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**SEARCH AND CHOICE
IN TRANSPORT SYSTEMS PLANNING :
SUMMARY REPORT**

by

Marvin L. Manheim

with

Earl R. Rulter and Kiran U. Bhatt

**SEARCH AND CHOICE IN TRANSPORT SYSTEMS PLANNING
Volume I of a Series**

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SEARCH AND CHOICE IN TRANSPORT SYSTEMS PLANNING

Volume I of a Series

Sponsored by the U.S. Department of
Transportation, the General Motors Grant for
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Prepared in cooperation with the
M.I.T. Urban Systems Laboratory

Transportation Systems Division
Department of Civil Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

June 1968

ABSTRACT

There are many options open for manipulation of the transportation system, and many impacts on different groups which must be considered. Prediction of the impacts associated with a particular set of options requires prediction of the corresponding pattern of flows which will occur in the multimodal transportation network, using a complex system of models.

The problem of "search" is to generate alternative transportation systems sufficiently attractive to be worth testing by predicting the impacts. The problem of "choice" is to rank the alternatives based upon evaluation of their predicted impacts.

The objective of the research reported here was to design a program of research to develop techniques for searching out and choosing among transportation systems alternatives. The approach included investigation of the substantive problem, transportation systems analysis; investigation of the process of analysis; review of possible approaches to search; conduct of a "prototype analysis" to demonstrate concepts and techniques; development of specific experimental methods and techniques; and formulation of a program of research.

The basic conclusions are:

1. The core of the transportation systems problem is the prediction of equilibrium flows in networks, via supply-demand concepts.
2. Transportation is essentially discriminatory in its impacts; the differential impacts must be traced out explicitly.

3. The systematic analysis of transportation problems requires careful, sensitive exploration of tradeoffs among many options and impacts.

4. The prototype analysis demonstrates the feasibility of this approach, but also raises issues.

5. To resolve these issues, it is useful to view transportation systems analysis as a problem-solving process.

6. A variety of specific operational techniques can be developed to make transportation analysis a more efficient process.

The results of the research are summarized in this report and detailed in seventeen related volumes.

ACKNOWLEDGEMENTS

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Clearly, however, the opinions expressed herein are those of the individual authors and do not necessarily represent the views of any research sponsor.

The need for fundamental, exploratory research in this area was initially recognized by A. Scheffer Lang, then Deputy Undersecretary of Commerce for Transportation Research, (now Federal Railroad Administrator, Department of Transportation) and Henry W. Bruck, then Director, Transport Systems Planning Division, Office of High Speed Ground Transportation. Their interest and support stimulated the initiation of this project. The guidance and interest of Dr. Frank Hassler, Special Assistant for Systems Analysis to the Special Assistant to the Joint Chiefs of Staff for Strategic Mobility, Department of Defense; and of Dr. Edwin I. Golding of the Office

of Systems Analysis, Department of Transportation, are also gratefully acknowledged. Dr. Golding in particular encouraged us to show the relevance of this research to transportation policy through the 'prototype analysis.'

The authors would particularly like to express their appreciation to Miss Victoria Brooks, who assisted in the early stages of preparation of this report; to Mrs. Nancy Siegmann who supervised the production of the drafts of the reports; and to Miss Linda Leavitt, who supervised the editing and final printing.

Since this report is a summary of the research done by a number of people, there are many contributions by others than the indicated authors. Specific pieces of text extracted from other reports in this series have been referenced appropriately. Where the relation to work of other project staff is less clearly defined, every attempt has been made to acknowledge the particular efforts.

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Chapter I
INTRODUCTION

1.0 Why Search and Choice?

We Americans are a gadget-oriented culture; our first priorities are always hardware. We are fascinated by the supersonic transport, the air-cushion vehicle, the "tube-train" concepts of high-speed ground transportation. We can almost always find support for development of equipment, while planning an analysis, which leads only to clarification of alternatives and their impacts, has much harder going. Certainly, these "soft" studies get far less coverage in the press than the new gadgets.

So it is with transportation. Historically, transportation engineers have always felt more comfortable dealing with the "hard" issues - vehicle design, concrete mix, navigation and propulsion systems, precise geometric layout of highways - than with the impacts these transportation systems and facilities have on society. This is no longer feasible, however - for now it has become clear that transportation is not a question of hardware alone, but of social and political choice.

At its core, transportation is a technological problem, insofar as the alternatives open to us are constrained by the present state of technology. However, the real issues in transportation are not the alternative technologies, but their ramifications: the impacts which each alternative transportation system has upon the various segments of a society.

To explore this further, consider the range of choices open to us. The most basic transportation decision, choice of mode, involves specification of largely technological parameters: choice of propulsion system, supporting way, guidance system, and vehicle shape and dimensions. These parameters establish a basic envelope within which further decisions can be made about the performance characteristics of the links. The structure of the

network, and how the system will be operated. The resultant of all these decisions is a particular transportation system design.

Each particular system thus specified can also be characterized by the pattern of services it provides, and particularly by the differences in services provided to various groups, both users and non-users. The bundle of impacts of such a system is varied and large, as is the number and variety of groups affected.

This leads us to the definition of "search and choice". Search is this problem: given a statement of goals, can we design a transportation system which seems reasonably likely to achieve those goals. Choice is the converse problem: given several alternative transportation systems, can we determine which is the preferred alternative. Of course, there is a certain sequence implied here: first, we go through the search process to develop several alternatives. Then, we "test" each of the alternatives by inputting them to a set of predictive models, to identify the consequences which each alternative might have in the real world. Finally, we evaluate those consequences and come up with a preference ordering over the alternatives.

Why is search and choice an issue worth discussing? For a quick answer, let us review briefly several transportation systems problems currently being studied:

- a. Research and development of new transportation technology. What cost and service characteristics should new technologies achieve? What kinds of urban transportation or high speed ground transportation systems should we be trying to develop? Do we simply exploit the most easily available technology, or do we try to steer research and development to achieve a technology that will meet some need?

b. Regional transportation systems, such as the Northeast Corridor.

What pattern of services should be provided over the next 40 years? Should new facilities reinforce the pattern of existing transportation lines, or should the existing system be modified in fundamental ways? Is it sufficient to increase service characteristics through improvement to existing facilities, vehicles, and operating procedures, or are completely new facilities and equipment desirable? Where should new facilities be built? What are the noise and air pollution ramifications of the alternatives?

c. The urban highway crisis. Many of our metropolitan area transportation systems are predominantly highway-oriented, with little or no role for rail rapid transit or other public transportation systems. A highway-oriented system generally serves the upper-and middle-income car-owning suburbanites better than the central city resident. Generally, the construction of a highway system does not improve the low-income, elderly, or handicapped. Not only does it not improve their accessibility, but it also may violently disrupt their lives - for construction of new highway facilities often displaces substantial numbers of these same families.

In each of these problems, there are many issues. Obviously, new technologies which provide better service at lower cost in dollars and land area are needed. But there is a more fundamental issue, that of social equity. Every transportation system change is potentially an improvement for some groups and a disaster for others. These differentials must be considered explicitly in making transportation system decisions.

Thus, the problem of searching out and choosing among transportation systems alternatives covers the spectrum from the basic physics and economics of transport technologies, to the politics of social change. On the one hand, the range of transportation alternatives is growing rapidly; on the other hand, there are many dynamics in our society with which transportation interacts. The problem of search and choice is to bridge these two concerns in a sensitive, operational way.

2.0 Recognition of the Problem

Ferguson has laid out some of the issues in developing systems alternatives:¹

At one time the preparation of an urban transportation plan was approached as an engineering problem that had as its principal goal the development of a workable solution. Today, workability alone may not be enough. True, plans for urban transportation systems must be functional; but plans must also represent an efficient allocation of resources and a step toward the achievement of a better overall urban environment. These more complex demands on the urban transportation plan mean that a meaningful solution can be achieved only after a thorough search for alternative workable transportation systems that have been evaluated in terms of their various attributes.

He went on to point out that there has been very little research on the process of developing transportation systems alternatives. Further, the systems alternatives which have been studied in most urban areas have been heavily biased toward existing and committed systems.

This problem became even more evident in the context of transport systems planning for the Northeast Corridor region of the United States. In this effort, a wide range of alternative transportation technologies were being considered, some of which might have profound effects on the region. The spectrum of possibilities for specific systems in the region is immense, and their ramifications complex. Research in searching out and choosing among alternatives was needed.

The need for fundamental, exploratory research in this area was recognized by A. Scheffer Lang, then Deputy Undersecretary of Commerce for Transportation Research, and Henry W. Bruck, then Director, Transport Systems Planning Division, Office of High Speed Ground Transportation. Their interest and support stimulated the initiation of this research project.

¹Ferguson, George A., "Development of Transportation Systems Alternatives", in TRANSPORTATION SYSTEM EVALUATION, Highway Research Record 148, Washington, D. C.: Highway Research Board (1966).

3.0 Objectives of the Research Program

The basic objective of this research project was the design of a program of methodological research on the construction of transportation system alternatives, through review of relevant methodologies and procedural models, and theoretical developments and initial experiments. During the course of this work, M.I.T. was requested to redirect a part of the effort, in order to design and carry out a prototype analysis to demonstrate the methodology and concepts being developed in this project.

4.0 Organization of the Report

The report of this research is presented in a number of volumes. Volume I is a summary report, presenting an overview of search and choice in transport systems planning. Included also in Volume I are abstracts of all the other volumes in the series. The remaining volumes contain detailed expositions of specific portions of the research. In addition, completed theses have been transmitted separately.

The conduct of this research followed generally the lines initially laid out in an early philosophical paper.¹ The following were the major areas of emphasis in the research:

- a. investigation of the nature of the substantive problem, transportation systems analysis
- b. investigation of the nature of the analysis process
- c. review of possible approaches to search
- d. development of a "prototype analysis" to demonstrate concepts and techniques
- e. formulation of a program of research.

The results of research in these areas are summarized in the following chapters of this volume.² The basic argument in these chapters is as follows:

- a. Chapter II: The Substantive Problem-Transportation Systems Analysis

There are many options open for manipulating the transportation

¹Manheim, Marvin L., "Transportation, Problem-Solving, and the Effective Use of Computers," TRANSPORTATION SYSTEM EVALUATION, op. cit.

²This summary volume draws heavily on material in other reports of this series.

system, and many impacts which must be considered. To predict the impacts associated with a particular set of options requires prediction of the corresponding pattern of flows which will occur in the multi-mode transportation network. The basic logic of this prediction is that of supply-demand equilibrium. However, making this logic operational in the network context requires a complex system of models. Thus, to predict the impacts associated with only one alternative transportation system requires significant computational resources.

This equilibrium framework is present to some extent in urban transportation and other transportation systems activities. However, urban transportation procedures do not implement the equilibrium framework as effectively as they might.

The problem of "search" is to generate alternative transportation systems sufficiently attractive to be worth "testing" by predicting the impacts. The problem of "choice" is to rank the alternatives based upon evaluation of their predicted impacts. To systematically analyse a transportation problem, a wide variety of alternative options must be explored and their differential impacts traced out explicitly.

A simple model which illustrates the ideas presented is described.

b. Chapter III: A Prototype Analysis - The Northeast Corridor

To demonstrate the feasibility and utility of systematic analysis in the supply-demand equilibrium context, a "prototype analysis of passenger transportation in the Northeast Corridor was conducted. A problem-oriented computer language was developed (through additions to previous capabilities), and a realistic data base was assembled. The computer language allows use of such options as fare and frequency of service, as well as network changes; and finds network equilibrium consistent

with the Baumol-Quandt multi-mode demand model, through a variable increment approach. The outputs identify the impact of the resulting equilibrium flow pattern on various users and transportation operators, on government taxes and revenues, and on regional growth (based upon simple models).

This computer language provides a "laboratory" in which experiments can be conducted to simulate the effects of policy changes on the transportation system. To demonstrate some of the experiments possible with this computerized laboratory, analyses were made of a simplified representation of the Northeast Corridor transportation system (five zones, four transportation modes).

These analyses demonstrate:

1. the feasibility of developing a supply-demand equilibrium model for transportation analysis;
2. the difference between equilibrium and non-equilibrium approaches to the problem;
3. how different options and impacts can be included in a network model so that their interactions can be studied;
4. how tradeoffs between options can be explored;
5. the technique of differential impact analysis through tracing out impacts among different actors as the options are varied;
6. sensitivity analyses;
7. effects of alternate time-stagings of investments.

c. Chapter IV: The Problem-Solving Process in Transportation Systems Analysis:

The supply-demand equilibrium formulation provides a mechanism for predicting the impacts associated with a particular set of options.

Prediction is only part of the problem, however. Search techniques are required to generate alternative sets of options, as well as procedures for evaluating the impacts and choosing among the alternatives. Thus, systematic analysis in transportation is complex, and transportation systems analysis must be viewed as a problem-solving process.

After review of the limitations of the "rational" model of decision-making, a theoretical model (the PSP model) is proposed in answer to these limitations. The applicability of the PSP model is demonstrated through review of the prototype analysis. Several operational implications of the PSP model are described, including DODO, a computerized information system for organizing the data of many computer runs; network aggregation; and the goal fabric technique. Computer graphics and the treatment of uncertainty are also discussed. Finally, the interaction of the technical analysis with the political process is discussed, leading to a conception of an evolutionary planning process for evolutionary transportation systems.

d. Chapter V: Search:

There is no single procedure for generating alternative transportation systems (to be tested in the flow prediction models) which is the best to use. Instead, a variety of search procedures might be used in a flexible way in an interactive computer environment. Useful procedures will include mathematical optimization formulations (including branch and bound techniques) as well as heuristic procedures. Multi-level structures and other more complex search strategies should be developed and tested.

e. Chapter VI: Summary of Conclusions, Recommendations and other Results:

The conclusions of the research, particularly the recommended program of further research, and the specific techniques developed, are summarized.

The major conclusions and recommendations are:

1. Transportation systems should be analysed as network equilibrium problems.
2. Systematic analysis of alternative transportation policies requires exploration of tradeoffs among options with explicit identification of differential impacts.
3. The prototype analysis of the Northeast Corridor demonstrates the feasibility of systematic analysis in a network equilibrium context.
4. The process of analysis in transportation must be organized as a problem-solving process, with iterative, flexible structure, which interacts over time with the political process.
5. A balanced program of research in "methods for searching out and choosing among transportation systems alternatives" should include research on:
 - a. the substantive problem - development of models for transportation analysis, including supply, demand, resource requirements, demand shifts, and network equilibrium, in a modular, flexible system of models;
 - b. the analysis process - development of procedures and techniques for organizing and structuring analysis, including
 - (i) an interactive, flexible software environment,
 - (ii) a variety of search procedures,
 - (iii) network aggregation procedures,
 - (iv) decision-oriented data organization capabilities such as DODO;

(v) flexible evaluation procedures such as goal fabric analysis, and

(vi) techniques for evolutionary planning in the face of uncertainty;

c. prototype analyses - to stimulate and guide research in the substantive problem and in the analysis process, a series of prototype analyses of specific transportation systems problems should be conducted.

5.0 Summary of Conclusions

Stated as concisely as possible, our basic conclusions are:

1. The core of the transportation systems problem is the prediction of equilibrium flows in networks, via supply-demand concepts.
2. Transportation is essentially discriminatory in its impacts; the differential impacts must be traced out explicitly.
3. The systematic analysis of transportation problems requires careful, sensitive exploration of tradeoffs among many options and impacts.
4. The prototype analysis demonstrates the feasibility of this approach, but also raises issues.
5. To resolve these issues, it is useful to view transportation systems analysis as a problem-solving process.
6. A variety of specific operational techniques can be developed to make transportation analysis a more efficient process.

Chapter II

THE SUBSTANTIVE PROBLEM - TRANSPORTATION SYSTEMS ANALYSIS

1.0 Introduction

The objective of this chapter is to outline the basic structure of a transportation systems analysis. This is an essential prelude to any discussion of the problem of search and choice.

2.0 The Basic Transportation Options

There is a wide spectrum of aspects of a transportation system which can be varied. Not all of these aspects are open to a single decision-maker, nor are all open at the same time. This spectrum of options, or "decision variables," may be summarized as follows:

1. technology - Development and/or implementation of new combinations of transportation components which enable transportation services to be offered in ways which were not previously available. Examples: containers, containerships and piggy-back trucks and rail cars; the supersonic transport; new urban mass transportation concepts, such as the Westinghouse "Skybus" system, and the various "Genie"-¹ type systems featuring dynamically routed and scheduled vehicles.

Options about technology include fundamental decisions about the means of propulsion; the medium through which the vehicle travels, and supporting way and suspension systems; vehicle size, shape and characteristics; guidance and control system; cargo or passenger compartment characteristics and basic services provided; typical route and network structure; general mode of operations, and other characteristics. Decisions must be made about these options within the constraints of technological feasibility, but there is a wide range of options nevertheless, even at the present state of transportation technology (and we are about to see a very rapid growth in the variety of specific technologies available

¹Hanson, Mark, (ed.) PROJECT METRAN, Cambridge, Mass: M.I.T. Press (1966); Department of Housing and Urban Development, TOMORROW'S TRANSPORTATION, Washington, D.C.: Government Printing Office (1968).

for urban, inter-urban, and developing country contexts).¹

2. networks - Options about networks include the general configurational pattern of the network as well as the approximate geographic location of the links of the network. Examples are the typical grid system of many of our cities, versus a series of radial and concentric circles.

3. link characteristics - Networks consist of links and modes. Links correspond to routes, such as highways, airways, rail lines, urban streets. Where it is necessary to model the characteristics of intersection points within a single mode - such as highway intersections, rail yards - and of transfer points between modes - airports, rail terminals, bus stops - these are also represented as links.² Nodes simply express the connectivity relations of links in the network. Options include the detailed physical location of links and nodes; and such characteristics of the links as impact upon flows as: the choice of technology, as well as the number of lanes of highway or tracks, railroad, the grades and curves of the roadway, the type of

¹ Clearly, the repertory of technologies available at a particular time constrains the possible detailed decisions about system design. One could easily argue that the current impasse in the highway-mass transit controversy arises because neither alternative is wholly satisfactory - and only new technologies for urban transportation will resolve the political conflicts.

² Generally we will adopt the convention of most transportation network analyses and assume all flow properties are represented in links while nodes create no barriers to flow. Where node properties should be modeled - as clearly the transfer time at a rail terminal or airport - we will do so by a subnetwork of links in the model which represents, and has the same properties as, the nodes. Thus, nodes only serve to express the topology of a network.

signalling or traffic control, the internal layout of a freight terminal, etc.

4. vehicles - Most transportation modes have vehicles (exceptions: pipelines, conveyors). The major options include the numbers of vehicles in the system, and their characteristics. (Note that the choice of technology or technologies sets broad ranges to such options as networks, links, vehicles, and operating policies, but detailed decisions must still be made within the feasible range.)

