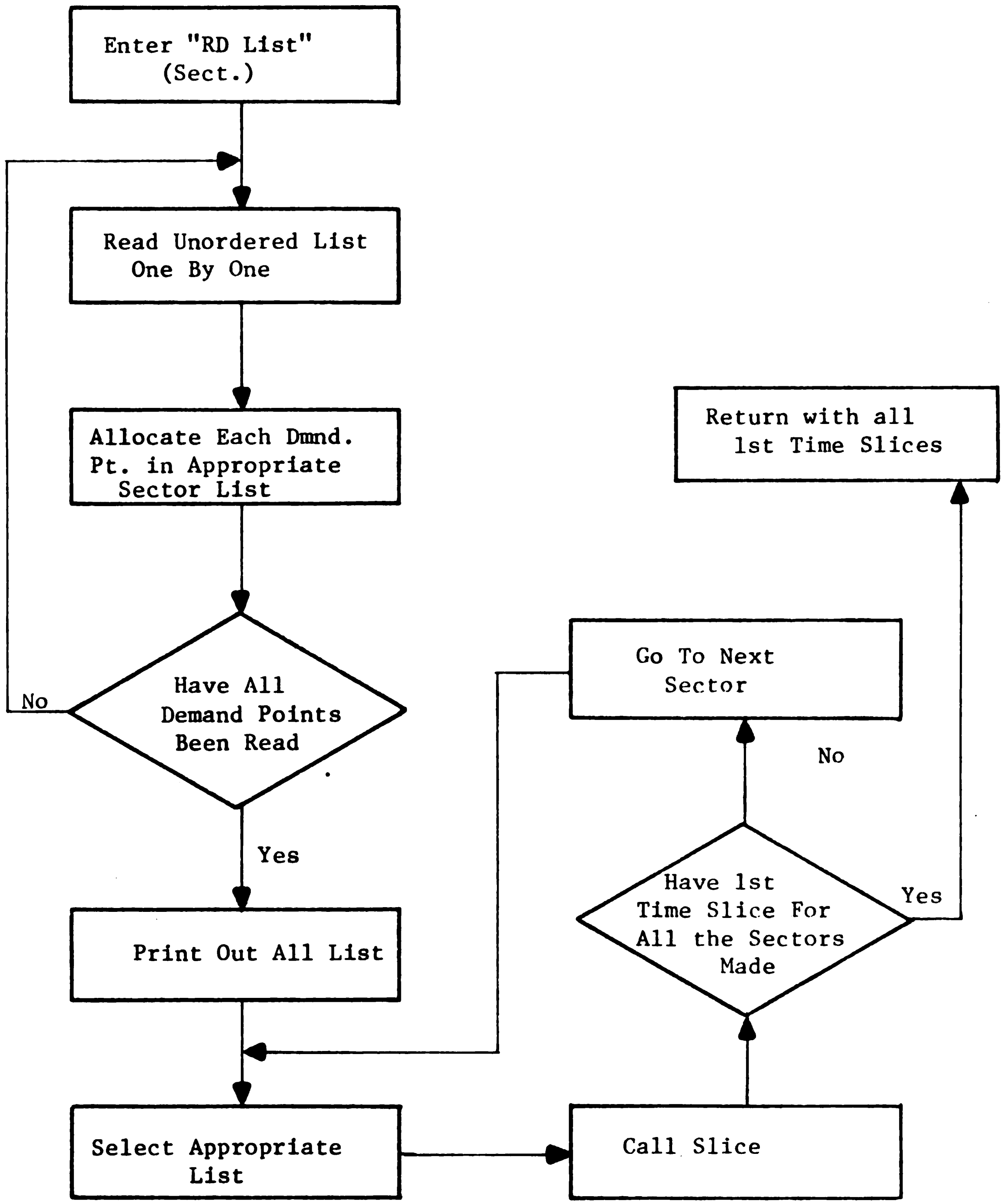



A
Call "Slice"
Prepares List for Pick Up and Delivery of Passengers for all Sectors
Call "D List"
Call "BS Pool"
Assigns Bus to Demand
Execute Service and Collect Statistics
a) by passengers
b) by bus
Print Tour Statistics
Are There Any More Demand For Service?
YES
NO
Call "STATIS"
End

