THE APPLICATION OF SYSTEMS ENGINEERING TECHNIQUES TO THE ANALYSIS OF INTERCITY TRAVEL

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CHAPTER I

THE RESEARCH PROBLEM

Introduction

The solving of traffic and highway problems often eludes the present methods of research. There is no doubt that today people have the skills and techniques to build better highways and safer vehicles, but successful research depends on attitudes, concepts, and imagination and these have not kept pace with the ever-increasing complexities of highway transportation. Research, to be successful, must proceed through the successive steps of measurement, analysis, and interpretation. This is required in order to understand the status quo of a given transportation system. But understanding the status quo of a system is not sufficient for the planning phase of transportation research. Researchers are in the technological position of being able to implement almost any given transportation system. But the questions of which system is to be built to satisfy man's desire to travel and what effects will these facilities have on man's travel patterns have evaded identification by modern day transportation planners.

Statement of the Problem

Transportation planning requires an accurate estimation of travel demands. Accurate travel demand estimation requires knowledge of the factors which generate travel as well as those factors which impede travel flow. Present planning models do not allow the traffic engineer to determine precise travel demand estimates on a regional intercity transportation network.

Considerable effort has been devoted to the study of the positive factors of trip generation and distribution but little is known of the negative side. Positive factors in travel demand are those factors which increase the number of trips generated and attracted by various origins and destinations, while the negative factors tend to decrease trip interchanges. During the past decade, transportation modeling has been dominated by the following hypothesis: The interaction between any two populations can be expected to be directly related to their size; and since distance involves friction, inconvenience, and cost, such interaction can be expected to be inversely related to distance. This hypothesis leads to such conclusions as the number of trips between two places will be the same whether they are connected by a limited access freeway or separated by an impassible ravine. Little has been done to question this basic hypothesis or to attempt to relate the impeding factors of traffic flow to the physical characteristics of the transportation system. This thesis will attempt to do both.

Many researchers have concluded that a sufficient explanation of the negative factors involved in the travel phenomenon lies in distance. A few, however, have dared to speak out on the dangers of oversimplifying traffic impeding factors. Greenshields (21) for one has stated that "a fallacy to which the traffic planner clings is that time of travel is the only important variable to be considered."

This thesis is concerned with the components of travel impedance and travel modeling. In particular it is concerned with the characteristics of a given highway network and how these characteristics affect intercity travel. Such factors as access control, geometric width, gradient, curvature, surface condition, are but just a few of the factors which will be of concern in this thesis. An intercity travel model based upon the concepts of linear graph theory is investigated.

Approach to the Problem

The approach used in this thesis involves the use of techniques of system analysis which were developed primarily for the analysis of electrical networks. However, during the past few years this fundamental approach of analysis has been applied usefully to many other areas, such as mechanical, hydraulic, and heat transfer systems. Analysis of an intercity transportation network also seems amenable to this technique, namely analysis by linear graph theory.

A system, as the term is used here, refers to an orderly arrangement of interrelated elements acting together to achieve a specific purpose. Thus, a system must have an avowed purpose, be free of extraneous or mathematically redundant parts, and have elements or components joined in an orderly fashion. Discussion in this thesis is limited to systems made up of components having only two terminals, although there is no limit on the number of terminals the components may have in general systems theory (17). The selection of the units that will serve as components depends first on what type of system is being analyzed (i.e., transportation, electrical, sewage treatment) and second, on the specific questions to be answered by the analysis of the system. For example, in a study of traffic flow the components selected for study in an intraurban setting would be quite different from those needed on the interurban scale.

Linear graph theory is an orderly technique for formulating the mathematical characteristics of a physical system. The principles of linear graph theory are stated briefly in Chapter III. A more detailed discussion of the subject is given in Mimeographed notes by Yarlagadda (61) and two of the prominent texts in the field (34) (37).

The essential steps for computation of a systems' characteristics are these:

(1) To establish a mathematical description of the relevant physical characteristics of the system components expressed in terms of measurements.

(2) To establish in mathematical form, and in terms of measurements from a knowledge of the component characteristics and their mode of interconnection, the characteristics of the system; i.e., a mathematical model of the system.

Components are described mathematically by relating two measurements of the components in "isolation" from other components. The measurements must be such that one is a "through" (or series) measurement, which when summed at each vertex of the system graph must equal zero, and the other is an "across" (or parallel) measurement, which when summed around each circuit of the system graph must equal zero. The relationship between the "through" and "across" measurements is expressed mathematically and called the terminal equation of each of the components. The details of how this information is incorporated to arrive at the system solution are given in Chapter III.

Particularly attention is given in the modeling to the character of travel impedance. An Ohm's law type relationship is hypothesized for each highway setment in the network. Travel demand, the "across" variable, acts analogously to potential difference in an electric circuit, while traffic flow, the "through" variable, is the counterpart of current flow in a passive element.

A unique travel impedance parameter is associated with each highway segment. This parameter, analogous to resistance in an electric circuit, is related to both the physical characteristics of the highway segment and to travel cost along the segment.

Significance of the Problem

When one examines research conclusions in the area of travel forecasting the need for additional study of travel impedance becomes quite clear. Heanue and Pyers (25) state:

> Additional research is also needed to examine the impedance effect of physical or topographical features on travel. More insight into basic causes of the impedance is essential to the development of comprehensive techniques for projecting the impedance.

Similar conclusions have been reached by others involved in the transportation planning process. Travel impedance effects have also been felt in the trip generation process. The number of trips generated at any given node will tend to increase as its physical accessibility increases. In trip distribution travel impedance effects the trip interchange proportions. Traffic appears to assign itself in a minimum energy (minimum impedance) fashion between alternative routes and modes. Thus, the area of travel impedance is surely one worthy of additional study -- particularly when the method of analysis (linear graph theory) offers the possibility of contributing some new and interesting concepts to the traffic problem.

Summary

This chapter has provided an introduction to the study of intercity travel and indicated the particular problem of concern in this thesis namely: the modeling of intercity travel impedance through linear graph analysis. Analysis by linear graph theoretic techniques has been shown to be useful in the modeling of electrical systems and the extension of these techniques to transportation flow analysis, seems a natural one. Particular attention will be given to the accurate representation and significance of travel impedance for the route components in the travel system.

CHAPTER II

REVIEW OF RELATED LITERATURE

Introduction

This chapter describes and discusses previous research in transportation planning. It will give a brief account of the traffic estimation process and the models used to date to study the travel phenomena. The problem of traffic estimation can be loosely divided into three parts, i.e., the problems of (1) trip generation, (2) trip distribution, and (3) traffic assignment. Trip generation refers to the process of estimating the number of trips originating from a certain area; trip distribution refers to the way in which these trips are distributed over possible destinations; and traffic assignment refers to the way in which trips are assigned to alternative routes and modes of travel. In the discussion which follows special attention will be given to the way in which travel impedance has entered into the analysis of each phase of the transportation planning process. Also included will be a review of studies in traffic quality and the application of linear graph theory to socio-economic problems in general and transportation problems in particular.

Trip Generation

The ultimate goal of trip generation analysis is to establish an adequate functional relationship between trip end-volume and the land use and socio-economic characteristics of the units from which they originate or to which they are destined. Research in this area is dominated by the application of multiple regression techniques to relate the trip end-volumes to variables in the study unit which may affect the generation or attraction capacity of the unit. Most research has been concerned with the urban setting with trips stratified by trip purpose. Variables found significant in the urban transportation planning process have been classified into three basic categories; demographic, economic, and land use. Examples of demographic data used include total population, school enrollment, and the number of household units in a particular zone. Economic data includes such items as total employment, median income, automobile ownership, and retail sales. Specified activities in a zone and other selected categories of information are considered as elements of basic land use data.

In a study of intercity travel characteristics in Missouri by Hosford (28), it was determined that only a few factors need be considered to reasonably estimate trip attraction factors for a given trip purpose. Hosford included the total population of a zone, the number of car registrations, and the total number of males and females employed in determining zonal attraction indices. For estimating personal business trips he included the urban population of the zone, the sum of school enrollment, service employment, and retail trade employment while deleting the previously mentioned factors of total males and females employed in the zone. For social-recreational and vacation trips, he found that only total population and a rating of parks, lakes, and seashores in the zone needed to be considered. For each trip purpose, Hosford employed a travel deterrance factor, which he called the "f" factor, that was a linear function of travel time between any two zones.

Studies by Basore, Mylorie, Brokke, and Whiteside (4) (41) (9) (58) have concluded that for the analysis of intercity travel demand only one generation variable need be considered. Basore concluded that the total personal income of a region is highly correlated with its trip generation and attraction capacity. Mylorie, Brokke, and Whiteside employ the total population of the region as its generation factor. The studies cited demonstrated good results when aggregate trips (trips not stratified by trip purpose) are the desired result. In each study the travel impedance function is related to distance only.

Kassoff and Deutchman (32) directed their attention to the consequences associated with alternate approaches to the trip generation process. In particular, their concern was whether data aggregated for all trip purposes or disaggregated data yielded better results. Their conclusions were that aggregate data procedures were slightly inferior statistically to approaches where the data were disaggregated by trip purpose. Their research dealt with the urban area, however, and it is questionable whether these results can be generalized to the laeger scale required for the analysis of intercity travel.

When work trips are analyzed in an urban setting, a more detailed breakdown of travel creation factors is required than is the case for intercity trips for all purposes.

It should also be pointed out that the desire for intercity travel at a level in excess of the actuality of the occurrence is believed to be an inherent factor in our society (36).

Trip Distribution

Trip distribution analysis is the process by which the trips derived in the trip generation process are distributed between competing destination zones in the study area. Trip distribution methods have been generally divided into two basic types: (1) growth factor techniques, and (2) mathematical travel methods. The basic philosophy underlying growth factor methods is that present travel patterns can be projected into the future on the basis of anticipated differential zonal growth rates. The mathematical travel formulas are expressions which distribute trips on the basis of various assumptions on the "form" of the trip distribution phenomena and on observations of the characteristics of the land-use pattern and the transportation system.

The following discussion will present the basic model theory and a discussion of the results obtained from the application of the three most widely used trip distribution procedures: (1) the Fratar Method, (2) the Intervening Opportunities Model, and (3) the Gravity Model. These model descriptions have been abstracted from two well-known sources on the subject (25) (55).

The Fratar Method

The Fratar Method is based on the assumption that the change in trips in an interchange is directly proportional to the change in trips in the origin and destination zones contributing to the interchange. It is an iterative procedure which transforms a base year trip table into a future year trip table by application of growth factors to each origin and destination zone. Thus, the Fratar procedure expands existing travel patterns by considering growth in each portion of the study area without any specific consideration of the transportation network. If changes in the travel impedance between zones were sufficient to bring about changes in travel patterns in the forecast year, the Fratar or any other growth factor technique would not reflect this. Another shortcoming of this method is that it does not allow for any origin or destination zones to enter or leave the system under study. If there were no trips between two zones in the base year, no amount of growth in either zone could produce trips in the forecast year. In general, the Fratar growth factor procedure expands trips correctly for stable areas but shows significant weakness in areas undergoing land use changes. These problem areas have caused most researchers to abandon the Fratar procedure in favor of the mathematical travel formulas discussed next.

The Intervening Opportunities Model

The intervening opportunities model utilizes a probability concept which in essence requires that a trip remain as short as possible, lengthening only as it fails to find an acceptable destination at lesser distance. More precisely, the model states that the probability that a trip will terminate within some volume of destination points is equal to the probability that this volume contains an acceptable destination, times the probability that an acceptable destination closer to the origin of the trip has not been found. Mathematically this can be expressed as:

$$T_{ij} = T_i e^{-LD}[1 - e^{LD_j}]$$

where:

T_{ij} = trips originating in zone i with destinations in zone j

T_i = trip origins in zone i

D = trip destinations considered before zone j (i.e., destinations closer to zone i than zone j is to zone i)

D_j = trip destinations in zone j

L = probability per destination of the acceptability of the destination at the zone under consideration; L is an empirically derived function describing the rate of trip decay with increasing trip destinations and increasing trip length

e = base of natural logarithms

Thus, spatial separation for the intervening opportunities model is measured in terms of the number of intervening opportunities as opposed to travel time, cost, or distance between zones used by the gravity model which will be discussed in the section which follows.

The intervening opportunities model has found most wide acceptance in urban travel studies (52). Its application to intercity travel seems to be weakened by the difficulty encountered in determining the "L" factors, and the usually greater inhomogeneity of destinations.

The Gravity Model

The gravity model is perhaps the most widely used and tested approach to the problem of trip distribution (28). It has been used in many forms but its most basic form resembles closely Newton's gravitational law for masses. One of the simplest formulations of the gravity model may be expressed mathematically as follows:

$$T_{ij} = \frac{a_o \cdot P_i \cdot P_j}{d_{ij}^2}$$

where:

T_{ij} = the measure of traffic between zone i and j

P_i = the population of zone i

a_o = a parameter to be estimated from data

d_{ij}^2 = distance between zone i and j squared

Thus, the traffic between i and j is directly proportional to the product of the two populations and inversely proportional to the square of the distance between them. The assumption that T_{ij} is directly proportional to P_iP_j may be justified in the following manner (49). Other things being equal, traffic is proportional to the number of possible pairwise interactions between members of the two populations. The number of possible pairwise interactions is clearly P_iP_j. The denominator in the gravity model expression given above is introduced on the grounds that the gravitational attraction between two nodes is attenuated by some impedance factor, in this case expressed as a function of the distance between the two nodes. An intuitively satisfying justification for the form of the denominator in the gravity model is suggested by Basore (4). If the region surrounding any origin node is considered to be homogeneous in its attraction characteristics, the number of possible destinations would be proportional to distance. Thus, the attraction of any one destination at a distance d from the origin would be inversely proportional to d. Therefore, the distance squared term which appears in the denominator of the simple gravity expression may be considered proper in the idealized form of the model.

The basic form of the gravity model has been modified in many ways. In certain instances the numerator factors have been weighted and/or raised to some appropriate exponent. Many examples exist where the attraction factor of one area is made up of many characteristics of the area -- socio-economic, demographic, etc. (28) (62). All models which have the characteristics described above and in the equation given earlier may be called gravity models. Such models have often been employed to explain intraurban travel (55) and somewhat less often to explain interurban travel.

The impedance factor found to be most significant when the gravity model is applied to urban areas is travel time. Generally, travel time is introduced into the model through the use of travel time factors. These factors are used to measure how important travel time is to the selection of a given destination. Trips are normally divided into categories by trip purpose and different travel time factors are developed for each trip purpose. Travel time then takes the place of distance in the basic gravity model formulations and the travel time factor serves as the exponent of time (45). Travel time factors have also been used in the analysis of intercity travel (28).

When one examines the results of the application of the gravity model it is seen that in certain cases inaccurate trip predictions result. One common error in prediction results when two zones are close to each other. In this case the model usually results in overprediction of interzonal trips. This would be expected by examination of the model. As the distance between any two zones approaches zero the estimated trips between the zones becomes infinite. Inaccurate predictions from gravity models may be due to two basically different factors.

First, gravity models may be fundamentally "wrong" for explaining interurban travel. Second, gravity models may never have been implemented properly. By this second statement, it is implied that the proper combination of variables may never have been employed. A reasonably strong case may be made for either of the positions stated above.

Let us examine the first hypothesis in more detail with particular attention given to the role of city size in demand for intercity travel.

The gravity formula would predict a proportional increase in intercity trips as the size of the cities under consideration increase. This is not borne out by observations, as is indicated by Figure 1, or supported by theory (5).

Intercity travel enables individuals to satisfy their desires in areas other than the one in which they live. Opportunities to satisfy these desires increase with city size, since as city size increases so does the number and variety of goods available for consumption and the opportunities for entertainment. Thus, it might be expected that as city size increases the amount of travel away from the city by residents decreases and the amount of travel to it by non-residents from smaller cities increases. This is essentially borne out by the relationship shown in the graph of Figure 1; as the population of a city increases the external trips per resident decrease. This conclusion is of little solace to the urban traffic planner but is quite significant in the study of intercity travel.

When the above conclusions, drawn from observations of data, are combined with the concepts of Cristallus Central Place Theory (53), the following statements above city size and intercity travel may be made:

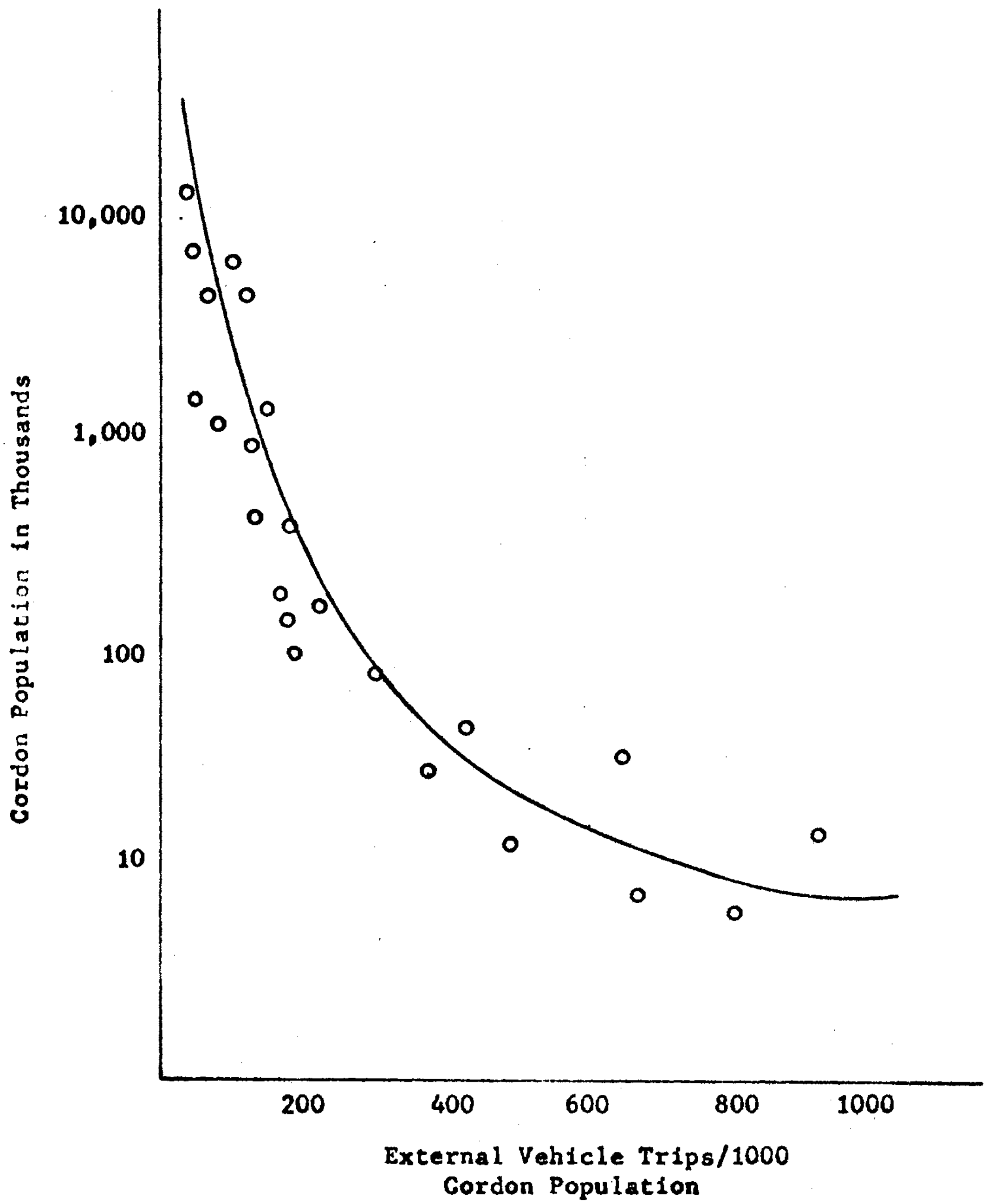

Figure 1. City Size in Relation to External Cordon Crossings

(1) Most intercity travel gravitates toward the larger cities in a hierarchial manner as people attempt to satisfy their desires for goods and services; (2) The ability of a city to satisfy desires is indicative of the attraction it possesses; (3) A city attracts trips from its trading area; (4) Since travel requires time, money, and inconvenience it is assumed that a person would, in most cases, minimize these impeding factors to travel.

Thus, the travel between any two cities may be explained more readily by the differences in the two cities in both size and function, than by the product of their populations, total personal incomes, or a combination of such factors.

Traffic Assignment

Traffic assignment is the process of allocating a given set of trip interchanges to a specific transportation system. It should be noted that the above definition includes not only the loading of a zone-to-zone trip table on a highway network but also the assignment of trips to competing nodes in the transportation system. Since the research reported on in this thesis is concerned with the analysis of an intercity highway network, a discussion of modal split analysis will not be included here.

Traffic assignment models to date are based on the solution of the classic problem of determining the shortest path through a maze (55). This is accomplished through the establishment of a set of minimum path trees. Travel is assigned to a network based on the minimum impedance path from origin to destination. In general this assignment is made on an "all or nothing" basis. For example, in many studies the traffic volume between two zones is assigned to the route with the shortest travel time and nothing is assigned to any of the many alternative routes. This "all or nothing" hypothesis is the prime weakness of current assignment techniques. A model which will more realistically reflect the travelers route-choice decision is needed.