5. system operating policies - This set of options includes the full spectrum of decisions about how the transportation system is operated. The networks, links and vehicles establish an envelope of possibilities; within that envelope a large variety of detailed operating decisions must be made. These options include: routes and schedules of the vehicles; types of service to be offered, including various services auxiliary to transportation (passenger meal services; diversion and reconsignment privileges for freight); prices to be charged (both general pricing policy and specific pricing decisions); financing, subsidy, and taxing schemes; regulatory decisions; etc. Some of these operating policy options can be varied almost on a day-to-day basis; others, such as pricing policy and regulatory decisions of entry of new carriers, may be unchanged for decades.

This set of transportation options fully defines the space of possible transportation plans and policies. However, these options are not exercised in a vacuum, but in the context of a system of social and economic activities.

3.0 The Non-Transportation Options: The Activity System

The activity system is defined as all the social, economic, political and other transactions which take place over space and time in a particular region. These transactions, both actual and potential, determine the demand for transportation, and, in turn, the levels and spatial patterns of these interactions are affected in part by the transportation services provided. Therefore, in modelling transportation systems, we must clearly identify those options in the activity system which will be expressed in the demands on the system:

1. travel options - These are the options open to every potential user of the transportation system: whether to make a trip at all, where to make it, when, and how - by what mode and route. These options apply to the individual traveler and to the shipper of freight. The decisions actually made by the shipper or traveler will be based in part upon the perceived characteristics of the transportation system, and in part upon the actual and potential patterns of transactions in the activity system. The aggregate result of all the individual decisions about travel are expressed as the demand for transportation.

2. activity system options - Almost all of the social, economic and political actors in the activity system has a wide range of options about how, when and where he will conduct his activities. Over the long term, these options profoundly influence the demand for transportation. For example, as major changes in a

transportation system are made over time, the spatial pattern of population and economic activity will change, as actors exercise their options for changing the location or scale of their activities.

Forces within the economy external to the transportation system, such as housing subsidies or mortgage policy, may impact on the spatial pattern of activity, and thus affect the demand for transportation.

These options are in the hands of a large variety of public and private decision-makers. In many transportation analyses, most of these options must be treated as exogenous, completely uncontrollable by the transportation analyst: for example, rate of economic growth, sectoral and regional patterns of growth, aggregate population. The exercise of some of these options by various decision-makers will be partially influenced by transportation; transportation will affect the detailed distribution of population and employment within a region. Still other options are controllable to some extent in explicit coordination with transportation options - such non-transport options as control of land-use through zoning and land development incentives.

Whether fully controllable or not, however, the full set of transportation and activity system options must be considered in any analysis.

4.0 The Impacts of Transportation

When evaluating alternative transportation systems, one would like to consider all relevant impacts. Any change in the transportation system can potentially affect a large variety of groups and interests.

The prospective impacts can be grouped as follows:

1. users - by location within the region, by trip purpose and by socio-economic group; examples: suburban resident commuting to central city job; low-income non-car-owning resident of center city traveling to health facilities;
2. operators - by mode by link; examples: air carrier, trucker, highway maintenance agency, port authority, toll bridge operator;
3. physical - by type of impact, by link; examples: families, jobs, taxable values displaced by new construction; pollution of immediate environment through noise, fumes, air pollution, and ground water changes;
4. functional - by location within region, by type; examples: changes in retail sales areas of shopping center; changes in production costs; changes in land values;
5. governmental - by location, by level; examples: local¹ state, national representatives; citizen groups.

An essential characteristic of transportation is the differential incidence of its impacts. Some groups will gain from any transportation

¹For alternative typologies see Kanwit, Edmond L., "Some Aspects of the Social Impact of Urban Transportation;" Edwin N. Thomas and Joseph L. Schofer, "Information Requirements for Evaluating the Social Impacts of Transportation Investments;" Nash, William W., Jr., "Disaggregative Impact Studies: their potential use in transport decisions," TRANSPORTATION: A SERVICE, New York: New York Academy of Sciences (1968).

system change; others may lose. Therefore, transportation choices are essentially socio-political choices: the interests of different groups must be balanced.

5.0 Prediction: basic concepts

Any proposed change in a transportation system (or a completely new system), can be expressed in terms of the options identified above. The problem of prediction is to anticipate the impacts which a particular proposal will have: that is, we need procedures for predicting the impacts associated with any sets of options. (Figure II-1). In transportation, the impacts depend upon the pattern of flows in the network which will result from the particular set of options.

The core of the transportation analysis problem is the prediction of network flows: specification of the transportation system T and the activity system A implies the pattern of flows F . Once the options with respect to transportation and the activity system are specified, the flows in the system are a consequence of those options. Prediction of these flows is necessary for evaluation of the impacts.

The general framework for the prediction of network flows is that of the equilibrium between supply and demand.¹ All the transportation system options, T , can be expressed in a set of "supply functions," S ; all the non-transportation options, A , in a set of "demand functions," D . Then, within the constraints of the transportation channels specified

¹Wohl, Martin, and Brian V. Martin, *TRAFFIC SYSTEM ANALYSIS FOR ENGINEERS AND PLANNERS*, New York: McGraw-Hill (1967); Hershdorfer, Alan, "Predicting the Equilibrium of Supply and Demand: Location Theory and Transportation Flow Models," *PAPERS SEVENTH ANNUAL MEETING, Transportation Research Forum* (1966); Manheim, Marvin L., "Principles of Transport Systems Analysis," *loc. cit.*; Beckmann, Martin, "On the Theory of Traffic Flow in Networks," *TRAFFIC QUARTERLY* (January 1967); Jewell, V. S., "Models for Traffic Assignment," *TRANSPORTATION RESEARCH* 1:1 (1967); Nelson, James R., "Pricing Transport Services," in Gary Fromm, (ed.), *TRANSPORT INVESTMENT AND ECONOMIC DEVELOPMENT*, Washington D.C.: The Brookings Institute (1965); Heflebower, Richard B., "Characteristics of Transport Modes," in Fromm, *op. cit.*

THE PREDICTION PROBLEM:

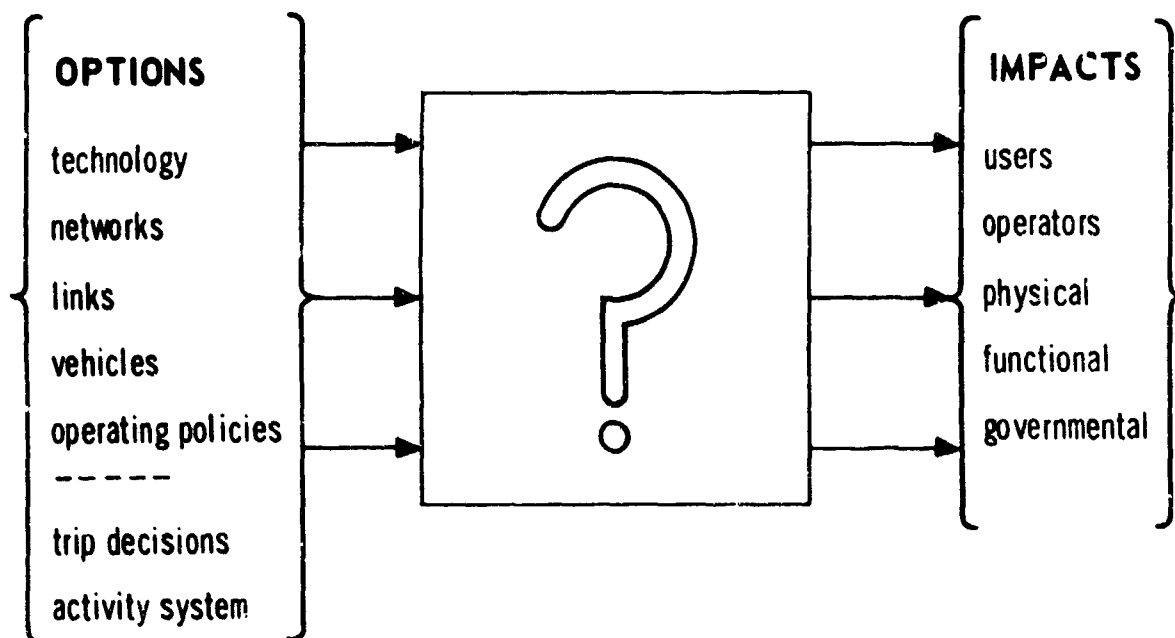


Figure II-1: The Prediction Problem

as part of T , the equilibrium of S and D is a pattern of flows, F . The elements of this pattern, F , are the volumes and characteristics of the flows over each link of the transportation network: what flows over a link, from what origin zones, to what destination zones, at what speed, cost, etc.

The key concept allowing this formulation to be workable is that of a vector, L , of "service" variables. The level of service, L , which a particular set of transportation facilities provides can be expressed in terms of travel time (mean and variance), trip costs (fares and other out-of-pocket costs, as well as indirect costs such as car ownership), safety, comfort (real and psychological) and other characteristics. These service variables both characterize the transportation system, and serve as the basis for the demands for transportation.¹

The general structure of this analysis problem can be expressed concisely:²

1. Definition of variables:

T = specification of transportation system, in terms of full set of options.

A = specification of activity system (including exogenous characteristics).

L = service characteristics of a particular flow or set of flows.

V = volume of flows

¹The difference between perceived and actual service characteristics may be large and significant. Here, we shall make no distinction. Cf. Wohl and Martin, op. cit.

²These variables are all vectors, matrices, or n -dimensional arrays.

F = pattern of flows in the system = (L, V)

2. Supply functions:

$$L = S(T, V)$$

3. Demand functions:

$$V = D(A, L)$$

4. Equilibrium:

$$\begin{cases} L = S(T, V) \\ V = D(A, L) \end{cases} \rightarrow (V_o, L_o)$$

i. e.

$$(T, A) \rightarrow F = (V, L)$$

In words: the level of service (L) which the transportation system supplies is a function (S) of the transportation options (T) and the volume of flow (V). The volume of flow desiring transportation is a function (D) of the activity system options (A) and the level of service (L). The pattern of flows (F) consists of the volumes and the service levels experienced by those volumes. The flow pattern which will actually occur for given (T, A) is the equilibrium solution to the supply and demand relations (2) and (3).

The graphical interpretation of this formulation is shown in Figure II-2, Simple Equilibrium. In this figure V and L are assumed one-dimensional. Specification of T and A implies supply and demand functions S and D . These in turn imply an equilibrium flow pattern F , comprising a volume V , and trip cost, or "negative" level of service, L_o .

The value of this formulation is illustrated by Figure II-3, System Improvement. S_o is the supply function of the previous system, with

EQUILIBRIUM

$$\begin{array}{lcl}
 T \Rightarrow L = S(V, T) & \Rightarrow & F = (V_0, L_0) \\
 A \Rightarrow V = D(L, A) & &
 \end{array}$$

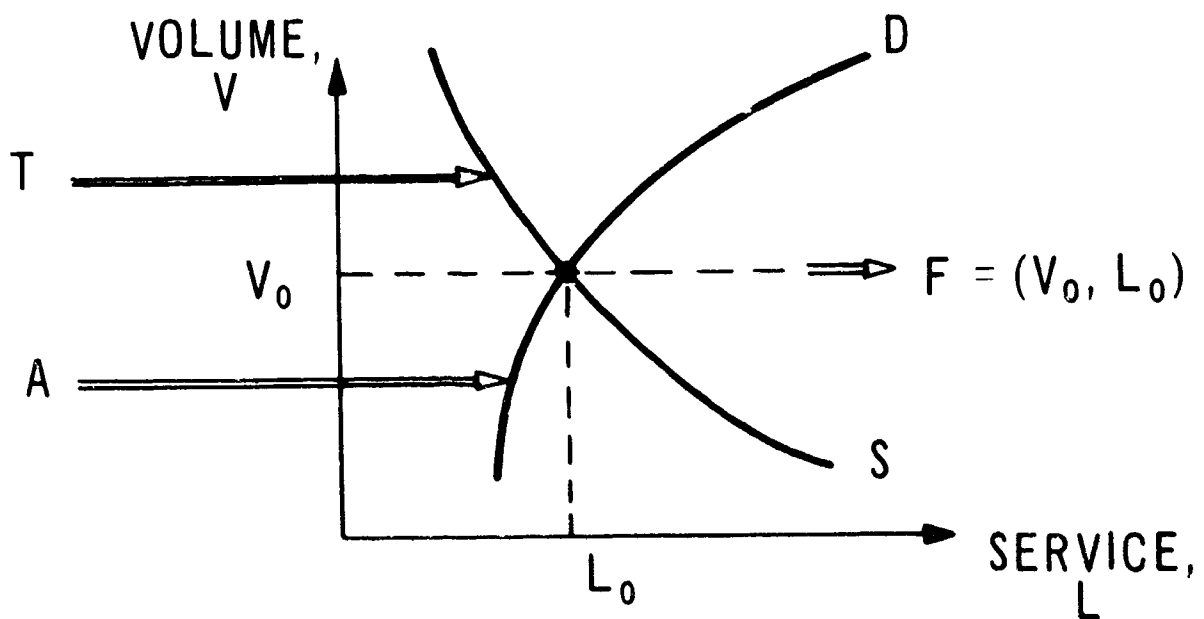


Figure II-2: Simple Equilibrium

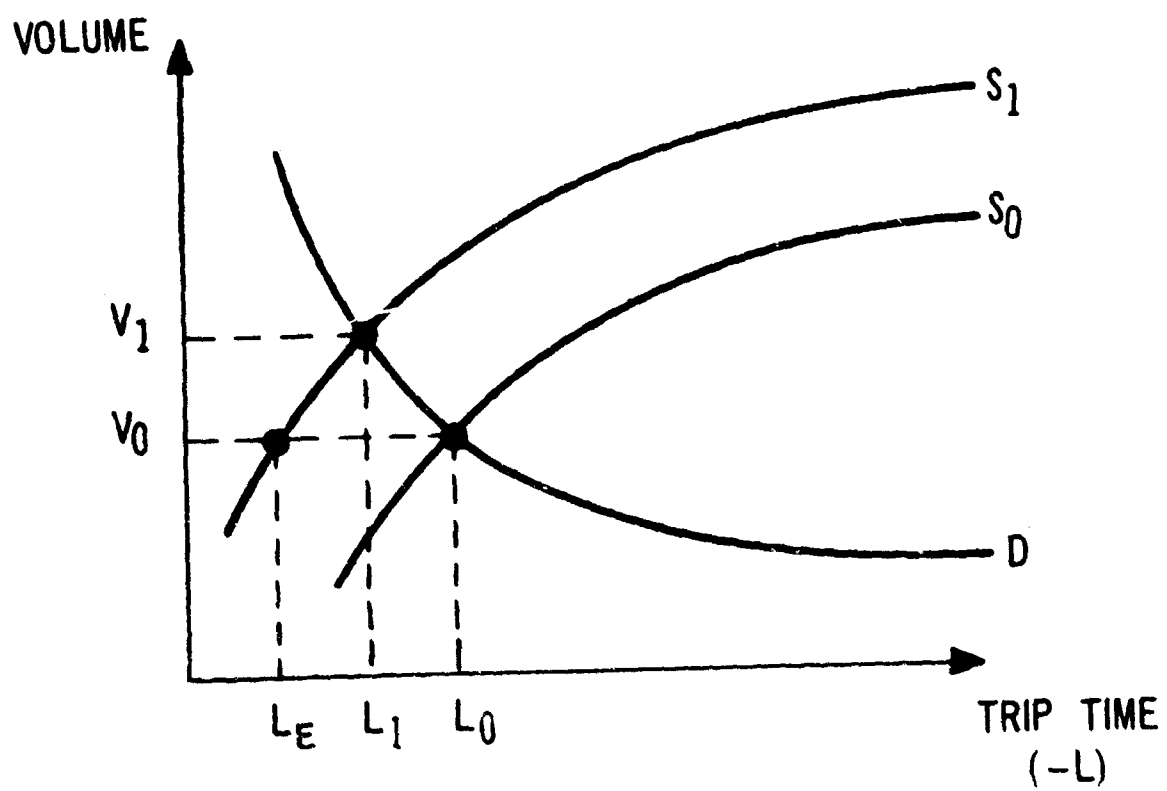


Figure II-3: System Improvement

corresponding equilibrium flow pattern $F_0 = (V_0, L_0)$. Consider a possible improved system, S_1 . If we assume the existing volume of travel, V_0 , will occur on the new system as on the previous, we would anticipate a service level L_e , i.e., a lower trip time because of the improved facility. However, assuming a constant volume level is erroneous, for the travel volume will increase because of the increased level of service (decreased trip time). The extent of this increase in travel is given by the demand function, D . Thus, the actual flow pattern resulting will be that given by the equilibrium of D and S_1 : $F = (V_1, L_1)$. That is, the traffic volume will increase, and the level of service will be intermediate between L_0 and L_e .¹

The prediction of flows in a network is based, in principle, on this theory of equilibrium between supply and demand. In practice, prediction of equilibrium flows in networks is generally difficult and expensive; and as discussed below, most present techniques for predicting network flows leave much to be desired.

The major, but by no means only, difficulty in translating this conceptual framework into practice is the role of the network in constraining the equilibrium flow pattern:²

¹Of course, since it takes time to implement transportation system improvements and population and travel continues to increase, the demand curve D may meanwhile have shifted upward and to the right. Thus, the new equilibrium (V_1, L_1) may actually occur such that L_1 is greater than L_0 : the level of service over the new system is actually more than the level of service over the previous system at the initial period, but it is better than the level of service which would have resulted from the old supply function and the new shifted demand function.

²Cf. especially Beckmann; Jewell; Horshdorfer, *op. cit.* Also, Schwartz, Jesse G., NETWORK FLOW AND SYNTHESIS MODELS FOR TRANSPORTATION PLANNING: A SURVEY, Research Report R68-49, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1968), Volume X in a series.

1. Multiple demand functions - The area to be studied is divided into zones; there is a different demand function for each pair of zones (origin and destination), for different groups of prospective trip-makers, and for different trip purposes (passengers) or commodity types (freight). Further, the demand for transportation between each zone pair is a function of the level of service vector, not a single "price."

2. Multiple supply functions - Each link of the network is represented by a different supply function. Note that because L is generally a vector with time, cost, safety, etc., as components, both the supply and demand functions are potentially very complex.

3. Finding the equilibrium pattern of flows - Instead of a simple graphical exercise, the calculation of the equilibrium flows is a difficult problem. Some of the conceptual and computational difficulties are:

- a. the level of service perceived by a trip between two zones depends upon which path is taken through the network;
- b. the level of service over any path is a function of the level of service over each of the links in that path (e.g. trip time equals the sum of the times over each link in the path);
- c. the level of service over a link is a function of the total volume over that link (as given by that link's supply function);
- d. the total volume over a link is composed, in general, of flows between many different zone pairs;
- e. the equilibrium flow pattern is not unique; a mechanism of trip behavior must be assumed in order to determine a unique

equilibrium.¹

- f. the actual computational procedures may be difficult and expensive.

¹One set of assumptions leads to the traffic assignment approach of urban transportation studies; other types of assumptions lead to various mathematical programming formulations. See references cited in previous footnote. For examples of computational assumptions, see: Ruiter, Earl R., A PROTOTYPE ANALYSIS, Research Report R68-41, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume II of a Series.