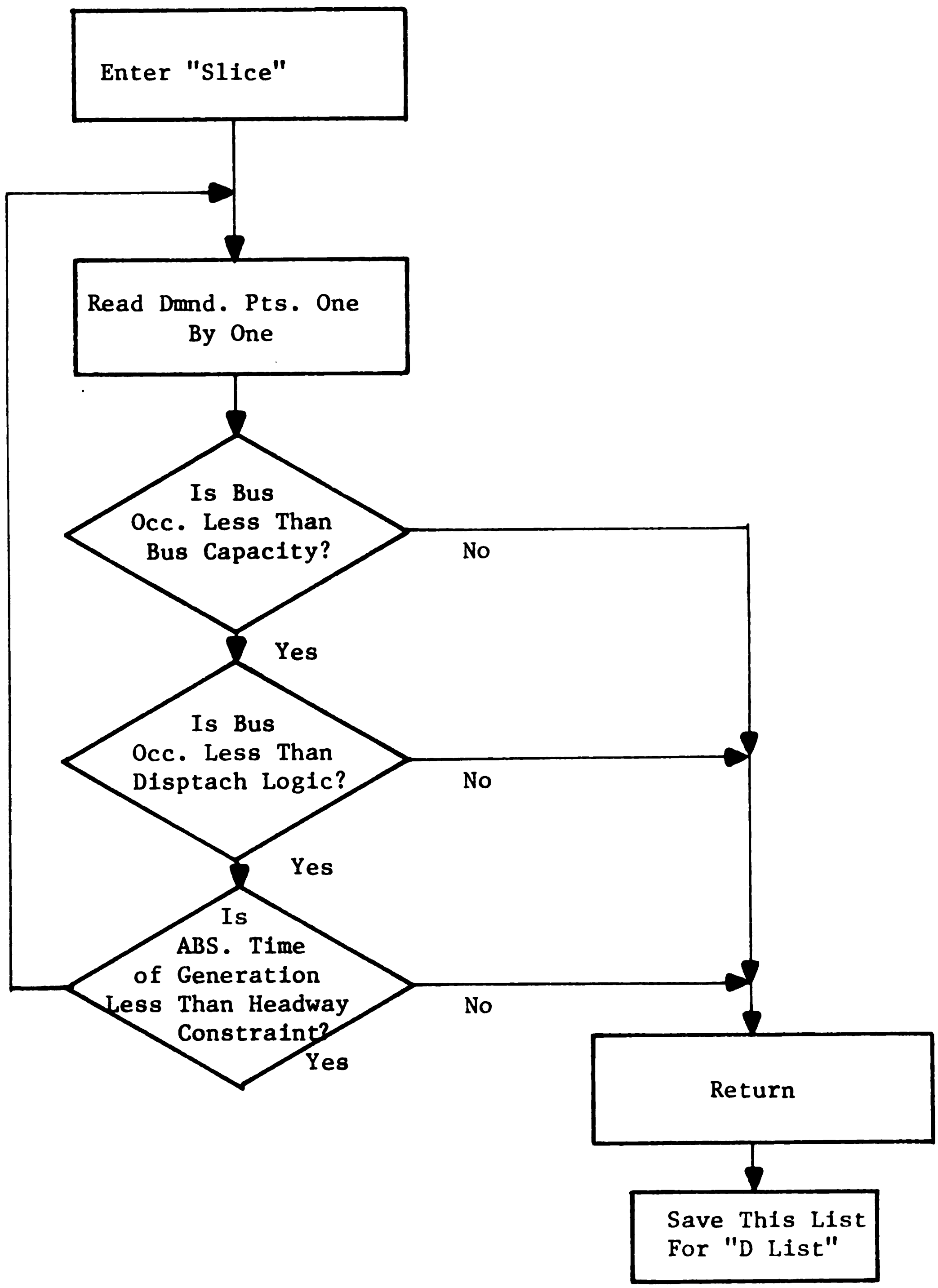
SUBROUTINE "GENERATE"