Traffic Quality

Recognition of the importance of aesthetic factors in determining travel behavior has led several researchers to attempt to express quantitatively the effect of comfort and convenience factors on traffic flow. Greenshields was one of the first to derive a mathematical expression for "quality of traffic flow" (21) (22) (23). He postulated that highway travel is improved as the time and effort needed to travel on the network are reduced to a minimum. In the limit, the ultimate in transportation would be experienced if one could step into his vehicle, press a button, and immediately be at his destination -- no time required, and no effort needed to change direction or speed. Using the change of speed and direction as measures of quality, Greenshields has derived a dimensionless number which he asserts characterizes travel on a given route. He compares his traffic number with other numbers which characterize flow -- the Reynolds number for flow in pipes, and the Fronde number for flow in open channels, etc. Greenshield's traffic number correlates with, but does not measure directly, cost, comfort, and safety.

Michaels (40) makes use of an attitude scale to determine the priorities given by drivers to the factors which affect their route choice decisions. He concludes that alternative highway routes are judged by the user in the following order: (1) time savings, (2) direct and indirect operating cost savings, and (3) comfort and convenience savings.

Riedesel and Cook (50) attempt to quantify the aesthetic, social, and economic effects of a proposed highway on the area it serves, and to relate these effects to cost and service considerations so that rational, systematic comparisons of alternative routes can be made.

Applications of Linear Graph Theory

Mathematical models of physical systems based on models of the system components and their pattern of interconnection have been well established (34). Many of the applications of the methodology of linear graph analysis to the study of socio-economic system problems can be attributed to Herman Koenig. He has demonstrated the application of this methodology in establishing discrete state models of nonprofit organizations. Problems of optimization in distribution logistics, production-inventory scheduling of the firm, and optimum geographical location of consumer oriented facilities have been approached through the analysis of linear graphs. Currently research is being conducted on ecological systems problems with the aid of system modeling techniques.

Ellis has made use of a system theory model for determining statewide recreational traffic flows in the state of Michigan (14). Ellis used travel time raised to a fixed exponent as a measure of travel resistance in his model. His results have been compared with those obtained from the application of a gravity model for the same recreational system. The system theory model proved to yield slightly better results than the gravity model (15).

Grecco and Breuning have applied linear graph analysis to work-trip and shopping-trip distribution. They were particularly concerned with the generation and distribution phase of the analysis process. Attention was given to the factors that generate and attract work trips and how these trips are distributed. A combination of trip frequency and travel time was used to determine the resistance factors for the urban route components in the network (19).

McLaughlin has used linear graph theory in combination with diversion curves to study the problem of urban traffic assignment. He developed a "value function", which he related to travelers route choice decisions. He has tested his model with actual travel counts in an urban area and found the results quite satisfactory (42).

Pearson reported on the development of a measure of air travel desire from a model of intercity travel which makes use of graph theoretic techniques. His model produced acceptable results when tested with Canadian air travel data (47).

The above studies have demonstrated the varied use of graph theory analysis in socio-economic and transportation system problems. Its application to the study of intercity travel impedance seems a reasonable extension.

Summary

This chapter has reviewed selected research studies on the three phases of the transportation planning process which are applicable to the problem of interest in this thesis. Travel impedance has been shown to relate to trip generation, trip distribution, and traffic assignment. Studies in the determination of traffic quality have shown the importance of the social and aesthetic factors in travel behavior. These studies indicate, however, that it is actual travel time and cost which are most important in determining travel patterns. Both cost and time are directly related to the design and condition of the highway system. These physical characteristics of the network will be considered in the models of the route components which will follow.

CHAPTER III

LINEAR GRAPH THEORY

Introduction

"Systems engineering" has moved to the fore as one of the many new and sophisticated terms of this past decade. There are those who believe that it is the same old engineering process with a new title. Others believe that it is both new and different because of its ready adaptation to the multi-disciplinary approach and of its emphasis on the system and its components. The first phase of system theory as presented here is concerned specifically with a method for developing mathematical models of systems of interconnected components. The second phase of system theory is concerned primarily with the use of mathematical models is simulating the behavioral characteristics of systems of interacting components as a function of the system structure. Thus, system theory can, in general, be divided into two broad aspects: (1) modeling theory -- the process of generating a model of the system from the system structure, i.e., the models of the constituent components and their interconnection pattern, and (2) behavioral theory -- the process of analyzing the solution characteristics of the system model in order to simulate the physical behavior of the system as a function of a change in its structural features, parameters, or forcing functions.

The material presented in this chapter is intended to provide the reader who is not familiar with the systems modeling in general, and modeling by the use of linear graphs in particular, with the basic fundamentals of the process. The material presented is abstracted from two prominent texts in the field (34) (37) and notes prepared by Yarlagadda (61).

Linear Graph Analysis

By definition, a system is a collection of discrete components, each having certain definable characteristics, together with a prescribed pattern of interconnections or interrelations. Components of a system may be pieces of physical hardware - such as a hydraulic servovalve, an amplifier, a two-terminal inductor, or a three-terminal transistor - or they may represent less precisely defined components encountered in socio-economic or biological systems. The analysis made in this thesis is for two-terminal components although the application of linear graph theory is in no way restricted to such components.

Linear graph analysis provides the vehicle to formulate a mathematical model of a system and includes two essential features (1) a model of the characteristics of the components, and (2) a model of their interconnection patterns. A fundamental axiom of the approach is that the mathematical models of the components are independent of how the components are interconnected. This implies that the various components can be "removed" either literally or conceptaully from the remaining components and studied in "isolation" to establish models of their characteristics. It is precisely this feature that makes this approach a universal tool of analysis -- the analyst can go as far as he wishes in breaking down a system in search of "building blocks" that are sufficiently simple to be modeled.

Linear graph theory is an orderly technique for formulating the mathematical characteristics of a system. The steps in the solution of a system by linear graph analysis are illustrated by the block diagram of Figure 2.

The discussion which follows is detailed enough to present the reader with a familiarization with the techniques, yet brief enough to force further inquiry into the references previously cited. As mentioned earlier, because of the elemental nature of the work that follows, discussion will be limited to systems made up of two-terminal components. For computation of the system characteristics, two steps are necessary; namely:

(1) To establish a mathematical model of the relevant physical characteristics of the system components from theory and measurements.

(2) To establish in mathematical terms a model of the system - from a knowledge of the component characteristics and their mode of interconnection.

An oriented linear graph is a collection of oriented elements which provides the basis for mathematically describing a system. Since certain terminology might be unfamiliar to some readers, the following brief definitions will be given. These definitions and the fundamental postulates of system theory will provide the foundation upon which the formulation techniques are based. A basic familiarization with the terminology of set theory is assumed.

Definitions

(1) Element or Edge - An element or edge is a line segment

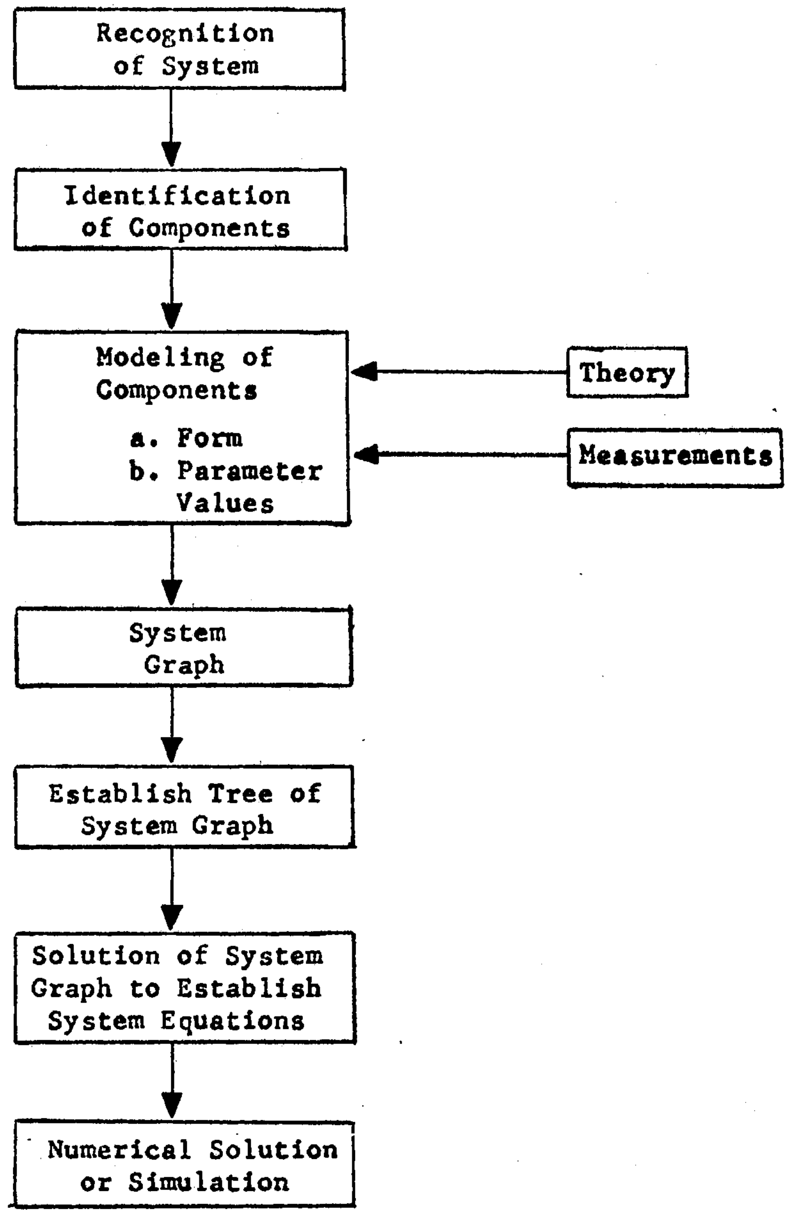

Figure 2. Steps in Solution of a Physical System by Linear Graph Theory

(arc) with its end points.

(2) Vertex - A vertex is an end point of an element or edge.

(3) Oriented Element - An element with an ordered pair of vertices.

(4) Oriented graph - a collection of oriented elements.

(5) Subgraph - Any subset of the elements of a graph.

(6) Path - A path is a sequence (E_1 , E_2, E_3 , ...) of elements of a graph such that the terminal vertex of each element coincides with the initial vertex of the succeeding element.

(7) Connected graph - A graph is connected if there exists at least one path between every pair of vertices.

(8) Distinct path - Two paths are distinct if they have no vertices in common other than the terminal vertices.

(9) Circuit - A circuit is a connected subgraph such that there are exactly two distinct paths between any pair of vertices of the subgraph.

(10) Tree - A tree is a connected subgraph of a connected graph such that it contains all the vertices of the graph and has no circuits.

(11) Branch - A branch is an element of a tree.

(12) Co-tree- A subgraph, which is the complement of a tree.

(13) Chord - An element of the co-tree is chord.

(14) Cut set - A cut set of a connected graph is a set of elements such that (a) If this set of element is

removed from the graph, the graph becomes two parts by counting the isolated vertices also as parts;

(b) No proper subset of these elements has the above property.

Postulates

In the mathematical analysis of any given type of physical system (electrical, thermal, mechanical, etc.), the tie between the mathematics and the system is generally accomplished through the use of two basic complementary variables; the "across" or X variable and the "through" or Y variable. Typical complementary variables used for modeling the characteristics of physical and socio-economic processes are given in Table I.

The terminal characteristics of a linear "non-dynamic" component may be completely described by an equation which relates the X and Y variables of the following form:

$$Y = GX \ . \tag{3.0}$$

This equation, which is referred to as the terminal equation, plus the terminal graph of the component, forms the terminal representation of the component. Although a linear relationship is shown in Equation (3.0), there is no such restriction on the form of the component equations in general. The techniques of linear graph theory can be applied to any lumped system, whether or not it is composed of linear elements. There is no reason why systems considered via this technique should not be allowed to contain nonlinear elements, as the word "linear" in linear graph connotes "line" in the geometrical sense and should not be

TABLE I

COMPLEMENTARY VARIABLES FOR TYPICAL PROCESSES

Process	Across Variable (X)	Through Variable (Y)
Electrical	Voltage	Current
Mechanical Translational	Translational Velocity	Force
Mechanical Rotational	Angular Velocity	Torque
Economic	Price per unit	Goods transferred per unit time
Hydraulic	Pressure	Flow rate
Heat Transfer	Temperature	Heat flow
Urban Travel	Density	Flow rate
Intercity Travel	Desire	Flow
General	Propensity	Flow

confused with the use of linear in the algebraic sense.

It need only be required that the components be described mathematically by relating the measurements X and Y on the component taken in isolation. These measurements on the component are independent of the system in which it is used. These measurements must be such that one is a "through" (or series) measurement, Y, which when summed at the vertices of a graph must equal zero, and the other is an "across" (or parallel) measurement, X, which when summed around a circuit of elements must equal zero. The selection of the proper X and Y measurements for the intercity transportation problem considered in this thesis will be presented in Chapter IV.

The performance of a system depends not only on the individual components, but also in the way they are connected. An interconnection model is also necessary before a solution can be obtained. If the terminal graphs of a set of components are interconnected in a one-to-one correspondence with the union of physical components, the result is a collection of line segments known as a system graph. The interconnection model satisfies two fundamental postulates. These postulates, the familiar Kirchoff's laws for electrical networks or Newton's first law and the compatibility law in mechanics are stated below.

Vertex Postulate. Let the system graph of a system contain "e" oriented elements and let Y_i represent the fundamental through variable of the i^{th} element, then at the v^{th} vertex of the graph,

$$\sum_{i=1}^{e} a_i Y_i = 0$$

where:

$a_i = 0$ if the i^{th} element is not incident at the v^{th} vertex

$a_i = 1$ if the i^{th} element is oriented away from the v^{th} vertex

$a_i = -1$ if the i^{th} element is oriented toward the v^{th} vertex.

Circuit Postulate. Let the system graph of a physical system contain "e" oriented elements and let X_i represent the fundamental across variable of the i^{th} element, then for the j^{th} circuit of the graph

$$\sum_{i=1}^{e} b_i X_i = 0$$

where:

$b_i = 0$ if the i^{th} element is not in the j^{th} circuit

$b_i = 1$ if the orientation of the i^{th} element is the same as the orientation chosen for the j^{th} circuit

$b_i = -1$ if the orientation of the i^{th} element is opposite to that of the j^{th} circuit.

Regardless of the complexity of any given system, it can be solved by the combined use of the terminal equations, and the circuit and vertex equations. However, not all of these equations are independent equations. To select the minimum number of independent equations for the system analysis, the fundamental cut set and fundamental circuit equations are used in lieu of the above postulates. These equations can be developed by using the following techniques.

The vertex postulate implies that one equation in the through variables Y can be written at each vertex of the system graph. The circuit postulate implies that one equation in the across variables X can be written for each circuit. Since these equations are not normally independent, it is useful to establish a tree of the graph which will guarantee a set of independent equations. This tree, called the formulation tree, is used to establish the fundamental circuit and cut set equations defined below.

Fundamental Circuit Equations

A tree is selected from the elements of the system graph. Since there are many such trees, the one actually used in the analysis is called the formulation tree as indicated above. The number of independent circuit equations will be equal to the number of chords (elements of the co-tree). The fundamental circuit equations are developed by including one and exactly one chord for each circuit written in accordance with the circuit postulate. A direction orientation is assigned to each chord used. When the across variables are separated into branches and chords, the independent circuit equations are given by the product of the circuit matrix and a column vector of the across variables.

$$\begin{bmatrix} B_{f1} & I \end{bmatrix} \begin{bmatrix} X_b \\ X_c \end{bmatrix} = 0 \qquad (3.1)$$

where:

B_{f1} is a coefficient matrix corresponding to the branches

I is an identity matrix corresponding to the chords

X_b is the column vector of the branch across variables

X_c is the column vector of the chord across variables.

The $e - v + 1$ fundamental circuit equations are defined by the circuit postulate and, thus, the matrix $\begin{bmatrix} B_{f1} & I \end{bmatrix}$ is of order $(e - v + 1) \times e$, where e is the number of elements in the system graph and v is the number of vertices. A completion of the matrix product gives the across variables of the chords explicitly as

$$X_c = -B_{f1} \; X_b \; . \tag{3.2}$$

Fundamental Cut Set Equations

A convenient set of independent equations in the through variables may be established by applying the vertex postulate in the following manner. The fundamental set of cut sets with respect to a tree is the set formed by each branch of the tree and all chords for which the fundamental circuit (with respect to the tree) contains this branch. The independent cut set equations are given by the matrix product of the cut set matrix and the column vector of the through variables. Symbolically, the fundamental cut set equations take this form:

$$\begin{bmatrix} I & C_{f1} \end{bmatrix} \begin{bmatrix} Y_b \\ Y_c \end{bmatrix} = 0 \tag{3.3}$$

where:

C_{f1} is a coefficient matrix corresponding to the chords

I is an identity matrix corresponding to the tree

Y_b is a column vector of the branch through variables

Y_c is a column vector of the chord through variables.

The fundamental cut set equations are defined by the vertex postulate and, thus, the matrix $\begin{bmatrix} I & C_{f1} \end{bmatrix}$ has order $(v - 1) \times e$. The branch through variables may be expressed explicitly as:

$$Y_b = -C_{f1} \; Y_c \; . \tag{3.4}$$

If a tree is selected from a graph, and the fundamental circuit and cut set matrices are formed with the columns of $B = \left[B_{\ell 1} \;\; I\right]$ and $C = \left[I \;\; C_{\ell 1}\right]$ arranged in the same order, it may be shown that:

$$C\,B^T = 0 \quad \text{and} \quad B\,C^T = 0 \tag{3.5}$$

which implies

$$C_{\ell 1} = -B_{\ell 1}{}^T \quad \text{or} \quad B_{\ell 1} = -C_{\ell 1}{}^T . \tag{3.6}$$

Thus, the fundamental cut set matrix corresponding to a tree can be uniquely determined from the fundamental circuit matrix of the same tree, and vice versa (61).

Formulation

The analysis of a system is based on the establishment of terminal equations, the fundamental cut set equations and the fundamental circuit equations. The formulation requires that the given across variables (acrss drivers) be placed in the branches (X_{b-1}) of a tree and the given through variables (through drivers) be placed in the chords (Y_{c-2}) of the co-tree. This assignment keeps the algebra involved in the solution of the system equations at a minimum and assures that a solution can be found. Several formulation procedures are available to the systems analyst, depending upon the form of the terminal equations and the number of independent equations afforded by each procedure. The branch formulation procedure is utilized in the solutions presented in later chapters, and, thus, will be outlined in general form here.

General Branch Form. The derivation of the general branch equations requires that the terminal equations be explicit in the through variables. The coupling parameter matrices G_{12} and G_{21} are zero since two terminal components are assumed and, thus, G_{11} and G_{22} are diagonal. This leads to some simplification in the matrix calculations as it shall be seen later in the development.

$$\begin{bmatrix} Y_{b-2} \\ Y_{c-1} \end{bmatrix} = \begin{bmatrix} G_{11} & 0 \\ 0 & G_{22} \end{bmatrix} \begin{bmatrix} X_{b-2} \\ X_{c-1} \end{bmatrix} . \tag{3.7}$$

The fundamental cut set equations are

$$\begin{bmatrix} I & 0 & C_{11} & C_{12} \\ 0 & I & C_{22} & C_{22} \end{bmatrix} \begin{bmatrix} Y_{b-1} \\ Y_{b-2} \\ Y_{c-1} \\ Y_{c-2} \end{bmatrix} = 0 . \tag{3.8}$$

Expanding Equation (3.8) such that Y_{b-2} and Y_{c-1} are in different columns yields:

$$\begin{bmatrix} I & C_{12} \\ 0 & C_{22} \end{bmatrix} \begin{bmatrix} Y_{b-1} \\ Y_{c-2} \end{bmatrix} + \begin{bmatrix} 0 & C_{11} \\ I & C_{21} \end{bmatrix} \begin{bmatrix} Y_{b-2} \\ Y_{c-1} \end{bmatrix} = 0 . \tag{3.9}$$

The terminal Equations (3.7) are substituted in (3.9)

$$\begin{bmatrix} I & C_{12} \\ 0 & C_{22} \end{bmatrix} \begin{bmatrix} Y_{b-1} \\ Y_{c-2} \end{bmatrix} + \begin{bmatrix} 0 & C_{11} \\ I & C_{21} \end{bmatrix} \begin{bmatrix} G_{11} & 0 \\ 0 & G_{22} \end{bmatrix} \begin{bmatrix} X_{b-2} \\ X_{c-1} \end{bmatrix} = 0 . \tag{3.10}$$

Now, X_{c-1} is expressed in terms of X_{b-1} and X_{b-2} from the circuit equations and Equation (3.6)

$$\begin{bmatrix} -C_{11}^T & -C_{21}^T & I & 0 \\ -C_{12}^T & -C_{22}^T & 0 & I \end{bmatrix} \begin{bmatrix} X_{b-1} \\ X_{b-2} \\ X_{a-1} \\ X_{a-2} \end{bmatrix} = 0 \,. \tag{3.11}$$

Expanding (3.11), one has

$$\begin{bmatrix} -C_{11}^T & -C_{21}^T \\ -C_{12}^T & -C_{22}^T \end{bmatrix} \begin{bmatrix} X_{b-1} \\ X_{b-2} \end{bmatrix} + \begin{bmatrix} I \\ 0 \end{bmatrix} \begin{bmatrix} X_{a-1} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} \begin{bmatrix} X_{a-2} \end{bmatrix} = 0 \,. \tag{3.12}$$

Taking the top set of equations and the identity $X_{b-2} = X_{b-2}$ yields:

$$\begin{bmatrix} X_{b-2} \\ X_{a-1} \end{bmatrix} = \begin{bmatrix} 0 & I \\ C_{11}^T & C_{21}^T \end{bmatrix} \begin{bmatrix} X_{b-1} \\ X_{b-2} \end{bmatrix} \tag{3.13}$$

Substituting (3.13) into (3.10),

$$\begin{bmatrix} I & C_{12} \\ 0 & C_{22} \end{bmatrix} \begin{bmatrix} Y_{b-1} \\ Y_{a-2} \end{bmatrix} + \begin{bmatrix} 0 & C_{11} \\ I & C_{21} \end{bmatrix} \begin{bmatrix} G_{11} & 0 \\ 0 & G_{22} \end{bmatrix} \begin{bmatrix} 0 & I \\ C_{11}^T & C_{21}^T \end{bmatrix} \begin{bmatrix} X_{b-1} \\ X_{b-2} \end{bmatrix} = 0 \tag{3.14}$$

or

$$\begin{bmatrix} I & C_{12} \\ 0 & C_{22} \end{bmatrix} \begin{bmatrix} Y_{b-1} \\ Y_{a-2} \end{bmatrix} + \begin{bmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{bmatrix} \begin{bmatrix} X_{b-1} \\ X_{b-2} \end{bmatrix} = 0 \tag{3.15}$$

where W_{11}, etc., are coefficient sub matrices of the matrix triple product in (3.14).