5.1 Note on terminology

The use of the term 'supply functions' should be explained. In economic theory, supply function is usually defined as the relationship between selling price and the volume of output that would be offered at any given price. This led to the use by Wohl¹ of the price-volume curve, indicating the price perceived by the user of a highway link as a function of the volume of users over that link. In general, however, price is not a sufficient indicator of what a user perceives, as indicated by our stress on L , level of service, as a vector. The traditional usage of supply curves looks at the individual firm (or groups of firms) as an actor operating according to his own internal logic. In this view, the external observer is solely concerned with trying to identify the volume that would be offered as a function of some externally given price, where that price is determined in the marketplace or through some other mechanisms.

We do not want to assume away the logic of that decision of what volume to offer. Rather, we want to break out the decision variables which are within the control of the firm and include those in our vector of options. Thus, for a carrier, the question of fare and schedule may, actually, be internally-determined decisions based upon maximizing net revenue (or some other criterion.) However, from our point of view as system analysts, we do not want to assume we know that decision rule, but want to be able to vary those options - schedule frequency

¹ Wohl and Martin, *op. cit.*, section 5.4.1

and fare - explicitly. That is, we want to deal with the full vector of options explicitly, regardless of which actors have control over particular subsets of options. Then, we are in a position to try to identify those options which are within the control of that particular agency or firm for whom we are doing the analysis, and anticipate how the other options will be manipulated by the actors who have control over these other options. As we may be able to influence those decisions of other actors directly or indirectly, it is important that we not subsume the decision-making logic of each of these actors into our predictive models. Therefore, we have chosen to keep all of the decision options external to the prediction process, and have developed the usage of the supply function as indicated.

The question may well be asked, why continue to call this a supply function if it does in fact depart from the traditional economic notion? The answer is - that this function still plays the role of indicating the relationship between service and volume which will influence consumer behavior in the marketplace - it does give a supply relationship which will interact with demand functions in determining market equilibrium. However, it is important to realize that the production process is thus represented by two functional relationships: the supply function or level of service as a function of volume; and the resources function, which gives costs or resources consumed (land, labor, capital, etc.) as a function of volume, both conditional on specification of the nature of the production process - that is the transportation options, T.

6.0 Prediction Models

To fully implement this analysis approach, five major types of models are required:¹

1. supply models - to determine for any specified setting of the options what the level of service will be for various flow volumes. Examples: travel time over a rail link as a function of train length, schedule frequency, roadway, etc., and volume of passengers; volume-travel time curves as used in traffic assignment procedures.
2. resource models - to determine the resources consumed - land, labor, capital - in providing a particular level of service with specified options.
3. demand models - to determine the volume of travel demanded, and its composition, at various levels of service.
4. network equilibrium analysis - to predict the volumes that will actually flow in a network for a particular set of supply and demand functions; short-term equilibrium.
5. demand shift models - to predict the long-term changes in the spatial distribution and structure of the activity system as a consequence of the short-run equilibrium pattern of flows - the "feedback" effect of transportation on land use.

These five are the basic prediction models in transportation. The interrelationships among them are illustrated in Figure II-4.

This structuring of the transportation systems analysis problem incorporates several hypotheses. The first hypothesis is that this is a

¹The assistance of A. S. Lang in the initial development of this typology (August, 1964) is gratefully acknowledged.

BASIC PREDICTION MODELS

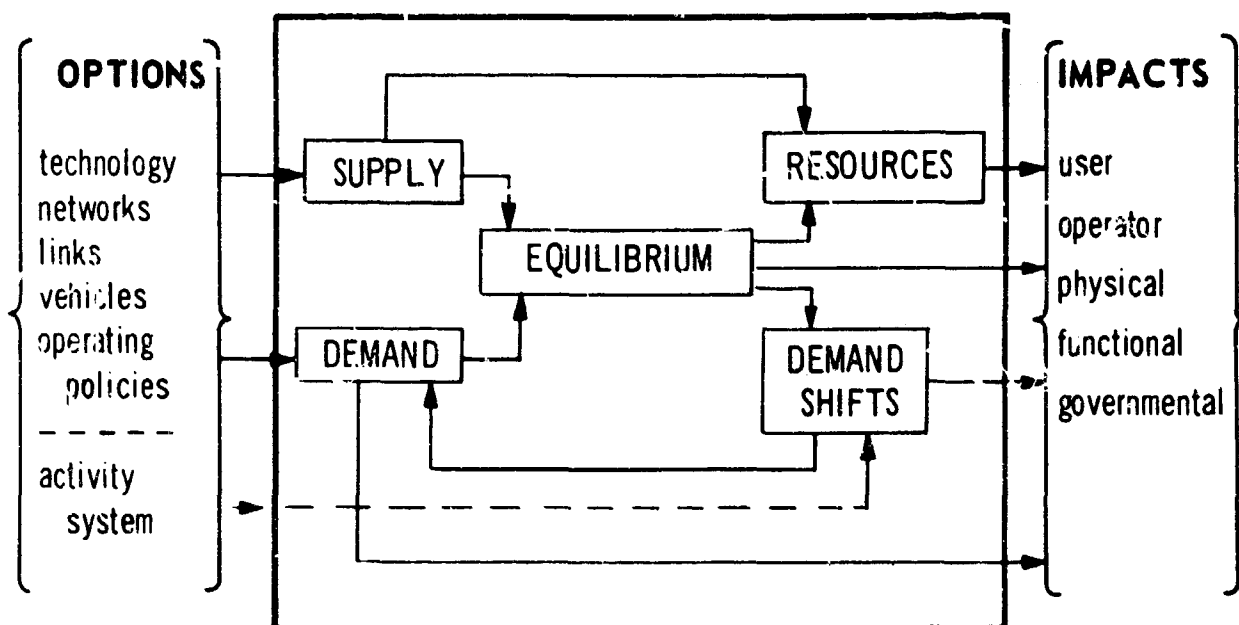


Figure II-4

complete and useful summary of the types of options and impacts. The second hypothesis is that it is meaningful to model transportation technology from two perspectives: in terms of the service perceived by prospective users, the "supply" functions; and in terms of the resources consumed in providing that transportation service - the resource functions.¹ The third hypothesis is that it is useful to separate short-term and long-term equilibrium: the short-term responses of transportation users, in a "transportation market" with the activity system fixed, as represented by the demand functions; and the long-term responses of users and others in a larger, more general market, the total economy, as represented by the demand shifts. The fourth hypothesis, which in a sense is the operational test of the second and third hypotheses, is that valid predictive models can indeed be constructed.

At present, in addition to the modest set of models developed at M.I.T. for the Prototype Analysis,² there are several transportation systems analysis activities in which this framework is being applied, implicitly if not explicitly. Three major areas are:

1. urban transportation planning
2. Northeast Corridor Project
3. Harvard Transport Research Program.

The prediction portion of the urban transportation planning process, as it has been established in almost all of the metropolitan areas of the United States, consists of variants of the following

¹Cf. next section.

² See Chapter III, Ruiter, op. cit.

sequence:¹

1. project land use, population and employment changes;
2. predict trip ends generated in each zone;
3. predict interzonal distribution of trip ends (e.g., using gravity or opportunity models);
4. predict modal split;
5. predict distribution of flows over the proposed network.

As pointed out by Wohl and Martin; Deen; and others,² there are serious internal inconsistencies in this sequence of steps, from the point of view of an equilibrium analysis. For example, the estimation of trip ends assumes implicitly a general level of service in the system, and a level of service is assumed explicitly for input to the interzonal distribution calculations (e.g., using a gravity model). The last step of the process, traffic assignment, predicts an "actual" level of service, or set of travel times, for flows in the network. However, the initial estimates of level of service used for trip generation and distribution are rarely revised to be consistent with the travel times which are predicted by the traffic assignment.

In spite of these inconsistencies, and other limitations, the structure implicit in urban transportation planning is fundamentally that of the supply-demand equilibrium framework. The supply functions

¹Martin, Brian V., F. W. Memmott, and A. J. Bone, PRINCIPLES AND TECHNIQUES OF PREDICTING FUTURE DEMAND FOR URBAN AREA TRANSPORTATION, M.I.T. Report No. 3, Cambridge, Mass: M.I.T. Press, 1961

²Wohl and Martin, *op. cit.*; Deen, Thomas B., "Discussion on papers by Campbell and George," paper presented at 47th Annual Meeting of the Highway Research Board, Washington, D.C., 1968; Tanner, J. C., "Traffic Generation and Forecasting," TRAFFIC ENGINEERING AND CONTROL, 8:3 (July 1966), pp. 164-165.

are represented as volume-travel time functions, or simply link capacities and travel times. The demand functions are represented by the sequence of predicting trip ends, interzonal distribution of trips and modal split. The network equilibrium model is the "traffic assignment" process, with the various "capacity restraint" formulations representing explicit attempts to find equilibrium in the network, given fixed demands. (All-or-nothing assignments are obviously very difficult to justify as a meaningful prediction of "equilibrium" flows.) The resource requirements models are represented in a variety of ad hoc calculations: right-of-way, construction and operating costs, etc. Demand shifts models are sometimes explicit, as when land use models are used to predict the effects of differential changes in accessibilities on the location of population and economic activities.

Perhaps one of the most significant needs in urban transportation planning is to revise the models and procedures to incorporate the equilibrium approach more explicitly. The present procedures represent a series of ad-hoc approximations, as a pragmatic approach to the problem of predicting flows in networks. A new generation of urban transportation models should be developed, on the sounder theoretical basis of explicit supply-demand equilibrium analysis.

In the Northeast Corridor Transportation project's system of models, this equilibrium structure is more explicit. Although not yet fully operational, this system of models is described in several documents.¹ There are explicit demand models for passengers and

¹Bruck, H. W., Marvin L. Manheim, and Paul W. Shuldiner, "Transport Systems Planning as a Process: The Northeast Corridor Example," PROCEEDINGS OF THE TRANSPORTATION RESEARCH FORUM, 1967; Technical Paper No. 5, "Study Design," Northeast Corridor Project, June 1966; various unpublished documents.

freight;¹ technology models to produce supply and resource functions; a network simulator to predict network equilibrium (although it is not yet clear whether this will be a consistent equilibrium - i.e. something other than all-or-nothing), and demand shift models for forecasting changes in interregional and intraregional location and intensities of economic activities as a function of changes in transportation and other factors.²

The Harvard Transport Research Program models are designed for use in planning investment in transportation in developing countries.³ Several explicit technology models are used for predicting cost-service characteristics of highways, rail, and intermodal transfer points. Demand is derived from a macro-economic model, containing an inter-regional input-out model; these are also used to predict demand shifts. Network equilibrium is found with a modified traffic assignment approach.

These are very cursory descriptions of highly sophisticated systems of models; they simply point out how the basic framework outlined above underlies several major transportation analysis efforts. Yet, in spite of the magnitude of effort which has gone into development of the model systems described, there are still major difficulties with implementing this framework in a thoroughly satisfactory way. Constructing

¹ Quandt, R. E., and W. J. Baumol, "Abstract Mode Model: Theory and Measurement", J. REGIONAL SCIENCE 6:2 (1966).

² Bruck, H. W., Stephen H. Pu'nan, and Wilbur A. Steger, "Evaluation of Alternative Transportation Proposals: The Northeast Corridor," J. AMERICAN INSTITUTE OF PLANNERS 32:322-333, November 1966.

³ Roberts, Paul O., and David T. Kresge, MODELS FOR TRANSPORT SYSTEM SIMULATION, Discussion Paper No. 65, Cambridge, Massachusetts: Harvard University and the Brookings Institution (November 1967).

demand models is always difficult, particularly because of the lack of good data for model calibration, as was demonstrated in Plourde's efforts to test the Baumol-Quandt model for metropolitan travel.¹

The understanding of the structure of transportation supply functions and resource requirements models, particularly with respect to basically new technologies, is very elementary and many difficult problems remain.² The problem of computing supply - demand equilibrium in networks was described above. There is a significant amount of effort underway in exploring various computational approaches to this problem, ranging from simulation approaches to mathematical optimization

¹Plourde, Rodney, CONSUMER PREFERENCES AND THE ABSTRACT MODE MODEL, Research Report R68-51, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1968), Volume XII in a Series. See further: Kraft, Gerald, and Martin Wohl, "New Directions for Passenger Demand Analysis and Forecasting," TRANSPORTATION RESEARCH 1:3 (1967); Baumol and Quandt, loc. cit.; Soberman, Richard M., "Approaches to Regional Transportation Models," PROCEEDINGS SEVENTH ANNUAL MEETING, TRANSPORTATION RESEARCH FORUM (1966), pp. 357-366; Martin, Memmott and Bone, loc. cit.

²Stafford, Joseph H., and J. C. Prokopy, PRODUCTION FUNCTIONS: MODELS OF TRANSPORT TECHNOLOGY, Research Report R68-45, Cambridge, Mass.: M.I.T. (1968) Volume VI of a series; Hay, William W., AN INTRODUCTION TO TRANSPORTATION ENGINEERING, New York: John Wiley and Sons (1961); Heflebower, Richard B., "Characteristics of Transport Modes", in Gary Fromm (ed.), TRANSPORT INVESTMENT AND ECONOMIC DEVELOPMENT, Washington, D. C.: The Brookings Institution (1965); Meyer, John R., M. J. Peck, J. Stenason, and C. Zwick, THE ECONOMICS OF COMPETITION IN THE TRANSPORTATION INDUSTRIES, Cambridge, Mass.: Harvard University Press (1960); Soberman, Richard M., TRANSPORTATION TECHNOLOGY FOR DEVELOPING REGIONS, Cambridge, Mass. M.I.T. Press (1967); Spiegelberg, C. H., et al, EVALUATION STUDY OF TRANSPORT VEHICLES, Report No. D6-2067, Renton, Washington: The Boeing Company (1964); Morlok, Edward K., AN ANALYSIS OF TRANSPORT TECHNOLOGY AND NETWORK STRUCTURE, Unpublished Ph.D. Dissertation, Northwestern University (June 1967); Lang, A Scheffer, and Richard M. Soberman, URBAN RAIL TRANSIT, Cambridge, Mass.: M.I.T. Press (1964); Meyer, John R. J. F. Kain, and M. Wohl, THE URBAN TRANSPORTATION PROBLEM, Cambridge, Mass.: Harvard University Press (1965).

applications for certain special cases.¹ The problems become even more complex when equilibrium is to be determined for multiple time periods, where vehicle schedules may be adjusted to meet the transient fluctuations in demand.²

To predict demand shifts, that is, changes in land use, population, and the structure of social and economic activity generally, is perhaps the most difficult problem of all. This requires, not only understanding the basic structure of the social and economic system and the influence of a variety of policy levers on that system, but also identifying the specific role of transportation in modifying growth patterns. Even in urban land use model development, an area of significant activity in the past, there is still a great gap between what would be desirable in terms of land use prediction models and what has actually been implemented³.

¹Beckmann; Jewell; Hershdorfer; Schwartz; op. cit.

²Devanney, J.W., III, TRANSPORTATION SCHEDULING UNDER MULTI-DIMENSIONAL DEMAND LEVELS, Sc.D. Thesis, M.I.T., 1967

³Hemmens, George C., (editor), URBAN DEVELOPMENT MODELS, Special Report 97, Washington, D. C.: Highway Research Board (1968). See also Roberts and Kresge, op cit.; Bruck, Putman, and Steger, op. cit.

7.0 The Problem of Search and Choice

The system of basic models discussed in the preceding section is the core of the analysis problem, but not the whole of it. The framework of equilibrium analysis provides a basis for prediction of the impacts associated with a particular set of options. However, there still remain several major issues:

1. The problem of search - how to generate a set of options in the first place - that is, how to formulate a complete, meaningful, well-specified transportation system strategy, which is worth "testing" in the complex system of prediction models.

2. The problem of choice - given the predicted impacts of several alternative specifications of options, how to evaluate the impacts and choose among the alternatives. The difficulties in choice arise because an essential characteristic of transportation is the differential incidence of its impacts. Some groups will gain from any transportation system change; others may lose. In a realistic network context, there are many user, operator, and other groups, and the interactions among them are complex.

Therefore, transportation choices are essentially socio-political choices: the interests of different groups must be balanced.¹ The

¹This does not mean that negative impacts of a system on some group are inevitable. It may well be possible, particularly with complementary programs, such as relocation subsidies, industrial development, job training, etc., to develop a concerted strategy such that no single group is hurt unduly. But to do this requires careful, sensitive analysis of the transportation alternatives and their impacts; and imaginative coordination of transportation and non-transportation options.

development of a real-world, implementable transportation plan or policy requires more than just the prediction of impacts of one or two alternatives. Feasible, desirable solutions can be developed only through a careful and sensitive analysis, in a systematic way, of a variety of alternatives and their impacts.

Systematic analysis in transportation requires that a wide variety of alternative options be explored, and their differential impacts traced out explicitly. In figures II-5 and II-6, we illustrate the systematic exploration of the range of options for a single link. We assume that this link is of sufficient length and importance that we in fact have the full range of decision options open to us. We can choose alternative technologies for this link - for example, mass transit, highway, automatic bus on separate right-of-way or some new technology. We can change the network configuration in this area, introducing several links to supplement this one or change the relationship of this link with other links by adding or eliminating intersections between links. We can change the characteristics of the link itself by changing its physical location, widening it, etc. We also have options regarding the number and type of vehicles which will run over this link, as well as speeds, schedules, stopping times, fares etc.

