A DYNAMIC SIMULATION MODEL
FOR URBAN MASS
TRANSPORTATION SYSTEMS

by

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ABSTRACT

The urban mass transportation problem (general problem) is described. The problem analyzed in this study, the dynamic trip assignment problem, is derived from the general problem.

A literature survey introduces mainly two types of models for urban mass transportation problems: Optimization models and Simulation models. Different approaches and modelling techniques used for both of them are discussed.

A discrete-time simulation model together with a digital computer program is developed for our problem. The main objective of the model is to employ the existing resources in a near optimum way. A better operating characteristics and service level are, therefore, to be obtained. Alternative urban mass transportation systems to the existing one are developed by changing the characteristics of the system in terms of changed route structures and number of vehicles on each route. Simplifications and assumptions made throughout the model are explained. A list of the computer program is included.

As an illustrative example, the model is applied to the urban mass transportation system of the Anatolian Region of Istanbul. The existing system and five generated scenarios are simulated for 3-hours of real-time operations. Results are summarized and it is shown that the model performs the way we intend it to. The model is efficient with systems having up to 60 nodes in their networks and 200 vehicles.

Conclusions and recommendations for future studies are presented.

ÖZET

Kitle taşımacılığı problemi genel olarak tanımlanmış ve bu çalışmada ele alınan problem, dinamik yolcu yükleme problemi, genel problemden çıkarılmıştır.

Literatür araştırması kitle taşımacılığı problemi için ana olarak iki modeli tanıtır: Eniyileme ve benzetim modelleri. Her iki modelde kullanılan değişik yaklaşımlar ve modelleme teknikleri tartışılmıştır.

Basamaksal bilgisayar programı ile beraber bir ayrık-zaman benzetim modeli problemimiz için geliştirilmiştir. Modelin ana amacı eldeki imkanları daha iyi kullanmak, dolayısı ile daha iyi işletme şartları ve hizmet seviyesi elde etmektir. Mevcut kitle taşımacılık sistemine alternatifler, sistemin hat yapısı ve hatlardaki araç sayısını değiştirerek bulunmuştur. Modelde ele alınan varsayımlar açıklanmıştır. Bilgisayar programının listesi verilmiştir.

Bir örnek olarak model İstanbul'un Anadolu Yakasının kitle taşımacılık sistemine uygulanmıştır. Mevcut sistem ve geliştirilen beş senaryo üç-saatlik bir süre için test edilmiştir. Sonuçlar özetlenmiş ve modelin amacına uygun çalıştığı gösterilmiştir. Model, seriminde 60 düğüme ve 200 araca sahip sistemlerde verimli olarak çalışmaktadır.

Sonuçlar ve daha sonraki çalışmalar için tavsiyelere yer verilmiştir.

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

It is customary to base urban transport systems on the concept of mathematical models. The general philosophy of the modelling process is that there is a regularity in the habits of urban population which establishes certain patterns in the movements of the people. These patterns are detected by the systematic collection and inventory of transportation data, and they are described by mathematical models involving various constants and other parameters related to social and economic characteristics of the population, and the location of various activities throughout the study.

One of the widely used models for urban transportation systems is the simulation models. A major portion of the simulation models focus on the static aspects of urban transportation systems. However, the static assumption that the external inputs to the system do not vary with time may not be applicable in some real life situations. The literature is sparse, there are a few papers on dynamic aspects of urban transportation systems. Some of them are based on the system dynamics approach, i.e., simulation models which consider transportation in some greater and spatial context, while others are devoted to the optimization problems of network flows, total cost of the network, etc.

In this study, a dynamic model to evaluate the performance of urban mass transportation systems is developed and a simulation technique is introduced as a solution technique. It is then applied to a large system, the Anatolian Region of Istanbul urban mass transport system and it is tried to employ the existing resources in a near optimum way.

1.2. OBJECTIVES AND SCOPE OF THE STUDY

The objectives of the study are:

1. To develop a mathematical model of urban mass transport systems with dynamic inputs,
2. To simulate the above model,
3. To evaluate the performance of urban mass transport systems and to employ the existing resources in a near optimum way.

In this study, a discrete-time model for the dynamic aspects of urban mass transport systems is formulated. The methodology basically comprises of differential equations approximated by difference equations for the possibility of digital computer simulation. The model is designed to be applied to large metropolitan areas. The main inputs of the model are the existing network, travel demand, travel time and distance between nodes and the vehicle capacities. Route structure and the number of vehicles on each route must also be supplied to the model. The simulation is carried out to evaluate the performance of the existing system according to various criteria which will be explained in Chapters 2 and 4. Then, the different scenarios are generated by changing the characteristics of the system in terms of changed routes. Finally, the results of these scenarios are compared with each other and with the existing one. It is aimed that these comparisons will lead us to the near optimum way of employing the existing resources.

Computational experience with the model is reported. The model appears to be very promising, it can handle the problems having up to 60 nodes in their networks and upto 200 vehicles.

1.3. ORGANIZATION OF PRESENTATION

The definition of urban mass transportation problem and the problem analyzed in this study are presented in Chapter 2.

In order to place this study in the proper perspective, a review of the most important models for urban mass transportation systems is given in Chapter 3.

Chapter 4 presents the decision criteria, the inputs, the variables and the output of the model. This chapter also deals with the evaluation of the performance of urban mass transportation systems. The computational experience with the model is reported in Chapter 5. An urban mass transportation system of the Anatolian Region of Istanbul is selected for this purpose. Chapter 6 summarizes the study and presents conclusions and recommendations. An Appendix explains the organization of the computer program developed and lists the computer program and the inputs of the system studied in Chapter 5.

CHAPTER 2

DEFINITION OF THE PROBLEM

2.1. THE URBAN MASS TRANSPORTATION PROBLEM (GENERAL PROBLEM)

Urban mass transport systems have recently gained wide attention from people all over the world, specialist and laymen alike. This is brought about with the advent of energy shortages, concern for the environment, and economic considerations, as well as concern for the so-called "transportation poor". These are people who have no access to usage of private auto, either because they cannot affort to own a car or because they cannot drive one. These people, who constitute a far larger proportion of the population than is generally realized, must rely on urban mass transport systems for their transportation needs.

Urban area is the basic component of urban mass transport systems. Urban areas consist of parcels of land occupied by various types of physical facilities, or adapted spaces, that house one or more types of human activities. These adapted spaces are serviced by other types of physical facilities such as transport, water supply, and sewage services. Inurban mass transportation systems, it is common to design a network representing the urban area under study. This network can be classified in different groups, each of them describes it in different details. These details depend on the purpose and volume of the study. In order to describe the network, urban area is first of all divided into a few sectors, then into smaller districts and finally into zones. The zones are the basic subareas used in studies and are chosen so that each has uniform land characteristics. The division of the area into zones is based on two considerations:

a. The size of the zones should not be so large that each zone loses its identity and uniformity of socioeconomic characteristics, and

b. The number of zones should not be so large that the size of networks exceeds the capacity of analytical tools.

In a zone system, all trips of a zone start or end at a point-zone centroid. Zone centroids are only an approximation and it is important that they are reasonably representative of travel activities in their zones. Thus, zone centroids which are also known as nodes, are the most immediate contact individual traveller have with the system. The other component of the network is link. It connects two nodes and it represent the roads of urban areas along which vehicles travel.

Urban mass transport systems deal with the movements of persons in urban areas. In these systems there are two dimensions of urban travel demand that are of interest and these are: the spatial patterns of travel demand that exist throughout an urban region, and the times throughout the day at which spatial patterns of travel demand occur.

The movements of persons are realized by means of a number of modes of travel. The modes of travel that are of interest in urban mass transport systems are usually buses, trolleybuses, metro and waterways. However, there are some alternative modes of travel that must be considered in urban mass transportation planning studies. One alternative is walking which is considered to be available to all travellers. The other alternative is private vehicles and they are considered to be available only to tripmakers whose households own a car. There may be other modes of travel depending on the area under study.

The preferences between these modes of travel are usually determined depending on such factors as the time and cost travel, comfort, safety, etc. So, travel time and distance between nodes and fares are important characteristics of urban mass transportation problems. In order to describe the travel activities properly in urban areas, the route structure and the number of vehicles on each route should also be supplied to the system.

Urban mass transportation systems are complicated systems. They have many features that make their modelling more difficult than other transportation systems. These difficulties reflect the fact that the urban mass transportation network is intrinsically complex than a highway network. This is because a network is not just the set of roads along which vehicles travel. Fares may have a complex structure. Finances are very directly affected by levels of patronage. There is not a simple relationship between the level of service provided by a route and the number of travellers using it. Furthermore, urban mass transportation systems do not offer a door-to-door service, thus major components of journey time are spended in access or to egress from the network. In general, one should go through the following considerations in modelling an urban mass transportation system.

The first thing to do is to define the objective function. The objectives in an urban mass transportation problem usually include one or more of the following considerations:

- Increase the level of service:

The level of service is a measure of the service offered to the customers by the operations of the urban mass transportation systems. It depends on factors such as safety, comfort and travel time of passengers, reliability, speed, frequency and punctuality of vehicles, etc. Some of these factors can easily be quantitatively measured or estimated. For example, the speed of vehicles, frequency of vehicles, travel time of passengers, punctuality of vehicles can easily be estimated in units of time. Whereas it is difficult to define units of measurement for factors like safety and comfort of passengers, reliability of vehicles, etc. Furthermore, it is also quite a difficult job to combine all these factors into a single quantity measure 'level of service'.

- Decrease operating costs and increase revenues:

Operating costs and revenues are measures of the benefit to be obtained from the operation of the urban mass transportation system. They are considered from the viewpoint of system operating staffs. Revenues are directly affected by levels of patronage. The number of tickets sold is therefore the major determinant of revenues. Operating costs depend on the monthly expenditures. Thus, it is possible to estimate these factors in monetary units.

- Increase the flexibility of operations

The flexibility of operations allows to adopt the urban mass transportation systems to future changes in travel demand, road network, transportation technology. It is difficult to define a unit of measurement for this consideration.

- Increase the operational efficiency

The operational efficiency depends on such factors as utilization of vehicles, number of customers served, number of miles travelled, etc. These factors can be easily quantitatively measured.

Above some of the most important considerations that should be included in the objectives of an urban mass transportation system are stated. However, it should be emphasized that it is very difficult to combine all these considerations into a real valued objective function. The main reason for this is that it is impossible to evaluate all relevant factors in the same units and usually there will not be a full agreement about the relative preferences of those factors among the decision makers.

Some constraints on the urban mass transportation problems will always be present. They usually arise from the structure of the system. Below some of the most common of these will be stated.

- Number and type of vehicles may be fixed
- Total monetary investments may not be allowed to exceed a certain level
- Monthly (or weekly) operational expenditure may be limited
- The physical road system (network configuration) may be fixed

- The route structure may be fixed
- There may be upper and lower bounds on flows on some roads
- There may be lower bounds on the number and frequency of vehicles to certain areas.