Since X_{b-1} and Y_{c-2} are known functions, the solution is determined by solving the equations contained in the lower set of (3.15) for X_{b-2}.

$$C_{22} \cdot Y_{c-2} + W_{21} \cdot X_{b-1} + W_{22} \cdot X_{b-2} = 0 \qquad (3.16)$$

$$X_{b-2} = W_{22}^{-1} \left[-W_{21} \; X_{b-1} - C_{22} \; Y_{c-2} \right] \qquad (3.17)$$

where:

X_{b-2} are the unknown branch across variables

Y_{c-2} are the specified through drivers in the co-tree

X_{b-1} are the specified across variables in the tree.

The number of equations to be solved is $v - 1 - Nx$, where v is the number of vertices and Nx is the number of driver elements for which across variables are known.

Summary

The general formulation technique presented here may be used when the system is made up of two terminal algebraic components. It is necessary that the elements with specified across variables (X_{b-1}) be included as branches of the formulation tree and those elements with specified through variables (Y_{c-2}) be included as chords. The number of unknown branch across variables in the set (X_{b-2}) determines the number of independent equations in the final branch form.

By proper substitution and matrix manipulation, Equation (3.17) can be solved for numerical answers. The computer program used to carry out the solution of the branch formulation highway travel model is given in Appendix B.

CHAPTER IV

THE HIGHWAY TRAVEL MODEL

Introduction

This chapter will be devoted to a description of the intercity travel model developed and tested in this thesis. This model employs the techniques of linear graph analysis to solve for traffic flows on the route components under varying travel impedance conditions. The role of highway design and condition is given special attention through the development of an equivalent distance factor which is applied to the route components to determine the relative deterrence to travel encountered on each route.

The Study Area

The Oklahoma state highway system is divided into eight regions for the purpose of planning and representation. Each district is represented by an appointed commissioner, who is responsible for evaluation of the needs for road improvements within his district. In order to aid the commissioners with their planning decisions, the state highway department planning division conducts extensive highway needs studies and prepares a report which summarizes the condition of all highways within each district. The results of that report (44) are used to determine the impedance of the route components described later in this chapter.

Each of the eight commissioners' districts shown in Figure 3 contains about ten counties, but not all districts have the degree of inhomogeneity in road type and condition or city size to be suitable as a representative test area for the modeling presented here. The area chosen for consideration is the 1st highway commissioner's district. It is composed of ten counties, Ottawa, Delaware, Mayes, Craig, Nowata, Rogers, Tulsa, Washington, Pawnee, and Osage, in the northeastern part of the state. This district is characterized by various terrain, varied road types -- from limited access tollways to ill repaired blacktop highways -- and varied city sizes. Another factor influencing the choice of district #1 is the availability of origin-destination surveys for various cities within its boundaries. Of the thirty-five such studies conducted during a five year period from 1964-1968, district #1 was fortunate to get more than its normal share. In particular origin-destination studies were conducted in Nowata (43), Miami (39), Pawhuska (46), Hominy (27), and Vinita (57), during 1966-1968. The information contained in these surveys proved invaluable in providing input and test data for the models presented later in this chapter.

Definition and Modeling of Components

The system to be studied in this section consists of all cities, which have populations over 2,500, their associated surrounding regions in the 1st highway commissioner's district and the road system of the district. Three types of components are identified in the system:

(1) Origin areas for travelers.

(2) Highway links.

(3) Destination areas for travelers.

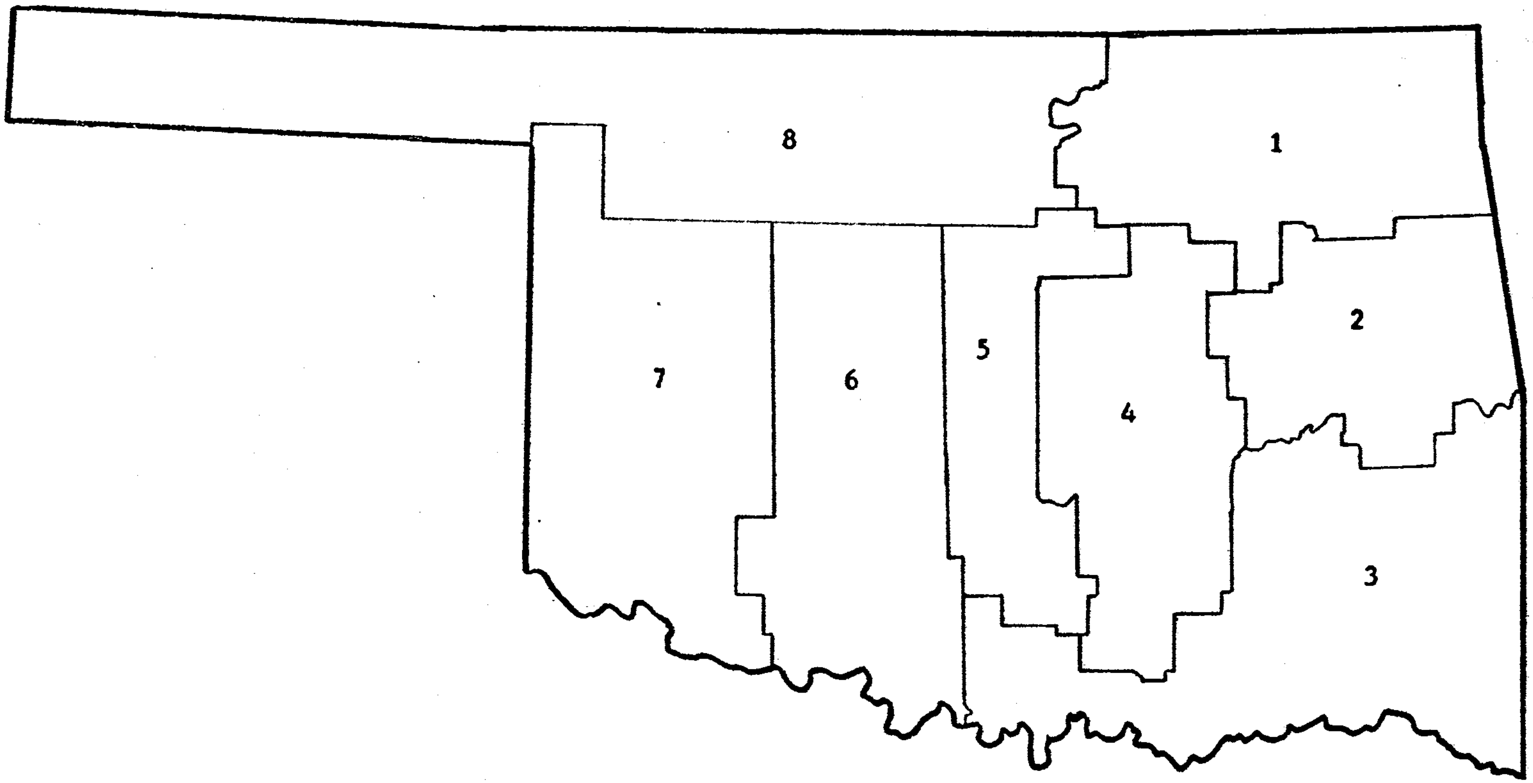

Figure 3. Oklahoma Highway Commissioner Districts

Each component is modeled by means of an oriented line segment and an equation relating two variables X and Y. The Y variable is taken to be the flow of vehicles in each component, measured on a per day basis. It would be quite feasible to consider the measure of the Y variable to be vehicles/month or per week rather than per day, if the data were available in such a format. The variable X is taken to be the propensity to travel, or the demand pressure to travel. Propensity to travel is considered to be annilated by the process of making a trip from an origin area to an appropriate destination.

Origin Areas

The origin areas are modeled as two-terminal flow drivers of known magnitudes. Their component equations are taken as:

$$Y_{oi} = \text{Known} \qquad i = 1,\ldots\ldots..25 \qquad (4.0)$$

The known magnitude is taken to be the number of trips/day originating from each origin area zone. These trip volumes are assumed to be directly proportional to the personal income of the zone. Each origin is represented by a point source emanating from a node which is considered to be at the activity centroid of each zone. For all zones the activity centroid is defined by a city of population over 2,500. These cities together with the regions they represent are shown in Figure 4. The boundaries shown do not represent distinct geographical boundaries in all cases but rather indicate in general the origin area study unit. The personal income data used for trip generation analysis for each origin area was only available on a per county level of resolution. In order to arrive at estimates for the generation capabilities of some of the smaller geographic units, it was necessary to assume that the

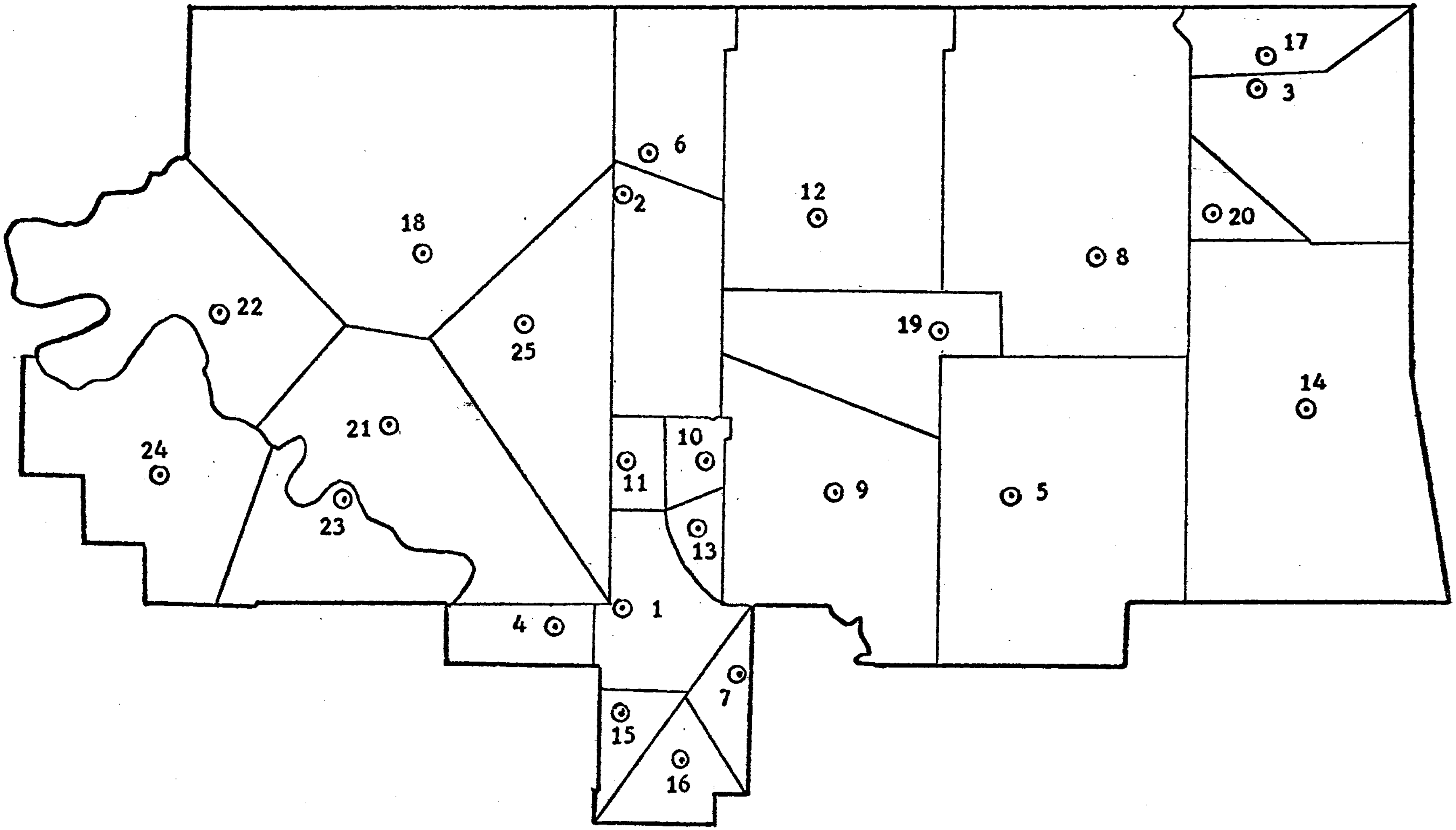

Figure 4. Travel Generation/Attraction Zones of the First Commissioner District

personal income of the region was proportional to the city size in urban areas and uniformly distributed in rural areas. The line segment representing an origin area is considered to be connected in the system linear graph of Figure 5 from an arbitrary reference point (not shown in the figure for clarity) and the appropriate activity centroid. The orientation is taken as away from the datum as each origin zone is sequentially considered in the analysis.

Highway Links

It is postulated that the highway links connected by the origin and destination areas could be modeled as:

$$Y_{hj} = G_j X_{hj} \qquad j = 1,2,\ldots\ldots,50 \qquad (4.1)$$

The parameter G_j represents "ease of travel"; i.e., if $1/G_j$ is large, the flow of vehicles for a given propensity difference across a link is small. It is postulated that for the trip purposes considered here two factors of the route are influential; the time and effort required to travel the route, and the direct out-of-pocket expenses incurred in so doing. Time and effort effects will be measured through the development of the "equivalent distance" parameter for each route component. Note that travel distance, as such, is considered to be a less representative measure of trip deterrence than time and effort. It has been discovered in previous studies that for many trip-making purposes people are willing to choose a longer route if they can save time and effort by so doing. Cost of travel is also considered as a measure of trip impedance and will include such factors as road user costs, fuel, tires, oil, maintenance and repairs, depreciation, time costs and extra charges such

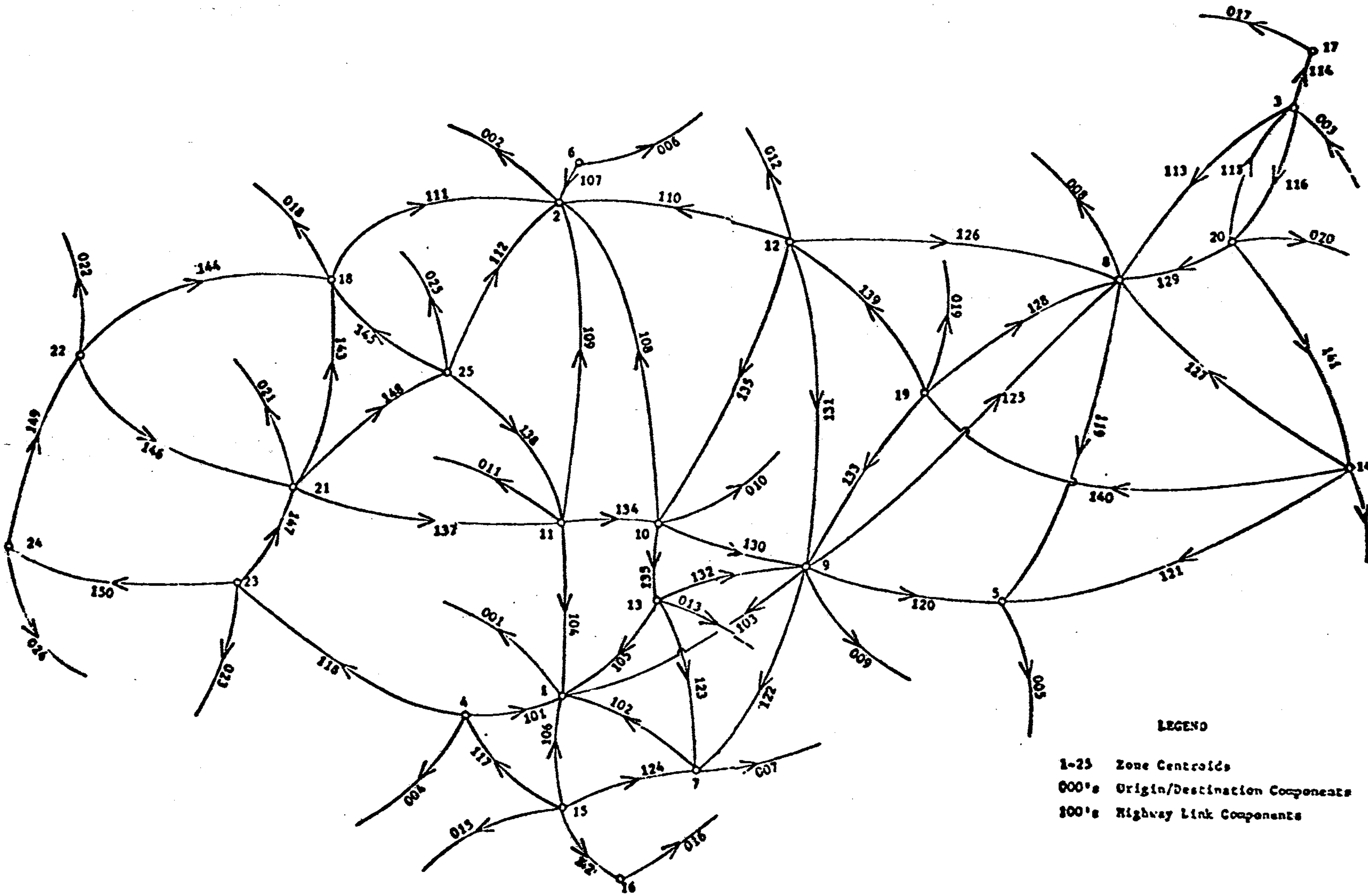

Figure 5. System Linear Graph for the First Commissioner District Highway Network

as toll costs. The "equivalent distance" concept as a measure of travel impedance is now examined more closely.

The equivalent distance, DEQ, for any highway link is obtained by examining its design and current condition. These two factors are broken down further into their component parts and points are assigned to each -- a total of 100 points implying a road of excellent design and condition, (i.e., one which would allow free traffic flow at a speed of 60 mph). This free flow condition must be considered to be within the volume design limitations of the particular roadway since the effect of traffic congestion upon travel impedance is not explicitly considered. This is a reasonable approach for intercity travel in the area under study but would obviously be an improper assumption if one were studying the urban travel patterns within the city of Tulsa. The data used to obtain a measure of the design and condition of each road section considered in the study was obtained from the state Highway Department (44). A sample of this data is shown in Appendix A. The weights given in the sufficiency rating assignment schedule shown in Table II are based on many years of observation and experience of the Department.

The general expression for the equivalent distance factor of a given link is devised as follows:

$$DEQ_j = \sum_{k=1}^{n} (2)^{P}\left(\frac{d_{jk}}{SR_{jk}}\right) \qquad (4.2)$$

where:

DEQ_j = equivalent distance factor for the jth link.

d_{jk} = length in miles of the kth subsection of link j.

TABLE II

SUFFICIENCY RATING ASSIGNMENT SCHEDULE

Design		Condition	
Surface width	16	Foundation	14
Surface type	8	Wearing surface	10
Shoulder width and type	6	Drainage	7
Curvature	8	Shoulders	4
Gradient	5		
Stopping sight distance	8	Total Condition Rating	35
Passing opportunity	8		
Hazards	6		
Total Design Rating	65	Total Roadway Rating	65 + 35 = 100

SR_{jk} = percentage design and condition sufficiency rating for the kth subsection of link j.