Changes in this particular link will impact differently on each of the groups shown in the figure. In particular, we have identified several user groups - AB and CD, as well as the group of all other users; the operator of this particular facility, the operators of all other facilities, and the physical and functional impacts. In figure 6, we show how changes in the options for this particular link, as reflected solely in speed over

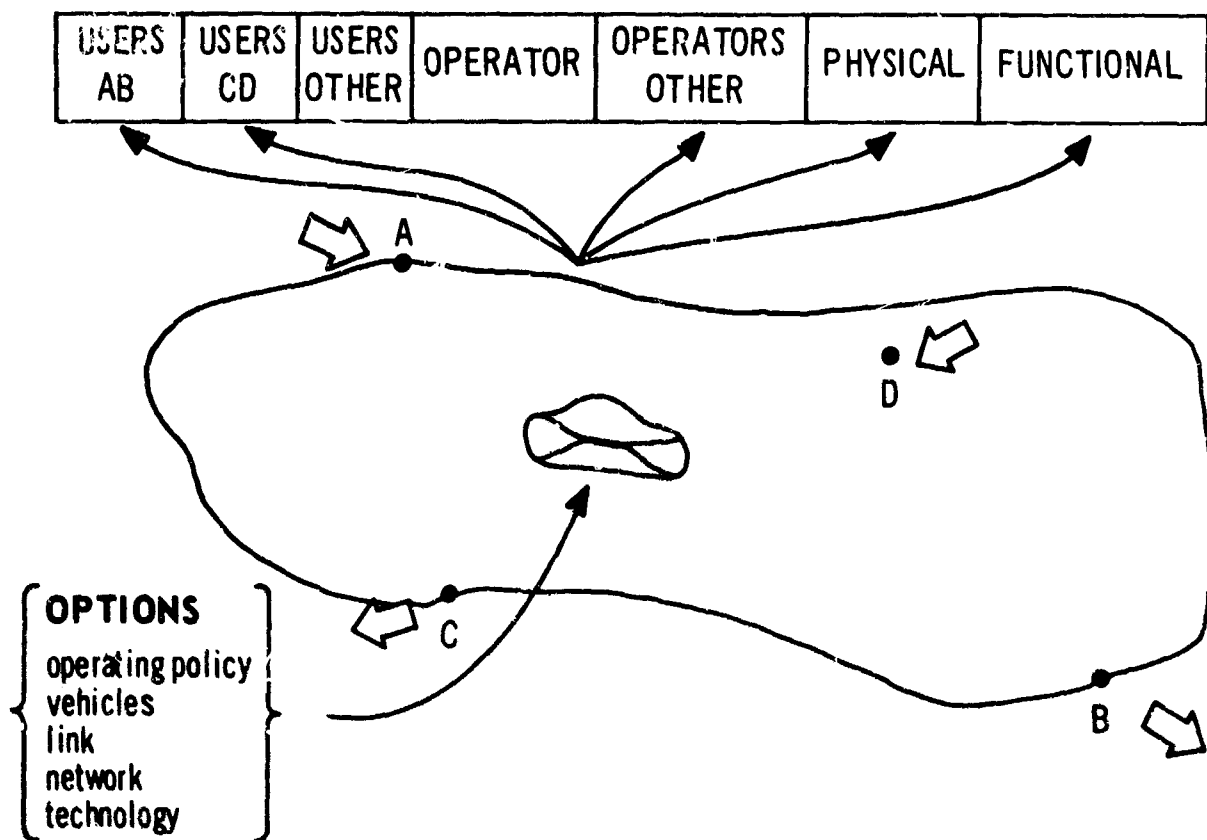


Figure II-5: Changes in a network

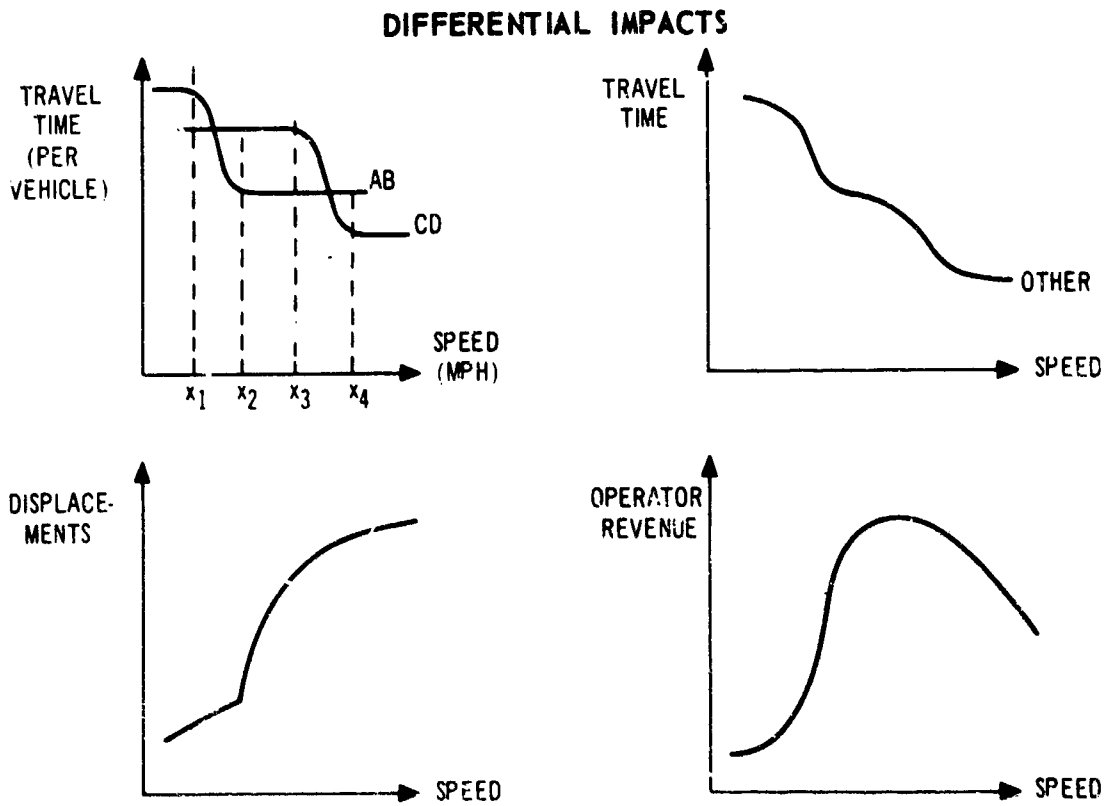


Figure II-6

the link, might impact differentially on the various actors. (This is hypothetical; the actual variations would be a property of the network at hand.)

We may have already examined a particular set of options, and thus know its impact on each of the actors. However, in general, we are very uncertain about the changes in these impacts which will occur if we make relatively small changes in these options. This is precisely because of the complexity of the supply-demand interactions in the network.

This is the real difficulty in analysis of a large, complex, multi-mode transportation system, such as that of the Northeast Corridor region (Boston to Washington, D. C.). Instead of changes to just one link, we have a potential of changes to, or introduction of, a very large number of links--interstate highways, other highways, conventional jet aircraft routes, V/STOL routes, and new high-speed ground transportation systems, such as tube trains or tracked air-cushion vehicle systems. Furthermore, we are concerned with the impacts on a correspondingly very large number of groups. Clearly, it is not a trivial problem to identify the set of options which has the most desired impacts.

What is required is a systematic exploration of the options, carefully tracing out the differential impacts on each group. The set of prediction models serves as a vehicle for assisting in this; but additional techniques are required. Procedures are required for systematically searching out and choosing among transportation alternatives, in order to develop equitable transportation system changes which explicitly recognize the differential incidence of impacts.

8.0 A Simple Model¹

To demonstrate concisely the essential issues in an equilibrium analysis, a very simple model of transportation will be described. This model illustrates the following:

- a. representation of the options by explicit variables
- b. explicit representation of differential impacts
- c. the relationships between options and impacts
- d. the level of service vector, and its relation to the options
- e. explicit equilibrium formulation
- f. the resource requirements vector, and its relation to options and impacts.

To show these issues in the simplest possible way, network effects are ignored - we assume a simple link. As with all other aspects of this model, this simplifying assumption can be relaxed.

8.1 Approach

The structure of this model is based upon visualizing transportation as a "production process", in which alternative

¹An early version of this model was circulated in June 1968 as unpublished discussion paper T-35; later versions, relaxing the various assumptions, are in process. Initiation of this model was stimulated by the work of Franz Frisch. The contributions of Joseph H. Stafford and Karl Guenther to later refinements are gratefully acknowledged. Stafford has proposed an alternative formulation, cf. Stafford and Prokopy, PRODUCTION FUNCTIONS: MODELS OF TRANSPORT TECHNOLOGY, op. cit. The general approach of the present development was influenced by lectures and notes of Ernst Frankel, and Robert Simpson; and by the work of Morlok, Lang and Soberman; and Wohl. Cf. Morlok, Edward K., AN ANALYSIS OF TRANSPORT TECHNOLOGY AND NETWORK STRUCTURE, Unpublished Ph.D. dissertation, Northwestern University (June 1967); Lang, A. Scheffer, and Richard M. Soberman, URBAN RAIL TRANSIT, Cambridge, Mass: M.I.T. Press (1964); Meyer, John R., J. F. Kain, and M. Wohl, THE URBAN TRANSPORTATION PROBLEM, Cambridge, Mass: Harvard University Press (1965), Especially pp. 271-295. See also bibliography in Morlok.

combinations of resources can be applied to produce transportation.

We characterize transportation by a production function ϕ in this way:

$$\phi(C, L, V, T) = 0$$

where: T = specification of transportation options

V = volume of flows actually moving through the system

L = level of service provided by the system to passengers and/or freight moving through it

C = resources consumed - "costs" incurred in providing and operating the transportation system

In general, each of these variables is vector-valued: it has many components. The options T include specification of technology type, network configuration, link and vehicle characteristics, operating procedures, pricing, etc. The volume V may include mix of flows by type - passengers, heavy cargo, light cargo, etc. The level of service L includes trip time, waiting time, reliability, out-of-pocket costs, etc. The resources consumed C include land, fuel, labor, construction materials, etc.

The function ϕ describes a surface in (C, L, V) space, for given T . That is, if we specify certain "design" characteristics of the system (the options T), then as a function of the volume of flows V through the system, we want to be able to trace out the resources consumed, C , and the service provided to users, L . Although C and L are both "outputs" of the system,¹ we distinguish L as that set of characteristics of the system which, perceived by the users, influence their demand for transportation. That is, the demand $V = D(L, A)$, where A is a description of the socio-economic pattern of activities.

¹See Nerlove.

To emphasize this, we may write, instead of ϕ , the following:

$$\phi(C, L, V, T) = 0 \quad \Longleftrightarrow \quad \begin{cases} L = S(V, T) \\ C = R(V, T) \end{cases}$$

That is, we separate out the "resources consumed" and the "service provided" components of ϕ , by distinguishing a "supply" function S and a "resources" function R .

Once we can characterize transportation in this way, we are ready to make two further steps. First, in recognition of the equilibrium context, we introduce Demand, Network Equilibrium, and Demand Shift models. Second, we recognize that we are concerned with the impacts of these options on a variety of actors: users of the system, operators, etc. Thus, our objectives are to characterize technology in such a way that we can trace out, in a network equilibrium context, how impacts among different actors vary as we vary the options T .

8.2 Transportation Options, T :

Consider the following components of the vector of options T :

NETWORK AND LINKS:

- CAPF = capacity of fixed facilities in vehicles per hour (two-way)
 DIST = distance in miles between the two points served

VEHICLES:

- VAVG = vehicle cruise speed in miles per hour
 PLOAD = payload of vehicle (passengers or tons)
 NVEH = no. of vehicles in the system

OPERATING:

- FARE = fare charged to user per trip

SUBS	= government subsidy to operator	\$/hr.
TAX	= user tax rate,	\$/passenger
TECHNOLOGY:		
CFFIX	= fixed costs of fixed facilities	\$/mile/hr ¹
CVFIX	= variable costs of fixed facilities	\$/vehicle/mile/hr.
CFVEH	= fixed costs of vehicles,	\$/vehicle/hr.
CVVEH	= variable costs of vehicles	\$/vehicle/mile/hr.
CCAP	= fixed costs of fixed facilities per unit of capacity	\$/mi./hr per vehicle/hr.

That is, in this simple model, to specify a particular transportation system we specify $\underline{T} = (\text{CAPF, DIST, VAVG, PLOAD, FARE, SUBS, TAX; CFFIX, CFVEH, CVVEH, CCAP.})^2$

8.3 Level of Service, L

The characteristics of the system which will influence demand for transportation are:

TTRIP = total trip time

TWAIT = average wait time - time spent waiting for a vehicle to arrive

FARE = fare paid by user

That is, $\underline{L} = (\text{TTRIP, TWAIT, FARE}).$

¹ All costs are assumed brought back to present worth in \$/hr. considering interest, life, salvage value, time streams, etc.

² Ultimately, we should be able to derive the cost variables (CFFIX, etc.) and other parameters as explicit functions of some basic technology parameters.

8.4 Resources Consumed, C

The resources consumed can be expressed, we assume, as dollar costs:

CFTOT = total fixed costs (\$/hr.)

CVTOT = total variable costs (\$/hr.)

CTOT = total costs (\$/hr.)

That is, $\underline{C} = (CFTOT, CVTOT, CTOT)$

8.5 Basic Relationships

The structure of the model can now be established. In this simple model, we assume all vehicles operate continuously in cycling at uniform headway over the single link.

NTRIP = number of vehicle round trips per hour

TIME = vehicle trip time, one-way

VAVAIL = available volume (available "capacity")

$$(1) \text{ TIME} = \text{DIST}/\text{VAVG}$$

$$(2) \text{ NTRIP} = ((\text{NVEH} \cdot \text{VAVG}) / (2 \cdot \text{DIST})) \leq \text{CAPF}$$

or

$$(3) \text{ NVEH} \leq (2 \cdot \text{CAPF} \cdot \text{DIST} / \text{VAVG})$$

$$(4) \text{ VAVAIL} = (\text{NTRIP} \cdot \text{PLOAD})$$

$$= (\text{NVEH} \cdot \text{VAVG} \cdot \text{PLOAD}) / (2 \cdot \text{DIST})$$

$$\leq (\text{CAPF} \cdot \text{PLOAD})$$

HDWAY = average interval between vehicles

$$(5) \text{ HDWAY} = 1/\text{NTRIP} = (2 \cdot \text{DIST}) / (\text{NVEH} \cdot \text{VAVG})$$

WAIT = expected wait time (assumed one-half the interval between vehicles)

$$(6) \text{ WAIT} = (\text{HDWAY}/2) = (\text{DIST}/\text{NVEH} \cdot \text{VAVG})$$

TTRIP = Total Trip Time

$$(7) \text{ TTRIP} = \text{TIME} + \text{WAIT} = (\text{DIST}/\text{VAVG}) (1 + 1/\text{NVEH})$$

These establish the basic physical relationships of the system, and provide a basis for costing out the resource requirements.

CFTOT = total fixed costs

CVTOT = total variable costs

CTOT = total costs

$$(8) \text{ CFTOT} = (\text{CFFIX} \cdot \text{DIST}) + (\text{CFVEH} \cdot \text{NVEH})$$

$$(9) \text{ CFFIX} = \text{CAPF} \cdot \text{CCAP}$$

$$(10) \text{ CFTOT} = (\text{CAPF} \cdot \text{CCAP} \cdot \text{DIST}) + (\text{CFVEH} \cdot \text{NVEH})$$

$$(11) \text{ CVTOT} = (\text{CVFIX} \cdot 2 \cdot \text{NTRIP} \cdot \text{DIST}) + (\text{CVVEH} \cdot \text{CVVEH} \cdot \text{VAVG}) \\ = (\text{CVFIX} + \text{CVVEH}) (\text{NVEH} \cdot \text{VAVG})$$

$$(12) \text{ CTOT} = \text{CFTOT} + \text{CVTOT}$$

$$= (\text{CAPF} \cdot \text{CCAP} \cdot \text{DIST}) + (\text{CFVEH} \cdot \text{NVEH}) + (\text{NVEH} \cdot \text{VAVG}) (\text{CVVEH} + \text{CVFIX})$$

8.6 Predicting Equilibrium

Let us assume the demand function D is given as $V = D(\underline{L}) = D(\text{TTRIP}, \text{WAIT}, \text{FARE})$. The supply function S , is given by $\underline{L} = S(V, T)$, as derived above. The equilibrium pattern of flows $F = (V, L)$, can be determined from the simultaneous solution of these two relationships. Designate the equilibrium volume, V , as VOL . In this simple model, we assume VOL is specified, independent of L . Further, we assume that the service level L is not affected by VOL - there are no congestion effects; $L = S(V, T)$ becomes $L = S(T)$.¹

¹ This assumption can be relaxed to introduce congestion effects. One way is through a headway-speed-volume relation, developed as in the theory of traffic flow.

LOADF = load factor

$$(13) \text{ LOADF} = \text{VOL} / \text{VAVAIL}, \text{ LOADF} \leq 1$$

$$(14) \text{ LOADF} = (2 \cdot \text{DIST} \cdot \text{VOL}) / (\text{NVEH} \cdot \text{VAVG} \cdot \text{PLOAD})$$

$$(15) \text{ VOL} \leq (\text{CAPF} \cdot \text{PLOAD})$$

8.7 Evaluating Impacts

The user impacts are total travel time, and total fares paid. The impacts on the operator of the system are total fixed costs, and net revenue. The roles of government in supplying transportation are represented through (a) subsidy to operator, in dollars per year(per hour); (b) user tax.²

UTTRIP = user total travel time

$$(16) \text{ UTTRIP} = \text{VOL} \cdot \text{TTRIP}$$

UTFARE = user total fare

$$(17) \text{ UTFARE} = \text{VOL} \cdot \text{FARE}$$

OGROSS = operator gross revenue

$$(18) \text{ OGROSS} = (\text{FARE} - \text{TAX}) \text{VOL}$$

OSUBS = operator gross revenue from government

$$(19) \text{ OSUBS} = \text{SUBS}$$

ONET = operator net revenue

$$(20) \text{ ONET} = \text{OGROSS} + \text{OSUBS} - \text{CTOT} \\ = (\text{FARE} - \text{TAX}) \text{VOL} + \text{SUBS} - \text{CTOT}$$

GTAX = government user tax revenues

²No "indirect" impacts, such as those represented by changes in land use, land values, or commodity prices, are represented here. That is, there is no demand shift model. This assumption can be relaxed.

$$(21) \text{ GTAX} = \text{TAX} \cdot \text{VOL}$$

GSUBS = government subsidy

$$(22) \text{ CNET} = \text{GTAX} - \text{GSUBS}$$

$$(23) \text{ GNET} = (\text{TAX} \cdot \text{VOL}) - \text{SUBS}$$

$$(24) \text{ ONET} = (\text{FARE} \cdot \text{VOL}) - \text{CTOT} - \text{CNET}$$

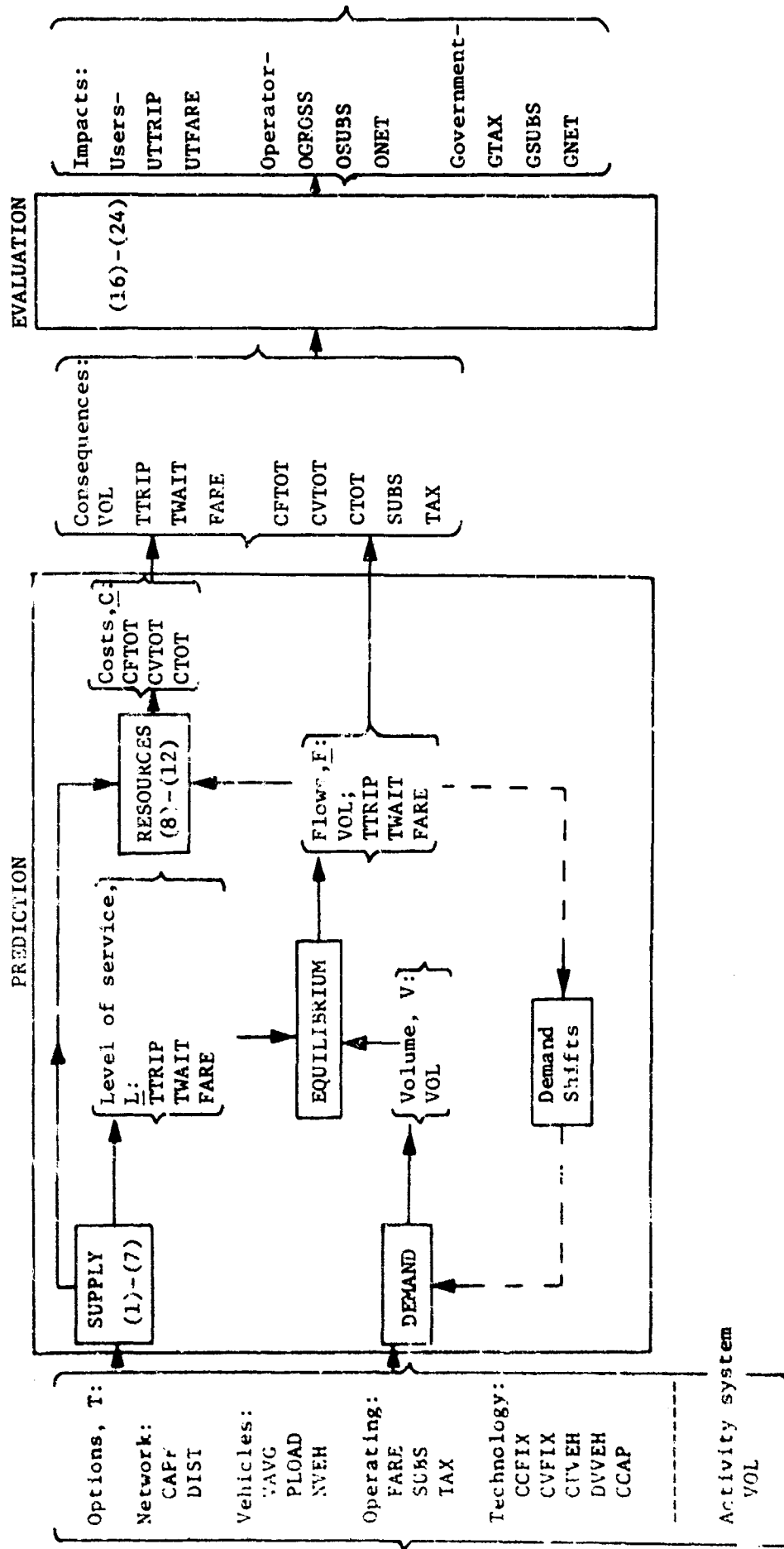
8.8 Discussion

In this simple example, we have described the options, impacts, and prediction and evaluation models. The options include choice of technology (represented by the cost coefficients CCAP, CFVEH, CVFIX, CVVEH); link characteristics (capacity, distance); vehicles (cruise speed, payload, number in system); and operating policy (fare, government subsidy, user tax). For simplicity, the network is assumed to be a single link. Very simple supply, demand, equilibrium, and resource requirement relations are developed. These lead to the prediction of impacts on a variety of groups: operators (fixed cost, variable cost, net revenue); users (total travel time, total fare expenditure); and government (subsidy, user tax revenue, net revenue). These are summarized in Figure II-7, Simple Model.