Also some of the factors explained in analyzing objectives may be appearing as constraints. For example, frequency of vehicles, safety level of passengers, utilization of vehicles may become constraints in an urban mass transportation problem.

The modelling of urban mass transportation systems also require some critical simplifying assumptions and observations about the operation of the system. Same of these are:

- In reality the travel demand changes Continuously with time. However, in most models it is assumed to be constant over certain periods of time.
- In reality the travel demand depends on (increases with) the level of service. Again, in most models it is assumed to independent of the level of service.
- In most models, path choices of travellers is drastically simplified.
- Factors like walking time, transfer time are quite important in the real systems.However, in most models they are very lightly treated.
- In reality the travel demand depends on (decreases with) the cost of travel. Whereas in most models this relationship is ignored.

The classification of the variables and parameters of the urban mass transportation problem is also important. The distinction between the variables and parameters largely depend on the objectives of the problem. Some of the possibilities are:

- travel demand
- travel time and distance
- number of vehicles of the routes
- capacities of the vehicles.
- route structure
- walking time
- cost of travel
- number and location of stops

3.2 PROBLEM ANALYZED IN THIS STUDY

Our problem provides in sight into the operation of the urban mass transportation system at two levels:User-benefit and operational.

At a user-benefit level, the objective is to increase the level of service. This objective consists of the following elements:

- Number of waiting passengers
- Total travelled time
- Capacities offered on links

At an operational level, the following elements are considered:

- Utilization of vehicles
- Number of transported people
- Number of tickets sold
- Passenger - Km
- Total travelled distance

The constraints on our problem:

- the number of vehicles are fixed
- the location and number of stops are fixed
- the capacities of vehicles are fixed.
- the physical road system is fixed.

The following constraints are not considered in our problem.

- A financial constraint on operating expenditure
- Upper bounds on link flows

The critical simplifying assumptions and observations in our problem are as follows:

- There is no relationship between the level of service provided by the urban mass-transportation system and the number of travellers using it.
- Walking and private-car are not considered as alternative modes of tr
- The travel demand is assumed to be constant for certain periods of time.
- Travel time, waiting time and walking time does not affect the path choice.

- Congestion is not treated.
- All transportation activities occur at nodes.
- Fares and other factors such as comfort, safety of passengers, reliability of vehicles do not affect the travel demand.

The other simplifying assumptions made in the path choice of passengers, loading and discharge processes will be explained in detail in Chapter 4.

The problem presented above is, in general, known as a dynamic trip assignment problem. In order to state our problem accurately, more information about the dynamic trip assignment problem will be given.

In the dynamic trip assignment, we are given a transportation network and a set of ordered pairs of points on the network that are called origin-destination (O/D) pair. For each (O/D) pair, there are given $GEN_{ij}(t)$ and $V_{ij}(t)$, $0 \leq t \leq T$: where $GEN_{ij}(t)$ is the rate which denotes the number of passengers generated at i to go to j for time period t, and where $V_{ij}(t)$ is the rate at which vehicles leave i at time t to go to j and T is the planning horizon. The assignment problem is to determine the passenger and vehicle flows on the links of the network satisfying specified conditions.

When the inputs, $GEN_{ij}(t)$ and $V_{ij}(t)$ vary with time t (as is really the case in most real life situations) the problem considered is a dynamic one. However, the surveys that must be undertaken to develop the dynamic inputs require long time, and, in addition, validating and processing them takes a considerable amount of effort. Time and money are limited for every study. So, some static inputs may be approximated as dynamic, particularly for large study areas and long planning horizons.

In our problem, the planning horizon T is divided into equal time intervals of suitably small length and the individual periods are denoted by $\{t|t= 1,2,...,T\}$. It is assumed that each link has a constant $BOARD_{ij}(t)$ denoting the number of boarding passengers at node i to go to j during period t and $CHANGE_{ij}(t)$ denoting the number of alighting passengers at node i to go to node j during period t. Furthermore, it is assumed that the number of boarding alighting, transferring and waiting passengers at node i at time t are deterministic and derived directly from the vehicle frequencies, capacities and travel demand between nodes. Let the state variable describing the number of waiting passengers at node i to go to j for time period t be $WAITP_{ij}(t) \geq 0$. The undamental state equations of the problem are:

$$WAITP_{ij}(t+\Delta t) = WAITP_{ij}(t) + \Delta t\ (GEN_{ij}(t)$$

$$+ CHANGE_{ij}(t) + BOARD_{ij}(t))$$

The initial conditions for the equations should be given.

In our problem, the objectives can not be measured in monetary units, and so the question of employing the existing resources in near optimum way must find expression through a value judgement. The individual measures of value associated with the system outputs is not given in our problem.

In this chapter, we have defined the urban mass transportation problem and the problem analyzed in this study. The types of approaches used in urban mass transportation planning studies and the modelling techniques will be discussed in the next chapter.

CHAPTER 3

URBAN MASS TRANSPORTATION MODELS
-- A SURVEY --

Urban mass transportation models are usually divided into two main groups; simulation models and optimization models. Different modelling and solution techniques can be applied to each of them. In this chapter, we will discuss, firstly, the type of approaches available for urban mass transportation planning process. Then, simulation models and optimization models will be compared according to the areas in which they are used. However, it is not the purpose of this chapter to give an exhaustive representation of all approaches, but only the most outstanding ones from the literature will be discussed.

3.1. SEQUENTIAL VERSUS AGGREGATE APPROACHES

These approaches require the study area to be divided into zones, furthermore, the network must be described as a set of nodes with interconnecting links.

I. Sequential Approach

The sequential approach is a common framework of a large variety of models. It does not describe individual travel or traveller but traffic flow and does not reflect the way traveller making decisions about the travel. For example, travel demand generation does not depend on the quality of transportation network |22,32|

The four successive steps are involved in this approach for transportation planning study:

1. Trip Generation
2. Trip Distribution
3. Modal Split
4. Route Assignment

These steps are generally applied in the indicated order, but some changes in this order may occur, e.g., the steps 1, 2 and 4 may be applied for each mode.

1. Trip Generation

The purpose of this step is to calculate the number of trips originating and destinating in each zone, in other words, the number of trips produced and attracted by each zone |5,22|.

The initial task of this step is to identify the trip types important to a particular planning study. The first level of trip classification used normally is a broad grouping into home-based and non-home-based trips. Home-based have one end of a trip at a household. Typical home-based trips are journeys to work, shopping and school. Examples of non-home-based trips are trips between work and shop and business trips between two employment places.

A number of studies have shown that a large percent of trips are produced by residential areas and attracted by employment centers, retail services, recreational areas and schools. So, the trips are produced by households whether they be origins or destinations. Households may be characterized in many ways but a large number of studies have shown that the following variables are the most important characteristics with respect to the major trip types such as work and shopping trips (1) the number of workers in a household, and (2) the household income, or some proxy of income, such as the number of cars per household.

Many of the trip attraction equations were developed in terms of floor areas such as retail floor area, service and office floor area. There have been difficulties in using floor area as the independent variable since the floor area consumed per employee varies between establishments and time. Other factors influencing trip attraction such as social and recreational trips, are not as well understood.

The trip-generation analysis method used commonly to date is regression analysis. Travel and land-use data may be analyzed using stepwise computer-based regression analysis programs.

A second method of trip-generation analysis is category analysis. Category analysis is simply a technique for estimating the trip-production rates for households which have been sorted into a number of separate categories according to a set of properties that characterize the households.

2. Trip Distribution

The purpose of this step is to obtain an O/D (Origin-Destination) matrix with entry (i,j) indicating the number of trips from zone i to zone j.

Any trip-distribution matrix which is synthesized during this step must satisfy the production and attraction trip end constraint equations. At the production end, the sum of the trip interchanges to all attraction zones must be equal to the trip-production magnitude estimated during this step. At the attraction end, the sum of the trip interchanges from all production zones must be equal to the trip-attraction magnitude estimated during the previous phases for all zones |4,25,26|.

In many of the earlier studies, growth-factor techniques were used. The Fratar growth-factor method is the most common one. This method estimates a horizon-year origin-destination matrix by assuming that this trip matrix is proportional to the base year matrix modified by the trip-end growth patterns of the zones under consideration. The basic deficiency of the technique is that the trip matrices estimated by the technique are not sensitive to changes in the properties of transport networks.

Three trip-distribution models are also available as the gravity model, the intervening opportunities model, and the competing opportunities model, which may be classified as stochastic trip distribution models. These models estimate trip distribution patterns by synthesizing a matrix containing the probabilities that a trip produced in a given zone will find an attraction opportunity in a specific destination zone. These probabilities are derived from the knowledge of the distribution of attraction opportunities in an urban area and travel time properties of the area. Each of the three stochastic type trip distribution models calculates these probabilities in a different way.

Another method for trip distribution is the entropy method. It uses the gravity model in conjunction with trip ends which have been disaggregated into an individual traveller.

The transportation problem formulation of linear programming has also been used for trip distribution analysis. The objective function is to minimize the total amount of travel time in moving between origin and destination zones for tripmakers. The distribution of trips is subject to the two trip-end constraint equations referred to earlier in this section.

3. Modal Split

The purpose of this step is to develop a procedure that simulates the manner in which tripmakers travelling between an origin and destination pairs will choose between the diffe-rent modes of transportation |5,22,27|.

The earlier modal split models consider all travellers, but it is now common to partition the travellers into two groups: captive tripmakers and choice tripmakers. Captive tripmakers are defined as those persons without access to a car for a particular trip, while choice tripmakers are those persons with access to a car.

The early modal split models were of two types: trip-end and trip-interchange modals. Trip-end models are used between the trip generation and trip-distribution steps and tend to emphasize captive riders, while the trip-interchange models are used between the trip-distribution and route-assignment steps and focus principally on choice riders.

A number of observers have pointed to the lack of sensitivity of the earlier modal split models as well as to the absence of any sound behavioral basis to the models. An improved basis for modal split estimation is provided by the concept of the generalized cost of travel in combination with a binary choice stochastic modal split model.

The transportation modes are described by the concept of generalized cost which includes time spent in the vehicles, waiting time, the number of interchanges, the fare paid and other factors such as convenience, regularity, safety, etc. Generalized cost is developed from some weighted linear combination of the above factors. Thus, when considering optional modes for a certain trip the generalized costs associated with each of the modes are calculated. The simplest decision criteria is to assume that all trips will be made by the cheapest mode. An alternative to this deterministic approach is to assume that the trips distribute themselves on the alternative modes depending on the ratio of generalized costs of each mode. However, the general form of the interdependence between generalized cost and modal split has not been developed yet. This is presumably due to the fact that our knowledge about what is conditioning travellers' choice of mode is very limited, e.g., trip purpose, trip length, traveller characteristics affect the choice of the optinal mode.

4. Route Assignment

The object of the route assignment step is to distribute the trips made by each mode between each origin and destination pair over the links of their respective networks |5,7,15,22|.