P = a binary variable such that P = 0 if the kth subsection of link j is rural and P = 1 if the kth subsection of link j is urban.

n = total number of subsections of link j.

An example of the use of this general expression for the determination of the equivalent distance measure is given for two dissimilar route sections. This example points out the effects of design and condition of the roadway on its equivalent length. First, link number 102 which is chosen to represent State Highway 51 between Broken Arrow and Tulsa (the Broken Arrow Expressway), is examined. A careful examination of Figure 6 showing the major roadways in the study area and the system linear graph (Figure 5) points out the element assignment pattern of the system graph. An element in the graph is placed in one to one correspondence with either a route component or an origin/destination component. From the data (44) it is seen that this road section is a limited access divided four lane highway consisting of 3.9 miles rating 100, 4.2 miles rating 92, and 5.0 miles with a 99 rating. The equivalent distance constant for this section would be obtained as follows:

$$DEQ_{102} = \frac{3.9}{1.0} + \frac{4.2}{.92} + \frac{5.0}{.99} = 13.5$$

This compares to an actual highway distance of 13.1 miles.

Second link number 135 which is chosen to represent highway 169 between Collinsville and Nowata is examined. Upon examining the data (44), it is seen that this two lane roadway is made up of sections in three counties which vary considerably in both design and condition.

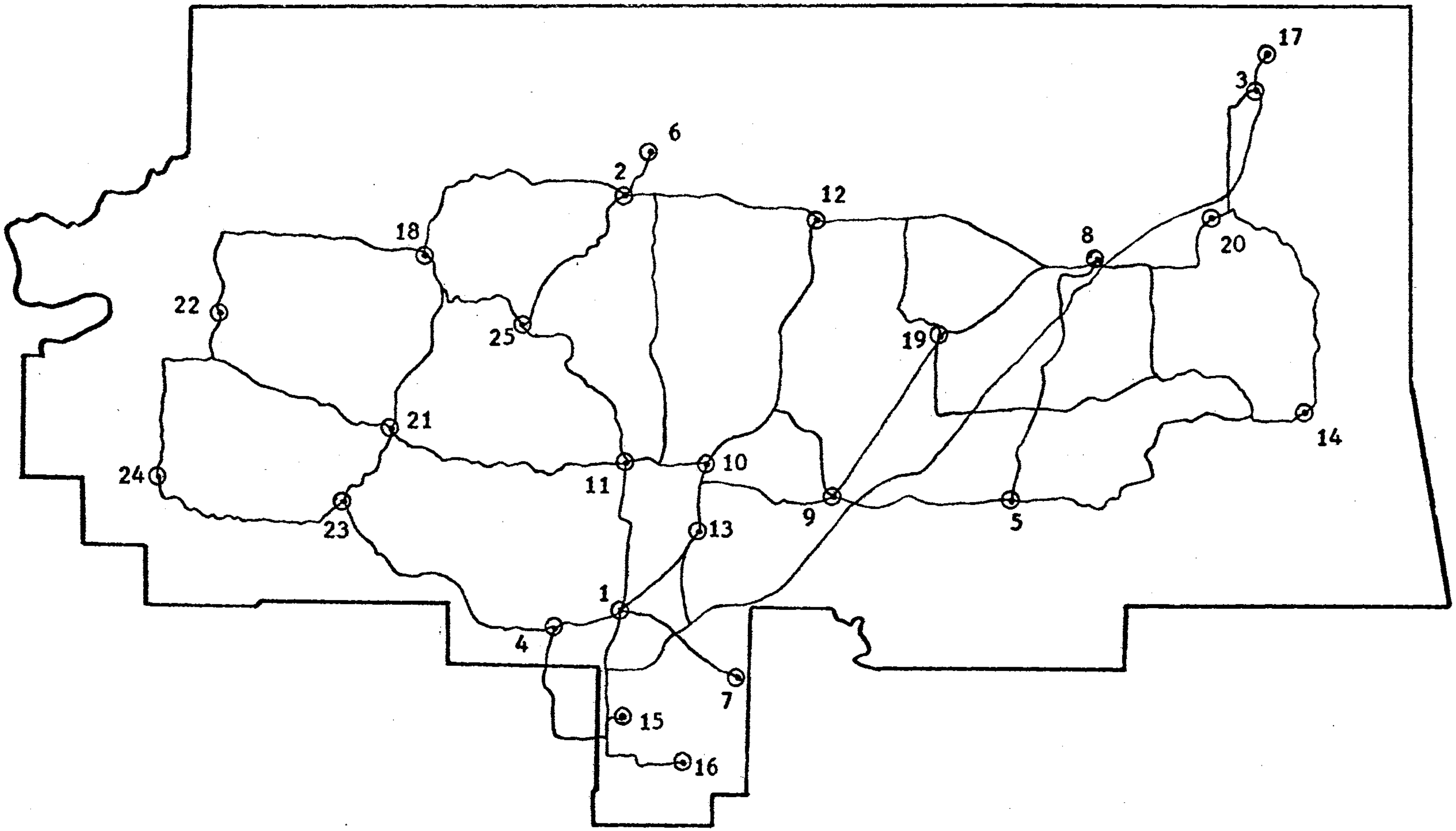

Figure 6. Major Interior Highways of the First Commissioner District

In addition, some sections of the roadway pass through urban areas. The equivalent distance constant for section 135 would be obtained as:

$$DEQ_{135} = \frac{1.0}{.55} + \frac{2.8}{.60} + \frac{4.4}{.48} + \frac{2.0}{.60} + \frac{0.7(2)}{.57} + \frac{4.9}{.50} +$$

$$\frac{0.4(2)}{.53} + \frac{1.8}{.58} + \frac{1.3}{.92} + \frac{2.0}{.68} + \frac{6.8}{.65} + \frac{0.6(2)}{.85} = 42.4 \ .$$

This compares with an actual highway distance of 28.7 miles for link number 135. All urban road sections, except urban expressways, have had their equivalent distance factors doubled to adequately account for the normal increase in impedance encountered in urban areas (the free flow speed condition in an urban area is approximately one-half of that for a rural section).

Equivalent Distance Conductance. The parameter G_j based on the equivalent distance concept for each highway link is defined as follows:

$$G_j = \frac{K_d}{(D_j)^2}\left(\frac{D_j}{DEQ_j}\right) \qquad (4.3)$$

where

D_j = the total length of the jth link.

DEQ_j = the equivalent distance factor for the jth link.

K_d = the dimensional adjustment constant - fixed for all route components.

Thus, it is seen from the above that as the condition of a given route decreases the "deterrence to travel" factor increases according to the ratio (D_j/DEQ_j). It is appropriate to check various hypothetical conditions for the component model to see if the results predicted by the component equations satisfy the researcher's intuition. Assume that the potential for travel x on any given link is known and constant over some time interval when the design or condition of a subsection of the route is changed. Suppose that the link is modified in such a way as to decrease the equivalent distance perceived by the travel consumer. What would we expect? Does the component model accurately reflect this expectation? The answer is "yes", as DEQ decreases the deterrence to travel factor also decreases and an increase in the actual flow of trips on the route would be anticipated. Similar situations allowing for changes in the component equation variables and parameters verify intuitively the structure of the component equations. Table III shows a comparison of the actual highway distances, air distances, and equivalent distances for each component. (Some route distances are shown less than air distances; this is because of slight location errors in the data used as input for the calculations of air distances by the BPR programs.)

Operator Cost Conductance. The use of operator cost as a measure of route conductance takes the following form:

$$G_j = \frac{K_c}{C_{ij}} \tag{4.4}$$

where:

C_{ij} = the total out of pocket and time costs of traveling from zone i to zone j.

K_c = the dimensional adjustment constant - fixed for all route components.

TABLE III

LINK DISTANCE COMPARISONS

Link Number	Nodes Connected	Air Distance (miles)	Route Distance (miles)	EQ Distance (miles)
101	1-4	8	5.4	14.4
102	1-7	15	13.1	13.5
103	1-9	23	29.1	32.7
104	1-11	12	15.4	36.1
105	1-13	11	12.9	36.9
106	1-15	9	10.7	20.2
107	2-6	5	3.9	7.5
108	2-10	28	29.3	39.3
109	2-11	26	29.8	39.5
110	2-12	21	21.7	46.7
111	2-18	25	23.9	41.0
112	2-25	16	17.7	39.4
113	3-8	24	24.5	27.6
114	3-17	4	4.9	9.8
115	3-20	13	13.7	23.2
116	3-20	13	12.1	13.1
117	4-15	12	16.9	47.2
118	4-23	20	25.0	45.5
119	5-8	23	28.0	35.5
120	5-9	17	16.4	27.4
121	5-14	30	38.3	92.1
122	7-9	20	27.7	30.7
123	7-13	15	18.8	20.7
124	7-15	13	16.1	18.6
125	8-9	31	31.7	36.1
126	8-12	21	27.2	38.9
127	8-14	27	35.4	63.5
128	8-19	15	16.6	24.8
129	8-20	14	14.8	23.5
130	9-10	11	17.2	42.3
131	9-12	26	30.5	45.3
132	9-13	13	19.1	58.5
133	9-19	17	19.6	28.8
134	10-11	9	8.6	20.2
135	10-12	27	28.7	42.4
136	10-13	6	8.1	36.2
137	11-21	23	23.7	38.7
138	11-25	19	26.3	40.3
139	12-19	14	22.7	32.9
140	14-19	37	48.3	76.5
141	14-20	20	28.9	55.8
142	15-16	9	12.3	21.0
143	18-21	17	14.8	23.6
144	18-22	19	27.8	34.8
145	18-15	14	15.2	38.6

TABLE III (Continued)

Link Number	Nodes Connected	Air Distance (miles)	Route Distance (miles)	EQ Distance (miles)
146	21-22	24	25.6	35.1
147	21-23	9	9.6	23.7
148	21-25	17	25.6	48.3
149	22-24	17	20.8	30.2
150	23-24	17	21.2	35.9

The total costs are determined as follows:

$$C_{ij} = C_v d_{ij} + C_t t_{ij} + C_{tl} \qquad (4.5)$$

where:

C_v = vehicle operating costs per mile.

d_{ij} = route distance in miles from zone i to zone j.

C_t = time costs per minute.

t_{ij} = travel time in minutes from zone i to zone j.

C_{tl} = toll costs, other unusual costs.

The travel time for each link was determined by examining its equivalent distance coefficient and assuming that under a 100% rating condition one could travel at a rate of one mile/minute. An intuitive test of this form of the highway component equations is also in order. As the cost of travel on any link increases for a given constant propensity to travel the flow of trips on the link tends to decrease. The total highway travel costs given in Table IV were derived by appropriate use of the tables for determining road user costs for Passenger Cars in Rural areas included in Appendix C.

Destination Areas

The destination areas are modeled in terms of an attraction index of each area. The attraction index is taken to be directly proportional to the personal income of the area. In the linear graph theory model the destination component equations take the form:

$$Y_{di} = K_a A_i X_{di} \qquad i = 1,2,\ldots..25 \qquad (4.6)$$

TABLE IV

HIGHWAY TRAVEL COSTS

Link Number	Nodes Connected	Operating Cost (dollars)	Time Cost (dollars)	Total Cost (dollars)
101	1-4	.25	.43	.68
102	1-7	.90	.40	1.30
103	1-9	1.74	.98	2.72
104	1-11	.74	1.08	1.82
105	1-13	.62	1.10	1.72
106	1-15	.52	.60	1.12
107	2-6	.19	.22	.41
108	2-10	1.64	1.18	2.82
109	2-11	1.67	1.18	2.85
110	2-12	1.04	1.41	2.45
111	2-18	1.64	1.23	2.87
112	2-25	.85	1.18	2.03
113	3-8	1.47	.82	2.69*
114	3-17	.23	.29	.52
115	3-20	.68	.69	1.37
116	3-20	.78	.39	1.37*
117	4-15	.81	1.42	2.23
118	4-23	1.20	1.36	2.56
119	5-8	1.73	1.06	2.79
120	5-9	.82	.82	1.64
121	5-14	1.84	2.78	4.62
122	7-9	1.80	.92	2.92*
123	7-13	1.22	.62	1.84
124	7-15	.96	.55	1.51
125	8-9	1.90	1.05	3.70*
126	8-12	1.53	1.16	2.69
127	8-14	1.75	1.91	3.66
128	8-19	.86	.74	1.60
129	8-20	.73	.70	1.43
130	9-10	.82	1.27	2.09
131	9-12	1.61	1.36	2.97
132	9-13	.91	1.75	2.66
133	9-19	1.01	.86	1.87
134	10-11	.41	.60	1.01
135	10-12	1.52	1.27	2.79
136	10-13	.38	1.08	1.46
137	11-12	1.18	1.16	2.34
138	11-25	1.40	1.21	2.61
139	12-19	1.20	.98	2.18
140	14-19	2.47	2.29	4.76
141	14-20	1.38	1.70	3.08
142	15-16	.62	.63	1.25
143	18-21	.75	.71	1.46
144	18-22	1.72	1.04	2.76
145	18-25	.73	1.15	1.88

TABLE IV (Continued)

Link Number	Nodes Connected	Operating Cost (dollars)	Time Cost (dollars)	Total Cost (dollars)
146	21-22	1.43	1.05	2.48
147	21-23	.46	.71	1.17
148	21-25	1.25	1.45	2.70
149	22-24	1.10	.90	2.00
150	23-24	1.08	1.07	2.15

*Includes turnpike toll charges.

where:

K_a = the dimensional adjustment constant - fixed for all destination components.

A_i = the attraction index of destination area i.

Y_{di} = the flow of trips/day through the ith destination component.

X_{di} = the travel demand pressure causing the flow.

Since no satisfactory measurement technique has been devised to quantify the conceptually interesting variable X_{di}, a formulation procedure, the branch equation method previously described, was used in the solution. This procedure does not require knowledge of the across variable -- only flows need measuring.

Model Formulation and Solution

With the component equations outlined in the previous section and the system linear graph shown in Figure 5, the model formulation is now complete. All that appears to remain is an appropriate choice of a formulation tree and the solution should follow the form outlined in the branch equation method given in Chapter III. However, since each origin area is also a destination area and vice versa this procedure will lead to erroneous results. That is, trips which originate at zone i destined to zone j would be calcelled in part by trips originating at zone j with destination zone i, due to the algebraic summation of these trips along route ij. Thus, an alternative solution procedure is needed which will account for these unrealistic cancellations. The "net" flow of travel from zone i to zone j is not of interest, but rather the total volume of flow on each route.

To accomplish this goal the well-known Superposition Principle is modified to realistically reflect the transportation problem at hand.

> At any point of a linear network, the response to a number of excitations (through and/or across drivers) acting simultaneously is equal to the sum of the absolute values of the responses at that point due to each excitation acting alone in the network.

Note that the modification is in the summation of the responses -- sum of absolute values replaces algebraic sum in the normal superposition principle.

In the problem of concern here, this statement implies that one may consider each zone to act as an origin zone while other zones appear as destinations, calculate the flows of trips on each route component and then proceed to the next zone. The total volume of trips on any route component will be equal to the sum of the absolute values of the trips contributed by each origin area. In each step of this process, the solution is obtained by the branch formulation procedure outlined in Chapter III with the modified superposition principle applied to find the total travel values.

The impedance values for the components shown in the system linear graph of Figure 5 have been related to two quite dissimilar quantities. In the case of the highway components, the impedance was taken to be proportional to road length, design, and condition through the route equivalent distance, or to the cost of travel. In the case of destination components the component conductance was directly related to the personal income of the region the component was chosen to represent. In order that the model be calibrated to accurately reflect traffic flow on the route components it is necessary to examine the dimensional adjustment constants given in the component equations with some care. The implementation of the calibration procedure and its affect on the distribution of traffic over the network is best explained in terms of the following simple example.

Consider the system linear graph shown in Figure 7 representing a hypothetical area composed of three origin/destination components and three route components.

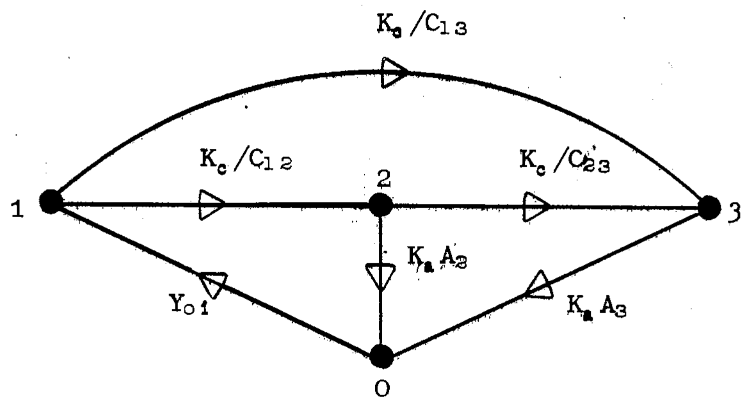

Figure 7. Calibration Example System Graph

The route component impedance is represented by operator costs as given in Equation (4.4). The destination areas are modeled in terms of the personal income attractiveness of each zone as given in Equation (4.6). The single origin area is modeled as a flow driver of known magnitude in accordance with Equation (4.0).

The calibration of the model is as follows: From available origin/destination surveys for the study area, the number of trips observed at zones 2 and 3 may be obtained. The dimensional adjustment constants, K_c and K_a, are adjusted by regression analysis so that the summation of the squared differences between the observed trips and the predicted trips is as small as possible. This adjustment does not affect the total number of trips in the network entering the data node, but only how these trips are distributed on the network and between alternative destinations. Further, it should be understood that these two constants are the only two constants needed in the analysis regardless of size of the network considered.

The solution of the system shown in Figure 5 was accomplished through use of the computer program given in Appendix B which is an application of the branch formulation technique. The results of the various computer runs are presented in tabular form in Table V.

Summary

This chapter has been devoted to the development of the component models defined for the Highway Travel system. Special attention has been given to accurate reflection of the effects of highway design and condition and travel costs in formulating the component models for the two-terminal highway components. Origin and destination area components were defined and modeled. The origin areas were modeled as known through drivers, the destination areas as two-terminal passive components with their impedance values inversely proportional to the personal income of the destination zone. The highway links were modeled as two-terminal passive components, with both travel costs and equivalent distance used to reflect the deterring influence on travel.

The solution procedure for determining the trip volumes on each highway component is as follows: Each origin area is sequentially excited with its known trip generation volumes while all other areas are viewed as possible destinations. The total volume of trips on any given link is taken to be the absolute sum of trips created by each origin area. This summation is obtained by application of a modified form of the superposition principle. The results of the numerical solution are shown in Table V.

The two calibration constants are used to reflect the proportionality of trips to personal income in the case of the origin/destination components and trips to reciprocal impedance in the case of highway components. These constants were obtained by examining the distribution of known trips from origin/destination surveys for selected cities within the study region. Since the system contains only known through drivers and no across drivers these constants do not have any effect on the total trips generated in the network. They do, however, effect the distribution of trips along the various highway links and destination zone components. The values chosen were those which most nearly reflected travel patterns for the areas with known origin/destination data. This is in effect the calibration check for the model.

CHAPTER V

MODEL COMPARISONS

Introduction

It is difficult to ascertain the utility of any new alternative approach to transportation analysis without comparing it with some accepted standard analysis approach. The Bureau of Public Roads System 360 Transportation Planning Package developed by Brokke and his associates has been widely used and accepted in the study of urban patterns. It has to a lesser extent been used in the analysis of intercity travel. In the discussion which follows, the results will be seen of applying a modified form of the BPR package to the study area considered in this thesis. The modification results from the use of an intuitive gravity model developed by Basore et al., for the generation of the trip tables required by the package. The trip table generation model was developed for a study of statewide travel patterns in Oklahoma and the results of applying the model have shown it to reasonably reflect travel patterns on a statewide basis. The use of this procedure on a smaller geographical area should present no unusual difficulties. The results of the application of the modified BPR procedure to the 1st Commissioner's District should provide an interesting and enlightening comparison for the results of the linear graph analysis presented in Chapter IV.

The BPR programs were obtained on magnetic tape from Jerry Howell of the State Highway Department. They were made operational on Oklahoma

State University's IBM 360-65 system with the assistance of Iris McPherson of the University Computer Center.

The Modified BPR Model

The following discussion provides a brief description of the BPR programs used in the analysis of travel patterns in the 1st Commissioner's District. The programs were executed as outlined in the flow diagram given in Figure 8. The reader is referred to Appendix B and the program documentation (56) for more insight into the use of the BRP battery.

Build Spiderweb Network (BLDSPWB)

The purpose of this program is to prepare a spiderweb network description from connector cards and coordinate cards supplied by the user. The program was originally written by Brokke (9) for use in a ntionwide highway travel study but has been successfully used for studies of smaller geographic units. A spiderweb network is a network of nodes and links connecting these nodes. The spiderweb network developed for the 1st Commissioner's District is shown in Figure 8. The nodes shown in Figure 8 represent the activity centroids of the zones defined for the linear graph model. Although the links do not represent actual highway links, they were chosen to resemble, as closely as possible, the actual highway network of the region. A comparison of Figure 6 and Figure 9 will demonstrate this fact.