Although this model is indeed very simple, it does demonstrate the major aspects of a transportation systems analysis. The options and impacts are represented explicitly. The impacts are related to the options in an explicit way, via the equilibrium formulation, level of service vector, and resource requirements vector. The differential impacts on users, operator, and government are clearly identified. The usefulness of even this simple a model is demonstrated by Meyer, Kain and Wohl, in their analysis of urban transportation technologies,¹ and by Stafford's

¹ op.cit., especially pp. 271-295

Figure II-7: Simple Model



discussion of some of the key tradeoffs in transportation.¹

To make this model more realistic, every element can be extended. For example, an explicit demand relation, $VOL = D(L)$ can be added, as well as congestion effects - $L = S(V,T)$; the influence of network structure; demand shifts, etc. A number of such extensions to this simple model are currently being explored.

The Prototype Analysis system (see Chapter III) extends this model to the network context, with explicit demand functions, demand shifts, and congestion effects in a multi-mode network.

¹Stafford, op. cit.

9.0 Summary - Transportation Systems Analysis: The Substantive Problem

Our review of the substantive issues in transportation systems analysis leads us to the following conclusions:

1. There are a variety of options which can be manipulated as instruments of transport systems policy in a region.
2. In manipulating these options, the impacts among a variety of different groups in the region must be considered.
3. In general, predicting the impacts corresponding to any particular set of options is difficult. In order to predict the impacts, it is necessary to predict the corresponding pattern of flows which will occur in the transportation network.
4. The prediction of flows is based upon the concept of equilibrium between supply and demand within the constraining channels of the transportation network. The supply-demand framework expresses the following relationships:
 - a. The volume of people or goods which will use the system is the function of the level of service which the system provides, as well as the spatial pattern of social and economic activities.
 - b. The level of service provided by a particular transportation system is a function of the volume of flows moving through that system.
 - c. The two previous statements imply that there is an equilibrium pattern of flows in the system, consisting of the volume of flows and the level of service which those flows incur.

- d. As a consequence of the equilibrium pattern of flows at any point in time, changes can occur in the spatial pattern of social and economic activity in successive time periods.
- e. The resources consumed by providing transportation are a function of the volume of flows through the system, the level of service which is provided, and the specification of the system.
- f. As a consequence of the resources consumed in providing transportation, there are potentially impacts on the spatial pattern of social and economic activity (for example, construction impacts or noise pollution impacts).

Any analysis of a transportation system must initially consider these relationships, even if the influence of some should later be found negligible in a particular context.

- 5. To accomplish this prediction in the network context, five types of models are required: supply models, resource requirements models, demand models, network equilibrium models, and demand shift models.
- 6. This same basic five-component model structure underlies urban transportation planning, Northeast Corridor, and the Harvard Transport Program model. However, present urban transportation planning procedures do not implement the equilibrium concept as effectively as they might.
- 7. Although versions of these five models are now in use, substantial additional research and data collection is required to develop a fully satisfactory set of prediction models.

8. In addition to prediction, there must also be evaluation and choice procedures, to compare the impacts of alternative sets of options and choose among them.
9. There must also be search procedures for generating reasonably feasible actions for testing in the prediction models.
10. To systematically analyse a transportation problem, a wide variety of options must be explored and their differential impacts traced out explicitly.
11. A simple example illustrates the options and their relation to differential impacts by means of the equilibrium concept.
12. In the network context, prediction is complex; searching out and choosing among alternatives is difficult.
13. The problem of search and choice is, how to systematically search out and choose among transportation systems alternatives, with careful consideration of the differential impacts on various groups, in a network context.

Chapter III

A PROTOTYPE ANALYSIS - THE NORTHEAST CORRIDOR

1.0 Introduction¹

In the preceding chapter, the basic problem of transportation systems analysis was described, and the argument developed that the core of the analysis problem is the prediction of flows in networks from the viewpoint of supply-demand equilibrium. The discussion emphasized the multiplicity of options and impacts, the potential substitutability among options, and the need for consideration of differential impacts.

The preceding chapter defined the problem of search and choice in transportation systems analysis: to systematically analyze the range of options, tracing out their differential impacts, using a flow equilibrium approach. The question then arises: is this feasible? can systematic analysis be implemented, in a network context? what problems arise?

To demonstrate the feasibility and utility of systematic analysis in the supply-demand equilibrium context, a "prototype" analysis of passenger transportation in the Northeast Corridor region was conducted. (Clearly, the models could be used for many other contexts as well.) To the maximum extent feasible, realistic data was used. The result demonstrates how the analytical approaches and techniques can be applied to improve policy decisions. However, the result is not of sufficient detail or comprehensiveness to be used for policy decisions without further calibration and modifications of the models and substantial

1

This chapter draws heavily from Ruiter, Earl R., A PROTOTYPE ANALYSIS, Research Report R68-41, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume II of a Series.

additional data.

To do this "prototype analysis," it was necessary to develop a set of models for transportation systems analysis. As pointed out in the preceding chapter, there have been major elements of this formulation present in urban transportation analysis, the Harvard Transport Model, the Northeast Corridor model system. However, each of these had limitations for use as an experimental system for the purposes of this project. Therefore, it was decided to develop a system of models for use as a "prototype" transportation systems analysis capability. These models, in the form of computer programs, provided a "laboratory" for experiments in systematic analysis in transportation.

This laboratory was implemented as TRANSET II, a new subsystem of ICES, the Integrated Civil Engineering System.¹ This subsystem is a problem-oriented command-structured language for transportation systems analyses, and thus is designed for ease of use by analysts without computer training. For example, to create a new regional transportation network by adding a link to a network previously

¹Daniel Roos, ICES SYSTEM DESIGN, Cambridge, Mass: M.I.T. Press (1967). The development of TRANSET II is based upon additions and changes to an earlier subsystem for urban transportation analysis, TRANSET I, C.F. Earl R. Ruiter, ICES TRANSET I: TRANSPORTATION NETWORK ANALYSIS - ENGINEERING USERS' MANUAL, Research Report R68-10, Cambridge, Mass: Department of Civil Engineering, M.I.T. (March, 1968)

stored in the computer, the analyst might give the computer this problem-oriented language command:

MODIFY NETWORK 'BASE' FORMING 'NEWRAIL' ADD LINK FROM
56 TO 97, DISTANCE 37.2, LANES 6, VOLUME/DELAY 4.

In this example, BASE is the previously-stored network, NEWRAIL the name to be given to the new network. The modification consists of a link from node 56 to 97, with the indicated length, number of lanes, and supply function (volume/delay curve number 4). Such problem-oriented language capabilities enable the analyst to use the computer models in a much more flexible and efficient manner than with more traditional forms of programs.

As a system of computer models, TRANSET II provides the capability to analyze transportation problems by predicting supply and demand equilibrium in a multi-modal transportation network.¹ Some of the particular features of TRANSET II are: (a) the capability to express transportation policy options through technology choices, network configuration, link characteristics, fares, frequency of service, subsidy, and tax policy; (b) the use of the Baumol-Quandt abstract mode demand model; (c) incremental assignment techniques as an approach to calculating equilibrium; and (d) explicit evaluation routines for tracing out impacts on different groups.

¹ Ruiter, Earl R., A PROTOTYPE ANALYSIS. Research Report R68-41, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1968), Volume II of a Series.

With the cooperation of the Northeast Corridor project of the Department of Transportation, data was obtained through which the Northeast Corridor network was modelled in two forms: a five-district and a twenty-nine district version, with the networks modelled at corresponding levels of abstraction. The resulting models then served as the basis for a number of analyses.

Using the TRANSET II model system as a laboratory, numerous experiments have been conducted using the five-district data. These experiments demonstrate:

- a. the feasibility of developing a supply-demand equilibrium model for transportation analysis;
- b. the difference between equilibrium and non-equilibrium approaches to the problem;
- c. how different options and impacts can be included in a single model so that their interactions can be explored systematically;
- d. how trade-offs between options can be explored;
- e. the technique of differential impact analysis through tracing out impacts among different actors as the options are varied;
- f. sensitivity analyses;
- g. effects of alternative time-stagings of actions.

In this chapter, we will describe briefly the capabilities of TRANSET II, some of the experiments conducted, and the issues raised by these experiments.

2.0 The Prototype Analysis System: TRANSET II

In the preceding chapter, the nature of the transportation systems analysis problem was described in terms of options, impacts, and the basic structure of the set of prediction models. It is useful to describe the set of models developed for the Prototype Analysis in these same terms. (See Figure- III-1, Prototype Analysis Model System)

2.1 Options

The basic options, and the corresponding elements of TRANSET II, are as follows:

a. TECHNOLOGIES

- (i) volume - travel time functions: Each function gives travel time in minutes per mile per lane, as a function of volume in passengers per day (up to 14 volume-delay functions can be specified).
- (ii) cruising speed, for each mode (up to 4 modes).
- (iii) cost structure - for each mode, fixed cost in dollars per year and variable cost in dollars per passenger mile.

b. NETWORK: The multi-modal network is specified by listing for each link, its origin and destination node.

c. LINKS: for each link in the network, its length in miles, number of "lanes", and volume-delay function

Figure III-1. Prototype Analysis Model System

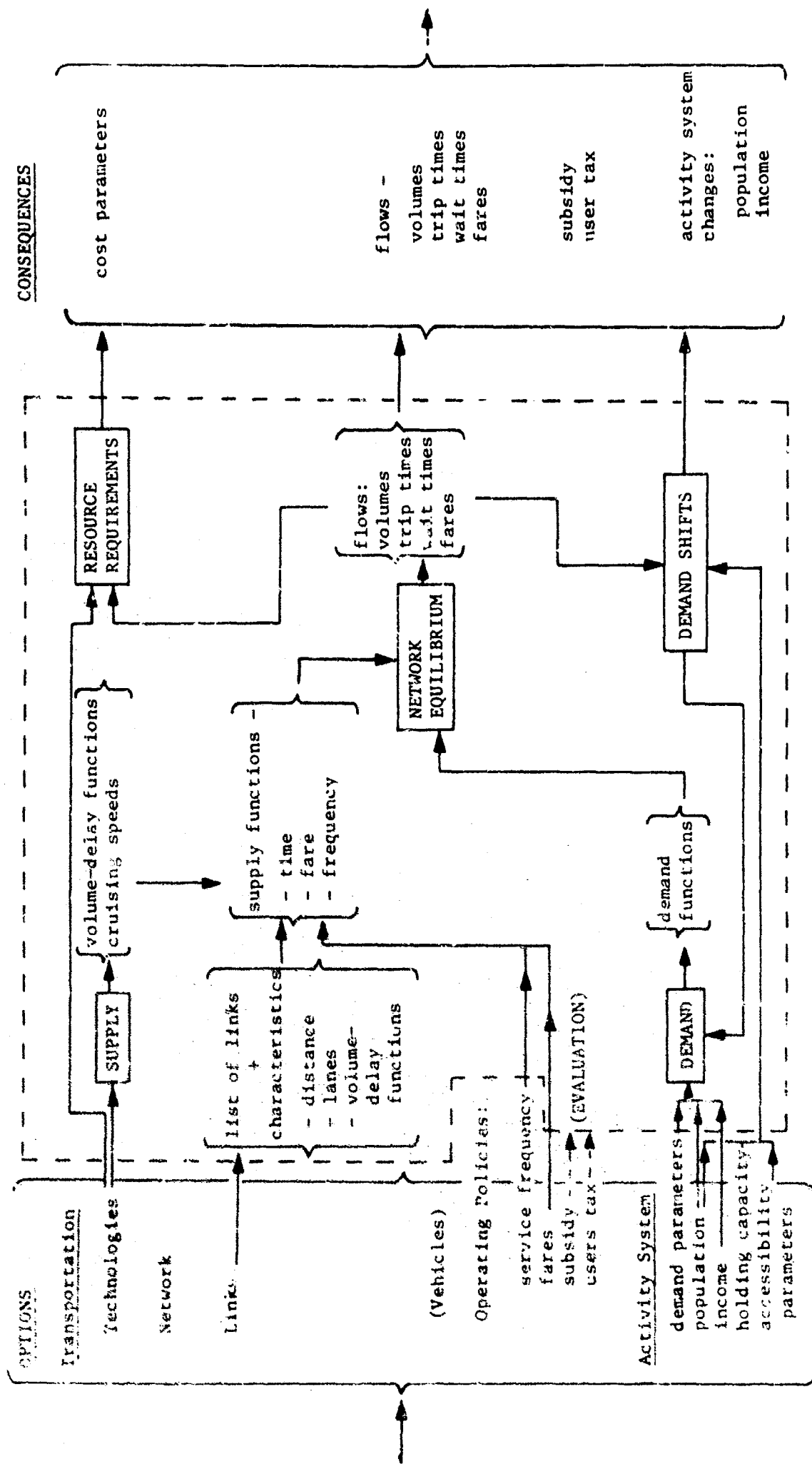
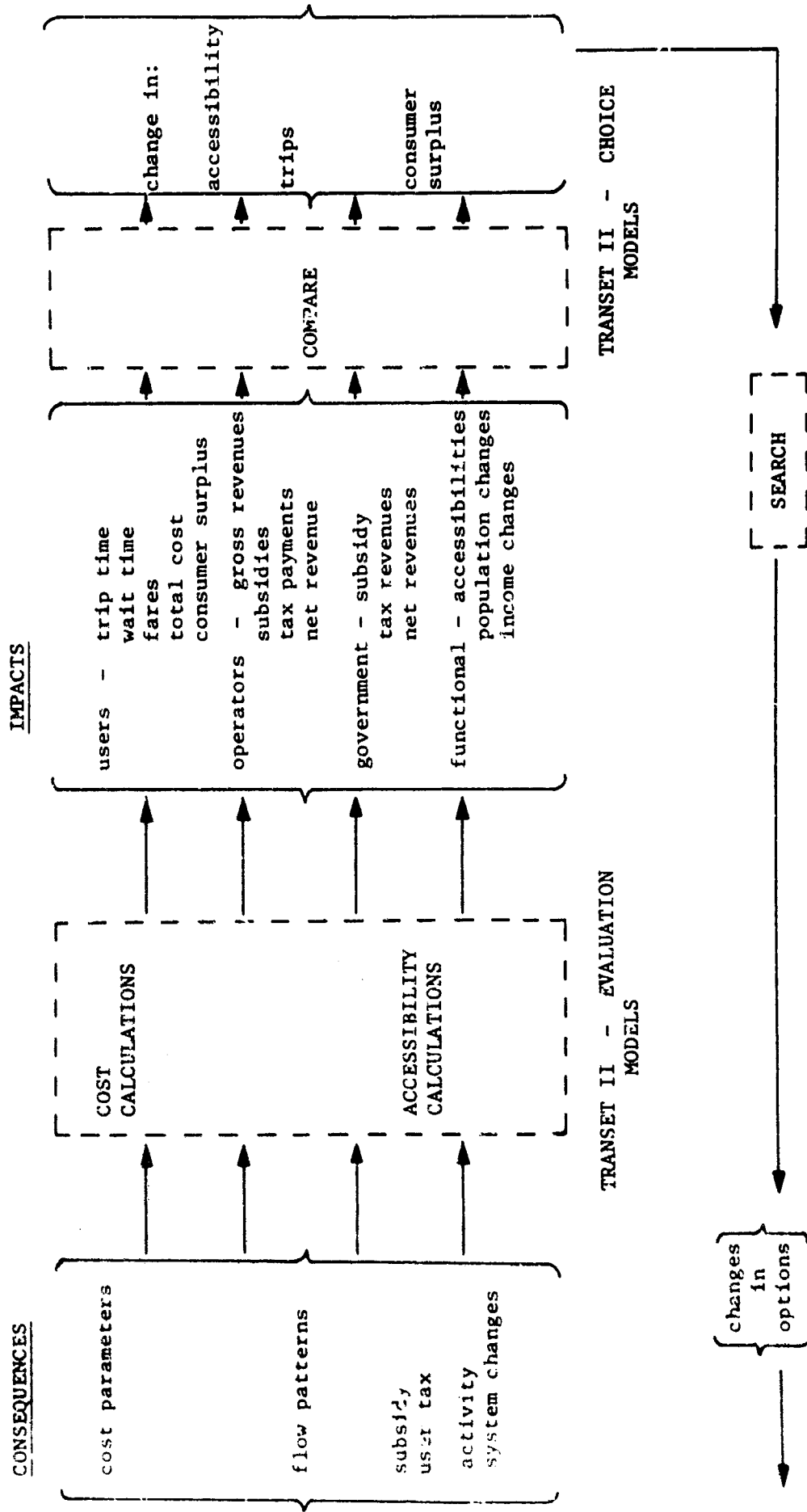


Figure III-1. continued



- d. VEHICLES: no explicit specification of vehicles
- e. OPERATING POLICIES:
 - (i) frequency of service- for each mode and pair of origin - destination districts
 - (ii) fare - for each mode and pair of origin-destination districts, in cost per passenger
 - (iii) subsidy - for each mode, total subsidy in dollars per year
 - (iv) user tax - for each mode, as a percentage of the fare
- f. ACTIVITY SYSTEM:
 - (i) for each district-base year total population, per capita income, and population holding capacity
 - (ii) travel demand parameters - for Baumol-Quandt model, 11 parameters.