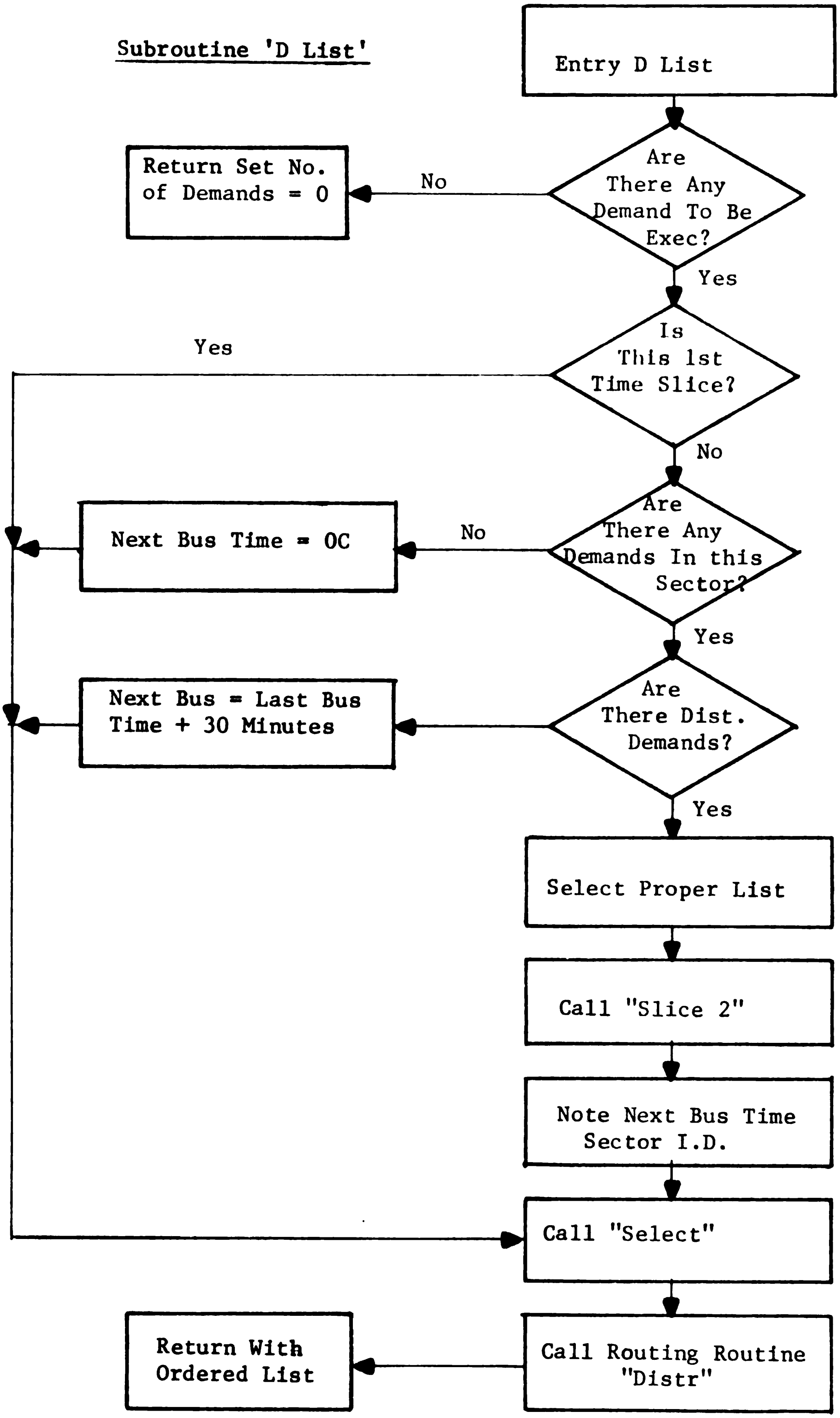
Subroutine "RD List"