The BLDSPWB program accepts up to 8,170 nodes and 8 connectors for each node. Unfortunately, eight-way intersections are extremely rare in nature, and the use of eight connectors for each node would make the

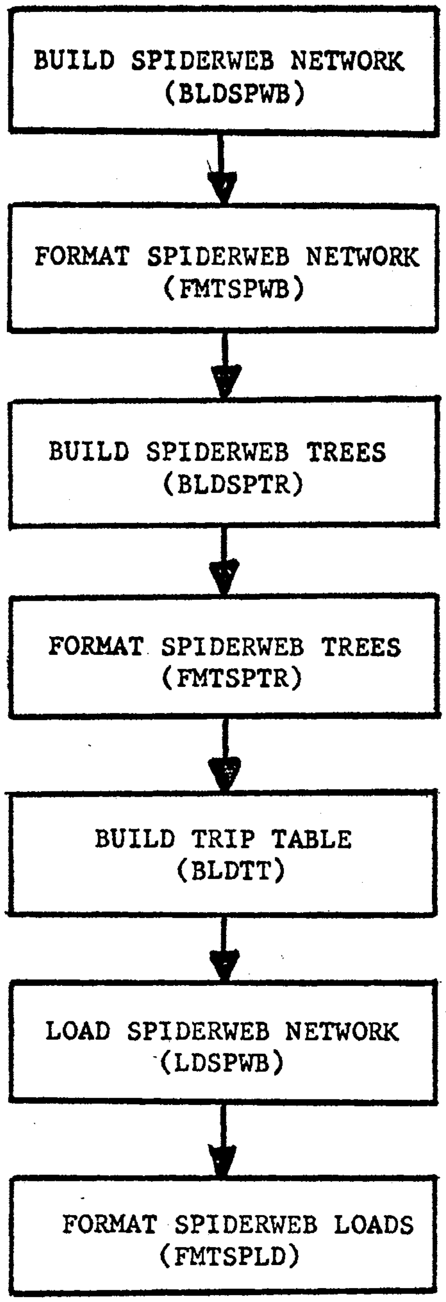

Figure 8. Modified BPR Program Execution Flow Chart

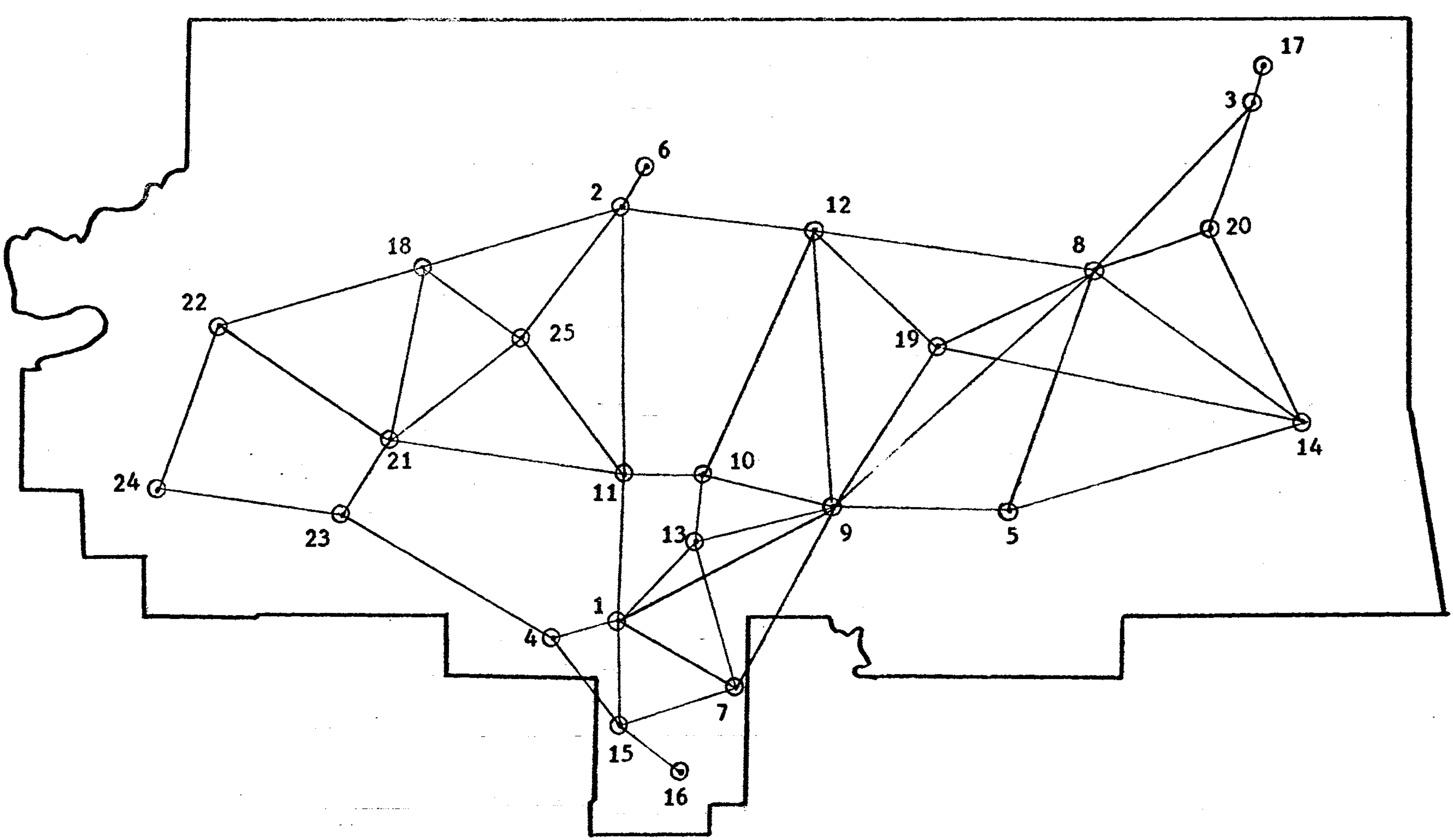

Figure 9. Spiderweb Network for the First Commissioner District

network representation more schematic than real. Thus, for most nodes fewer than eight connectors were used.

The advantage of using the full complement of connector options comes in studying travel demand (4), where some connections can be viewed as potential routes or desired lines of travel.

A description of the input data required by the program and the appropriate execution cards are shown in Appendix B.

Format Spiderweb Network (FMTSPWB)

The purpose of this program is to provide a standard format output of the spiderweb network description built by BLDSPWB. There are no program options, and the formatted output consists of the link impedance and link distance (these should be equal) and the corresponding speed on the link. In addition, the zone number and name are formatted. The formatted output also supplies the x-y coordinates of each node. A listing of the execution setup for this program is shown in Appendix B. The formatted output is shown in Appendix B.

Build Spiderweb Trees (BLDSPTR)

The purpose of this program is to provide a file of minimum path trees, one tree for each node based on link length. The program has the option of building either minimum travel time path trees or minimum distance path trees. The option chosen was minimum distance path trees. A minimum path tree may be defined as a record indicating the shortest route from a given node to all other nodes in the spiderweb network. These trees, one for each network node, are used in determining the proper loading of trips on the network. The computer listing required for execution of BLDSPTR is shown in Appendix B.

Format Spiderweb Trees (FMTSPTR)

The purpose of this program is to provide a standard format printout of selected minimum path trees. This output may be studied by the user as a check on the minimum distance routings created by the BLDSPTR program. It may also provide information which will allow deletion of a link included in the original spiderweb network. Up to thirteen trees may be printed out in any one execution of the program. A sample listing of the standard formatted output is given in Appendix B. The computer input required for execution is shown in Appendix B.

Build Trip Table (BLDTT)

The purpose of this program is to provide a trip table - a list of trip interchange volumes. It was originally developed for the Oklahoma Transportation Study conducted by the Multidisciplinary Studies Group at Oklahoma State University (4). It employs the intuitive gravity model described in Chapter II, and has been calibrated and tested for the State of Oklahoma. The output subroutine allows for a standard formatting of the predicted trip interchange and trip end volumes. The program requires as input the location of each node in the spiderweb network and the personal income of the zone the node represents. A description, listings, and sample output of the program is given in Appendix B. This program is the only program executed in the flow chart of Figure 8 which is not a standard part of the BPR package.

The trip interchanges generated by the program are assumed to be symmetrical and only the upper triangle trip table matrix is shown in Appendix B.

Load Spiderweb Network (LDSPWB)

The purpose of this program is to provide a loaded spiderweb network. Trips generated by the BLDTT program are loaded onto the network via the minimum path tree record produced by BLDSPTR. The LDSPWB loads the links of the spiderweb network with trip volumes such that if a link is a member of a minimum path tree connecting a pair of nodes, the trip volume for that pair of nodes generated by BLDTT is loaded onto that link. The BPR package does not provide unidirectional loading, so it is necessary to load volumes from one-half the trip table matrix (above the diagonal) and then transpose the matrix and add the loads from the second one-half of the trip table (below the diagonal).

The computer listing necessary for execution of LDSPWB is given in Appendix B.

Format Spiderweb Loads (FMTSPLD)

The purpose of this program is to provide a standard formatted output of the loaded spiderweb network. The program lists the total network volumes for each spiderweb network link. A listing of this program is shown in Appendix B. Sample output is shown in Appendix B.

Comparison of Results

The results obtained from the numerical solution of the linear graph highway travel model and the modified BPR model are shown in

Table V. They are compared with actual traffic volumes recorded in the study area by the Planning Division of the State Highway Department. It should be pointed out that these observed volumes include through trips. That is, trips which have either an origin or destination external to the study area. The study area has been considered as a closed system and neither the through driver origin volumes in the linear graph model nor the traffic generation model used in the modified BPR approach account for through traffic volumes. Therefore, it is necessary to deduct from the actual volumes that portion which are due to through traffic movements before conclusions can be drawn about how well the various models predict travel patterns. This is very difficult if not impossible to accomplish since through trips vary from 10% of the total volume on some minor highways to as much as 70% on limited access highways.

There are several observations one may make upon careful examination of the model results. First, as predicted, the BPR model appears to overestimate trips for nodes which are in very close proximity. This is due to the unrealistic underestimation of travel impedance for such situations. Brokke (9) developed the model for trips of length greater than 20 miles and makes no claims concerning its validity for short trips. It is also seen that certain links in the network were seldom included as an element in a minimum path tree and, thus, little or no traffic was assigned to this route by the BPR routines. This is evidenced most clearly by Link #140, the longest link in the spiderweb network. There appears to be a tendency for the BPR model to underestimate traffic flow between the smaller (smaller in personal income) zones.

TABLE V

PREDICTED VOLUME COMPARISONS

Link Number	Actual Volume[1] trips/day	BPR Volume trips/day	EQ Distance Volume[2] trips/day	Cost Volume[3] trips/day
101	17,300	79,333	30,946	23,112
102	16,000	9,202	24,025	17.632
103	17,400	3,482	9,212	4,261
104	5,200	16,662	9,111	9,747
105	2,700	18,320	7,463	5,127
106	9,500	21,626	6,230	6,262
107	5,200	28,746	17,012	11,262
108	3,900	4,126	1,236	4,121
109	A	A	1,230	3,461
110	1,900	484	926	2,537
111	1,600	162	913	2,961
112	1,100	374	712	2,847
113	1,300	348	961	2,892
114	10,300	5,438	12,047	4,261
115	6,200	208	1,420	4,723
116	3,100	B	2,063	3,123
117	9,000	338	12,291	6,307
118	3,100	780	964	4,128
119	3,700	106	631	2,623
120	3,100	1,348	1,264	1,467
121	700	100	61	128
122	6,300	146	2,174	3,126
123	11,300	238	1,008	6,120
124	9,500	620	1,132	4,578
125	7,000	506	3,124	2,072
126	1,200	184	631	672
127	500	34	94	574
128	2,000	102	738	327
129	2,500	196	614	1,024
130	2,100	546	1,010	523
131	1,300	50	562	431
132	2,100	192	1,240	1,020
133	2,700	476	2,346	1,021
134	1,900	1,266	1,637	1,117
135	2,000	346	361	634
136	6,200	7,396	964	1,232
137	1,300	796	431	327
138	1,100	820	238	832
139	650	132	782	703
140	500	4	31	534
141	1,700	50	127	511
142	700	3,998	2,612	700
143	1,600	42	931	516
144	750	36	433	222

TABLE V (Continued)

Link Number	Actual Volume[1] trips/day	BPR Volume trips/day	EQ Distance Volume[2] trips/day	Cost Volume[3] trips/day
145	850	340	227	328
146	1,000	106	463	904
147	2,100	210	3,261	1,081
148	850	94	372	264
149	750	16	564	392
150	1,500	166	431	361

[1]Source: Map of Oklahoma Average Daily Traffic Volumes for the State Highway System, Planning Division Oklahoma State Highway Department, 1969.

[2]Dimensional Adjustment Constant Values $K_a = 1 \times 10^9$, $K_d = 1$

[3]Dimensional Adjustment Constant Values $K_a = 1 \times 10^9$, $K_c = 2 \quad 10^{-3}$

[A]Both link 108 and 109 correspond to highway 75 for a major portion of their length.

[B]Only one link may be used in the spiderweb network between any two nodes.

The linear graph results provide an interesting contrast to the BPR predictions in some cases. When the equivalent distance concept was used in modeling the route components, it is seen that the results appear to compare slightly better with the actual volumes than did the modified BPR predictions. The predicted trip volumes appear to be unusually high for the Tulsa region, however. This is due in part to the high conductance (low impedance) of this destination component. Tulsa appears as a sizable "sink" for trips emanating in the zones adjacent to zone 1. The large variations in predicted volumes on the various route components are a result of the exaggerated effects of the distance squared factor in the highway component equations. To this extent both the BPR and linear graph models seem to have a weakness. Perhaps a model which placed considerable weight on the effects of congestion in urban areas would yield better results.

The use of total operating cost as a measure of travel impedance had a smoothing effect on the wide ranged projections of both the equivalent distance linear graph model and the modified BPR model. This is a result of the surprisingly little difference in actual travel costs over many dissimilar route sections in the network. This smoothing tends to make the attraction indices of the destination areas become more important in the assignment process than the impedance of the travel paths. Thus, routes entering regions with large attraction indices carry a large percentage of the traffic generated in the study area.

Summary

This chapter has been devoted to the development of the Modified BPR model for the study area, to permit a comparison of the results of its application with those obtained from the linear graph theoretic approach presented in Chapters III and IV.

The description of each phase of the modified BPR procedure should supply the reader with a basic understanding of the intercity travel model most widely used and accepted today. The results of the linear graph theoretic approach and the development of an equivalent distance factor and travel cost factors for the highway network compare quite favorably with the modified BPR prediction for the study area. Most important is the distinction between the traffic assignment procedure employed by each technique. The systems model distributes trips on a minimum energy fashion while the BPR procedure employs the less satisfying all-or-nothing assignment.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

This thesis has been devoted to the modeling of intercity travel through the application of analysis techniques of linear graph theory. This approach has lead to a rigorous examination of the effects of highway design and condition and travel costs on traffic distribution patterns. The problems of trip generation, trip distribution and traffic assignment have been approached through the common linear graph analysis method. The determination of the transportation network characteristics has followed a general systematic procedure; namely:

(1) An establishment of a mathematic description of the relevant characteristics of the system components expressed in terms of measurements.

(2) An establishment in mathematical form and in terms of measurements, from a knowledge of the component characteristics and their mode of interconnection, the characteristics of the system; i.e., a mathematical model of the system.

As a review of the literature progressed, the need for an accurate measure of the negative aspects of the travel phenomena became apparent. Several researchers pointed out the need for further study into the effects of "traffic quality" variables on trip-making behavior. The necessity for accurate component models in the linear graph theory approach makes this approach especially applicable to intercity travel patterns. Previous studies have concluded that actual travel time and travel cost are the most important deterring parameters in determining travel behavior. Both cost and time are directly related to the design and condition of the highway system.

The general branch formulation technique of linear graph theory was modified in the numerical solution of the highway travel model. This modification resulted from an unusual application of the Superposition Principle to the network problem. The components modeled were all defined as linear two terminal components, although there is neither a restriction to consideration of only a two terminal component or linear components in the linear graph approach in general. The use of the word "linear" in linear graph theory is derived from the word "line" and in no way precludes the use of nonlinear dynamic component models in the systems analysis.

The study area was chosen so as to be representative in both economic and demographic respects of the southwest region. Although the region was considered as a closed area for the purposes of this study, there is no such limitation to the analysis procedure presented here. The effects of zones which are external to any given study area may be easily incorporated into the model and would greatly enhance its validity.

The components defined in the study were: (1) origin area components, (2) highway link components, and (3) destination area components. The origin areas were modeled as through variable drivers of known magnitudes. The highway links were modeled as two terminal passive elements. The conductance of each link being taken as inversely related to a measure of its equivalent distance. The equivalent distance of each component was obtained from data representing the design and condition of the link. The highway link components were also modeled with total travel cost chosen to reflect the impedance of each link. The destination area components were modeled as two terminal passive elements whose conduction was taken to be directly related to the personal income generated within the area.

The numerical solution procedure allowed for the consideration of each origin area sequentially, with the actual travel predicted on any given link being the absolute sum of trips contributed by all origins acting together.

The modified BPR model developed and tested by Basore et al. (4) was implemented for the study area considered in this thesis. The results of the BPR model were compared with those obtained through the linear graph theory approach. The results of these simulations still leaves one with dissatisfaction concerning the ability of any given model to adequately explain all phases of travel behavior. The system theory method does, however, intuitively explain many of the areas of weakness of the modified BPR approach.

Conclusions

The primary objective of the research reported on here was to develop a model of intercity travel flow which accurately included the effects of travel impedance. The justification for this research and for further research into the application of linear graph theory to problems of traffic forecasting can be evaluated on the basis of the following conclusions:

(1) Models of this type have many advantages. The parameters which influence travel patterns can be better understood through testing and evaluation in a mathematical model. A procedure for keeping the model up to date can be devised which will make periodic tests and adjustments possible.

(2) The complex interactions of travelers, facilities, origins, and destinations cannot be simply stated in equation form without formulation techniques such as linear graph theory.

(3) Through the use of linear graph theory, it is possible to establish a mathematical model of the relevant physical characteristics of system components in terms of measurements.

(4) A mathematical model of the system can be formulated in terms of the characteristics of the components and their mode of interconnection.

(5) Changes in system parameters can be made easily without disturbing the principles of the technique.

(6) The linear graph approach provides for a balanced flow between origins and destinations. (In contrast, the BPR loading program assigns traffic on an all-or-nothing basis.)

The novelty in the approach, i.e., the system theory approach, has been the introduction of the modified Superposition Principle. It has numerous possible extensions and applications in general problems of distribution logistics, and has been shown to be a useful and meaningful extension of network theory in the analysis of transportation systems.

The applicability of this procedure is limited only by the memory size of the computers used to compute the necessary matrix inverses and perform the matrix multiplications required in the solution procedure. Although this would have been a considerable weakness in the possibility of extension of the model to higher order systems a few years ago, advances in computer technology and matrix manipulation techniques have overcome any such deficiencies.

An interesting conclusion is drawn when comparing the linear graph model with the intervening opportunities model presented in the literature review. By its inherent nature, the linear graph approach <u>includes</u> the effect of intervening opportunities in a deterministic way. That is, travelers select links according to the relative path impedance, not on an all-or-nothing basis. They are allowed to drop off at any destination along any link-route in a proportion determined by this relative resistance of the various paths as seen from that point. The model was not formulated with this specific objective in view, however. The aim at first was to model the highway link components correctly by accurate reflection of the effects of highway design, condition, and travel costs.

Since the model requires only the trip volume magnitudes at each origin zone as input data, the number of rather expensive and time consuming origin and destination surveys needed for intercity travel analysys may be reduced. After calibration of the model from O/D data only highway trip counters would be needed to provide analysis data for the model. These counters could be placed on all major routes leaving any particular origin area.

Finally, the principal contribution of this study has been the demonstration that the use of linear graph theory has considerable promise in the anslysis of intercity transportation systems. The method of formulation is such that the relevant physical characteristics of the system components may be easily obtained in terms of actual measurements. This is of particular consequence when the parameter values must be derived from empirical data as was demonstrated by the development of the equivalent distance concept as a measure of route impedance. The equivalent distance function was developed to relate the design and condition of a roadway impeding effect on trip-making activity. The traffic flows along the route components obtained from the linear graph approach compared favorably with results obtained from the modified BPR procedure.

Recommendations for Further Research

There are a number of desirable investigations and extensions related to this research that could be considered. These investigations might include:

(1) a test of the model in another study area;

(2) a consideration of the use of time-varying impedance and attraction parameters;

(3) a sensitivity analysis of the effects of changes in the parameter adjustment (calibration) constants;

(4) an application of the model for specific trip purposes;

(5) a study of the effects of alternate impedance functions for the highway link components and destination components;

(6) an application of the model to studies of modal split analysis, where the path conductance would correspond to the attractiveness of alternate transport modes; and

(7) an inclusion of the effects of through traffic in the analysis of intercity travel.