2.2 Impacts

The impacts which are predicted are the following:

- a. USERS:
 - (i) total volume of passengers served, by mode, by origin, by destination
 - (ii) total trip time, by mode, by origin, by destination
 - (iii) wait time, by mode, by origin, by destination
 - (iv) fare paid, by mode, by origin, by destination

b. OPERATORS:

- (i) total cost, including fixed and variable, by mode
- (ii) gross revenue, by mode, by origin district
- (iii) net revenue, by mode

c. GOVERNMENT:

- (i) total subsidy, by mode
- (ii) total user tax revenue, by mode
- (iii) net revenue, by mode

d. PHYSICAL: none

e. FUNCTIONAL:

- (i) accessibility, by origin district, by mode
- (ii) population and income change, by district

2.3 Consequences

To determine these impacts, the following consequences must be predicted by the network equilibrium analysis:

a. FLOW VOLUMES:

- (i) interzonal flow volumes - passenger trips, by mode, by origin, by destination
- (ii) link flow volumes - total passenger flow for each link

b. LEVELS OF SERVICE:

- (i) interzonal trip times, by mode, by origin, by destination

- (ii) interzonal wait times, by mode, by origin, by destination (a fraction of the inverse of frequency of service, which is specified as input)
- (iii) interzonal total travel times - wait times plus trip times, by mode, by origin, by destination
- (iv) link speeds and travel times
- (v) interzonal fares - by mode, by origin, by destination (specified as input)

c. RESOURCE REQUIREMENTS:

- (i) total fixed plus variable cost, by mode
- (ii) total user tax revenues, by mode
- (iii) total government subsidy, by mode

d. ACTIVITY SYSTEM CHANGES:

- (i) accessibility, by mode, by district
- (ii) change in population and per capita income, by district

2.4 Prediction Models

The consequences described are predicted from the options using the prediction models briefly described in this section. More detailed descriptions are in the report on the prototype analysis.²

² Ruiter, op. cit.

- a. demand model - The demand model is an early version of the Baumol-Quandt abstract mode model.
- b. supply and resource requirements models - The supply models are external to the computer programs. Hand calculations and engineering judgment are used to develop the basic functions required: cost coefficients for each mode, volume-delay functions and cruising speed estimates. These are then input explicitly to TRANSET II as data.
- c. network equilibrium - The approach for computing equilibrium flows in the multi-modal network is an incremental-loading traffic assignment procedure, with variable increment, and consistent with the Baumol-Quandt model.
- d. demand shifts - An extremely simple model for computing the distribution of population is provided. The growth of each district in the region is computed as a weighted function of accessibility, present population, holding capacity, and an exogenously-specified regional growth rate.

2.5 Evaluation

The impacts on the various groups are determined from the predicted consequences. In order to evaluate alternative systems, it is necessary to aggregate these consequences to produce various overall measures of the impacts of each alternative. The following evaluation "models" are, with the exception of accessibility and consumer surplus,

simple summations over zones and/or modes. (Accessibility and consumer surplus are computed consistent with the Baumol-Quandt model.¹) That is, where aggregate measures of impact are constructed, each group is weighted equally: e.g., all modes, origins and/or destinations are weighted equally when passenger hours or total fares or revenues are summed to various aggregate levels. Some of these measures are directly specified as input (e.g., subsidy); others are functions of the predicted flow patterns.

a. USERS:

- (i) total trip time - by mode, by origin; by mode; system total
- (ii) total wait time - by mode, by origin; by mode; system total
- (iii) average travel time - by mode, by origin; by mode; system total
- (iv) average fare - by mode, by origin; by mode; system total
- (v) user total cost - for specified utilities (relative weights of trip time, wait time, and fare), a weighted total cost is computed, and aggregated - by mode, by origin; by mode; system total

b. OPERATORS:

- (i) gross revenue from user fares - by mode, by origin; by mode; system total
- (ii) gross revenue from government subsidy - by mode; system total

¹ Ruiter, Earl R., op. cit.

(iii) gross payment to government via user tax - by mode;
system total

(iv) net revenue - by mode; system total

c. GOVERNMENT:

(i) subsidy to operators - by mode; system total

(ii) user tax revenues from operators - by mode; system
total

(iii) net revenue - by mode; system total

d. FUNCTIONAL:

(i) accessibilities - by origin, by mode; by origin; by
mode; system total

(ii) population change - by zone

(iii) income change - by zone

These component and aggregated measures can be used in evaluating such comprehensive objectives as: regional growth pattern; income distribution; fiscal feasibility; political feasibility.

3.0 Problem-Oriented Language Commands

TRANSET II is a set of computer programs which is designed for maximum ease of use by the transportation analyst. This is achieved in part through the problem-oriented language capability of TRANSET: to specify a particular analysis sequence, the analyst sets up a series of problem-oriented language commands. The basic commands which have been developed are summarized below. A more complete description is provided in the Prototype Analysis report.¹

Two features of TRANSET which provide particularly useful capabilities to the analyst are:

- (1) the ability to store and retrieve data from disc files, as needed;
- (2) the ability to assign any arbitrary name to a block of data.

For example, the analyst can name, and store, several alternative transportation networks, such as 'BASE', 'NEWRAIL', 'VSTOL', '1965-1', '1965-2', etc.

3.1 To Generate a Transportation System Alternative

a. Transportation options:

- (i) READ NETWORK - for general network characteristics
- (ii) LINKS - for network connectivity and link characteristics
- (iii) READ VOLUME DELAY SET - for generalized supply functions

¹ Ruiter, Earl R., op. cit.

(iv) INPUT MODAL SERVICE DATA - for modal interzonal fares
and frequencies

(v) INPUT MODAL COST DATA - for modal cost parameters

b. Activity System Options

(i) INPUT DISTRICT DATA - for populations, incomes, and
holding capacities, for each district (zone)

(ii) INPUT MODAL SPLIT PARAMETERS - for demand model parameters

In addition to specifying a completely new alternative, it is also possible to generate an alternative by using portions of another alternative previously stored in the computer:

c. To save an alternative on secondary storage as a permanent file,
for future reference:

(i) STORE - for networks and volume-delay sets

(ii) KEEP - for modal and district data

d. To modify an alternative previously stored on secondary storage
to create a new one:

(i) MODIFY NETWORK - name of network to be changed

ADD LINK

DELETE LINK specification of changes

CHANGE LINK

(ii) REVISE MODAL DATA - name of data to be changed

MODE COST

MODE FREQUENCY specification of changes

- (111) REVISE DISTRICT DATA - name of data to be changed
 DISTRICT - specification of changes

3.2 To Predict Consequences

- a. PREDICT POTENTIAL TRIPS - generate estimated trip demands
- b. PREDICT ACTUAL TRIPS - predict network equilibrium flow pattern, including volumes and travel times
- c. PREDICT DISTRICT DATA - generate new populations and incomes

3.3 To Evaluate Impacts

- a. Display flow pattern consequences:

- (1) REQUEST FINAL -

LINK data

MINIMUM PATHS

TRAVEL TIMES

SYSTEM TRAVEL

TIME DISTRIBUTION

INTERZONAL TRIPS

- (11) PRINT TRIP MATRIX

- (111) In graphical form, via plotter or other display device:

PLOT NETWORK

DISPLAY LINK VOLUMES, TRAVEL TIMES, SPEEDS

DISPLAY INTERZONAL VOLUMES, TRAVEL TIMES, SPEEDS

- b. EVALUATE COSTS for user, operator, and governmental impacts
- c. EVALUATE ACCESSIBILITY for functional impacts

3.4 To Compare Two Alternatives

- a. COMPARE TRIPS - for a summary of the differences between the two flow patterns
- b. COMPARE SURPLUSES - for comparison of user benefits, as measured by consumer surplus
- c. COMPARE ACCESSIBILITIES - for functional impacts

3.5 Utility Commands

In addition to the above, there are available in TRANSET II a variety of utility commands - for editing data, obtaining intermediate results during the course of the computations, filing data on computer disc storage, etc. These are detailed in the Prototype Analysis report.

3.6 Example: Use of the Commands

As an example of the prototype analysis system, and of the TRANSET II commands, runs using all major commands are presented in this section.

The area chosen for all prototype analysis system runs is the Northeast Corridor, stretching along the Atlantic coast between the Boston and Washington, D.C., metropolitan areas. The corridor includes the District of Columbia and all or part of nine states: Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland, and Virginia. This area represents the corridor study area, as defined by the Department of Transportation Northeast Corridor Transportation Project

(NEC).¹ The corridor fringe areas, such as southern New Hampshire and central Pennsylvania, have not been included in the prototype analysis study area.

For the purposes of these analyses, this area has been divided into five very large districts, each made up of a number of NEC superdistricts. These districts include the following metropolitan centers and their surrounding areas:

District 1: Washington and Baltimore; NEC superdistricts 1 through 3

District 2: Philadelphia, Atlantic City, Wilmington, and Trenton;
NEC superdistricts 4 through 10

District 3: New York City; NEC superdistricts 11 through 19

District 4: Hartford, New Haven, and Springfield; NEC super-
districts 20, 21, 25, 26, and 27

District 5: Boston, Worcester, Providence; NEC superdistricts 22,
23, 24, 28, and 29

A map of the analysis area is shown in Figure III-2.

Three modes of intercity travel - air, rail, and private automobile - are included in the analysis. The air and rail systems are each represented by a single terminal in each of the five districts. For each district, these two terminals represent the total capacity of all airports and train stations within the district. Auto trips require no terminal, but are assumed both to begin and end their trips by passing through the central portion of a major city.

¹ Glancy, David M., "Description of the Area System for the Northeast Corridor Transportation Project," Northeast Corridor Transportation Project Technical Paper No. 2, December 1965.

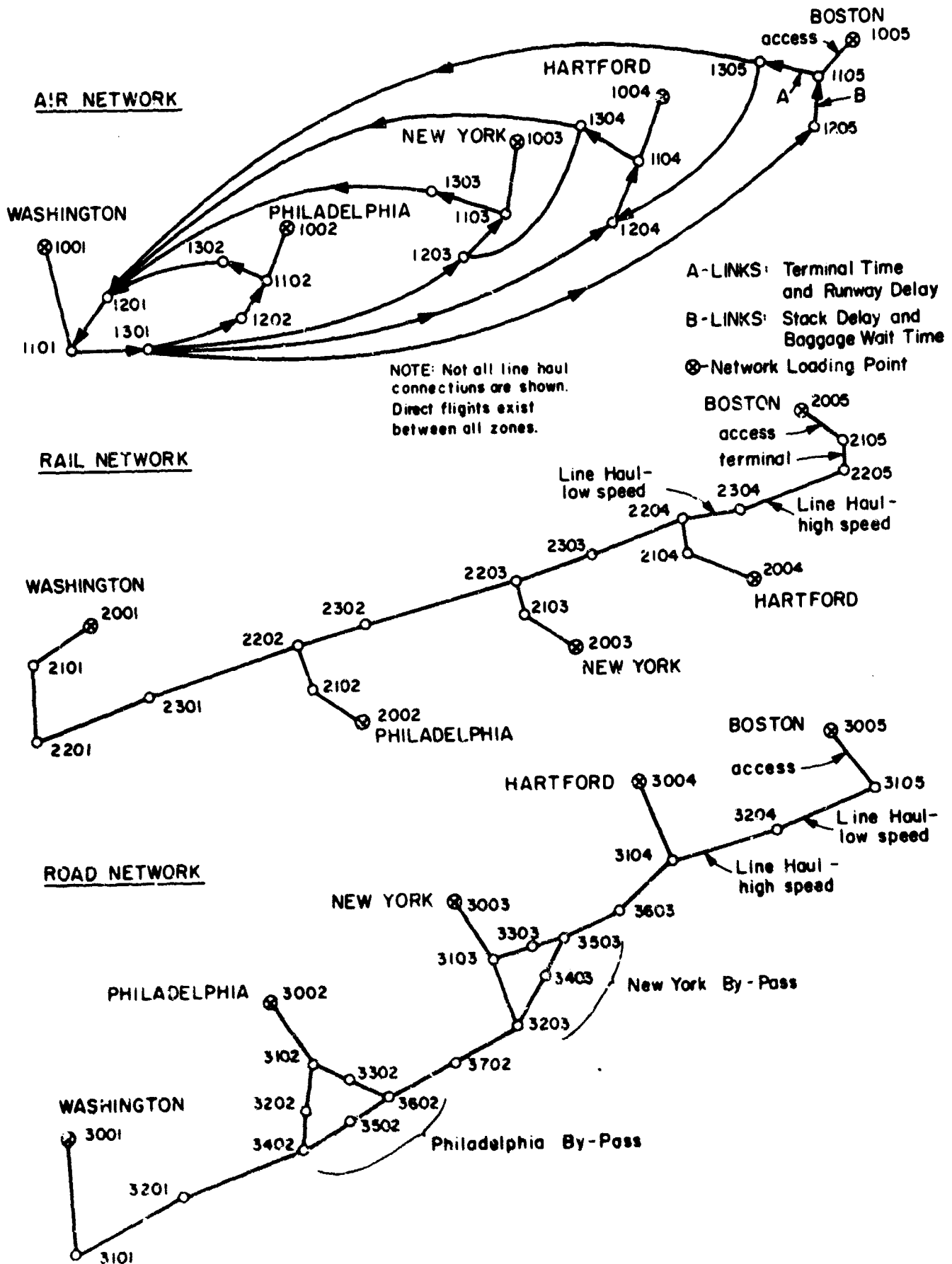


Figure III-2: The Northeast Corridor Base Case Network

Most of the example runs show the establishment of a "Base Case" against which a wide range of alternatives can be compared. This base case corresponds most closely to the actual situation in the Northeast Corridor in 1965, although portions of the data represent other years, from 1960 to 1967.

The example problem has been divided quite arbitrarily into seven runs, each of which can be performed separately from the others, as long as the sequence is not changed. Alternatively, all runs can be part of the same computer job.

The summary of the example runs is followed by listings of the input and partial listings of the output.

The data is discussed in detail in Chapter IV of the Prototype Analysis report.

Run 1 - Network and Supply Function Definition: In the first run, network and volume-delay function data are read, edited, and stored in permanent files for future reference.

Run 2 - District Data Definition: In the second run, district populations, per capita incomes, and holding capacities, and system-wide demand model parameters are read and stored in permanent files for future reference.

Run 3 - Modal Data Definition: Interdistrict fares and service frequencies, and modal cost parameters are read and stored in this run.

Run 4 - Calculation of Estimated Trip Demands: In Runs 1 through 3, all data on the transportation and activity system have been read, edited, and stored. These data can now be used to obtain a matrix of estimated trip demands, and demand function data in the form of generation rate functions. Potential trip demands are estimated on the basis of the cruise speeds specified as part of the modal data. After calculating these estimated demands, they can be stored as permanent files, available for future use.

Run 5 - Equilibrium and Impacts: The data defined or calculated in each of the previous runs is used in the fifth run to predict an equilibrium set of flows and to determine selected impacts of these flows. After retrieving the data from storage (by LOAD and GET commands, the desired computational accuracy is specified (the variable increment size) and the name under which the predicted flow pattern is to be filed. Then the incremental approach to equilibrium computation is begun.

Following the completion of the equilibrium computation, a number of impacts are displayed:

1. The PRINT TRIP command is used to show the relationships between actual and estimated trip demand for each zone pair.
2. Cost data and actual trips are displayed by mode and origin district, by mode, and as totals for the entire analysis area. Costs to users, operators, and government are summarized, by the EVALUATE COSTS command.
3. Accessibilities are computed.

Run 6 - Flow Pattern Summaries: Because the flow pattern data were saved in network 'BASE' as a permanent file, it is possible in the sixth run to display various summaries of this information:

1. Ratios of volume to capacity for each link in the network are useful in locating congested areas. It must, however, be remembered that a number of volume-delay curves have no congestion at their capacity points (access links, railroad terminal links, etc.)
2. In the second table, all link flow descriptors - volumes, speeds, and times - are shown for every link.
3. Travel times from each origin to each destination are shown in the third table.

Run 7 - Use of Two Alternatives: Runs 1-6 have analysed a single transportation system alternative. On the basis of the various summaries of predicted impacts, a new alternative would be developed. For example, alternative 'NEWRAIL' represents the upgrading of the rail system so that inter-city travel times would average 90 miles per hour.

Once the new alternative has been specified to the system, through use of the MODIFY commands, or through runs similar to 1 through 3, the impacts for it would be predicted by a series of runs similar to 4 through 6. Then 'BASE' and

'NEWRAIL' can be compared, as shown in this example, to determine in what respects one is better than the other in terms of such measures as district accessibilities, total trips, and consumer surpluses.