The route assignment step is in every way equivalent to the modal split step, a certain trip is to be undertaken and a choice is made among alternative routes from the origin to the destination of the trip. Thus, the route assignment models are also based on the concept of generalized costs. One of the principal deficiencies of the sequential models is that the modal split calculation presupposes that the costs of each mode for a certain trip is known. However, the costs depend on which route is applied and the route is not found until the last step in the sequential models, the route assignment step.

Many route assignment models assign all trips between an origin and destination to a single shortest time path (or other measures of disutility). These "all-or-nothing" assignment models are computationally very efficient, but do not reflect traveller behavior. Also, the resulting assignment can be very sensitive to small changes in link travel times. To overcome these shortcomings, many multipath assignment models have been developed. These models allocate trips between a particular origin and destination to several good paths and can be divided into two approaches: capacity restraint models which consider congestion effects on travel time and models which do not. Many of the models which consider congestion effects iterate with an all-or-nothing model to obtain multipath assignment. Those models which do not consider congestion effects use many methods to obtain multiple paths:ranking paths, random selection methods, etc. Many of these models require enumeration of paths.

Sometimes, it is necessary to consider a capacitated network in which link flows must obey the enequalities:

$$0 \leq F_{ij} \leq U_{ij}$$

The quantities U_{ij} are link capacities and, with little loss in generality, can be assumed to be positive integers. The above inequalities are generally applied to the optimization models as an additional constraint in the route assignment.

In studying realistic assignment problems, it is imperative to take into account the effects of traffic congestion by allowing travel costs to increase with traffic flow. The relation between the traffice flow and the travel costs has been discussed, and various algorithms have been proposed. One of them is developed by Smock |23| and it is an iterative procedure containing two main steps. In the first step, the costs are assumed to be fixed and the load of every link in terms of routes is calculated. The second step recalculates the costs of every link according to the load just found. The algorithm terminates when there is no difference in route assignments between the two iteration. Let k be the iteration numbers and let (i,j) be any link in the network. Then,

$$F^k(i,j)=g((i,j),C^k(i,j)) = \text{the flow in link } (i,j) \text{ with the cost } C^k(i,j)$$

$$\ell^k=(i,j) = \frac{1}{k}\left(F^1(i,j) + \dots F^k(i,j)\right) = \text{the load in link } (i,j)$$

$$C^k(i,j) = h\left(\ell^{k-1}(i,j)\right)$$

The letters g and h are generally analytical forms which should be defined before any practical application.

There is a general attitude among transport planners that the all-or-nothing assignment technique provides adequate information for transport planning that is undertaken for conditions expected some 20 years ahead. The more-sophisticated assignment techniques can probably be justified for shorterrun traffic engineering problems.

II. Aggregate Approach

The aggregate approach is just an aggregation of the four steps of the sequential approach into one step.

The theoretical foundation of the aggregate abstract mode models is the theory of equilibrium which is taken from economics, between the supply and the demand. The main idea is for a certain transportation the service level will decrease for an increase in travel demand and the travel demand will increase for increasing service level, and an equilibrium results from the interaction between these two effects.

The models based on this approach find the number of trips between each zone by each mode of the transportation system as a function of several variables such as the mean income of origin zone, the number of inhabitants in origin zone, the frequency of each mode, the travel time between zones by each mode etc. at a single step |5,11,21,22|.

One of the earliest models to be introduced was that developed by Quandt and Baumol |5|. It has the following form:

$$t_{ij}{}^{m} = ap_i^b \, p_j^c \, q_i{}^{e} \, q_j{}^{f} \, f(d_{ij}{}^{m}) \, f(z_{ij})^{m} \qquad (3.1)$$

where $t_{ij}{}^{m}$ - the number of trips between zones i and j by mode m.

p,q - characteristics of zones i and j such as population and employment which are determinants of travel demand.

$d_{ij}{}^{m}$ - the travel time by mode m between zones i and j

z_{ij}^{m} - the generalized cost of travel by mode m between zones i and j.

Equation (3.1) is linear in the logarithms of the variables and the parameters a,b,c,e and f may be estimated from empirical data by multiple regression analysis.

If we compare aggregate models and sequential models empirically, this does not show any difference between these two model types in their ability to reproduce an existing travel pattern, e.g., an O/D matrix. However, the principal advantages of the aggregate ones are the introduction of a new mode of travel easily in the model context and forecasting travel demand and modal choice magnitudes jointly and not independently.

The level of trip-making is assumed to be too sensitive to the quality level of the transportation system in the aggregate models. This would result in overestimating the effects of changes in the system in the future. Although, the validity of the aggregate model can be questioned, this model is able to reveal the structure of the travel demand as a whole.

3.2. NON-BEHAVIORAL VERSUS BEHAVIORAL APPROACHES

The behavioral-type approach is based on the behavior of the individual choice. The basic assumption of this approach is that the individual traveller will minimize the generalized cost or disutility function subject to some constraints such as time, money, etc; depending on his travel purpose |5,22,30|.

Two types of assumption can be applied for behavioral approach. The first one is the deterministic assumption which claims that the individual traveller will select the feasible combination of goods that minimize his disutility and assumes that all individuals will act in the same way against a certain stimulus.

The second one is the stochastic assumption which assumes that different individuals with identical travel demand will respond differently to the same supply of transportation.

One of the attractive qualities of the behavioral approach over the non-behavioral one is that, it includes the behavior of the individual travellers as the factors controlling the trip, the modal split, etc. into the models. This type of a model is also independent of the zoning system, especially in the calibration stage and use a relatively limited amount of survey data.

The focus of behavioral type-models is on individual behavior rather than zonally aggregated behavior, but the need for an explicit aggregation arises in order to expand the decisions to the level of the desired macro (zonal) level applications. Several of such aggregation procedures exist |5|.

3.3. STATIC VERSUS DYNAMIC APPROACHES

All approaches reviewed so far in this chapter are static, so the models will also be static (stationary) models. They try to reach an equilibrium, e.g., between the travel demand and the supply of transportation, but if the delays are considered, the state of equilibrium may never be reached. The dynamic approach considers the existence of delays. Although the dynamic approach is rarely seen in transportation planning area, some models have been set out using system dynamics simulation methodology |16,17,18,31|.

The system dynamics models take the transportation system as only a smaller part of the greater geographic and economic system |18|. Application of the system dynamics models on real life situations are still lacking. This is partly due to the estimation of feedback loops which are the fundamental elements in system dynamics. Our knowledge about the feedback loops is still not sufficient.

Dynamic approach is also used in the transport network optimization problems. Many transport networks have to be made for many situations at different times and these networks and situations have strong relationships with each other. One example of this type of problem was stated as follows: |25|

$$\max_{C(t)} \int_{t_o}^{t_e} S_t(X(t),\ C(t))\,dt \tag{3.2}$$

subject to:

$$\begin{aligned} &AX(t) = 0, \quad X(t) \geq 0 \\ &G_t(X(t),\ C(t)) = 0 \qquad\qquad \text{for } t_o \leq t \leq t_e \\ &H(X(t),\ C(t)) >, = , < 0 \end{aligned}$$

in which

C(t) - (vector of functions of the) dimensions of the links

X(t) - (vector of functions of) traffic flows.

S_t - social surplus function for period t

G_t - set of functions describing the behavior of the travellers in period t

H - set of remaining constraints

t_o - starting point of time

t_e - ending point of time.

3.4. SIMULATION MODELS VERSUS OPTIMIZATION MODELS

We have discussed a number of approaches used in transportation planning study in the earlier sections. It should be noted that they are the complements of each other in designing urban transportation models. A complete transportation study demands a combination of one of the two approaches discussed in Sections 3.1. 3.2 and 3.3. e.g.. in the modal split step of the models which are based on the sequential approach;behavioral or non-behavioral approaches and dynamic or static approaches should be applied.

Simulation models are applied extensively in every type of urban mass transportation problems. Optimization techniques, however, are generally used for the control and guidance of transportation systems. There is a considerable agreement that insofar as optimization methods are relevant to transportation plan development, their role should be restricted to that of generating broad alternative network configurations and constraints should be used to determine some first approximations to transportation network plans. On the whole , however, there appears to be an agreement that mathematical programming and perhaps even optimal control methods could be useful in the design phase, keeping in mind that subsequent analysis, evaluation and adjustments to the inital design would be developing urban transportation studies concerned with investment or improvement problems largely using the optimization technique.

Optimization techniques are used generally in the following areas:

3.4.1. The Design of Transportation Networks

This problem can be formulated in many different ways considering different initial conditions, system behavior, primary objectives, and constraints. The different algorithms are also available for solving the model set up |5,22,25,26|.

It must be pointed out that the feedback between traffic assignment and trip distribution is essentially important in the evaluation of new networks. Most trip distribution models use as parameters the interzonal travel times or costs but in general these depend on the network and the traffic assigned to it. Thus, the output of the traffic assignment program is required as an input to the trip distribution program. On the other hand, the output of trip distribution program, giving the interzonal trips, forms an essential input to the traffic assignment program.

The objective of the models can be to find the optimal geometry of the new network, the optimal expansion of the network or the optimal improvement of the network and the constraints are usually to minimize travel cost, building cost, road investment and maintanence costs. An example of this type of study was given in Section 3 of Chapter 3.

3.4.2. Optimal Scheduling

Scheduling methodology applied to virtually all modes of transportation, especially buses. This methodology defines the routing network of the urban transportation and finds the frequency by which each route is served |5,25,26,27|.

For the problems of public passenger transportation in urban areas, the models set out will be more complicated. The desire of applying optimization techniques to real size problems results in some heuristic optimization algorithms.

CHAPTER 4

A SIMULATION MODEL

Based on the assumptions and structure defined in Chapter 2, a discrete-time simulation model for dynamic trip assignment problem is developed. In this section, this model will be presented.

4.1. INPUTS OF THE MODEL

4.1.1. Network Description

In the model, each node is denoted by lower case letters i,j,... = 1,2,...,NSTOP, where NSTOP is the total number of nodes. Nodes are the reference points by which the system is organized. A link joining node i to node j is denoted by (i,j).

4.1.2. Travel Demand

The travel demandis represented by an NSTOP x NSTOP matrix which is called GEN in the model. The entry (i,j) of this matrix gives the number of trips made between node i and node j per minute.

4.1.3. Travel Time and Distance

The travel time and travel distance are defined with the matrices ITIME and IDIST which both are NSTOP x NSTOP matrices. The (i,j)th entry of ITIME gives the travel time in minutes between node i and node j, and the (i,j)th entry of IDIST gives the travel distance by vehicles in kilometers between node i and node j. However, if there is no direct connection between these nodes, the value assigned to the corresponding entry will be zero for both matrices.

4.1.4. Definition of the Routes and Vehicles

In the model, paths represent the routes. All paths are directed paths The direction of the route should be given, i.e., the starting and ending terminal stops may not be the same. Thus, the same geographical route will always take two different path numbers depending on the direction.