Before realistic tests of the model may be extended, improvements must be made in the type of data collected for transportation analysis. Data must be collected with the view in mind that it will provide answers to specific questions about the travel phenomena. The formulation of rigorous mathematical models leads to such questions.

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APPENDIX A

SAMPLE SUFFICIENCY RATING DATA

TABLE VI

SUFFICIENCY RATING REPORT

OKLAHOMA STATE HIGHWAYS - PLANNING DIVISION - SUFFICIENCY RATING REPORT - JULY 1, 1968 COMMISSIONER DISTRICT 1 COUNTY TULSA

F.A. System	Function	Highway Number	Control Section Number	Roadway or Bridge Subsection	Roadway or Bridge Length: Rural	Roadway or Bridge Length: Urban	Average Daily Traffic	Surface or Bridge: Type	Surface or Bridge: Width	Curb or Shoulder: Type	Curb or Shoulder: Width	Bridge Load Limit	Ratings: Basic Sufficiency	Ratings: Priority Adjusted	Capacity Adequacy	Design Class	No. Lanes	Access Cont. Bridge Type	Grading Type	Improvement Type	Alignment Corr. Factor	Estimated Improvement Cost in Thousands: Grade & Drain	Base & Surface	R W & Other	Structure	Total
1	2	U169	72-34	X001	67		3200	X031	24			16	77	48		07	3	1		02	10				59	59
1	2	U169	72-34	010	2.80		2900	4222	22	3	4		60	54	2	07	3	0	3	04	06	157	194	95		446
1	2	U169	72-34	X020	244		2900	X032	22			16	72	54		07	3	1		03	10				145	145
1	2	U169	72 34	X028	545		2900	X032	22			16	73	54		07	3	1		03	10				350	350
1	2	U169	72 34	X032	361		2900	X031	22			16	72	54		07	3	1		03	10				232	232
1	2	U169	72-34	X035	444		2900	X032	22			16	70	54		07	3	1		03	10				285	285
1	2	S011	72-36	000	3.80		950	7011	18	3	4		31	36	1	08	2	0	3	04	10	322	418	152		892
1	2	S011	72-36	X020	310		950	X032	15			10	36	36		08	2	1		03	10				169	169
1	2	S011	72-36	038	SKIATOCK	.14	1800	7011	18	3	4		43	57	1	08	2	0	3	07	10	12	15	5		32
2	2	S011	72-36	039		.08	4000	7011	24	4			59	65	1	08	2	0	3	07	10	7	9	4		20
2	2	S011	72-36	X039		45	4000	X031	20			16	61	65		08	2	1		05	10					
2	2	S011	72-36	040		.15	5000	7011	24	3	11		62	65	1	27	4	0	6	08	10	17	26	5		48
2	2	S011	72-36	X041		43	5000	X031	28			15	89	65		27	4	2		02	10				29	29
1	1	S011	72-36	042	3.70		4700	9670	24	3	8		68	48	3	02	4	2	4	04	10	895	984	411	285	2,575
1	1	S011	72 36	X047	42		4700	X028	44			20	95	48		02	4	2		05	10					
1	1	S011	72 36	X062	22		4700	X028	40			20	91	48		02	4	2		05	10					
1	1	S011	72 36	X065	22		4700	X028	40			20	91	48		02	4	2		05	10					
1	1	S011	72-36	X071	33		4700	X028	40			20	93	48		02	4	2		03	10				73	73
1	1	S011	72-36	079	1.00		4900	7011	22	2	8		52	30	3	02	4	2	4	04	10	242	266	111	77	696
1	1	S011	72-36	X079	405		4900	X032	26			20	81	30		02	4	2		03	10				73	73
1	1	S011	72-36	X084	32		4900	X028	38			20	89	30		02	4	2		05	10					
1	1	S011	72-36	089	SPERRY	.40	4900	7011	22	3	8		67	60	2	02	4	2	4	04	10	97	106	44	31	278
1	1	S011	72-36	093	2.80		5000	7011	22	2	8		50	28	3	02	4	2	4	04	10	678	745	311	216	1,950
1	1	S011	72-36	X112	41		5000	X028	32			20	84	28		02	4	2		05	10					
1	1	S011	72 36	X115	181		5000	X031	26			20	80	28		02	4	1		03	10				448	448
1	1	S011	72 36	121	TULSA	2.00	7000	7670	48	4			60	50	3	22	4	2	7	09	10	260	582	2,492		3,334
1	1	S011	72-36	X121			7000							50		22	4	5		03	10				169	169
1	1	S011	72-36	X131			7000							50		22	4	6		03	10				169	169
1	1	S011	72-36	X138		22	7000	X028	41			20	88	50		22	4	1		03	10				537	537
1	1	S011	72-36	141		2.60	12800	7670	48	4			68	52	3	22	4	2	7	09	10	338	757	5,112		6,207
1	1	S011	72-36	X141			12800							52		22	4	6		03	10				160	160
1	1	S011	72-36	X146										52		22	4	1		03	10				207	207
1	1	S011	72-36	X149										52		22	4	5		03	10				156	156
1	1	S011	72-36	X153			12800							52		22	4	2		03	10				62	62
1	1	S011	72-36	X155			12800							52		22	4	6		03	10				267	267
1	1	S011	72-36	X157		111	12800	X031	50			20	93	52		22	4	5		03	10				169	169
1	1	S011	72-36	X167		61	12800	X031	48			20	85	52		22	4	1		05	10					
1	2	S011	72-40	000	TULSA	.30	12300	7011	36	4			78		2											

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SOURCE: Reference (44)

APPENDIX B

COMPUTER PROGRAM LISTINGS AND SAMPLE OUTPUTS

Program SOLVE

This program was used to construct the branch equation matrix for the highway system described in the system linear graph of Figure 5, and to solve for the destination through variables. These results were used to obtain values for the route through variables. The program is written in Fortran IV and was executed via remote terminal operation on the CDC 3300 computer at Oregon State University. In addition to the program, the following data cards were used:

1 card, constants k_1 , k_2 , k_3

25 cards, destination attraction indices (total personal income)

50 cards, equivalent distance and cost values for the highway links

25 cards, a list of passive elements in each fundamental cutset, with signs, first entry number of elements in cutset for control of DO loops

25 cards, a list of origin trip entries in the Y vector.

This data has been presented in tabular form earlier in this thesis and will not be repeated here. Statement number 11 was modified for the calculation of the impedance of the route components on a cost basis. The EDIT mode of operation was used in executing the program on the remote terminal. This allows for changes to be made in either the source deck or the data as the program steps are executed. This is an important feature since each node is to represent both an origin area and a destination during separate runs of the program.

The matrix inversion subroutine MATINV was adapted from the Computer Center Library. Several matrix inversion subroutines were available but this particular one was recommended by Mr. George Lewis of the Computer Center as the most accurate.

Two measures of numerical accuracy were used, both rule-of-thumb, since for larger order systems it would not be feasible to compute GG^{-1} and compare it to the unit matrix. The first check was the size of the determinant of G. This determinant is computed as a normal feature of MATINV. It was typically on the order of 10^{60} for the constants chosen, a large value which precludes the likelihood of calling for a division by a small number. The second check was the application of the cutset postulate at the reference node of the graph. Here, at each step, one origin "leaves" and all destinations "enter" and, thus, the destination trip predicted should equal the total of the origin trips generated. While it is not possible to state conclusively that the numerical error of any particular entry of the inverse or any particular destination or route volume computation is zero, it seems reasonable to expect any such error to be within 3 to 4 percent. A listing of program SOLVE is given in Table VII.

TABLE VII

LISTING OF PROGRAM SOLVE

```
*JOB,[71053],[ELEN],[OWEN D OSBORNE]
COPY,O=SOLVE
      PROGRAM SOLVE
      DIMENSION G(25,26),KUTSET(25,16),E(75),CONS(2),ATT(25),DIF(25)
     $,PCT(25)
      COMMON G,KUTSET
      READ(60,105) CONS(I),I=1,3
  105 FORMAT(15X,3F5.0)
      WRITE(61,300) CONS(I),I=1,3
  300 FORMAT(15H CONSTANTS ARE ,3F7.3///)
C
C     READ MATRIX E FROM CARDS
C
      DO 10 I=1,25
      READ(60,100),ATTR
  100 FORMAT(11X,F4.1)
   10 E(I)=CONS(1)*ATTR
      WRITE(61,301) I,E(I),I=1,25
  301 FORMAT (26HATTRACTION OF DESTINATION ,I2,4H IS ,F7.4/)
      DO 11 I=26,75
      READ(60,101) C,DEQ,D
  101 FORMAT(15X,3F4.3)
   11 E(I)=CONS(2)/D*DEQ
      WRITE(61,400)I,E(I),I=26,75
  400 FORMAT(6H LINK ,I3,10H VALUE IS ,F7.4/)
C
C     READ IN CUTSETS
C
      READ(60,103) (KUTSET(I,J),J=(,16),I=1,25
  103 FORM.T(11X,16I4)
C
C     BUILD DIAGONAL ELEMENT OF MATRIX G FROM ARRAY E
C
      DO 40 I=1,25
      DO 20 J=1,25
   20 G(I,J)=0
      NI=KUTSET(I,1)+1
      DO 23 J=2,N1
      M=KUTSET(I,J)
      IF(M)21,991,22
   21 G(I,I)=G(I,I)+E(-M)
      GO TO 23
   22 G(I,I)=G(I,I)+E(M)
   23 CONTINUE
C
C     BUILD OFF DIAGONAL ELEMENTS OF MATRIX - UPPER TRIANGLE ONLY
C
      JJ=I+1
      DO 40 J=JJ,25
      N2=KUTSET(J,1)+1
      KSW=0
      DO 40 K=2,N1
      DO 40 L=2,N2
      IF(KUTSET(I,K)-KUTSET(J,L))30,32,30
   30 IF(KUTSET(I,K)+KUTSET(J,L))40,32,40
   32 KPROD1 = KUTSET(I,K)*KUTSET(J,L)
      IF(KSW)33,34,33
   33 IF(KPROD1*KPROD)992,992,35
   34 KSW=1
```

TABLE VII (Continued)

```
      KPROD=KPROD1
   35 M=KUTSET(I,K)
      IF(M)36,37,37
   36 M=-M
   37 IF(KPROD)38,39,39
   38 G(I,J)=G(I,J)-E(M)
      GO TO 40
   39 G(I,J)=G(I,J)+E(M)
   40 CONTINUE
C
C     FILL IN LOWER TRIANGLE OF MATRIX G
C
      DO 41 I=1,25
      N1=I+1
      DO 41 J=N1,25
   41 G(J,I)=G(I,J)
      WRITE(61,201)(G(I,J),J=1,5),I=1,5
  201 FORMAT(5(5E17.10/))
      READ(60,104)G(I,26),I=1,25
  104 FORMAT(15X,F8.0)
      CALL MATINV (G,25,G(1,26),1,DETERM)
      WRITE(61,201)(G(I,J),J=1,5),I=1,5
C
C     PREMULTIPLY BY MATRIX D
C
      SUM=0
      DISC=0
      PCTO=0
      DO 70 I=1,25
   70 DIF(I)=0
      DO 60 I=1,25
      READ(60,600)ATT(I)
  600 FORMAT(15X,F8.0)
      G(I,26)=G(I,26)*E(I)
      SUM=SUM+G(I,26)
      DIF(I)=G(I,26)-ATT(I)
      DISC=DISC+DIF(I)
      PCTO=PCTO+PCT(I)
   60 WRITE(61,200)I,E(I),G(I,26),DIF(I),PCT(I)
  200 FORMAT(13H DESTINATION,I2,14H ATTRACTION = ,F7.4,9H TRIPS = ,F10.0
     $,10H ERROR IS ,F10.0,11H PCT OUT =,F5.0/)
      WRITE(61,500)SUM,DISC
  500 FORMAT(7H SUM = ,2(E20.10)///)
      WRITE(61,700)PCTO
  700 FORMAT(8H PCTO = ,F8.0//)
      WRITE(61,202)DETERM
  202 FORMAT(12H0DETERMINANT,,E20.10)
      GO TO 999
C
C     ERROR ROUTINES
C
  991 WRITE(61,901)I,J
  901 FORMAT(15H1ERROR ON CARD ,I3,27H OF CUTSET. ELEMENT INDEX =,I2,
     $9H IS ZERO.///)
      GO TO 999
  992 WRITE(61,902) I,J
  902 FORMAT(16A1ERROR ON CARDS ,I3,5H AND ,I3,31H OF CUTSET. SIGNS DO N
     $OT AGREE.///)
  999 CONTINUE
```

TABLE VII (Continued)

```
      RETURN
      END
      SUBROUTINE MATINV(A,N,B,M,DETERM)
      DIMENSION A(25,25),B(25,1),IPIVOT(25),INDEX(25,2),PIVOT(25)
C
C     INTIALIZATION
C
   10 DETERM=1.0
   15 DO 20 J=1,N
   20 IPIVOT(J)=0
   30 DO 550 I=1,N
C
C     SEARCH FOR PIVOT ELEMENT
C
   40 AMAX=0.0
   45 DO 105 J=1,N
   50 IF (IPIVOT(J)-1) 60, 105, 60
   60 DO 100 K=1,N
   70 IF (IPIVOT(K)-1) 80, 100, 740
   80 IF (ABSF(AMAX)-ABSF(A(J,K))) 85, 100, 100
   85 IROW=J
   90 ICOLUM=K
   95 AMAX=A(J,K)
  100 CONTINUE
  105 CONTINUE
  110 IPIVOT(ICOLUM)=IPIVOT(ICOLUM)+1
C
C     INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
C
  130 IF (IROW-ICOLUM) 140, 260, 140
  140 DETERM=-DETERM
  150 DO 200 L=1,N
  160 SWAP=A(IROW,L)
  170 A(IROW,L)=A(ICOLUM,L)
  200 A(ICOLUM,L)=SWAP
  205 IF(M) 260, 260, 210
  210 DO 250 L=1, M
  220 SWAP=B(IROW,L)
  230 B(IROW,L)=B(ICOLUM,L)
  250 B(ICOLUM,L)=SWAP
  260 INDEX(I,1)=IROW
  270 INDEX(I,2)=ICOLUM
  310 PIVOT(I)=A(ICOLUM,ICOLUM)
  320 DETERM=DETERM*PIVOT(I)
C
C     DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
  330 A(ICOLUM,ICOLUM)=1.0
  340 DO 350 L=1,N
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT(I)
  355 IF(M) 380, 380, 360
  360 DO 370 L=1,M
  370 B(ICOLUM,L)=B(ICOLUM,L)/PIVOT(I)
C
C     REDUCE NON-PIVOT ROWS
C
  380 DO 550 L1=1,N
  390 IF(L1-ICOLUM) 400, 550, 400
  400 T=A(L1,ICOLUM)
```

TABLE VII (Continued)

```
  420  A(L1,ICOLUM)=0.0
  430  DO 450 L=1,N
  450  A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
  455  IF(M) 550, 550, 460
  460  DO 500 L=1,M
  500  V(L1,L)=B(L1,L)-B(ICOLUM,L)*T
  550  CONTINUE
C
C      INTERCHANGE COLUMNS
C
  600  DO 710 I=1,N
  610  L=N+1-I
  620  IF (INDEX(L,1)-INDEX(L,2)) 630. 710, 630
  630  JROW=INDEX(L,1)
  640  JCOLUM=INDEX(L,2)
  650  DO 705 K=1,N
  660  SWAP=A(K,JROW)
  670  A(K,JROW)=A(K,JCOLUM)
  700  A(K,JCOLUM)=SWAP
  705  CONTINUE
  710  CONTINUE
  740  RETURN
  750  END
CALL,4.
RUN.
```

Program OWEN

This program was used to solve for the spiderweb loads using the modified BPR approach. The program is written in modular form machine language and was executed on the IBM SYSTEM 360 MODEL 65 computer at Oklahoma State University. Disk data sets replaced the original magnetic files used to store the outputs of each step in the program. The program was executed in seven steps as shown in Figure 7. A listing of the execution cards and data cards for the 25 node spiderweb network problem is shown in Table VIII. The sub-program BLDTT was written in Fortran IV and is shown in this Appendix. Sample standard format outputs for the 25 node spiderweb network are shown in Tables X, XI, XIII, and XIV.

TABLE VIII

LISTING OF PROGRAM OWEN

```
//OWEN    JOB (10652,499-44-8290,1,,,9001,3),'OWEN D OSBORNE',CLASS=B
/*RCUTE  PRINT HOLD
//JCBLIB DD DISP=OLD,
//           DSN=OSU.ACT10652.CHAP
//STEP01 EXEC PGM=BLDSPWB,TIME=(,10),REGION=30K
//DFNTAPE DD SYSOUT=A
//NWRCDD DD DISP=OLD,
//           DSN=OSU.ACT10652.SPNET
//SYSIN DD *
PAR,25,25,8,0
GO
    1 1624 2496          TULSA
    2 1625 2534          BARTLESVILLE
    3 1685 2544          MIAMI
    4 1616 2496          SAN SPRGS
    5 1662 2506          PRYOR
    6 1627 2538          DEWEY
    7 1637 2488          BROKEN ARROW
    8 1667 2528          VINITA
    9 1645 2506          CLAREMORE
   10 1634 2508          COL'VILL
   11 1625 2508          SKIATOOK
   12 1646 2532          NOWATA
   13 1633 2502          OWASSO
   14 1691 2515          JAY
   15 1624 2487          JENKS
   16 1630 2480          BIXBY
   17 1686 2548          COMMERCE
   18 1601 2528          P'HUSKA
   19 1654 2520          CHELSA
   20 1680 2532          AFTON
   21 1602 2511          HOMINY
   22 1582 2525          FAIRFAX
   23 1597 2503          CLEVELAND
   24 1581 2508          PAWNEE
   25 1614 2523          BARNSDALL
END
    1    4    7    9   11   13   15
    2    6   11   12   18   25
    3    8   17   20
    4   15   23
    5    8    9   14
    7    9   13   15
    8    9   12   14   19   20
    9   10   12   13   19
   10   11   12   13
   11   21   25
   12   19
   14   19   20
   15   16
   18   21   22   25
   21   22   23   25
   22   24
   23   24
END
//STEP02 EXEC PGM=FMTSPWB,TIME=(,10),REGION=20K
//DFNTAPE DD SYSOUT=A
//NWRCDI DD DISP=OLD,
//           DSN=OSU.ACT10652.SPNET
```

TABLE VIII (Continued)

```
//STEP03 EXEC PGM=BLDSPTR,TIME=(,10),REGION=25K
//DFNTAPE DD SYSOUT=A
//NWRCDI DD DISP=OLD,
//          DSN=OSU.ACT10652.SPNET
//PATHSO DD DISP=OLD,
//          DSN=OSU.ACT10652.TREES
//SYSIN DD *
TNALL
E00C6
//STEP04 EXEC PGM=FMTSPTR,TIME=(,10),REGION=25K
//DFNTAPE DD SYSOUT=A
//PATHSI DD DISP=OLD,
//          DSN=OSU.ACT10652.TREES
//SYSIN DD *
C        25    25    8
T         1     2    3    5    8   12   18   21
E
//STEP05 EXEC PGM=BLDTT,REGION=99K,TIME=(,15)
//FT05F001 DD *
   25     1     1     0   1.0
    1    36.11       96.00      1202.4
    2    36.44       95.59       131.5
    3    36.53       94.54        40.3
    4    36.11       96.08        40.3
    5    36.19       95.19        39.5
    6    36.47       95.56        36.3
    7    36.04       95.46        34.0
    8    36.39       95.13        28.6
    9    36.20       95.37        23.0
   10    36.21       95.49        20.6
   11    36.21       95.58        20.4
   12    36.42       95.36        18.8
   13    36.16       95.50        18.5
   14    36.27       94.48        17.6
   15    36.03       95.59        17.3
   16    35.57       95.53        17.2
   17    36.56       94.53        15.2
   18    36.39       96.24        14.4
   19    36.32       95.27        13.8
   20    36.42       94.59        12.2
   21    36.24       96.23        10.9
   22    36.36       96.45         9.7
   23    36.17       96.28         9.5
   24    36.21       96.46         9.2
   25    36.34       96.10         9.1
  0           TT
//FT06F001 DD SYSOUT=A
//FT08F001 DD DISP=OLD,
//       DSN=OSU.ACT10652.TT1,
//       DCB=(RECFM=VB,LRECL=3500,
//          BLKSIZE=3504)
//STEP06 EXEC PGM=LDSPWB,REGION=40K,TIME=(,15)
//DFNTAPE DD SYSOUT=A
//PATHSI DD DISP=OLD,
//          DSN=OSU.ACT10652.TREES
//TRIPSI DD DISP=OLD,DSN=OSU.ACT10652.TT1
//NWRCDI DD DISP=OLD,
//          DSN=OSU.ACT10652.SPNET
//NWRCDO DD DISP=(NEW,PASS),
```

TABLE VIII (Continued)

```
//          DSN=&&LDNET,UNIT=DISK,SPACE=(TRK,10),
//          DCB=(RECFM=VBS,LRECL=84,BLKSIZE=1000)
//SYSIN DD *,DCB=BLKSIZE=80
NL07      VOLAB      10  1-4      12     4     VOL  A TO B FIRST LOAD
NL08      VOLBA      11  1-4      16     4     VOL  B TO A FIRST LOAD
V1A-A        12    16
V2         LOCVAB1   12   92   2  VOLUME A-B FIRST LOAD
V2         LOCVAB2   16   94   2  VOLUME B-A FIRST LOAD
V2         RESERVE        96  76  19  WORDS
E
//STEP07 EXEC PGM=FMTSPLD,REGION=30K,TIME=(,15)
//NWRCDI DD DISP=(OLD,DELETE),
//          DSN=&&LDNET
//DENTAPE DD SYSOUT=A
//SYSIN DD *
L03 TOTAL LOAD            6 10L4 12+4 16
E
//
```

Program BLDTT

This program computes the predicted two-way trips between each pair of nodes for a given network and writes a disk file that is compatible with the LDSPWB program. In addition, the subroutine OUTPUT writes a standard format upper triangle trip table matrix. The output subroutine was written with the assistance of John and Fred Witz. The listing for the 25 node spiderweb network is shown in Table IX.