'BASE' and 'NEWRAIL' data can also be used to project population and economic activity into the future, when the new rail system will have been implemented and will affect population and economic growth.

```

$      EXAMPLE RUN 1 -- NETWORK AND SUPPLY FUNCTION DEFINITION
$      SPECIFY ONE OF THE ICFS SUBSYSTEMS
TRANSET
$      SET SCALE FACTOR LOW SO LONG-DISTANCE LINKS CAN BE USED.
USE SCALE FACTOR 5.0
$      GENERAL COMMAND FIRST -- READ IN NETWORK
READ NETWORK '5X3,1965', ZONES 15, VOL SET '3MODES,2'
$      FOLLOWED BY INDIVIDUAL ONE-WAY LINK CARDS
LINK 1 FROM 1001 TO 1101 DISTANCE 26.5 LANES 1 VOL/DELAY 2
$      IDENTIFIERS OMITTED FROM REMAINING LINK CARDS
$      DATA ITEMS ARE IN THE SAME SEQUENCE
LINK 2 1002 1102 27.5 1 2      $ ACCESS LINKS FROM ALL ZONES FIRST
LINK 3 1003 1103 21.2 1 2
LINK 4 1004 1104 30.4 1 2      $ FIRST DIGIT = MODE NUMBER
LINK 5 1005 1105 23.9 1 2      $ 1=AIR
LINK 6 2001 2101 18.0 1 2      $ 2=RAIL
LINK 7 2002 2102 11.4 1 3      $ 3=ROAD
LINK 8 2003 2103 16.8 1 3
LINK 9 2004 2104 12.7 1 3      $ SECOND DIGIT = NODE NUMBER WITHIN
LINK 10 2005 2105 15.5 1 3      $ DISTRICT
LINK 11 3001 3101 18.0 1 3      $ THIRD DIGIT = ALWAYS ZERO
LINK 12 3002 3102 11.4 1 3      $ FOURTH DIGIT=DISTRICT NUMBER
LINK 13 3003 3103 16.8 1 3
LINK 14 3004 3104 12.7 1 3      $ VOL/DELAY NUMBERS
LINK 15 3005 3105 15.5 1 3      $ 1 DUMMY LINKS
LINK 16 1101 1001 26.5 1 2      $ 2 AIR ACCESS LINKS
LINK 17 1102 1002 27.5 1 2      $ 3 ROAD AND RAIL ACCESS LINKS
LINK 18 1103 1003 21.2 1 2      $ 4 AIRPORT DEPARTURE LINKS
LINK 19 1104 1004 30.4 1 2      $ 5 RAIL STATION LINKS
LINK 20 1105 1005 23.9 1 2      $ 6 AIR LINE HAUL LINKS
LINK 21 2101 2001 18.0 1 3      $ 7 AIRPORT ARRIVAL LINKS
LINK 22 2102 2002 11.4 1 3      $ 8 HIGH SPEED RAIL
LINK 23 2103 2003 16.8 1 3      $ 9 LOW SPEED RAIL
LINK 24 2104 2004 12.7 1 3      $ 10 HIGH SPEED ROAD
LINK 25 2105 2005 15.5 1 3      $ 11 LOW SPEED ROAD
LINK 26 3101 3001 18.0 1 3
LINK 27 3102 3002 11.4 1 3
LINK 28 3103 3003 16.8 1 3
LINK 29 3104 3004 12.7 1 3
LINK 30 3105 3005 15.5 1 3
LINK 31 1001 2001 800 1 1      $ DUMMY LINKS
LINK 32 2001 3001 800 1 1
LINK 33 3001 1001 800 1 1
LINK 34 1002 2002 800 1 1
LINK 35 2002 3002 800 1 1
LINK 36 3002 1002 800 1 1
LINK 37 1003 2003 800 1 1
LINK 38 2003 3003 800 1 1
LINK 39 3003 1003 800 1 1
LINK 40 1004 2004 800 1 1
LINK 41 2004 3004 800 1 1
LINK 42 3004 1004 800 1 1
LINK 43 1005 2005 800 1 1
LINK 44 2005 3005 800 1 1
LINK 45 3005 1005 800 1 1

```

LINK 46	1101	1301	1	2	4	\$	TERMINAL LINKS
LINK 47	1201	1101	1	2	7	\$	AIRPORTS FIRST
LINK 48	1102	1302	1	3	4	\$	
LINK 49	1202	1102	1	3	7	\$	
LINK 50	1103	1303	1	6	4	\$	
LINK 51	1203	1103	1	6	7	\$	
LINK 52	1104	1304	1	3	4	\$	
LINK 53	1204	1104	1	3	7	\$	
LINK 54	1105	1305	1	4	4	\$	
LINK 55	1205	1105	1	4	7	\$	
LINK 56	2101	2201	1	1	5	\$	THEN RAILROAD STATION
LINK 57	2201	2101	1	1	5	\$	
LINK 58	2102	2202	1	1	5	\$	
LINK 59	2202	2102	1	1	5	\$	
LINK 60	2103	2203	1	1	5	\$	
LINK 61	2203	2103	1	1	5	\$	
LINK 62	2104	2204	1	1	5	\$	
LINK 63	2204	2104	1	1	5	\$	
LINK 64	2105	2205	1	1	5	\$	
LINK 65	2205	2105	1	1	5	\$	
LINK 66	1301	1202	120	1	6	\$	LINE HAUL AIR LINKS
LINK 67	1301	1203	228	1	6	\$	DIRECT CONNECTIONS BETWEEN ALL
LINK 68	1301	1204	325	1	6	\$	DISTRICTS
LINK 69	1301	1205	413	1	6	\$	
LINK 70	1302	1201	120	1	6	\$	
LINK 71	1302	1203	93	1	6	\$	
LINK 72	1302	1204	195	1	6	\$	
LINK 73	1302	1205	279	1	6	\$	
LINK 74	1303	1201	228	1	6	\$	
LINK 75	1303	1202	93	1	6	\$	
LINK 76	1303	1204	106	1	6	\$	
LINK 77	1303	1205	186	1	6	\$	
LINK 78	1304	1201	325	1	6	\$	
LINK 79	1304	1202	195	1	6	\$	
LINK 80	1304	1203	106	1	6	\$	
LINK 81	1304	1205	91	1	6	\$	
LINK 82	1305	1201	413	1	6	\$	
LINK 83	1305	1202	279	1	6	\$	
LINK 84	1305	1203	186	1	6	\$	
LINK 85	1305	1204	91	1	6	\$	
LINK 86	2201	2301	6.8	1	9	\$	BEGINNING OF RAIL LINKS
LINK 87	2301	2201	6.8	1	9	\$	
LINK 88	2301	2202	128.4	1	8	\$	
LINK 89	2202	2301	128.4	1	8	\$	
LINK 90	2202	2302	3.7	2	9	\$	
LINK 91	2302	2202	3.7	2	9	\$	
LINK 92	2302	2203	87.7	2	8	\$	
LINK 93	2203	2302	87.7	2	8	\$	
LINK 94	2203	2303	28.6	2	9	\$	
LINK 95	2303	2203	28.6	2	9	\$	
LINK 96	2303	2204	43.9	2	8	\$	
LINK 97	2204	2303	43.9	2	8	\$	
LINK 98	2204	2204	20.1	1	9	\$	
LINK 99	2204	2204	20.1	1	9	\$	
LINK 100	2204	2205	136.4	1	8	\$	

LINK 101	2205	2304	136.9	1	8	\$	
LINK 102	3101	3201	5.8	3	11	\$	ROAD LINKS
LINK 103	3201	3101	5.8	3	11	\$	
LINK 104	3201	3402	99.0	2	10	\$	
LINK 105	3402	3201	99.0	2	10	\$	
LINK 106	3102	3202	23.7	2	11	\$	
LINK 107	3202	3102	23.7	2	11	\$	
LINK 108	3202	3402	13.3	2	10	\$	
LINK 109	3402	3202	13.3	2	10	\$	
LINK 110	3102	3302	5.9	2	11	\$	
LINK 111	3302	3102	5.9	2	11	\$	
LINK 112	3302	3602	13.1	2	10	\$	
LINK 113	3602	3302	13.1	2	10	\$	
LINK 114	3402	3502	2.7	2	11	\$	
LINK 115	3502	3402	2.7	2	11	\$	
LINK 116	3502	3602	37.3	2	10	\$	
LINK 117	3602	3502	37.3	2	10	\$	
LINK 118	3602	3702	5.3	3	11	\$	
LINK 119	3702	3602	5.3	3	11	\$	
LINK 120	3702	3203	78.7	3	10	\$	
LINK 121	3203	3702	78.7	3	10	\$	
LINK 122	3103	3203	6.0	3	11	\$	
LINK 123	3203	3103	6.0	3	11	\$	
LINK 124	3103	3303	2.0	3	11	\$	
LINK 125	3303	3103	2.0	3	11	\$	
LINK 126	3203	3403	2.7	3	11	\$	
LINK 127	3403	3203	2.7	3	11	\$	
LINK 128	3303	3503	6.0	3	10	\$	
LINK 129	3503	3303	6.0	3	10	\$	
LINK 130	3403	3503	7.8	3	10	\$	
LINK 131	3503	3403	7.8	3	10	\$	
LINK 132	3503	3603	10.5	3	11	\$	
LINK 133	3603	3503	10.5	3	11	\$	
LINK 134	3603	3104	102.6	3	10	\$	
LINK 135	3104	3603	102.6	3	10	\$	
LINK 136	3104	3204	8.5	2	11	\$	
LINK 137	3204	3104	8.5	2	11	\$	
LINK 138	3204	3105	99.5	2	10	\$	
LINK 139	3105	3204	99.5	2	10	\$	

\$ ALL DATA CARDS HAVE BEEN READ,
 \$ BEGIN NETWORK CHECKING AND BUILDING
 EDIT NETWORK
 \$ FILE NETWORK FOR FUTURE REFERENCE
 STORE NETWORK
 \$ READ IN SUPPLY FUNCTION LIBRARY
 READ VOL/DELAY 13MODES,21, FUNCTIONS 11, POINTS/FUNCTION 4
 \$ DUMMY LINKS
 V/D 1 LOCAL 3 0 1 2 1 4 1 6 1
 \$ AIR ACCESS LINKS
 V/D 2 LOCAL 3 0 1.25 10000 1.25 11000 1.25 12000 1.25
 \$ ROAD, RAIL ACCESS LINKS
 V/D 3 LOCAL 3 0 1.667 10000 1.667 11000 1.667 12000 1.667
 \$ AIRPORT DEPARTURE LINKS
 V/D 4 LOC 3 0 28 1750 31.5 2240 39 2450 68
 \$ RAILROAD STATION LINKS

V/D 5 LOCAL 3 0 10 100000 10 110000 10 120000 10
\$ AIR LINE HAUL LINKS
V/D 6 EXP 3 0 .197 5000 .197 6000 .197 7000 .197
\$ AIRPORT ARRIVAL LINKS
V/D 7 EXP 3 0 15 1750 17 2240 23 2450 35
\$ HIGH SPEED RAIL
V/D 8 ART 3 0 .924 15000 1.09 35000 2.0 40000 5.0
\$ LOW SPEED RAIL
V/D 9 ART 3 0 2 15000 2.4 35000 4 40000 10
\$ HIGH SPEED ROAD
V/D 10 LOCAL 3 0 1 6400 1.2 8000 2.0 8800 4
\$ LOW SPEED ROAD
V/D 11 LOCAL 3 0 3 6400 3.6 8000 6 8800 12
EDIT
\$ FILE SUPPLY FUNCTIONS FOR FUTURE REFERENCE
STORE VOLUME DELAY SET
EJECT

```

$  EXAMPLE RUN 1 -- NETWORK AND SUPPLY FUNCTION DEFINITION
$  SPECIFY ONE OF THE ICF'S SUBSYSTEMS
TRANSET
$  SET SCALE FACTOR LOW SO LONG-DISTANCE LINKS CAN BE USED.
USE SCALE FACTOR 5.0
$  GENERAL COMMAND FIRST -- READ IN NETWORK
READ NETWORK 'SE3.1945', ZONES 15, VOL SET 'NODES.2'
NETWORK SE3.1945  INPUT NODES= 0  LINKS= 0
$  FOLLOWED BY INDIVIDUAL ONE-WAY LINK CARDS
LINK 1 FROM 1001 TO 1101 DISTANCE 26.5 LANE 1 VOL/Delay 7
$  IDENTIFIERS OBTAINED FROM REMAINING LINK CARDS
$  DATA ITEMS ARE IN THE SAME SEQUENCE
LINK 2 1002 1102 27.5 1 2          $ ACCESS LINKS FROM ALL ZONES FIRST
LINK 3 1003 1103 21.2 1 2
LINK 4 1004 1104 30.4 1 2          $ FIRST DIGIT = MODE NUMBER
LINK 5 1005 1105 23.9 1 2          $ 1=AIR
LINK 6 2001 2101 18.0 1 3          $ 2=RAIL
LINK 7 2002 2102 11.4 1 3          $ 3=ROAD
LINK 8 2003 2103 16.4 1 3
LINK 9 2004 2104 17.7 1 3          $ SECOND DIGIT = NODE NUMBER WITHIN
LINK 10 2005 2105 15.5 1 3         $ DISTRICT
LINK 11 3001 3101 18.0 1 3         $ THIRD DIGIT - ALWAYS ZERO
LINK 12 3002 3102 11.4 1 3         $ FOURTH DIGIT=DISTRICT NUMBER
LINK 13 3003 3103 16.8 1 3
LINK 14 3004 3104 12.7 1 3         $ VOL/DELAY NUMBERS
LINK 15 3005 3105 15.5 1 3         $ 1 DUMMY LINKS
LINK 16 1101 1201 26.5 1 2         $ 2 AIR ACCESS LINKS
LINK 17 1102 1202 27.5 1 2         $ 3 ROAD AND RAIL ACCESS LINKS
LINK 18 1103 1203 21.2 1 2         $ 4 AIRPORT DEPARTURE LINKS
LINK 19 1104 1204 30.4 1 2         $ 5 RAIL STATION LINKS

```

LINK 20 1105 1005 21.0 1 2	5 6 AIR LINE HAUL LINKS
LINK 21 2101 2901 18.0 1 3	5 7 AIRPORT ARRIVAL LINKS
LINK 22 2102 2002 11.4 1 2	5 8 HIGH SPEED RAIL
LINK 23 2103 2003 16.0 1 3	5 9 LOW SPEED RAIL
LINK 24 2104 2004 12.7 1 3	5 10 HIGH SPEED ROAD
LINK 25 2105 2005 15.5 1 3	5 11 LOW SPEED ROAD
LINK 26 3101 3001 18.0 1 3	5
LINK 27 3102 3002 11.4 1 2	5
LINK 28 3103 3003 16.0 1 3	5
LINK 29 3104 3004 12.7 1 3	5
LINK 30 3105 3005 15.5 1 3	5
LINK 31 1001 2001 800 1 1	5 DUMMY LINKS
LINK 32 2001 3001 800 1 1	5
LINK 33 1001 1001 800 1 1	5
LINK 34 1002 2002 800 1 1	5
LINK 35 2002 3002 800 1 1	5
LINK 36 3002 1002 800 1 1	5
LINK 37 1003 2003 800 1 1	5
LINK 38 2003 3003 800 1 1	5
LINK 39 3003 1003 800 1 1	5
LINK 40 1004 2004 800 1 1	5
LINK 41 2004 3004 800 1 1	5
LINK 42 3004 1004 800 1 1	5
LINK 43 1005 2005 800 1 1	5
LINK 44 2005 3005 800 1 1	5
LINK 45 3005 1005 800 1 1	5
LINK 46 1101 1301 1 2 4	5 TERMINAL LINKS
LINK 47 1201 1101 1 2 7	5 AIRPORTS FIRST
LINK 48 1102 1302 1 3 4	5
LINK 49 1202 1102 1 3 7	5
LINK 50 1103 1303 1 4 4	5

LINE 51 1203 1103 1 6 7	\$
LINE 52 1104 1304 1 3 4	\$
LINE 53 1204 1104 1 3 7	\$
LINE 54 1105 1305 1 4 4	\$
LINE 55 1205 1105 1 4 7	\$
LINE 56 2101 2201 1 1 5	\$ THEN RAILROAD STATION
LINE 57 2201 2101 1 1 5	
LINE 58 2102 2202 1 1 5	\$
LINE 59 2202 2102 1 1 5	\$
LINE 60 2103 2203 1 1 5	\$
LINE 61 2203 2103 1 1 5	\$
LINE 62 2104 2204 1 1 5	\$
LINE 63 2204 2104 1 1 5	\$
LINE 64 2105 2205 1 1 5	\$
LINE 65 2205 2105 1 1 5	\$
LINE 66 1301 1202 120 1 6	\$ LINE HAUL AIR LINKS
LINE 67 1301 1203 228 1 6	\$ DIRECT CONNECTIONS BETWEEN ALL
LINE 68 1301 1204 325 1 6	\$ DISTRICTS
LINE 69 1301 1205 413 1 6	\$
LINE 70 1302 1201 120 1 6	\$
LINE 71 1302 1203 93 1 6	\$
LINE 72 1302 1204 195 1 6	\$
LINE 73 1302 1205 273 1 6	\$
LINE 74 1303 1201 228 1 6	\$
LINE 75 1303 1202 93 1 6	\$
LINE 76 1303 1204 126 1 6	\$
LINE 77 1303 1205 196 1 6	\$
LINE 78 1304 1201 125 1 6	\$
LINE 79 1304 1202 195 1 6	\$
LINE 80 1304 1203 106 1 6	\$
LINE 91 1304 1205 91 1 6	\$

LINK 82	1305	1201	413	1	6	\$
LINK 83	1305	1202	274	1	6	\$
LINK 84	1305	1203	196	1	6	\$
LINK 85	1305	1204	91	1	6	\$
LINK 86	2201	2301	6.9	1	9	\$
LINK 87	2301	2201	6.8	1	9	\$
LINK 88	2301	2202	128.4	1	8	\$
LINK 89	2202	2301	128.4	1	8	\$
LINK 90	2202	2302	3.7	2	9	\$
LINK 91	2302	2202	3.7	2	9	\$
LINK 92	2302	2203	87.7	2	8	\$
LINK 93	2203	2302	87.7	2	8	\$
LINK 94	2203	2303	78.6	2	9	\$
LINK 95	2303	2203	78.6	2	9	\$
LINK 96	2303	2204	43.9	2	8	\$
LINK 97	2204	2303	43.9	2	8	\$
LINK 98	2204	2304	20.1	1	9	\$
LINK 99	2304	2204	20.1	1	9	\$
LINK 100	2304	2205	136.9	1	8	\$
LINK 101	2205	2304	136.9	1	8	\$
LINK 102	3101	3201	5.8	3	11	\$
LINK 103	3201	3101	5.8	3	11	\$
LINK 104	3201	3402	99.0	2	10	\$
LINK 105	3402	3201	99.0	2	10	\$
LINK 106	3102	3202	23.7	2	11	\$
LINK 107	3202	3102	23.7	2	11	\$
LINK 108	3202	3402	19.3	2	10	\$
LINK 109	3402	3202	19.3	2	10	\$
LINK 110	3102	3302	5.9	2	11	\$
LINK 111	3302	3102	5.9	2	11	\$
LINK 112	3302	3402	13.1	2	10	\$

\$ BEGINNING OF RAIL LINKS

\$ BEGINNING OF ROAD LINKS

LINE 113 3402 3302	13.1	2	10	\$
LINE 114 3402 3502	2.7	2	11	\$
LINE 115 3502 3402	2.7	2	11	\$
LINE 116 3502 3602	37.3	2	10	\$
LINE 117 3602 3502	37.3	2	10	\$
LINE 118 3602 3702	5.3	3	11	\$
LINE 119 3702 3602	5.3	3	11	\$
LINE 120 3702 3203	78.7	3	10	\$
LINE 121 3203 3702	78.7	3	10	\$
LINE 122 3103 3203	6.0	3	11	\$
LINE 123 3203 3103	6.0	3	11	\$
LINE 124 3103 3303	2.0	3	11	\$
LINE 125 3303 3103	2.0	3	11	\$
LINE 126 3203 3403	2.7	3	11	\$
LINE 127 3403 3203	2.7	3	11	\$
LINE 128 3303 3503	6.0	3	10	\$
LINE 129 3503 3303	6.0	3	10	\$
LINE 130 3403 3503	7.8	3	10	\$
LINE 131 3503 3403	7.8	3	10	\$
LINE 132 3503 3603	10.5	3	11	\$
LINE 133 3603 3503	10.5	3	11	\$
LINE 134 3603 3104	102.6	3	10	\$
LINE 135 3104 3603	102.6	3	10	\$
LINE 136 3104 3204	4.5	2	11	\$
LINE 137 3204 3104	4.5	2	11	\$
LINE 138 3204 3105	99.5	2	10	\$
LINE 139 3105 3204	99.5	2	10	\$