The routes are defined with the route-stop matrix NPASS. Let NTR be the total number of routes and MAXD be the maximum number of stops that one vehicle can pass on its route. The route-stop matrix is an NTR x MAXD matrix. The routes are denoted by lower case letter ir = 1,2,...,NTR. In the array of each route in the route-stop matrix, all stop number are tabulated starting from the terminal stop. If the number of stops of one route is less than MAXD, zeros are assigned in the array in order to increase the number to MAXD.

Each vehicle is represented by a lower case letter $\ell = 1,2,\ldots,NBUS$, where NBUS is the total number of vehicles. In the model, it is assumed that the vehicles follow the same routes during the planning horizon. The route numbers of the vehicles are loaded to a matrix IROFB and this matrix is an NBUSX2 matrix. The capacity of the vehicles are stored in an array CAP.

4.1.5. Time-Table

The time-table is an NBUSXNSTOP matrix that shows which vehicle will be at which stop at which time. The time of initial departure of each vehicle from the starting terminal stop should be supplied to the model initially. This is realized by using the time-table matrix. For each vehicle ℓ, the initial departure time from stop i is assigned to the entry (ℓ,i). Zero will be loaded to the other entries.

As explained in the previous section, the vehicles follow two different routes during the planning horizon. When the vehicle arrives at the ending terminal stop of its route, the route number of this vehicle is changed. In real life situations, the vehicle spends some time in order to change the route. In the model, these values are assumed to be known initially and are loaded to a NSTOP array - TIMSP.

4.2. FUNCTIONING OF THE MODEL

In this section, we will present the operation of the model based on the assumptions made in Chapter 2 and the inputs described in the previous sections of this chapter.

Initially, it is assumed that each individual traveller knows the route numbers which serve between his origin-destination pair. The path choice criteria will be explained in Section 3 in detail.

The main loop of the model is time. Time increment is one minute. For each minute, the following steps are carried out;

I. Each node of the network is examined separately. (Let the node under examination be i)

The time-table matrix is employed to determine whether there is an arriving vehicle(s) or not. For this purpose, the column i of this matrix is checked for every vehicle. If the value of ITABLE(ℓ,i) isequal to the period of interest, it means that vehicle ℓ is at node i for this period. So, two steps will be carried out:

I.1. No vehicle arrives node i

- Increase the number of waiting passengers at node i by the generated amount given as an input for this period.

I.2. There is an arriving vehicle(s) at node i:

Node i may be the starting or ending terminal node of the vehicle(s). So, three cases will be examined.

I.2.1. Node i is the starting terminal node.

- The available capacity is equal to the actual capacity of the vehicle.
- There is no disembarking passengers.
- Some waiting passengers board this vehicle according to the path choice criteria. The boarding process requires some simplifying assumptions and they will be explained in Section 4 in detail. This process reduces the number of waiting passengers.
- The time-table matrix is updated. Let the next node of vehicle ℓ on its route be j. Then, the (ℓ,j)th entry of the matrix which shows the time at which ℓ will be at stop j is calculated as follows:

$$\mathrm{ITABLE}(\ell,j) = \mathrm{ITABLE}(\ell,i) + \mathrm{ITIME}(i,j)$$

- The available capacity of the vehicle is decreased by the number of boarded passengers.

I.2.2. Node i is the ending terminal node.

- All passengers of the vehicle disembark. This process will be presented in Section 5 in detail.
- There is no boarding passengers.

- The route number of the vehicle is changed by using the IROFB matrix. Node i will be the starting terminal stop of the vehicle.
- The time-table matrix is updated. The initial departure time of the vehicle from node i is calculated. The new value is:

$$ITABLE(\ell,i) = ITABLE(\ell,i) + TIMSP(i)$$

- The available capacity of the vehicle is equal to the actual capacity.

I.2.3. Node i is the intermediate node.

- The availabe capacity is increased by the number of alighting passengers.
- Some passengers board the vehicle.
- The time-table matrix is updated as in the case I.2.1.
- The available capacity of the vehicle is decreased by the number of loaded passengers.

At the end of Step I.2, the number of waiting passengers at node i is increased by the number of generated passengers for the time of interest.

Step I is carried out for every node of the network separately. When this process is completed, the time is in-

increased by one minute, and Step 1 is applied for every node once more for the new time of interest. These processes continue till the end of the predetermined planning time.

Functioning of the model will be understood more clearly when the path choice, loading and discharge criteria are understood more clearly. They will be explained in the next three sections.

4.3. PATH CHOICE CRITERIA

A key assumption made in the model is that, in travelling from one part of the urban mass transportation network to another, all passengers will use the same geographical paths. This assumption is a common one in transportation studies, however, the way of finding these paths differs among them.

In most of the models, the path used is the one that has the minimum generalized cost. It is assumed that a trip consists of a number of different components, each of which has its effect on travellers' decisions. The components are in general, walking time, waiting time, time spent in the vehicle(s), the fare paid and the number of interchanges. These components are all to be reduced to one measure through interpretation as elements of generalized cost. When the calculation of the generalized cost of each path is completed, a shortest path algorithm is used for finding the minimum generalized cost path. Although, there are some substantial differences in approach, finding the shortest paths is a common procedure |12,25|. The concept of generalized cost has been subject to many criticisms, furthermore it has been suggested that this approach suffers from a number of theoretical and practical weaknesses |30|. However, over the last ten years, this concept has been gaining an increasing hold in both the theory and practice of transport planning. Generalized cost owes its popularity inlarge part to its simplicity. In particular, the large scale simulation models that are cornerstone of many transportation planning studies would be unworkable if a single index of this kind were unavailable.

In this study, we use another approach which is simpler and more adequate to our model. It is mainly based on the knowledge of the route structure. We would like to give some definitions before introducing our approach: As far as the individual traveller is concerned, a direct journey isa journey that can be made without changing vehicles. The alternative to a direct journey is a trip using at least two vehicles. An additional waiting time and interchange cost will, therefore, be incurred.

In the model, it is assumed that the individual traveller will always choose a journey that can be made directly, i.e., he chooses a trip that can be made without changing the vehicles. This is the case if there is a vehicle that runs between his origin-destination pair. If so, the path chosen will be the one which is followed by this vehicle. There may be more than one vehicle connecting the (O/D) pair directly and following the different paths. Thus, the path that he chooses may be more than one.

When a direct journey is not possible, the interchange of vehicles is necessary. It is assumed that the interchanges can only be made at the proper junctions. Junctions are the nodes where more than two links intersect. The junction is proper only if the direct journey is possible from this junction to the destination point of the traveller.

It is assumed that the travellers' preferences do not affect the level of service, the route structure and the number of vehicles on each route.

In the model, the path choice is carried out in two steps:

1. In this step, the direct journeys are determined in terms of route numbers. We can find the direct journeys by examining the arrays of the route-stop matrix - NPASS. The route numbers that serve between each pair are stored to the cell associated with thi pair. So, the individual traveller decides to

board the arriving vehicle at his origin stop or not from the knowledge of these data and the route number of the vehicle.

Let us explain this step with an example: Assume that the following route-stop matrix is given

NPASS(2,3)

$$\begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1 & 3 & 6 \\ 2 & 2 & 4 & 8 \end{array}$$

Let us examine the array of route 1. The vehicle which has a route number of 1 follows the path 1-3-6. So, the direct journeys between node 1 and node 3, and node 3 and node 6 can be made with this vehicle. In this step, route number 1 is stored to the cell of (1,3) and (3.6).

If the vehicle has a route number 2, the direct journey between node 2 and node 4, and node 4 and node 8 can be made with this vehicle. So, the number is stored to the array of (2,4) and (4,8).

2. The origin-destination pairs where a journey can not be made directly between them are taken into account in this step. In the model, all junction numbers are loaded to the array JUNC. A new

matrix ADJ is generated in order to help the interchange decisions. The (i,j)th entry of this matrix gives the number of routes connecting node i to node j directly. The entries of the matrix are loaded using the route-stop matrix, NPASS. For the origin-destination pairs considered in this step, first, all routes passing from the origin point are stored somewhere. Then for each route, the following steps are applied.

2.1. The next stop of the route is checked whether it is a junction or not.

   2.1.1. If it is a junction, it is checked whether there is a direct connection between this junction and the destination point of the traveller. The ADJ matrix is employed for this check.

   2.1.1a. If there is a direct connection, the traveller will choose this route in order to go to junction. Thus, step 2.1 ends at this point and the next route number stored is taken into account.

   2.1.1b. If there is not, we return to step 2.1 once more.

   2.1.2. If the next stop is not junction, we return to step 2.1.

The same process is applied to each route. The paths followed by the passengers of Step 2 are composed of two components. The first one is the path(s) of the vehicle(s) connecting the origin point to the adequate junctions directly. The second part is the path of the vehicle(s) connecting the adequate junctions to destination points. In the model, it is assumed that this type of passengers are the passengers between the origin points and adequate junctions, and the route numbers that are stored connects these points directly. When these passengers arrive at the junctions, they are treated as the passengers generated at the junction in order to go to their original destination points.

Let us explain this criteria with a simple example: Assume that the network of Figure 4.1 and the following route-stop matrix are given:

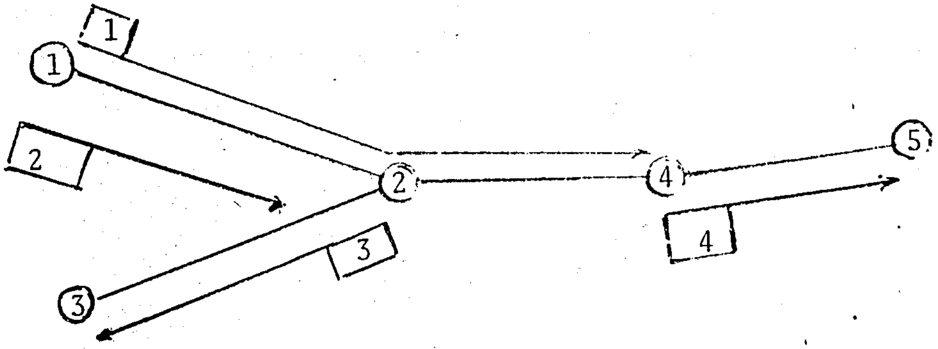

FIGURE 4.1. Direct Journey Path Choice.

$$\text{NPASS}(4,3)\qquad \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 1 & 2 & 4 \\ 2 & 1 & 2 & 0 \\ 3 & 2 & 3 & 0 \\ 4 & 4 & 5 & 0 \end{array}$$

The junction array and ADJ matrix will be:

JUNC(2)   2   4

$$\text{ADJ}(5,5)\qquad \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & 0 & 2 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 0 & 1 \\ 5 & 0 & 0 & 0 & 0 & 0. \end{array}$$

For simplicity, let us examine the passenger at stop 1

1. A direct journey is available for stop pairs (1,2) and (1,4).

Stop Pair	Route Numbers	
(1,2)	1	2
(1,4)	1	

2. The passengers of stop 3 and stop 5 can not make a direct journey. The passengers of stop 3 can take on vehicle 1 and vehicle 2 till the adequate junction

2. On the other hand, the adequate junction is stop 4, for passengers of stop 5, so they can take on vehicle 1.

The route numbers that will be stored are:

Stop Pair	Route Number	
(1,3)	1	2
(1,5)	1	

4.4. LOADING CRITERIA

In a simple one vehicle system, knowledge of demands for each direct journey allows direct calculation of loadings at each stop on its route. The number of passengers getting off at the stop is the sum of demands for direct journey that ends there, the number getting on is the sum of demands for direct journeys that start there, and the number carrying on is the sum of demands for those direct journeys that straddle the link. Thus, loading throughout the route is complete.