TABLE IX

LISTING OF PROGRAM BLDTT

```
//OWEN    JOB (10652,499-44-8290,1,,,9001,3),'OWEN D OSBORNE',CLASS=8
// EXEC FORTGCLG
//FORT.SYSIN DD *
      COMMON NR,N,NP,NN(100),IDEN1(100),IDEN2(100),N1,N2,M1,M2,G1,G2,
     # A1,A2,C(100,100),F(100,100),F1(100,100),D(100),P2(100),
     $S(100),S2(100),W1(100),W2(100)
      DIMENSION A(100),B(100),AR(100),BR(100),MTAB(100)
C
C     SPECIFY GRAVITY MODEL PARAMETERS FOR OUTPUT SUBROUTINE
C
      NP=25
      G1=440.
      M1=1
      N1=1
      A1=2.78
      READ(5,10) N,JKL,NR,NOTTO,TRPMU
   10 FORMAT(4I5,F10.3)
      WRITE(6,13)
   13 FORMAT(//1X,'GRAVITY MODEL USED TO GENERATE TRIP TABLE')
      WRITE(6,20)
   20 FORMAT(1H ,4HNODE,2X,8HLATITUDE,2X,9HLONGITUDE,2X,18HPERSONAL INC
     #OME M$)
      DO 30 KK=1,N
      READ(5,25) NO,DLAT,OLAT,DLON,OLON,EP,ID1,ID2
   25 FORMAT (I5,4X,F2.0,1X,F2.0,5X,F3.0,1X,F2.0,2X,F12.4,33X,2A4)
      WRITE(6,35)NO,DLAT,OLAT,DLON,OLON,EP,ID1,ID2
   35 FORMAT(1H ,I3,5X,F2.0,1X,F2.0,5X,F3.0,1X,F2.0,5X,F9.1,8X,2A4)
C
C     CONVERSION OF NODE COORDINATES TO RADIANS
C
      DOLAT = OLAT/60.0
      A(KK) = DLAT + DOLAT
      AR(KK) = A(KK)*3.14159/180.0
      DOLON = OLON/60.0
      B(KK) = DLON + DOLON
      BR(KK) = B(KK)*3.14159/180.0
      D(KK)=PI
      NN(KK) = NO
      IDEN1(KK)=ID1
      IDEN2(KK)=ID2
   30 CONTINUE
      DO 50 I=1,N
      AI = AR(I)
      BI = BR(I)
      DO 50 J=1,I
      IF(I-J) 40,45,40
   40 CONTINUE
      AJ = AR(J)
      BJ = BR(J)
C
C     CALCULATE GREAT CIRCLE DISTANCE BETWEEN NODES
C
      X=SIN(AI)*SIN(AJ)+COS(AI)*COS(AJ)*COS(BI-BJ)
      CIJ=3960.0*ATAN(SQRT(1.0-X**2)/X)
      GO TO 46
   45 CONTINUE
      CIJ = 100.0
   46 CONTINUE
      C(J,I)=CIJ
```

TABLE IX (Continued)

```
C
C     CALCULATE TRAVEL DEMANDS BETWEEN NODES
C
   50 F(J,I)=440.*(D(I)*D(J))/CIJ**2.78
C
C     SUM TRAVEL DEMANDS FOR EACH NODE
C
      S(1)=0.0
      DO 51 J=2,N
   51 S(1)=S(1)+F(1,J)
      K=N-1
      DO 53 I=2,K
      S(I)=0.0
      L=I+1
      DO 52 J=L,N
   52 S(I)=S(I)+F(I,J)
      M=I-1
      DO 53 J=1,M
   53 S(I)=S(I)+F(J,I)
      S(N)=0.0
      MM=N-1
      DO 54 J=1,MM
   54 S(N)=S(N)+F(J,N)
C
C     CREATE TWO-WAY TRIP TABLE
C
      DO 120 I=1,N
      DO 115 J=1,I
      F(J,I)=F(J,I)/2.
  115 F(I,J)=F(J,I)
  120 CONTINUE
C
C     WRITE TRIP TABLE
C
      NPURP=0
      DO 150 I=1,N
      K=1
      DO 145 J=1,N
      M1=F(I,J)
      IF(M1) 123,122,123
  123 K=K+1
  121 MTAB(K)=(J*262144)+M1
      NWD=K
  122 CONTINUE
  145 CONTINUE
      NZON=I*65536
      WRITE(8,125) NWD,NPURP,NZON,(MTAB(L),L=2,NWD)
  125 FORMAT(A4,2A2,95A4)
  150 CONTINUE
      CALL OUTPUT
      WRITE(6,200)
  200 FORMAT(////1X,'BUILD TRIP TABLE COMPLETE')
      CALL EXIT
      END
      SUBROUTINE OUTPUT
      REAL LAF,LAP
      LOGICAL MAU2,MAU3,MAU4,MAV1,MAV2,MAV3,MAV4
      COMMON NR,N,NP,NN(100),IDEN1(100),IDEN2(100),N1,N2,M1,M2,G1,G2,
     # A1,A2,D(100,100),F1(100,100),F2(100,100),P1(100),P2(100),
```

TABLE IX (Continued)

```
     #S1(100),S2(100),W1(100),W2(100)
      DIMENSION TA(20),UA2(100,100),UA3(100,100),UA4(100,100),VA1(100),
     #VA2(100),VA3(100),VA4(100),FMTN(10),FMTA(10),HAS(10)
      EQUIVALENCE (UA2,D),(UA3,F1),(UA4,F2),(VA1,P1)
      DATA FMTN/'(4X,','I3 ,',' 2X,',' ','X,','10(','F',' 12.','4',')))'/
      DATA FMTA/'(1X,','2A4,','    ',' ','X,','10(','F',' 12.','4',')))'/
      DATA HAS/'2','14','26','38','50','62','74','86','98','110'/
      DATA HAB, HA1, HA2, HA4/' ','1','2','4'/
      DATA HD, HF1, HF2, HP1, HP2, HW1, HW2, HS1, HS2, HE, HF
     #/    'D','F1','F2','P1','P2','W1','W2','S1','S2','E','F'/
    1 FORMAT(' ')
    2 FORMAT('0')
    3 FORMAT('-')
    9 FORMAT('1')
      READ (5,10) LAR,LAF,LAP,MAU2,MAU3,MAU4,MAV1,MAV2,MAV3,MAV4,NAT
   10 FORMAT(I1,2A1,4X,3L1,1X,4L1,I2)
      WRITE(6,9)
      WRITE(6,3)
      IF(NAT.LE.0)GO TO 140
      DO 139 IA=1,NAT
      READ (5,13) (TA(JA),JA=1,20)
   13 FORMAT (20A4)
      WRITE(6,14)(TA(JA),JA=1,20)
   14 FORMAT(26X,20A4)
  139 CONTINUE
  140 WRITE(6,3)
      IF(NP.EQ.0) NP=N
      WRITE(6,15)
   15 FORMAT (5X,'PROGRAM CONSTANTS:')
      WRITE (6,16) NR,N,NP
   16 FORMAT('-',10X,'RUN',I3,':',I5,' NODES;'I5,' PRIMARY NODES')
      WRITE (6,17) HA1,G1,M1,N1,A1
   17 FORMAT('-',10X,'EQUATION ',A1,': G=',E15.8,', M=', I5,', N='I5,
     # ', A=',F5.2)
      IF(LAR.LE.0)GO TO 180
      WRITE (6,17) HA2,G2,M2,N2,A2
  180 HAU1=HAB
      HAU2=HD
      HAU3=HF1
      HAU4=HF2
      HAV1=HP1
      LAR=LAR+1
      GOTO(210,215,220),LAR
  210 DO 214 IA=1,N
      VA2(IA)=P1(IA)
      VA3(IA)=W1(IA)
  214 VA4(IA)=S1(IA)
      MAV1=.TRUE.
      MAU4=.TRUE.
      HAV2=HP1
      HAV3=HW1
      HAV4=HS1
      GO TO 225
  215 DO 219 IA=1,N
      VA2(IA)=W1(IA)
      VA3(IA)=P2(IA)
  219 VA4(IA)=W2(IA)
      HAV2=HW1
      HAV3=HP2
```

TABLE IX (Continued)

```
      HAV4=HW2
      GO TO 225
  220 DO 224 IA=1,N
      VA2(IA)=S2(IA)
      VA3(IA)=P2(IA)
  224 VA4(IA)=W2(IA)
      HAV2=HS1
      HAV3=HP2
      HAV4=HS2
  225 IF(MAU2) HAU2=HAB
      IF(MAU3) HAU3=HAB
      IF(MAU4) HAU4=HAB
      IF(MAV1) HAV1=HAB
      IF(MAV2) HAV2=HAB
      IF(MAV3) HAV3=HAB
      IF(MAV4) HAV4=HAB
      IF(LAF.NE.HE) LAF=HF
      IF(LAP.EQ.HAB) LAP=HA4
      FMTN(7)=LAF
      FMTA(7)=LAF
      FMTN(9)=LAP
      FMTA(9)=LAP
      KAC2=0
      JAC2=(N+9)/10
      DO 890 JAC=1,JAC2
      FMTN(4)=HAS(1)
      FMTA(4)=HAS(1)
      KAC1=KAC2+1
      KAC2=KAC1+9
      IF(KAC2.GT.N)KAC2=N
      KAR2=0
      IF(JAC.LE.1)GO TO 700
      JACM1=JAC-1
      DO 599JAR=1,JACM1
      KAR1=KAR2+1
      KAR2=KAR1+9
      IF(JAR.GT.(NP+9)/10) GO TO 700
      WRITE(6,41) JAR,JAC,NR
   41 FORMAT('1PAGE ',I2,',',I2,5X,'RUN',I3)
      WRITE (6,42) HAU1,HAV1
   42 FORMAT(2X,A2,3X,A2,2X,10(5X,I3,4X) )
      WRITE(6,42) HAU2,HAV2,(NN(KAC),KAC=KAC1,KAC2)
      WRITE(6,43) HAU3,HAV3,(IDEN1(KAC),IDEN2(KAC),KAC=KAC1,KAC2)
   43 FORMAT(2X,A2,3X,A2,2X,10(2X,2A4,2X) )
      WRITE(6,43) HAU4,HAV4
      DO 589 KAR=KAR1,KAR2
      WRITE(6,2)
      IF(MAU2)GO TO 525
      WRITE(6,FMTN) NN(KAR),(UA2(KAR,KAC),KAC=KAC1,KAC2)
      GO TO 530
  525 WRITE (6,FMTN)NN(KAR)
  530 IF(MAU3) GO TO 535
      WRITE(6,FMTA) IDEN1(KAR),IDEN2(KAR),(UA3(KAR,KAC),KAC=KAC1,KAC2)
      GO TO 540
  535 WRITE(6,FMTA)IDEN1(KAR),IDEN2(KAR)
  540 IF(MAU4)GO TO 545
      WRITE(6,FMTA)HAV,HAB,(UA4(KAR,KAC),KAC=KAC1,KAC2)
      GO TO 550
  545 WRITE(6,1)
```

TABLE IX (Continued)

```
550 CONTINUE
589 CONTINUE
599 CONTINUE
700 WRITE(6,41) JAC,JAC,NR
    WRITE (6,42) HAU1,HAV1
    WRITE(6,42) HAU2,HAV2,(NN(KAC),KAC=KAC1,KAC2)
    WRITE(6,43) HAU3,HAV3,(IDEN1(KAC),IDEN2(KAC),KAC=KAC1,KAC2)
    WRITE(6,43) HAU4,HAV4
    LAM2=1
    IF(MAV2)LAM2=2
    IF(MAU2)LAM2=LAM2+2
    LAM3=1
    IF(MAV3) LAM3=2
    IF(MAU3)LAM3=LAM3+2
    LAM4=1
    IF(MAV4)LAM4=2
    IF(MAU4)LAM4=LAM4+2
    KA=0
    DO 889 KAR=KAC1,KAC2
    KA=KA+1
    KARP1=KAR+1
    IF(KAR.LT.KAC2)GO TO 809
    IF(LAM2.LE.2)LAM2=LAM2+2
    IF(LAM3.LE.2) LAM3=LAM3+2
    IF(LAM4.LE.2) LAM4=LAM4+2
809 FMTN(4)=HAS(KA)
    FMTA(4)=HAS(KA)
    WRITE(6,1)
    IF(MAV1) GO TO 815
    WRITE(6,FMTA) HAB,HAB,VA1(KAR)
    GO TO 820
815 WRITE(6,1)
820 GO TO (821,822,823,824),LAM2
821 WRITE(6,FMTN)NN(KAR),VA2(KAR),(UA2(KAR,KAC),KAC=KARP1,KAC2)
    GO TO 830
822 FMTN(4)=HAS(KA+1)
    WRITE(6,FMTN)NN(KAR),(UA2(KAR,KAC),KAC=KARP1,KAC2)
    FMTN(4)=HAS(KA)
    GO TO 830
823 WRITE(6,FMTN)NN(KAR),VA2(KAR)
    GO TO 830
824 WRITE(6,FMTN)NN(KAR)
830 GO TO(831,832,833,834),LAM3
831 WRITE(6,FMTA)IDEN1(KAR),IDEN2(KAR),VA3(KAR),
   #     (UA3(KAR,KAC), KAC = KARP1, KAC2)
    GO TO 840
832 FMTA(4)=HAS(KA+1)
    WRITE(6,FMTA) IDEN1(KAR),IDEN2(KAR),(UA3(KAR,KAC),KAC=KARP1,KAC2)
    FMTA(4)=HAS(KA)
    GO TO 840
833 WRITE(6,FMTA)IDEN1(KAR),IDEN2(KAR),VA3(KAR)
    GO TO 840
834 WRITE(6,FMTA)     IDEN1(KAR),IDEN2(KAR)
840 GO TO (841,842,843,844),LAM4
841 WRITE(6,FMTA)HAB,HAB,VA4(KAR),(UA4(KAR,KAC),KAC=KARP1,KAC2)
    GO TO 850
842 FMTA(4)=HAS(KA+1)
    WRITE(6,FMTA)HAB,HAB,(UA4(KAR,KAC),KAC=KARP1,KAC2)
    FMTA(4)=HAS(KA)
```

TABLE IX (Continued)

```
      GO TO 850
  843 WRITE(6,FMTA) HAB,HAB,VA4(KAR)
      GO TO 850
  844 WRITE(6,1)
  850 CONTINUE
  889 CONTINUE
  85C CONTINUE
      NCELL=N-10*(N/10)
      NROW=5*NCELL+10
      DO 900 K=1,NROW
 900  WRITE(6,1)
      RETURN
      END
//GO.SYSIN DD *
```

Program FORMAT SPIDERWEB NETWORK (FMTSPWB) Output

Table X gives the standard BPR record of the 25 node spiderweb network. It includes the coordinates of each node by node number, the length and impedance of each link, and the design speed of the link. The coding of information on link connection is interpreted as follows: in row one of Table X, node 1 - is connected to nodes 4, 7, 9, 11, 13, 15 with the length and impedance of each link 8, 15, 23, 12, 11, 9 miles, respectively. The design speed for each link is 60 mph.

TABLE X

OUTPUT LISTING OF PROGRAM (FMTSPWB)

NODE A DESCRIPTIVE DATA					LEGS ZERO AND FOUR				LEGS ONE AND FIVE				LEGS TWO AND SIX				LEGS THREE AND SEVEN			
NUMBER	STATE NAME	COUNTY NAME	COORDINATES X	Y	NODE B NO.LG	IMPEDANCE	DISTANCE	SPD	NODE B NO.LG	IMPEDANCE	DISTANCE	SPD	NODE B NO.LG	IMPEDANCE	DISTANCE	SPD	NODE B NO.LG	IMPEDANCE	DISTANCE	SPD
1	0		1624	2496	4.0	8	8	60.0	7.0	15	15	60.0	9.0	23	23	60.0	11.0	12	12	60.0
					13.0	11	11	60.0	15.0	9	9	60.0								
2	0		1625	2534	6.0	5	5	60.0	11.1	26	26	60.0	12.0	21	21	60.0	18.0	25	25	60.0
					25.0	16	16	60.0												
3	0		1685	2544	8.0	24	24	60.0	17.0	4	4	60.0	20.0	13	13	60.0				
4	0		1616	2496	1.0	8	8	60.0	15.1	12	12	60.0	23.0	20	20	60.0				
5	0		1662	2506	8.1	23	23	60.0	9.1	17	17	60.0	14.0	30	30	60.0				
6	0		1627	2538	2.0	5	5	60.0												
7	0		1637	2488	1.1	15	15	60.0	9.2	20	20	60.0	13.1	15	15	60.0	15.2	13	13	60.0
8	0		1667	2528	3.0	24	24	60.0	5.0	23	23	60.0	9.3	31	31	60.0	12.1	21	21	60.0
					14.1	27	27	60.0	19.0	15	15	60.0	20.1	14	14	60.0				
9	0		1645	2506	1.2	23	23	60.0	5.1	17	17	60.0	7.1	20	20	60.0	8.2	31	31	60.0
					10.0	11	11	60.0	12.2	26	26	60.0	13.2	13	13	60.0	19.1	17	17	60.0
10	0		1634	2508	9.4	11	11	60.0	11.2	9	9	60.0	12.3	27	27	60.0	13.3	6	6	60.0
11	0		1625	2508	1.3	12	12	60.0	2.1	26	26	60.0	10.1	9	9	60.0	21.0	23	23	60.0
					25.1	19	19	60.0												
12	0		1646	2532	2.2	21	21	60.0	8.3	21	21	60.0	9.5	26	26	60.0	10.2	27	27	60.0
					19.2	14	14	60.0												
13	0		1633	2502	1.4	11	11	60.0	7.2	15	15	60.0	9.6	13	13	60.0	10.3	6	6	60.0
14	0		1691	2515	5.2	30	30	60.0	8.4	27	27	60.0	19.3	37	37	60.0	20.2	20	20	60.0
15	0		1624	2487	1.5	9	9	60.0	4.1	12	12	60.0	7.3	13	13	60.0	16.0	9	9	60.0
16	0		1630	2480	15.3	9	9	60.0												
17	C		1686	2548	3.1	4	4	60.0												
18	0		1601	2528	2.3	25	25	60.0	21.1	17	17	60.0	22.0	19	19	60.0	25.2	14	14	60.0
19	0		1654	2520	8.5	15	15	60.0	9.7	17	17	60.0	12.4	14	14	60.0	14.2	37	37	60.0
2C	0		1680	2532	3.2	13	13	60.0	8.6	14	14	60.0	14.3	20	20	60.0				
21	0		1602	2511	11.3	23	23	60.0	18.1	17	17	60.0	22.1	24	24	60.0	23.1	9	9	60.0
					25.3	17	17	60.0												
22	0		1582	2525	18.2	19	19	60.0	21.2	24	24	60.0	24.0	17	17	60.0				
23	C		1597	2503	4.2	20	20	60.0	21.3	9	9	60.0	24.1	17	17	60.0				
24	0		1581	2508	22.2	17	17	60.0	23.2	17	17	60.0								
25	0		1614	2523	2.4	16	16	60.0	11.4	19	19	60.0	18.3	14	14	60.0	21.4	17	17	60.0

Program FORMAT SPIDERWEB TREES (FMTSPTR)

Output

Table XI shows a listing of the standard format output for two arbitrarily selected trees of the 25 node spiderweb network. The minimum distance paths are interpreted from the output listing as follows: in the tree from node 1 in Table XI, the first path begins at node 2, proceeds to node 11 and then to node 1; the second path begins at node 3, proceeds to node 8, then to node 9, and then to node 1, etc.