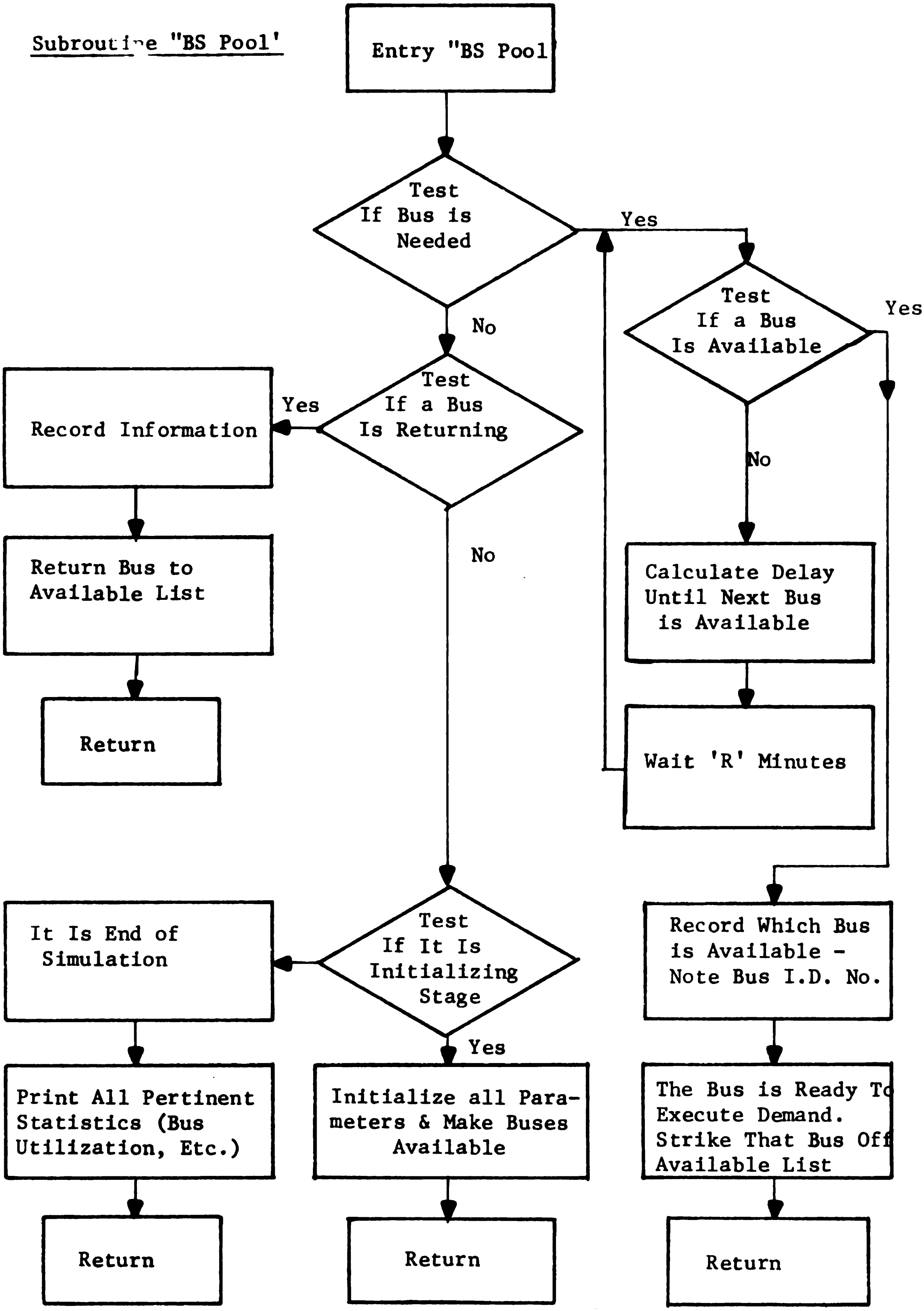


Subroutine "Slice"