Problems arise when vehicles multiply and traverse the same paths for part of their lengths. Where a direct journey can be made by more than one vehicle, demands for that direct journey must be distributed between them. Moreover, path choice decisions at one link are affected by path choice decisions 'upstream' since they will affect available capacity. Thus, at a particular stop, it no longer becomes possible to treat them as relatively simple functions of headway. This is because their prediction must resolve two types of competitive interaction. A simple two-vehicle situation is given in Figure 4.2.

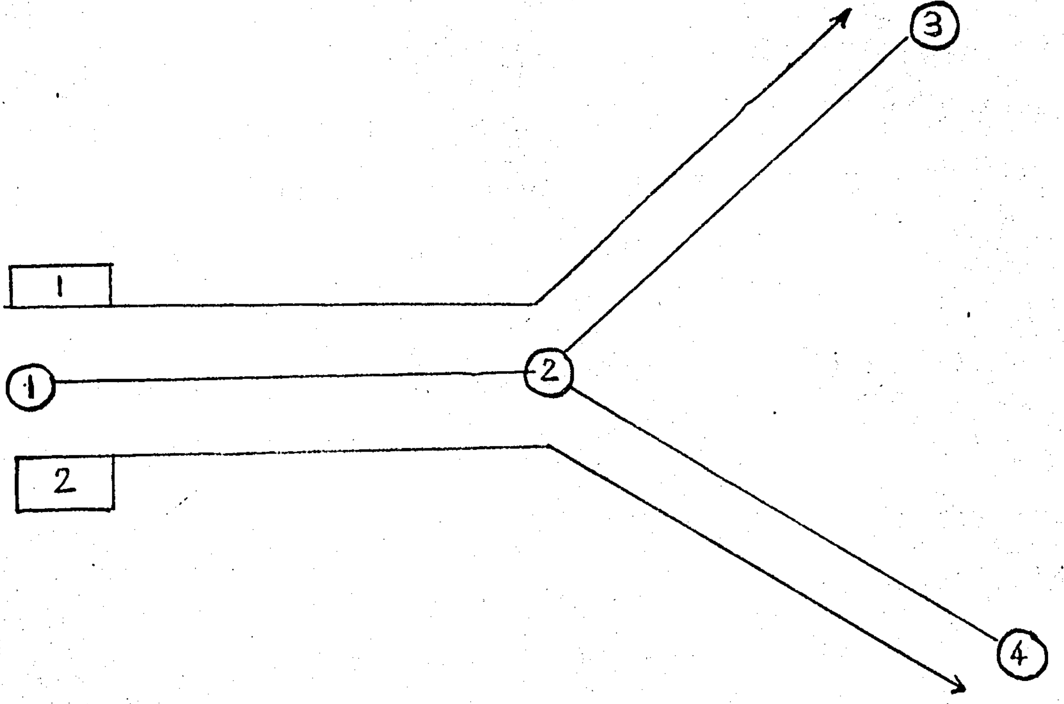

FIGURE 4.2. Simple Two-Vehicle Situation.

First, both vehicles can serve the direct journey from stop 1 to stop 2, so that demand for that direct journey must be distributed between the two competing services. Second, for the direct journey from stop 1 to stop 3, only vehicle 1 is appropriate. However, where capacity is limited, those making that direct journey must compete for seats with the proportion of those making the direct journey to stop 2 that have decided to board vehicle 1. Thus, there is a competition between routes for passengers and between passengers for seats.

In the model, loading of passengers to vehicles is evolved in successive steps. First of all, theavailable capacities of arriving vehicles at each stop are determined for the time of interest. The available capacity of the vehicle, at any stop, is obtained from the summation of the available capacity at the previous stop and the number of alighting passengers at this stop. An array AVSPC stores the available capacity of each vehicle until any change occurs in it.

Then, we are ready for further calculations of the loading process. Two cases will be examined.

1. Assume that only one vehicle arrives at the stop.
   a. If the number of passengers that have decided to board the vehicle is less than or equal to the available capacity: All passengers are loaded.

   b. If the number is greater than the capacity: The passengers are loaded with a weighted percentage. Let TOT be the total number of passengers that have decided to board vehicle ℓ. The number of passengers between stop i and stop j that will be loaded to the vehicle is (L(i,j)):

$$L(i,j) = \frac{WAITP(i,j)}{TOT} * AVSPC(\ell)$$

Let us explain this case with a numerical example. Assume that the network of Figure 4.2 and the following data are given:

WAITP(1,2) = 90

WAITP(1,3) = 30

AVSPC(1) = 40

$$\text{WAITP}(1,2) + \text{WAITP}(1,3) > \text{AVSPC}(1)$$

$$90 + 30 > 40$$

Then, the percentages for passengers of (1,2) and (1,3) is:

$$\text{Perc}(1,2) = \frac{\text{WAITP}(1,2)}{\text{WAITP}(1,2) + \text{WAITP}(1,3)} = \frac{90}{120} = 0.75$$

$$\text{Perc}(1,3) = \frac{\text{WAITP}(1,3)}{\text{WAITP}(1,2) + \text{WAITP}(1,3)} = \frac{30}{120} = 0.25$$

The number of passengers that are loaded to vehicle 1:

$$L(1,2) = 0.75 * \text{AVSPC}(1) = 0.75 * 40 = 30$$

$$L(1,3) = 0.25 * \text{AVSPC}(1) = 0.25 * 40 = 10$$

2. In the second case, assume that more than one vehicle arrives at the stop at the same time. The direct journeys between some stop pairs can be made by more than one vehicle, so demands must be distributed between them. This is done by using a percentage developed from the capacities of competitive vehicles. The percentage for one of the competitive vehicle is just the proportion of

the capacity of it to the total capacity of the competitive vehicles.

For example, consider the network of Figure 4.2. Assume that vehicle 1 and vehicle 2 start the journey from stop 1 at the same time. The following data is given:

WAITP(1,2) = 30
WAITP(1,3) = 50
WAITP(1,4) = 40

AVSPC(1) = 60
AVSPC(2) = 30

Passengers between stop 1 and stop 2 can make a direct journey by both of the vehicles. The distribution of demand to the vehicles is done by calculating the percentage P for each of them.

For vehicle 1: $$P_1 = \frac{AVSPC(1)}{AVSPC(1) + AVSPC(2)} = \frac{60}{30+60} = 2/3$$

For vehicle 2: $$P_2 = \frac{AVSPC(2)}{AVSPC(1) + AVSPC(2)} = \frac{30}{30+60} = 1/3$$

So, the number of passengers that have decided to board for each vehicle is:

For vehicle 1:

WAITP(1,2) = 30 * 2/3 = 20
WAITP(1,3) = 50

For vehicle 2:

WAITP(1,2) = 30 * 1/3 = 10

WAITP(1,4) = 40

Then, the calculations that are presented in case 1.b are carried out for the vehicles in order to find the number of passengers that is loaded to each of them. The number of boarding passengers are loaded to the matrix BOARD. It is an NBUS x NSTOP matrix, and the entry (ℓ,i) indicates the number of passenger getting on the vehicle ℓ in order to go to stop i, i.e., their destination point i. When the passengers are loaded to the vehicle, the stop where they get on is not important for the model. However, the destination point has an importance because it indicates the stop where these passengers will be discharged.

4.5. DISCHARGE CRITERIA

The last question is how, where and when the passengers that are loaded to the vehicles are to be discharged. We know that which vehicle will be at which stop at which time from the matrix called ITABLE. When a vehicle arrives at any stop, there will probably be an alighting passenger if this stop is not the starting terminal stop. There are two types of alighting passengers where each has different affects on the operation of the model.

1. The first type gets off because the stop at which the vehicle arrives is their destination points. The compositio

of passengers of the vehicles is stored in the BOARD matrix. For vehicle ℓ arriving at stop i, the number of alighting passengers will be equal to the value of BOARD(ℓ,i). The available capacity of vehicle ℓ increases by this amount.

2. The second type gets off because the stop at which the vehicle arrives is an adequate junction for the interchange of vehicles. It occurs only if the stop is a junction. If it is not, the followings will not be carried out. All passengers in the vehicle are examined according to their destination points.

   a. If their destination points are on the route of the vehicle, they will not get off.
   b. If not, it is checked whether a direct journey is possible between the junction and the destination point. The ADJ matrix is used for this purpose.

      1. If it is not, the passengers will not get off.
      2. If possible, they will be discharged. From this point on, they are considered as the passengers generated at this stop where destination points remain the same. The available capacity of the vehicle increases by this amount.

4.6. OUTPUTS OF THE MODEL

In this section, we will present the outputs of the model and the meaning of each output so as to help the evaluation of the urban mass transportation systems. All values are produced at the end of the planning period.

1. Waiting Passengers
    a. Number of waiting passengers between each node pair,
    b. Number of waiting passengers at each stop.
    c. Number of waiting passengers on the network as a whole.

These values give us the number of passengers that could not reach their destination points at the end of the planning period. We can find the number of people transported by the system using these values. The number of generated people was given as a rate with the (O/D) matrix. If we multiply the entries of this matrix with the corresponding time units for each time period, the number of passengers that must be served by the system during the planning horizon are found out. So, the number of passengers that reach their destinations is the difference between the generated passengers and the waiting passengers. This value is an important indice to determine the level of service.

2. Boarding Passengers
    a. Number of boarding passengers between each node pair,

b. Number of boarding passengers at each node,
c. Number of boarding passengers on the network.

The number of boarding passengers differs from the number of transported people because the interchange of vehicles has a direct effect on the calculation of this value. The passengers that change the vehicles are included in the system as a newly generated passenger depending on the number of interchanges. So, we can find the number of passengers that change the vehicles during the planning horizon and it is equal to the difference between the number of boarding passengers and the number of transported people. On the other hand, the number of boarding passengers are equal to the number of tickets sold. It is, therefore, an important indice at an operational level.

3. Link Load - Assigned Volume of Vehicles on Each Link:
In this part, the number of vehicles running on each link during the planning period is developed. These values are generally used to compare the alternative networks, e.g., to develop the relation between the passenger and vehicle volumes on every link.