TABLE XI

OUTPUT LISTING OF PROGRAM (FMTSPTR)

```
TREE FROM NODE      1

   2     11   HOME
   3      8       9   HOME
   4   HOME
   5      9
       CONTINUED IN TRACE      3
   6      2
       CONTINUED IN TRACE      2
   7   HOME
   8   CONTINUED IN TRACE      3
   9   CONTINUED IN TRACE      3
  10     13   HOME
  11   CONTINUED IN TRACE      2
  12     10
       CONTINUED IN TRACE     10
  13   CONTINUED IN TRACE     10
  14      5
       CONTINUED IN TRACE      5
  15   HOME
  16     15
       CONTINUED IN TRACE     15
  17      3
       CONTINUED IN TRACE      3
  18     25      11
       CONTINUED IN TRACE      2
  19      9
       CONTINUED IN TRACE      3
  20      8
       CONTINUED IN TRACE      3
  21     11
       CONTINUED IN TRACE      2
  22     21
       CONTINUED IN TRACE     21
  23      4
       CONTINUED IN TRACE      4
  24     23
       CONTINUED IN TRACE     23
  25   CONTINUED IN TRACE     18
```

```
TREE FROM NODE     21

   1     11   HOME
   2     25   HOME
   3      8       9      10      11
       CONTINUED IN TRACE      1
   4     23   HOME
   5      9
       CONTINUED IN TRACE      3
   6      2
       CONTINUED IN TRACE      2
   7      1
       CONTINUED IN TRACE      1
   8   CONTINUED IN TRACE      3
   9   CONTINUED IN TRACE      3
  10   CONTINUED IN TRACE      3
  11   CONTINUED IN TRACE      1
  12      2
       CONTINUED IN TRACE      2
  13     10
       CONTINUED IN TRACE      3
  14      5
       CONTINUED IN TRACE      5
  15      4
       CONTINUED IN TRACE      4
  16     15
       CONTINUED IN TRACE     15
  17      3
       CONTINUED IN TRACE      3
  18   HOME
  19      9
       CONTINUED IN TRACE      3
  20      8
       CONTINUED IN TRACE      3
  22   HOME
  23   CONTINUED IN TRACE      4
  24     23
       CONTINUED IN TRACE      4
  25   CONTINUED IN TRACE      2
```

Program BUILD TRIPTABLE (BLDTT) Output

Table XII shows the upper triangular matrix trip table output of the BLDTT program. The matrix was assumed to be symmetrical in the loading procedure employed by the LDSPWB program. The diagonal entries of the matrix represent the total summation of trips for each node. The link distance and predicted trip volumes are given as the off diagonal entries in the matrix.

TABLE XII

OUTPUT LISTING OF PROGRAM (BLDTT)

PAGE 1, 1 RUN 1

0 F1 S1	1 TULSA	2 B'VILLE	3 MIAMI	4 SA SPRIG	5 PRYOR	6 DEWEY	7 B ARROW	8 VINITA	9 CL'MORE	10 COL'VILL
1 TULSA	144028.	38. 2814.	78. 117.	8. 75535.	39. 778.	42. 603.	15. 8975.	54. 228.	24. 1813.	16. 5321.
2 B'VILLE		32078.	61. 26.	39. 88.	47. 52.	5. 27833.	46. 43.	43. 48.	34. 71.	28. 112.
3 MIAMI			5796.	84. 3.	46. 17.	58. 8.	74. 4.	24. 75.	55. 6.	63. 4.
4 SA SPRIG				76664.	46. 16.	43. 19.	22. 111.	60. 6.	31. 30.	21. 75.
5 PRYOR					1421.	47. 14.	31. 44.	24. 74.	17. 157.	28. 34.
6 DEWEY						28769.	50. 10.	41. 15.	36. 18.	31. 24.
7 B ARROW							10232.	51. 8.	20. 79.	20. 76.
8 VINITA								792.	31. 20.	39. 10.
9 CL'MORE									2766.	11. 238.
10 COL'VILL										7637.

TABLE XII (Continued)

PAGE 1, 2 RUN 1

D F1 S1	11 SKIATOOK	12 NOWATA	13 OWASSO	14 JAY	15 JENKS	16 BIXBY	17 COMMERCE	18 P'HUSKA	19 CHELSA	20 AFTON
1 TULSA	12. 11198.	42. 304.	11. 12390.	69. 71.	9. 18183.	18. 3182.	81. 40.	39. 283.	39. 274.	67. 54.
2 B'VILLE	27. 130.	21. 217.	33. 63.	69. 8.	47. 22.	54. 15.	62. 9.	24. 123.	33. 49.	55. 10.
3 MIAMI	70. 3.	41. 11.	67. 3.	31. 23.	83. 1.	85. 1.	4. 5328.	85. 1.	39. 9.	14. 153.
4 SA SPRIG	15. 198.	46. 8.	18. 110.	77. 2.	13. 267.	21. 61.	87. 1.	36. 12.	45. 6.	73. 1.
5 PRYCR	36. 16.	31. 24.	29. 28.	30. 23.	42. 10.	41. 10.	49. 5.	64. 2.	17. 95.	32. 13.
6 DEWEY	30. 25.	19. 79.	36. 14.	67. 2.	51. 5.	58. 3.	59. 3.	28. 23.	32. 14.	53. 3.
7 B ARROW	23. 52.	45. 7.	14. 164.	60. 3.	12. 241.	10. 382.	77. 1.	54. 3.	37. 9.	62. 2.
8 VINITA	47. 6.	22. 46.	43. 7.	27. 23.	60. 3.	61. 2.	27. 20.	66. 2.	15. 88.	14. 108.
9 CL'MORE	20. 53.	25. 24.	13. 148.	46. 4.	28. 16.	30. 13.	58. 2.	49. 3.	17. 56.	43. 3.
10 COL'VILL	9. 460.	27. 18.	6. 1173.	57. 2.	23. 26.	28. 15.	66. 1.	39. 5.	24. 18.	52. 2.

TABLE XII (Continued)

PAGE 1, 3 RUN 1

0 FI SI	21 HOMINY	22 FAIRFAX	23 CLV'LAND	24 PAWNEE	25 BARS'CAL
1 TULSA	26. 663.	51. 93.	27. 529.	44. 129.	28. 451.
2 B'VILLE	32. 41.	44. 16.	41. 18.	51. 10.	15. 263.
3 MIAMI	89. 1.	104. 0.	96. 1.	110. 0.	74. 1.
4 SA SPRIG	21. 44.	45. 4.	20. 41.	37. 7.	27. 18.
5 PRYOR	60. 2.	82. 1.	64. 2.	81. 1.	50. 3.
6 DEWEY	36. 8.	47. 3.	46. 4.	55. 2.	20. 36.
7 B ARROW	41. 5.	66. 1.	42. 4.	59. 7.	41. 4.
8 VINITA	67. 1.	85. 1.	74. 1.	89. 0.	53. 2.
9 CL'MORE	43. 3.	66. 1.	48. 2.	64. 1.	35. 5.
10 COL'VILL	32. 7.	55. 1.	37. 4.	53. 1.	25. 11.

TABLE XII (Continued)

PAGE 2, 2 RUN 1

0 FI S1	11 SKIATOOK	12 NOWATA	13 OWASSO	14 JAY	15 JENKS	16 BIXBY	17 COMMERCE	18 P'HUSKA	19 CHELSA	20 AFTON
11 SKIATOOK	12582.	32. 11.	10. 311.	65. 1.	21. 33.	28. 14.	72. 1.	32. 9.	31. 9.	60. 1.
12 NOWATA		856.	33. 9.	48. 3.	50. 3.	54. 2.	43. 4.	45. 3.	14. 70.	34. 5.
13 OWASSO			14533.	59. 2.	17. 51.	22. 26.	70. 1.	41. 4.	28. 10.	56. 1.
14 JAY				206.	72. 1.	70. 1.	34. 7.	9C. 0.	37. 5.	2C. 23.
15 JENKS					19140.	9. 276.	86. 0.	48. 2.	45. 3.	72. 1.
16 BIXBY						4018.	88. 0.	56. 1.	47. 2.	72. 1.
17 COMMERCE							5458.	86. 0.	42. 3.	17. 3C.
18 P'HUSKA								366.	53. 1.	79. 0.
19 CHELSA									734.	28. 7.
20 AFTON										421.

TABLE XII (Continued)

PAGE 2, 3 RUN 1

D F1 S1	21 HOMINY	22 FAIRFAX	23 CLV'LAND	24 PAWNEE	25 BARS'DAL
11	24.	47.	28.	45.	19.
SKIATOOK	15.	2.	8.	2.	24.
12	48.	64.	56.	69.	33.
NOWATA	2.	1.	1.	1.	5.
13	32.	56.	35.	52.	28.
OWASSO	6.	1.	4.	1.	7.
14	88.	109.	93.	110.	76.
JAY	0.	0.	0.	0.	0.
15	33.	57.	32.	48.	37.
JENKS	5.	1.	5.	1.	3.
16	42.	66.	40.	57.	45.
BIXBY	3.	1.	3.	1.	2.
17	91.	106.	99.	112.	75.
COMMERCE	0.	0.	0.	0.	0.
18	17.	20.	26.	29.	14.
PAWHUSKA	25.	15.	7.	5.	35.
19	53.	72.	59.	74.	40.
CHELSA	1.	0.	1.	0.	2.
20	80.	98.	87.	102.	66.
AFTON	0.	0.	0.	0.	0.

TABLE XII (Continued)

PAGE 3, 3 RUN 1

D F1 S1	21 HOMINY	22 FAIRFAX	23 CLV'LAND	24 PAWNEE	25 BARS'DAL
21 HOMINY	952.	25. 6.	9. 88.	22. 8.	17. 17.
22 FAIRFAX		170.	27. 4.	17. 14.	32. 2.
23 CLV'LAND			744.	17. 14.	26. 5.
24 PAWNEE				203.	37. 2.
25 BARS'DAL					898.

Program FORMAT SPIDERWEB LOADS

(FMTSPLD) Output

Table XIII shows the standard BPR format output for the trip volume loaded 25 node spiderweb network. The output is interpreted as follows: the link connecting nodes 1 and 4 is 8 miles long and has a volume of 76,333 trips/day; the link connecting nodes 1 and 7 is 15 miles long and has a volume of 9,202 trips/day, etc. The design speed for each link is 60 mph.

TABLE XIII

OUTPUT LISTING OF PROGRAM (FMTSPLD)

NODE A DESCRIPTION		LEG ZERO			LEG ONE			LEG TWO			LEG THREE			LEG FOUR			LEG FIVE			LEG SIX			LEG SEVEN		
NO.	STATE COUNTY	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST	NODE	ST	DIST
LOAD	IDENTIFICATION	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME	SPEED		VOLUME
1	0	4	0	8	7	0	15	9	0	23	11	0	12	13	0	11	15	0	9						
TOTAL	LOAD	60.0		76,333	60.0		9,202	60.0		3,482	60.0		16,622	60.0		18,320	60.0		21,626						
2	0	6	0	5	11	0	26	12	0	21	18	0	25	25	0	16									
TOTAL	LOAD	60.0		28,746	60.0		4,126	60.0		484	60.0		162	60.0		374									
3	0	8	0	24	17	0	4	20	0	13															
TOTAL	LOAD	60.0		348	60.0		5,438	60.0		208															
4	0	1	0	8	15	0	12	23	0	20															
TOTAL	LOAD	60.0		76,333	60.0		338	60.0		780															
5	0	8	0	23	9	0	17	14	0	30															
TOTAL	LOAD	60.0		106	60.0		1,348	60.0		100															
6	0	2	0	5																					
TOTAL	LOAD	60.0		28,746																					
7	0	1	0	15	9	0	20	13	0	15	15	0	13												
TOTAL	LOAD	60.0		9,202	60.0		146	60.0		238	60.0		620												
8	0	3	0	24	5	0	23	9	0	31	12	0	21	14	0	27	19	0	15	20	0	14			
TOTAL	LOAD	60.0		348	60.0		106	60.0		506	60.0		184	60.0		34	60.0		102	60.0		196			
9	0	1	0	23	5	0	17	7	0	20	8	0	31	10	0	11	12	0	26	13	0	13	19	0	17
TOTAL	LOAD	60.0		3,482	60.0		1,348	60.0		146	60.0		506	60.0		546	60.0		50	60.0		192	60.0		476
10	0	9	0	11	11	0	9	12	0	27	13	0	6												
TOTAL	LOAD	60.0		546	60.0		1,266	60.0		346	60.0		7,396												
11	0	1	0	12	2	0	26	10	0	9	21	0	23	25	0	19									
TOTAL	LOAD	60.0		16,622	60.0		4,126	60.0		1,266	60.0		796	60.0		820									
12	0	2	0	21	8	0	21	9	0	26	10	0	27	19	0	14									
TOTAL	LOAD	60.0		484	60.0		184	60.0		50	60.0		346	60.0		132									
13	0	1	0	11	7	0	15	9	0	13	10	0	6												
TOTAL	LOAD	60.0		18,320	60.0		238	60.0		192	60.0		7,396												
14	0	5	0	30	8	0	27	19	0	37	20	0	20												
TOTAL	LOAD	60.0		100	60.0		34	60.0		4	60.0		50												
15	0	1	0	9	4	0	12	7	0	13	16	0	9												
TOTAL	LOAD	60.0		21,626	60.0		338	60.0		620	60.0		3,998												
16	0	15	0	9																					
TOTAL	LOAD	60.0		3,998																					

TABLE XIII (Continued)

```
NODE A DESCRIPTION I   LEG ZERO  I   LEG ONE   I   LEG TWO   I  LEG THREE  I   LEG FOUR  I   LEG FIVE  I   LEG SIX   I  LEG SEVEN
NO.ISTATEI COUNTY  INODEISTI DISTINODEISTI DISTINODEISTI DISTINODEISTI DISTINODEISTI DISTINODEISTI DISTINODEISTI DISTINODEISTI DISTI
LOAD IDENTIFICATION ISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUMEISPEEDI VOLUME

  17  0                  3  0     4
TOTAL LOAD            60.0    5,438

  18  0                  2  0    25   21  0    17   22  0    19   25  0    14
TOTAL LOAD            60.0      162 60.0       42 60.0       36 60.0      340

  19  0                  8  0    15    9  0    17   12  0    14   14  0    37
TOTAL LOAD            60.0      102 60.0      476 60.0      132 60.0        4

  20  0                  3  0    13    8  0    14   14  0    20
TOTAL LOAD            60.0      208 60.0      196 60.0       50

  21  0                 11  0    23   18  0    17   22  0    24   23  0     9   25  0    17
TOTAL LOAD            60.0      796 60.0       42 60.0      106 60.0      210 60.0       94

  22  0                 18  0    19   21  0    24   24  0    17
TOTAL LOAD            60.0       36 60.0      106 60.0       16

  23  0                  4  0    20   21  0     9   24  0    17
TOTAL LOAD            60.0      780 60.0      210 60.0      166

  24  0                 22  0    17   23  0    17
TOTAL LOAD            60.0       16 60.0      166

  25  0                  2  0    16   11  0    19   18  0    14   21  0    17
TOTAL LOAD            60.0      374 60.0      820 60.0      340 60.0       94

SUBTOTAL FOR LOAD2.  NUMBER OF LINKS =    48   TOTAL DISTANCE =      835 MILES. AVE LINK LENGTH =    17 MI. TOTAL VOLUME =   207,251
TOTAL LOAD            AVE VOL PER LINK =   4,317 VEHICLE MILES =   1986,868 VEHICLE HOURS =      33,114 AVERAGE SPEED =  60.0 MPH

FMTSPLD (07/31/69) COMPLETE
```

APPENDIX C

SAMPLE ROAD USER COST DATA

TABLE XIV

ROAD USER COSTS FOR PASSENGER CARS IN RURAL AREAS

TANGENT 2-LANE HIGHWAYS

Pavement in Good Condition

User Costs, Cents Per Vehicle Mile for:

Free Operation

Running Speed mph	Gradient Class %	Fuel	Tires	Oil	Maint. and Repairs	Depreciation	Subtot. Oper. Costs	Time	Comfort and Conv.	Total Costs
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
32	0-3	1.85	0.21	0.15	1.20	1.50	4.91	4.84	0	9.75
	3-5	1.92	0.24	0.15	1.20	1.50	5.01	4.84	0	9.85
	5-7	2.01	0.31	0.15	1.20	1.50	5.17	4.84	0	10.01
	7-9	2.23	0.42	0.15	1.20	1.50	5.50	4.84	0	10.34
36	0-3	1.91	0.26	0.15	1.20	1.50	5.02	4.31	0	9.33
	3-5	2.00	0.30	0.15	1.20	1.50	5.15	4.31	0	9.46
	5-7	2.10	0.39	0.15	1.20	1.50	5.34	4.31	0	9.65
	7-9	2.34	0.52	0.15	1.20	1.50	5.71	4.31	0	10.02
40	0-3	2.00	0.32	0.18	1.20	1.50	5.20	3.88	0	9.08
	3-5	2.10	0.37	0.18	1.20	1.50	5.35	3.88	0	9.23
	5-7	2.22	0.48	0.18	1.20	1.50	5.58	3.88	0	9.46
	7-9	2.53	0.64	0.18	1.20	1.50	6.05	3.88	0	9.93
44	0-3	2.11	0.40	0.21	1.20	1.50	5.42	3.52	0	8.94
	3-5	2.23	0.46	0.21	1.20	1.50	5.60	3.52	0	9.12
	5-7	2.39	0.60	0.21	1.20	1.50	5.90	3.52	0	9.42
	7-9	2.75	0.80	0.21	1.20	1.50	6.46	3.52	0	9.98
48	0-3	2.27	0.50	0.24	1.20	1.50	5.71	3.23	0	8.94
	3-5	2.42	0.58	0.24	1.20	1.50	5.94	3.23	0	9.17
	5-7	2.62	0.75	0.24	1.20	1.50	6.31	3.23	0	9.54
	7-9	3.11	1.00	0.24	1.20	1.50	7.05	3.23	0	10.28
52	0-3	2.51	0.63	0.28	1.20	1.50	6.12	2.98	0	9.10
	3-5	2.71	0.72	0.28	1.20	1.50	6.41	2.98	0	9.39
	5-7	2.98	0.95	0.28	1.20	1.50	6.91	2.98	0	9.89
	7-9	3.65	1.26	0.28	1.20	1.50	7.89	2.98	0	10.87
56	0-3	2.91	0.75	0.37	1.20	1.50	6.73	2.77	0	9.50
	3-5	3.18	0.86	0.37	1.20	1.50	7.11	2.77	0	9.88
	5-7	3.60	1.12	0.37	1.20	1.50	7.79	2.77	0	10.56
60	0-3	3.65	0.84	0.52	1.20	1.50	7.71	2.58	0	10.29
	3-5	4.05	0.97	0.52	1.20	1.50	8.24	2.58	0	10.82

TABLE XIV (Continued)

TANGENT DIVIDED HIGHWAYS

Pavement in Good Condition

User Costs, Cents Per Vehicle Mile for:

Free Operation

Running Speed mph	Gradient Class %	Fuel	Tires	Oil	Maint. and Repairs	Depreciation	Subtot. Oper. Costs	Time	Comfort and Conv.	Total Costs
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
40	0-3	2.00	0.28	0.18	1.20	1.50	5.16	3.88	0	9.04
	3-5	2.10	0.33	0.18	1.20	1.50	5.31	3.88	0	9.19
	5-7	2.22	0.42	0.18	1.20	1.50	5.52	3.88	0	9.40
	7-9	2.53	0.57	0.18	1.20	1.50	5.98	3.88	0	9.86
44	0-3	2.09	0.34	0.21	1.20	1.50	5.34	3.52	0	8.86
	3-5	2.22	0.39	0.21	1.20	1.50	5.52	3.52	0	9.04
	5-7	2.35	0.51	0.21	1.20	1.50	5.77	3.52	0	9.29
	7-9	2.71	0.68	0.21	1.20	1.50	6.30	3.52	0	9.82
48	0-3	2.21	0.41	0.24	1.20	1.50	5.56	3.23	0	8.79
	3-5	2.35	0.47	0.24	1.20	1.50	5.76	3.23	0	8.99
	5-7	2.53	0.61	0.24	1.20	1.50	6.08	3.23	0	9.31
	7-9	2.95	0.81	0.24	1.20	1.50	6.70	3.23	0	9.93
52	0-3	2.34	0.47	0.29	1.20	1.50	5.80	2.98	0	8.78
	3-5	2.50	0.54	0.29	1.20	1.50	6.03	2.98	0	9.01
	5-7	2.72	0.71	0.29	1.20	1.50	6.42	2.98	0	9.40
	7-9	3.21	0.95	0.29	1.20	1.50	7.15	2.98	0	10.13
56	0-3	2.51	0.54	0.37	1.20	1.50	6.12	2.77	0	8.89
	3-5	2.71	0.62	0.37	1.20	1.50	6.40	2.77	0	9.17
	5-7	2.99	0.80	0.37	1.20	1.50	6.86	2.77	0	9.63
	7-9	3.58	1.07	0.37	1.20	1.50	7.72	2.77	0	10.49
60	0-3	2.73	0.56	0.52	1.20	1.50	6.51	2.58	0	9.09
	3-5	2.97	0.64	0.52	1.20	1.50	6.83	2.58	0	9.41

VITA

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