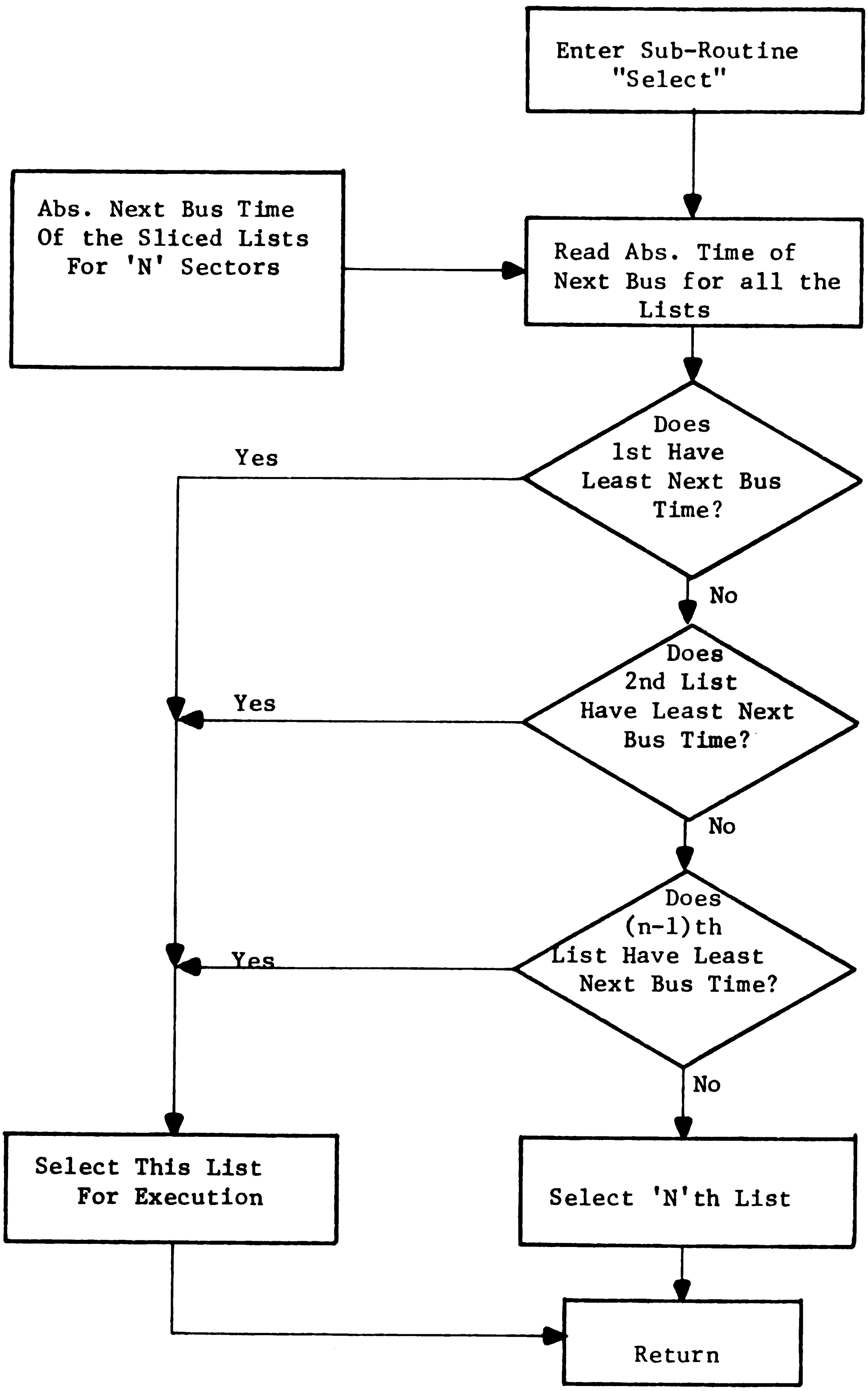


Subroutine 'D List'




Subrout i~e "BS Pool'
Entry "BS Pool
Test If Bus is Needed
Yes
No
Test If a Bus Is Available
Yes
No
Test If a Bus Is Returning
Yes
No
Record Information
Return Bus to Available List
Return
Calculate Delay Until Next Bus is Available
Wait 'R' Minutes
Test If It Is Initializing Stage
Yes
It Is End of Simulation
Print All Pertinent Statistics (Bus Utilization, Etc.)
Return
Initialize all Parameters & Make Buses Available
Return
Record Which Bus is Available - Note Bus I.D. No.
The Bus is Ready To Execute Demand. Strike That Bus Off Available List
Return

Subroutine "Select"



Subroutine Slice 2