4. Total Travelled Time:
This value gives the time spent by the vehicles of the system in order to transport the people which are calculated in part 1.

5. Total Travelled Distance

It gives the distance travelled by the vehicles. It can be an important indice at an operational level.

6. Vehicle-Passenger x Kilometer:

Passenger-Km is an important indice in determining the service levels. The travel demand and service capacity of the system may also be defined in terms of passenger-Km. Furthermore, it gives the capacity usage ratio of each vehicle.

7. Route-Passenger x Kilometer:

It is similar to the one explained above. In this case, the capacity usage ratio is calculated on the basis of the routes instead of the vehicles.

8. Total-Passenger x Kilometer:

The values obtained in part 7 are totalled for all routes. The comparisons can be made for the network as a whole.

9. Number of Passengers Transported by Each Vehicle.

10. Number of Passengers Transported by Each Route:

The values of part 9 and 10, give the effect of the modifications in route structure on the basis of a vehicle and a route respectively.

11. Capacity Usage Ratio of Each Vehicle:
One of the objectives of our problem is the efficient utilization of each vehicle. This value gives enough information for this purpose. When comparing the alternative systems, the changes in the capacity usage rates should be followed carefully.

12. Waiting time is an important indice used in determining the service levels. The number of waiting passengers for each minute can be easily determined. These numbers are totaled for the planning period. Then, in order to determine the mean waiting time for one traveller, the result is divided to the total number of passengers in the system.

4.7. EVALUATION OF THE MODEL

One of the main advantages of urban mass transportation systems, particularly bus systems, is the flexibility of route configurations. In recent years, the importance of reevaluation and change of routes has been realized. As explained earlier, we have evaluated the effect of these changes on urban mass transportation systems.

Development of alternatives causes problems in the evaluation studies. For small-sized networks, it may be possible to develop alternatives on the basis of intuition, but when the size of the network increases, the increase in both the number of criteria to be used in their evaluation makes it difficult and unreliable to develop alternatives by applying rules of thumb. A consistent, explicit procedure is required in order to identify the alternative course of action that is most likely to meet the stated objectives of the problem.

In designing alternative networks to be tested it is natural to think in terms of contrasts with the existing network. In this study, we have developed three types of alternative networks and these include:

1. The network with a low-frequency and a widespread route structure with many vehicles using very different roads,
2. The network with a high-frequency and a low-spread route structure concentrated on fewer roads,
3. The network with a high-frequency and a low-frequency routes which are combined with a percentage.

However, the development of alternatives must also be based on the experience gained from the operation of the system used for many years.

Another and relatively simple approach in developing alternatives is the alteration of the number of vehicles on the routes without making considerable change in the route structure.

Following the development of alternatives, the next step will be to discuss the value of outputs for each alternative. In this study, we have not attempted to develop a single effectiveness measure associated with the outputs. Unweighted results will ve viewed as the end product of the study. In other words, the implications of each alternative in terms of the outputs that appeared significant have been developed without making any attempt to judge the relative importance of various outputs. The last step of the evaluation, the choice of the best alternatives' is left to the decision makers'. Their choice will be based on the results generated by the model, their own experience and feelings, and their personal preferences among the effectiveness measures.

CHAPTER 5

AN APPLICATION -- A SIMULATION MODEL FOR URBAN MASS TRANSPORTATION SYSTEM OF THE ANATOLIAN REGION OF ISTANBUL

5.1. INTRODUCTION

One of the effective ways of developing the strengths and weaknesses of the transportation model is to operate the model with real life data. Our study incorporates with this type of application. The input requirements for this application were supplied by the study carried out for optimizing the urban mass transportation network of Istanbul by BUTSAE |32|. In this chapter, using some portion of that data, we have simulated the existing and proposed urban mass transportation networks of the Anatolian Region of Istanbul

5.2. INPUTS

5.2.1. Definition of the Network

Urban mass transportation network of Istanbul developed by BUTSAE |32| fulfills the requirements of our network definition

The whole network consists of 142 nodes and it can be geographically divided into two parts. In our analysis, we have used one part of the network, the Anatolian Part. It is presented in Figure A.1 in the Appendix.

Initially, the whole network has been designed as a bus network. Then, for a better analysis, it has been a necessity to introduce the train as a mode of travel. As a result, some buses and trains have started to follow the same paths and their trips have started or ended at the same nodes. On the other hand, two nodes may be connected only by one link. This causes some problems because the road and railways differ in such respects as the time and distance of travel. Consequently, the path followed by trains cannot be defined in terms of the nodes of a bus network. In order to avoid these problems, new nodes have been introduced for some zones. This is realized by introducing the artificial nodes where the distance and time of travel between the artificial node and the original node of these zones are assumed to be zero. At the end, the network of the Anatolian Region consists of 51 nodes.

5.2.2. Travel Time and Distance

Travel time and distance matrices have not been changed and they have been supplied to the model as they are in the study mentioned in Section 1 [32]. Tables A.1 and A.2 of the Appendix give these matrices.

5.2.3. Travel Demand (Origin-Destination Matrix)

In this study, the simulation is carried out for three-hour periods in the morning (between 6:30 and 9:30 a.m.). The (O/D) matrix developed by BUTSAE |32| is for the whole network of Istânbul and presents the total number of trips for three-hour periods. Thus, the following changes in this matrix are evolved in order to adopt it to our model.

1. It is assumed that the travel demand does not vary from minute to minute during the three-hour period, i.e., the demand is uniform. So, all entries of the (O/D) matrix are divided into 180 minutes. The result is an (O/D) matrix for the whole network of Istanbul which gives the number of trips per minute for each node pair.

2. In this case study, we need the travel demand for the Anatolian Region. We can not obtain it from the matrix developed at the end of step 1 because there are trips between the Anatolian Region and the European Region. Two steps are applied in order to obtain the matrix for the region of interest.

   a. All trips originating from the European Region to the Anatolian Region are assumed to be originated from three-nodes of the Anatolian Region.

The reason is that these trips can enter the Anatolian Region only from node 5, node 11 and node 18.

- These trips are distributed among the three nodes with a weighted percentage without changing their destination point.
- The percentage associated with each of the three nodes is developed from the knowledge of passenger volumes of the links connecting the European Region to the Anatolian Region |32| E.g. the percentage for node 5 is the proportion of the passenger volume of the link between the European Region and node 5 to the total passenger volumes of links connecting the two Region.

b. All trips originating from the Anatolian Region and destinating at the European Region are assumed to be deotinated at one of the three nodes.

- These trips are distributed among the three nodes where their origin points remain the same.
- The percentages are developed as in item a. However, the direction of the links and so the passenger volumes are different in this case.

It must be recognized that the (O/D) matrix developed as a result of the above steps gives the number of trips per minute by all modes of travel, i.e., it includes transit trips, private car trips, etc. The modal split step has not been carried out, and this causes some problems. We will discuss this point in Section 4.

The (O/D) matrix obtained for our study is given in Table A.3 of the Appendix with the new node numbers assigned by us.

5.2.4. Route Structure

As mentioned earlier, the only variable of the model is the route structure and the number of vehicles on each route. The routes connecting the Anatolian Region to the European Region are assumed to be started or ended at node 5 of the Anatolian Region which is the single point connecting the two regions. The existing route structure is taken as it is by making a change in the routes of the above type. The alternative route structures are developed according to the criteria explained in Section 7 of Chapter 4. The existing and alternative route structures are given in the Appendix.

5.2.5. Time-Table

The time-table matrix has not been available so we have loaded it. It is a (Number of Vehicles x Number of Stops) matrix which defines the departure time of vehicles from the stops on their routes. It is initially loaded at the start and end points according to the vehicle assignments to the routes. Half of the number of vehicles is assigned to one end, the other half to the other end. The initial departure frequency of the vehicles from the starting terminal stops is found by dividing the number of vehicles to the travel time of the route in one direction. The departure times of the vehicles from the initial stops of the assigned routes filled to the matrix with the periods found above. Then, the matrix is updated for each period by the model during the planning horizon.

Example:

Let (1-2-6-8) be a route with 60 minutes travel time in direction 1 to 8, and 50 minutes travel in direction 8 to 1. The number of buses assigned to this route in both directions is 10.

Initially, 5 buses are assigned to stop 1 and 5 buses are assigned to stop 8. The frequency in direction (1-8) is 5/60 = 1/12 and (8-1) is 5/50 = 1/10. Therefore, the initial elements of the time-table for these 10 buses will be as shown in Figure 5.1.

TIME-TABLE

→ Stop Number

Vehicle Numbers ↓		1	2	. . . . .	8	. . . .
	1	12				
	2	24				
	3	36				
	4	48				
	5	60				
	6				10	
	7				20	
	8				30	
	9				40	
	10				50	
	.					
	.					
	.					

FIGURE 5.1. Time-Table Matrix (Example).

The time spent at the terminal stops for trains is deterministic (15 minutes). For buses, however, no value can be assigned exactly, so we have generated a random variate between 1 and 10. These limits are based on the experience gained from the operation of the system for many years.

5.3. GENERATING THE SCENARIOS

In this case study, it is assumed that the number of buses and trains are constant. Therefore, in generating the scenarios, the route structure and the number of vehicles of the routes are subject to change.

In the existing system, there are two main centers which are node 11 (USKUDAR) and node 18 (KADIKOY). Almost all routes start from these nodes. The route structure is low-frequency with vehicles following long paths. Although predominantly low frequency, there are some high-frequency routes. The existing system includes 186 buses and 9 trains, and 70 routes (68 of them belong to the buses). The existing route structure is given in Table A.4 in the Appendix.

We have used two approaches in generating the scenarios:

1. We have decreased the number of low-frequency routes as much as possible, and as a result the number of high frequency routes has increased. This requires the introduction of new main centers. Two centers, node 9 (ALTUNIZADE) and node 35 (BOSTANCI) are developed for this purpose. These nodes have been selected as a consequence of a careful review of the travel demand and the characteristics of the network. Although, some routes of the existing system have remained the same, the number of vehicles on them has been altered.

2. We have modified the number of vehicles on the

routes of the existing and proposed systems without making a considerable change in the route structure.

Initially, the existing system has been simulated. The results appear in Table A.10 in the Appendix. The, five scenarios have been generated considering the results of the simulation, and the approaches mentioned above. The differences between the scenarios can be seen more clearly if the route structure of each scenario are examined one by one from the tables indicated below:

First Scenario: Some bus trips have been changed and some buses have been allocated to the new centers. However, this scenario does not differ very much from the existing one (Table A.5).

Second Scenario: Existing route structure has not been changed, but the number of buses of some routes has been changed (Table A.6).

Third Scenario: The number of buses and the sequence of stops of some routes of the existing system have been changed (Table A.7).

Fourth Scenario: The existing route has been modified completely based on approach 1 (Table A.8).

Fifth Scenario: The frequency of the routes of the fourth scenario has been increased, new high-frequency routes have been introduced. Thus, the vehicles follow short paths in this scenario (Table A.9).

It is obvious that the above presented scenarios are only a small percentage of the number of different scenarios that can be developed. A different and better scenario may be generated from a better comparison of the results of the scenarios and more information obtained from the operation of the system for many years. However, we believe that these scenarios are sufficient to show that the model will be helpful in employing the existing resources (vehicles) in a near optimum way.

5.4. RESULTS AND DISCUSSIONS

All results produced from the scenarios are in the form presented for the existing system in Table A.10 in the Appendix. However, the results of the five scenarios are given as a summary in Table A.11. The comparison of the alternative systems is presented as a summary in Table 5.1 in terms of a number of effectiveness measures.

The model developed has some weaknesses which some of them were discussed in the earlier chapter while others will be explained in the next chapter. However, there are some weak points particular to this case study. The most important ones are as follows:

1. In this application, the travel demand, i.e., the number of trips between (O/D) pairs is 324, 700 for 180 minutes. This number includes the trips of all modes of travel, such as, private car trips, transit trips, etc. However, the modes of travel are buses and trains in this application. Then, the passengers of other modes are assumed to be the passengers of them. Therefore, the number of passengers that want to make their trips by buses and trains are quite large in all of the scenarios. If the modal split had been carried out, there would be a different (O/D) matrices for each mode and the results would there, be more meaningful. The performance of the systems would be determined more accurately.

If we review the results, it can be seen that the number of passengers that have reached their destinations is about 25% of the total number at the end of 180 minutes. The performance of the systems is not so low in reality. While discussing the results, this point should be taken into account and the relative values of alternatives should be used in comparisons.

2. Another weak point of this application is in the assumptions made for developing the time-table. It is assumed

that the system starts to operate at 6 o'clock and nothing that changes the state of the system occurs up to this time. This assumption is not true in real life situations. Travel demand starts earlier than 6 o'clock and some vehicles will be at the second, third, ... stops while others will be continuing their trips at this time. Similarly, the system has been stopped at 12 o'clock although it is in operation. The assumption made in finding the departure frequencies is also not true in real life situations.

However, it has been necessary to use these assumptions since no alternative data was available.

3. Another weak point in the model is to assume that all trips between the Anatolian Region and European Region are distributed among the three nodes of the Anatolion Region with the same percentage. It is obvious that the distribution percentages differs between zones. For example, all trips of one zone of the European Region can enter the Anatolian Region from node 5.

In this section, we will roughly discuss the results of Table 5.1. It should be pointed out that these results are only a summary and a better discussion can be made with the detailed results. The effect of modifications in route str tures must be observed for each route and each vehicle. Furthermore, assigned volume of vehicles and passengers on each link of the network must be observed for the alternatives. The detailed study assists to develop the performance of the systems more precisely, e.g., in maximizing the accessibility to the system from all zones of the network.

As mentioned earlier, the model generates values for a number of effectiveness measures. Decision makers can develop a single composite effectiveness measure and this also assists in a better comparison. To give an example of how the decision maker should proceed with the provided information let us assume specific performance measures. At the operational level, the number of tickets sold could be a performance measure. In that case it can be seen that the fourth alternative is the best one. More than 10% increase can be realized if the fourth alternative is selected as a new urban mass transportation system.

At the service level, the number of waiting passengers, transported people and total-passengers x Km could be taken as a measure of performance. If we consider the waiting passengers, the fourth alternative is better than the others. However, it is not very different from the existing one. If we consider the last two measures, the fourth alternative is the most promising one once again. The number of transported people is increased by 1000 and the total-passenger x Km is increased by

15,000 in the fourth alternative.

We can, therefore, conclude that the existing resources will be employed in a better way with a network having high-frequency and low-spead route structure.

TABLE 5.1

COMPARISON OF THE EXISTING AND ALTERNATIVE SYSTEMS

	Existing	1st Alternative	2nd Alternative	3rd Alternative	4th Alternative	5th Alternative
Waiting Passengers	246,016	256,322	246,369	246,694	245,858	253,352
Transported People	77,884	68,378	78,391	78,006	78,842	69,548
Boarding Passengers (Tickets Sold)	114,265	120,423	113,243	115,241	128,455	115,213
Total Travelled Time	28,169	28,272	28,270	28,364	28,011	24,105
Total Passenger x Km	512,369	502,402	524,337	527,242	527,090	461,178

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Total Travelled Time	28,169	28,272	28,270	28,164	28,011	24,105
Total-Passenger x Km	512,369	502,402	524,337	527,242	527,090	461,178

CHAPTER 6

VALIDATION AND EXTENSIONS

6.1 VALIDATION

The most vexing question asked about a simulation model is 'How do you know it is valid? How do you know its predictions will come true?' Validation is, in general, to test the agreement between the behaviour of the model and that of the system. There is no such thing as the 'test' for validity. Rather, the experimenter must conduct a series of tests throughout the process of developing the model in order to build up his confidence.

In this section, we will briefly discuss the types of error, in the data used and in the procedure of our model and, then, introduce the statistical methods that can be used to test the validity of our model.

The main sources of error in the input of our model are:

1- Errors in the O/D matrix of the network,

2- Errors in the travel time and travel distance matrices,

3- Errors due to oversimplification of the coded network,

4- Errors in the observed volume of passengers and vehicles.

1- The potential errors in the O/D matrix arise because the matrix entries are obtained from the expansion of the limited sample of trips.

2- The travel time and distance matrices are constant throughout the planning horizon in the model. However, it is obvious that they change with time and depend largely on the load of links.

3- Major errors may occur due to the simplified way in which the network is coded for computer use. Only the major roads and junctions are normally considered and all trips are assumed to begin and end at a point - zone centroid. Network simplifications may, therefore, produce large errors on some links of the network.

4- It must be remembered that the so called 'actual counts' are themselves subject to error, and that even in an extensive counting program, only a limited sample of links is to be counted and most of these counts will be the counts of short duration.

Several assumptions were made in developing our model, any one of which can lead us to draw erroneous conslusions; and the main sources of error are:

1- Errors in the path-choice criteria

2- Errors in the loading criteria

3- Errors in the discharge criteria

1- In our model, every traveller uses the same geographical paths in travellig from one zone of the network to another and boards on the first incoming vehicle if it satisfies the path choice criteria. This assumption may not hold in real life. The traveller may not board the first incoming vehicle and wait another vehicle arrival considering such factor as time, seat availabilityetc.

2- The passengers are loaded according to the capacities of the arriving vehicles. This assumption may also not hold and they may be loaded considering other factors. E.g. comparing the travel time of each alternative.

3- In our model, we assume that all travellers alight at the pre determined stops.

It is clear that every traveller does not behave in a similar way.

In the remainder of this section, we will briefly present the tests of validity that can be applied to our model. However, most tests of validity of similation models involve comparing the performance of the simulator under historical operating conditions with the actual performance of the system. Unfortunately, we were unable to apply these tests because the historical data were not available.

(1) First of all, we must assure ourselves that our model performs the way we intend using a simple test data.

(2) Reasonableness is checked by emprically testing, appropriate statistical techniques. We will discuss briefly some of the useful and important statistical techniques.

- a- tests of means (t test or Mann-Whitney test)
- b- analysis of variance (F test)
- c- goodness of fit tests. (chi-square test)

When testing means, we are generally interested in whether two sets of sample data could have come from the same underlying population. These tests could be applied to our model easily if the historical data were available. Let's explain the statistical tests with an example.

Suppose that we have passenger flows observed for 5 days and the program that simulates the system is run to find 7 days' passenger flows. The results are:

System: 22.0, 22.5, 22.5, 24.0 and 23.5
Model : 24.5, 19.5, 25.5, 20.0, 18.0, 21.5 and 21.5

using 0.95 significance level, test to determine if there is a significant difference between the means of the system and that of the simulator.

$N_1=5$ (Sample Size)	$\overline{X}_1=22.9$ (Mean)	$S_1^2=0.68$ (Variance)
$N_2=7$	$\overline{X}_2=21.5$	$S_2^2=7.25$

To solve we first test : $\delta_1^2 = \delta_2^2$ and so calculate F-statistic by

$$F= \frac{\text{the larger } S^2}{\text{the Smaller } S^2} = \frac{7.25}{0.68} =10.66$$

Looking up the critical F volue in Table of the F-distribution | 6 | for 0.05 (1-0.95) with (7-1) and (5-1) degrees of freedom, we find F_{tab}=6.16. Since $F_{cal} > F_{tab}$, we eject that

Similarly, from the formulas developed for t, we can find that the calculated t is less than the critical t, we do not reject that the means are equal. We can conclude that even though the model produces values with the same mean, the statistical higher variance cause us to reexamine our model.

The chi-square statistic is used to test the hypothesis that a set of emprical data does not differ significantly from that which would be expected from some specified the oretical distribution. | 6 | The chi-square statistic is given by

$$\chi^2 = \sum^{k} \frac{(fo - fe)^2}{fe}$$

where

fo= observed frequency for each interval
fe= expected frequency for each interval predicted by the theoretical distribution

If $\chi^2=0$, then the observed and theoretical frequencies agree exactly, where as if $\chi^2>0$ they do not.

The data used in our model could be validated using these tests if the historical data were available.

A computer simulation model is in the simplest sence an input-output transformation device. One of the most obvious approaches to helping validate our model is to compare the outputs of the real world system and the model, using (if possible) identical inputs. By employing an appropriate test, (i.e.test means by the t test, test variances using the F-test) We could determine statistically if two samples are actually from different populations or 'practically' from the same population.
The final and the most important test for the validity of our model and the results obtained is the answer to the question, 'Does it make sense'. The professional judgement of the people most intimately familiar with the design and operation of a system is more valuable and valid than any statistical test. Because the historical data (actual counts) are also subject to error as mentioned previously. At stage, we can say that our model produces reasonable results.
observing the results produced from the application
The results were in accordance with the results produced by the study carried out by BUTSAE |32|.

6.2 EXTENSIONS

One of the main advantages of our model is that it is open for extensions. The extensions can be developed without changing the structure of the model and computer program completely. Some possibilities for extensions are as follows.

- The inputs of the model (O/D matrix, travel time) matrix can be made to vary with time Furthermore, they can be either deterministic or probabilistic. Let's examine these cases seperately.

- If the static inputs are deterministic:
For each input, only one matrix is supplied to the model (as in the case study in Chapter 5)

- If the dynamic inputs are deterministic:
Different matrices for the inputs for each time period are given.

- If the static inputs have probabilistic values:
The matrices containing the mean values and the distribution functions for the inputs are given. We generate random variables associated with each input only once and find the matrices.

- If the dynamic inputs are probabilistic:
The matrices containing the mean values and distribution functions for travel demand, travel

time and travel distance are given. At each minute, the random variables for each input are generated in order to find out the values of the inputs.

- It is possible to produce other performance measures from the operation of the model depending on the objective of interest. E.g. capacity usage ratio of each route, the proportion of the number of satisfied and unsatisfied passengers for each zone may be produced.
- The model allows a new mode of travel to be introduced in terms of its route structure, number of vehicles on the routes, and capacity.
- A different approach may be applied to path choices. E.g. the passengers may be assigned to shortest paths. Considering the time of travel.
- In the model, it is assumed that every traveller boards the first incoming vehicle if this vehicle satisfies the poth choice criteria. The traveller can make a preference among the arriving vehicles considering such factors as travel time, seat availability, etc.
- Loading of passengers to vehicles are realized considering the available capacities of competetive vehicles. Other factors such as travel time can be taken into account.
- The time spent by the vehicles at the intermediate stops is a function of the number and composition of passengers in the vehicles and the number of waiting passengers at the stops. Therefore, a function for the time

spent can be developed depending on the number of boarding and alighting passengers.

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APPENDIX A

A.1. COMPUTER IMPLEMENTATION

The model presented in the previous chapters has been programmed in FORTRAN IV, for the UNIVAC 1106 Computer. In the following section, a brief description of the organization of the computer model is given. The array dimensions are such that a network with up to 60 nodes, 80 routes and 200 vehicles can be handled. The computer model consists of two successive programs and storage space requirements are approximately 28,000 and 62,000 words respectively.

A.2. PROGRAM ORGANIZATION

The computer model has been developed to implement the model presented in Chapter 2 and Chapter 4. It consists of two programs which we call TRSIMXFP and TRSIMSM. In the first program, all data require to solve the state equations of the problem is found out. These are all time-independent values, specifically, the junction number, the number of junctions, the route numbers that are selected for each node pair according to path choice criteria, and the adjacency matrix showing the number of routes connecting the node pairs directly. It consists of one main program and three subroutines. Route-structure and travel time matrix are in the inputs of the first program. It is given in Figure A.1.

The inputs and outputs of the first program, and (O/D) and travel distance matrix are supplemented to the second program as an input. The second program is used to solve the state equations of the problem, and as a result, it produces all information required to evaluate the urban mass transportation systems. This program consists of one main program, twelve subroutines and one function. It is given in Figure A.2.

The organization of the computer model as a whole is roughly presented in Figure A.3.

A.3. DESCRIPTION OF THE INPUTS AND THE OUTPUTS OF THE APPLICATION IN CHAPTER 5.

I. The first three tables (Table A.1, A.2 and A.3) have the following form:

Node = 1

$N_{1,1}$ $N_{1,2}$ $\cdots$ $N_{1,10}$
$N_{1,11}$ $N_{1,12}$ $\cdots$ $N_{1,20}$
$\vdots$
$N_{1,41}$ $N_{1,42}$ $\cdots$ $N_{1,50}$
$N_{1,51}$

$\vdots$

Node = 51

$N_{51,1}$ $N_{51,2}$ $\cdots$ $N_{51,10}$
$N_{51,11}$ $N_{51,12}$ $\cdots$ $N_{51,20}$
$\vdots$
$N_{51,41}$ $N_{51,42}$ $\cdots$ $N_{51,50}$
$N_{51,51}$

At Table A.1 $N_{x,y}$ - Travel time in minutes from node x to node y

At Table A.2 $N_{x,y}$ - Travel distance in kilometers from node x to node y

At Table A.3 $N_{x,y}$ - Number of passengers/minute generated from node x to node y

Tables A.4 to A.9 present the existing and alternative route structures. The first column specifies the route number and the second through 18 specify the node number on the route in an ordered way. The last column contains the number of vehicles on the route.

II. The outputs of the model (Table A.10 to Table A.15) have the following form:

a. For the results produced for each stop pair:

$$\begin{array}{llll} N_{1,1} & N_{1,2} & \cdots & N_{1,10} \\ N_{1,11} & N_{1,12} & \cdots & N_{1,20} \\ \vdots & & & \\ N_{1,41} & N_{1,42} & \cdots & N_{1,50} \\ N_{1,51} & & & \end{array}$$

$$\begin{array}{llll} N_{2,1} & N_{2,2} & \cdots & N_{2,10} \\ N_{2,11} & N_{2,12} & \cdots & N_{2,20} \\ \vdots & & & \\ N_{2,41} & N_{2,42} & \cdots & N_{2,50} \\ N_{2,51} & & & \\ \vdots & & & \end{array}$$

$$\begin{array}{llll} N_{51,1} & N_{51,2} & \cdots & N_{51,10} \\ N_{51,11} & N_{51,12} & \cdots & N_{51,20} \\ \vdots & & & \\ N_{51,41} & N_{51,42} & \cdots & N_{51,50} \\ N_{51,51} & & & \end{array}$$

For Waiting Passengers $N_{x,y}$ - Number of passengers waiting at node x to go to node y

For Boarding Passengers $N_{x,y}$ - Number of boarded passengers at nod x to go to node y

For Link Load $N_{x,y}$ - Number of vehicles assigned to link (x,y)

b. For the results produced for each stop:

$$\begin{array}{llll} N_1 & N_2 & \cdots & N_{10} \\ N_{11} & N_{12} & \cdots & N_{20} \\ \vdots & & & \\ N_{41} & N_{42} & \cdots & N_{50} \\ N_{51} & & & \end{array}$$

For Waiting Passengers N_x - number of waiting passengers at node x

For Loading Passengers N_x - number of boarded passengers at node x

c. For Route-Passenger x Km:

$$\begin{array}{llll} N_1 & N_2 & \cdots & N_{10} \\ N_{11} & N_{12} & \cdots & N_{20} \\ \vdots & & & \\ N_{61} & N_{62} & \cdots & N_{70} \end{array}$$

N_x - Passenger x Km for route x.

d. For Bus-Passenger x Km and Load Factor:

$$\begin{array}{cccc} N_1 & N_2 & \cdots & N_{10} \\ N_{11} & N_{12} & \cdots & N_{20} \\ \vdots & & & \\ N_{171} & N_{172} & \cdots & N_{180} \\ N_{181} & N_{182} & \cdots & N_{185} \end{array}$$

N_x - Passenger x Km for vehicle x

or

N_x - Usage Rate of vehicle x

A.4. LIST OF SYMBOLS

The following symbols are used in the model and computer program:

I	node (stop) number
L	vehicle number
IR	route number
NSTOP	number of nodes
NBUS	number of vehicles
NTR	number of routes
NOFJ	number of junctions
NOB(IR)	number of vehicles on route IR
ISTARS(L)	starting terminal node of vehicle L

ILASTS(L)	ending terminal node of vehicle L
CAP(L)	total passenger capacity of vehicle L
AVSPC(L)	available passenger capacity of vehicle L
RPASKM(IR)	passenger x km of route IR
BPASKM(L)	passenger x km of vehicle L
ISEF(L)	number of trips made by vehicle L
WAITP(I,J)	number of waiting passengers at node I to go to node J
ITIME(I,J)	travel time between node I and node J
IBUSFL(I,J)	assigned volume of vehicles on link (I,J)
ADJEN(I,J)	number of routes connecting node I to node J directly
IDIST(I,J)	travel distance between node I and node J
ITABLE(L,I)	time-table matrix
NPASS(IR,M)	route-station (stop) matrix

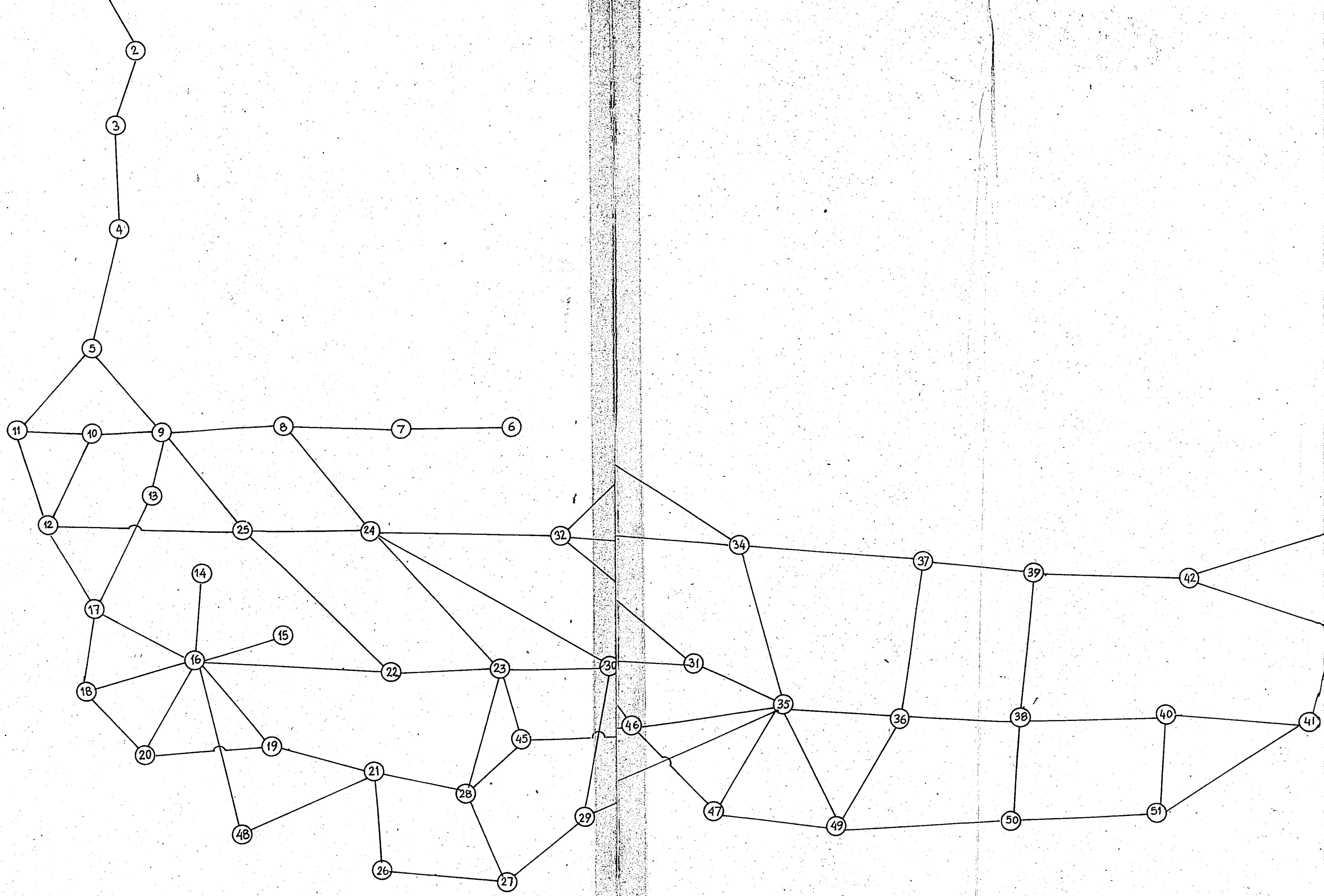

Figure A.1-a Urban Mass Transportation Network of the Anatolian Region of İstanbul