\$ ALL DATA CAPSUS HAVE BEEN READ, BEGIN NETWORK CHECKING AND BUILDING

FILE NRTMWR

FILE OF APR 0 SEQUENCE ERRORS

NODE NUMBER EQUIVALENT TABLE FOR NETWORK 813,1045

MACHINE 1.	ASSIGNED=	1	USER NODE NO.=	1001
MACHINE 2.	ASSIGNED=	2	USER NODE NO.=	1002
MACHINE 3.	ASSIGNED=	3	USER NODE NO.=	1003
MACHINE 4.	ASSIGNED=	4	USER NODE NO.=	1004
MACHINE 5.	ASSIGNED=	5	USER NODE NO.=	1005
MACHINE 6.	ASSIGNED=	6	USER NODE NO.=	2001
MACHINE 7.	ASSIGNED=	7	USER NODE NO.=	2002
MACHINE 8.	ASSIGNED=	8	USER NODE NO.=	2003
MACHINE 9.	ASSIGNED=	9	USER NODE NO.=	2004
MACHINE 10.	ASSIGNED=	10	USER NODE NO.=	2005
MACHINE 11.	ASSIGNED=	11	USER NODE NO.=	3001
MACHINE 12.	ASSIGNED=	12	USER NODE NO.=	3002
MACHINE 13.	ASSIGNED=	13	USER NODE NO.=	3003
MACHINE 14.	ASSIGNED=	14	USER NODE NO.=	3004
MACHINE 15.	ASSIGNED=	15	USER NODE NO.=	3005
MACHINE 16.	ASSIGNED=	16	USER NODE NO.=	1101
MACHINE 17.	ASSIGNED=	17	USER NODE NO.=	1102
MACHINE 18.	ASSIGNED=	18	USER NODE NO.=	1103
MACHINE 19.	ASSIGNED=	19	USER NODE NO.=	1104
MACHINE 20.	ASSIGNED=	20	USER NODE NO.=	1105
MACHINE 21.	ASSIGNED=	21	USER NODE NO.=	2101
MACHINE 22.	ASSIGNED=	22	USER NODE NO.=	2102
MACHINE 23.	ASSIGNED=	23	USER NODE NO.=	2103
MACHINE 24.	ASSIGNED=	24	USER NODE NO.=	2104
MACHINE 25.	ASSIGNED=	25	USER NODE NO.=	2105
MACHINE 26.	ASSIGNED=	26	USER NODE NO.=	3101
MACHINE 27.	ASSIGNED=	27	USER NODE NO.=	3102
MACHINE 28.	ASSIGNED=	28	USER NODE NO.=	3103
MACHINE 29.	ASSIGNED=	29	USER NODE NO.=	3104
MACHINE 30.	ASSIGNED=	30	USER NODE NO.=	3105
MACHINE 31.	ASSIGNED=	31	USER NODE NO.=	1201
MACHINE 32.	ASSIGNED=	32	USER NODE NO.=	1202
MACHINE 33.	ASSIGNED=	33	USER NODE NO.=	1203
MACHINE 34.	ASSIGNED=	34	USER NODE NO.=	1204
MACHINE 35.	ASSIGNED=	35	USER NODE NO.=	1205
MACHINE 36.	ASSIGNED=	36	USER NODE NO.=	2201
MACHINE 37.	ASSIGNED=	37	USER NODE NO.=	2202
MACHINE 38.	ASSIGNED=	38	USER NODE NO.=	2203
MACHINE 39.	ASSIGNED=	39	USER NODE NO.=	2204
MACHINE 40.	ASSIGNED=	40	USER NODE NO.=	2205
MACHINE 41.	ASSIGNED=	41	USER NODE NO.=	1301
MACHINE 42.	ASSIGNED=	42	USER NODE NO.=	1302
MACHINE 43.	ASSIGNED=	43	USER NODE NO.=	1303
MACHINE 44.	ASSIGNED=	44	USER NODE NO.=	1304
MACHINE 45.	ASSIGNED=	45	USER NODE NO.=	1305
MACHINE 46.	ASSIGNED=	46	USER NODE NO.=	2301
MACHINE 47.	ASSIGNED=	47	USER NODE NO.=	2302
MACHINE 48.	ASSIGNED=	48	USER NODE NO.=	2303
MACHINE 49.	ASSIGNED=	49	USER NODE NO.=	2304
MACHINE 50.	ASSIGNED=	50	USER NODE NO.=	3201
MACHINE 51.	ASSIGNED=	51	USER NODE NO.=	3202
MACHINE 52.	ASSIGNED=	52	USER NODE NO.=	3203
MACHINE 53.	ASSIGNED=	53	USER NODE NO.=	3204
MACHINE 54.	ASSIGNED=	54	USER NODE NO.=	3205
MACHINE 55.	ASSIGNED=	55	USER NODE NO.=	3206
MACHINE 56.	ASSIGNED=	56	USER NODE NO.=	3207
MACHINE 57.	ASSIGNED=	57	USER NODE NO.=	3208
MACHINE 58.	ASSIGNED=	58	USER NODE NO.=	3209
MACHINE 59.	ASSIGNED=	59	USER NODE NO.=	3210

MACHINE NO. ASSIGNED= NO USER NAME NO.= 3553
 MACHINE NO. ASSIGNED= 61 USER NAME NO.= 3603
 MACHINE NO. ASSIGNED= 62 USER NAME NO.= 3706

 THERE ARE 62 NODES AND 139 LINKS IN NETWORK SX3.1965
 NETWORK SX3.1965 HAS BEEN READ

 \$ FILE NETWORK FOR FUTURE REFERENCE
 STORE NETWORK
 NETWORK SX3.1965 HAS BEEN STORED ON DISK.
 \$ READ IN SUPPLY FUNCTION LIBRARY
 READ VOL/DELAY *MINES.2*, FUNCTIONS 11, POINTS/FUNCTION 4
 \$ DUMMY LINKS
 V/D 1 LOCAL 3 0 1 2 1 4 1 6 1
 \$ AIR ACCESS LINKS
 V/D 2 LOCAL 3 0 1.25 10000 1.25 11000 1.25 12000 1.25
 \$ ROAD, RAIL ACCESS LINKS
 V/D 3 LOCAL 3 0 1.667 10000 1.667 11000 1.667 12000 1.667
 \$ AIRPORT DEPARTURE LINKS
 V/D 4 LOCAL 3 0 28 1750 31.5 2240 39 2450 6A
 \$ RAILROAD STATION LINKS
 V/D 5 LOCAL 3 0 10 10000 10 11000 10 12000 10
 \$ AIR LINE HALL LINKS
 V/D 6 EXP 3 0 .197 5000 .197 6000 .197 7000 .197
 \$ AIRPORT ARRIVAL LINKS
 V/D 7 EXP 3 0 15 1750 17 2240 23 2450 35
 \$ HIGH SPEED RAIL
 V/C 8 ART 3 0 .974 12000 1.05 35000 2.0 40000 5.0
 \$ LOW SPEED RAIL
 V/D 9 ART 3 0 2 15000 2.4 35000 4 40000 10
 \$ HIGH SPEED ROAD
 V/D 10 LOCAL 3 0 1 400 1.2 8000 2.0 8000 4
 \$ LOW SPEED ROAD

V/D 11 17001 1 0 1 0000 3.0 0000 6 0000 12

1 1 1

FUNCTION 1 HAS NO ERRORS
 FUNCTION 2 HAS NO ERRORS
 FUNCTION 3 HAS NO ERRORS
 FUNCTION 4 HAS NO ERRORS
 FUNCTION 5 HAS NO ERRORS
 FUNCTION 6 HAS NO ERRORS
 FUNCTION 7 HAS NO ERRORS
 FUNCTION 8 HAS NO ERRORS
 FUNCTION 9 HAS NO ERRORS
 FUNCTION 10 HAS NO ERRORS
 FUNCTION 11 HAS NO ERRORS

VOLUME DELAY SET 300000, 2 HAS BEEN REAN

1 FILE SUPPLY FUNCTIONS FOR FUTURE REFERENCE

STORE VOLUME DELAY SET
 VOLUME DELAY SET 300000, 2 HAS BEEN STORED ON DISK.

EJECT

```
$      EXAMPLE RUN 2 -- DISTRICT DATA DEFINITION
TRANSET
$      READ IN DEMAND MODEL PARAMETERS
INPUT MODAL SPLIT PARAMETERS 1.805E5 .5 .5 .5 .5 -2.09 -2.18  -
      -.955 -2.74 0 .10
$      READ IN POPULATION, INCOME, AND HOLDING CAPACITY
$      FOR ALL DISTRICTS
INPUT DISTRICT DATA, DISTRICTS 5
DIST      1  4415  2135  5345 WASHINGTON
DIST      2  5448  2079  6104 PHILADELPHIA
DIST      3 16243  2414 20225 NEW YORK
DIST      4  2611  2131  3120 HARTFORD - NEW HAVEN
DIST      5  5278  2032  6544 BOSTON
$      FILE DISTRICT DATA FOR FUTURE REFERENCE
KEEP DISTRICT DATA '5CENTERS'
EJECT
```

```

5  EXAMPLE RUN 2 -- DISTRICT DATA DEFINITION
TRANSET
5  READ IN DEMAND MODEL PARAMETERS
INPUT TOTAL SPLIT PARAMETERS 1.055 5.5 5.5 -2.39 -2.18 -.955 -2.74 0 .10
5  READ IN POPULATION, INCOME AND FILLING CAPACITY FOR DISTRICTS
INPUT DISTRICT DATA, DISTRICTS 5
5  DIST 1 4415 2135 5345 WASHINGTON
5  DIST 2 5448 2079 6104 PHILADELPHIA
5  DIST 3 16243 2414 20225 NEW YORK
5  DIST 4 2411 7131 3120 WARTFORD - NEW HAVEN
5  DIST 5 5278 2032 6544 BOSTON
5  FILE DISTRICT DATA FOR FUTURE REFERENCE
KEEP DISTRICT DATA "SCENTERS"
TOTAL DATA SCENTERS HAS BEEN STORED ON DISK.
EJECT

```

\$ EXAMPLE RUN 3 -- MODAL DATA DEFINITION

TRANSET

\$ SPECIFY TRANSPORT POLICY OPTIONS OF FARE, SERVICE FREQUENCY

INPUT MODAL SERVICE DATA, MODES 3, DISTRICTS 5

DATA MODE 1, 'AIR', SPEED 200

COST	3.5	13.1	18.1	23.7	27.9
COST	13.1	1.0	12.4	21.0	25.6
COST	18.1	12.8	0.0	13.0	15.7
COST	23.7	21.0	14.1	2.8	10.6
COST	27.9	25.9	15.7	10.4	3.1
FREQ	13.0	23.1	21.2	8.9	18.7
FREQ	25.1	0.0	17.6	12.7	17.5
FREQ	22.1	19.6	0.0	10.2	37.7
FREQ	8.7	12.5	9.9	1.0	10.7
FREQ	19.8	18.9	36.6	10.2	4.5

DATA MODE 2 'RAIL', SPEED 50

COST	1.5	7.7	11.0	17.2	22.4
COST	7.7	2.2	6.1	12.8	18.7
COST	11.0	6.1	1.5	6.9	12.1
COST	17.2	12.8	6.8	2.8	6.8
COST	22.4	18.7	12.1	6.8	1.9
FREQ	10.5	21.5	20.0	13.7	11.8
FREQ	20.3	24.0	28.8	15.8	12.4
FREQ	17.9	29.4	38.2	17.9	11.4
FREQ	14.1	17.5	17.7	9.2	7.6
FREQ	12.4	13.0	11.8	7.9	9.1

DATA MODE 3, 'ROAD', SPEED 45

COST	00.00	03.34	05.80	08.17	10.55
COST	03.34	00.00	02.78	05.16	07.54
COST	05.80	02.78	00.00	02.62	05.00
COST	08.17	05.16	02.62	00.00	02.58
COST	10.55	07.54	05.00	02.53	00.00
FREQ	00.00	96.00	96.00	96.00	96.00
FREQ	96.00	00.00	96.00	96.00	96.00
FREQ	96.00	96.00	00.00	96.00	96.00
FREQ	96.00	96.00	96.00	00.00	96.00
FREQ	96.00	96.00	96.00	96.00	00.00

\$ SPECIFY TECHNOLOGICAL CHARACTERISTICS OF EACH MODE

INPUT MODAL COST DATA, MODE 'AIR', SUBSIDY 75000000 FIXED COST -

100000000 VARIABLE COST RATE .07 TAX RATE .05

INPUT MODAL COST DATA, MODE 'RAIL', SUBSIDY 0 FIXED COST -

80000000 VARIABLE COST RATE .02 TAX RATE .00

INPUT MODAL COST DATA, MODE 'ROAD', SUBSIDY 0 FIXED COST -

20000000 VARIABLE COST RATE .013 TAX RATE 0

\$ FILE MODAL DATA FOR FUTURE REFERENCE

KEEP MODAL DATA '5X3 NO.1'

ENDCT

```

0  EXAMPLE RUN 3 -- MODAL DATA OPTIMIZATION
TRANSET
1  SPECIFY TRANSPORT POLICY OPTIONS OF FARE, SERVICE FREQUENCY
INPUT MODAL SERVICE DATA, MODES 3, DISTRICTS
DATA MODE 1, 'AIR', SPEED 200
1  COST 3.5 13.1 10.1 23.7 22.9
4  COST 13.1 1.0 12.4 21.0 25.6
6  COST 10.1 12.0 0.0 13.0 15.7
5  COST 23.7 21.0 14.1 2.8 10.6
6  COST 27.9 25.9 15.7 10.4 3.1
6  FREQ 13.0 23.1 21.2 0.9 18.7
6  FREQ 25.1 0.0 17.6 17.7 17.5
6  FREQ 22.1 19.6 0.0 10.2 37.7
6  FREQ 0.7 12.5 9.9 1.0 10.7
5  FREQ 19.8 10.9 16.4 10.2 4.5
DATA MODE 2 'RAIL', SPEED 20
1  COST 1.5 7.7 11.0 17.2 22.4
6  COST 7.7 2.2 6.1 12.8 18.7
6  COST 11.0 4.1 1.5 6.9 12.1
6  COST 17.2 12.9 6.8 2.8 6.8
5  COST 22.4 18.7 12.1 6.8 1.9
6  FREQ 10.5 21.5 20.0 13.7 11.8
6  FREQ 20.3 24.0 28.8 15.8 12.4
6  FREQ 17.9 29.4 38.2 17.9 11.4
6  FREQ 14.1 17.5 17.7 9.2 7.6
6  FREQ 12.4 13.0 11.8 7.9 9.1
DATA MODE 3, 'ROAD', SPEED 45
1  COST 00.00 03.34 05.40 09.17 10.55
6  COST 03.34 00.00 02.78 05.16 07.54
6  COST 05.60 02.78 00.00 07.67 05.00

```

```

1  COST 02.17 05.16 02.67 00.00 02. 8
1  COST 10.55 07.54 05.00 02.53 00.00
1  FREQ 00.00 06.00 04.00 06.00 06.00
1  FREQ 06.00 00.00 06.00 06.00 06.00
1  FREQ 06.00 06.00 00.00 06.00 06.00
1  FREQ 06.00 06.00 06.00 00.00 06.
1  FREQ 06.00 06.00 06.00 06.00 00.00
1  FREQ 06.00 06.00 06.00 06.00 00.00
1  SPECIFY TECHNOLOGICAL CHARACTERISTICS OF EACH MODE
INPUT MODAL COST DATA: MODE 'AIR', SUBSIDY 75000000 FIXED COST 100000000 -
VARIABLE COST RATE .07 TAX RATE .05
INPUT MODAL COST DATA: MODE 'RAIL', SUBSIDY 0 FIXED COST 80000000 -
VARIABLE COST RATE .02 TAX RATE .00
INPUT MODAL COST DATA: MODE 'ROAD', SUBSIDY 0 FIXED COST 200000000 -
VARIABLE COST RATE .013 TAX RATE 0
1  FILE MODAL DATA FOR FUTURE REFERENCE
KEEP MODAL DATA 'S83 NO.1'
MODAL DATA S83 NO.1 HAS BEEN STORED ON DISK.
EJECT

```

\$ EXAMPLE RUN 4 -- CALCULATION OF ESTIMATED TRIP DEMANDS
TRANSET
\$ RETRIEVE DATA PREVIOUSLY FILED
LOAD NETWORK '5X3,1965'
GET DISTRICT DATA '5CENTERS'
GET MODAL DATA '5X3 NO.1'
PREDICT POTENTIAL TRIP 'BASE' GEN 'BASE'
\$ FILE ESTIMATED TRIPS AND DEMAND FUNCTION DATA
\$ FOR FUTURE REFERENCE
STORE TRIP MATRIX
STORE GEN RATE SET
EJECT


```

5  EXAMPLE RUN 5 -- CALCULATION OF ESTIMATED TRIP DEMANDS
TRANSET
5  RETRIEVE DATA PREVIOUSLY FILED
LOAD NETWORK '5X3,1965'
GET DISTRICT DATA 'SCENTERS'
GET MODEL DATA '5X3 WD.1'
PREDICT POTENTIAL TRIP 'BASE' GEN 'BASE'
5  FILE ESTIMATED TRIPS AND DEMAND FUNCTION DATA FOR FUTURE REFERENCE
STORE TRIP MATRIX
TRIP MATRIX BASE HAS BEEN STORED ON DISK.
STORE GEN RATE SET
GENERATION RATE SET HAS BEEN STORED IN DISK
EJECT

```

```

$      EXAMPLE RUN 5 -- EQUILIBRIUM AND IMPACTS
TRANSET
$      RETRIEVE DATA PREVIOUSLY FILED
LOAD NETWORK '5X3,1965'
LOAD TRIPS 'BASE'
LOAD VOL/DELAY SET '3MODES,2'
LOAD GEN/RATE SET 'BASE'
GET DISTRICT DATA '5CENTERS'
GET MODAL DATA '5X3 NO.1'
$      DEFINE VARIABLE INCREMENT
USE INCREMENT 50 PERCENT
$      SPECIFY NAME OF NETWORK WHICH WILL INCLUDE
$      THE EQUILIBRIUM CONDITIONS
SAVE ASSIGNMENT RESULTS IN NETWORK 'BASE'
$      START THE INCREMENTAL APPROACH TO EQUILIBRIUM COMPUTATION
PREDICT ACTUAL TRIPS
$      OUTPUT ACTUAL AND ESTIMATED TRIP DEMANDS
$      CONTRARY TO HEADING, TRIPS ARE IN PASSENGERS PER DAY
PRINT TRIP MATRIX 'BASE'
$      OBTAIN COST DATA BASED ON ACTUAL FLOW PATTERN
EVALUATE COSTS TIME VALUE 2.00 WAIT FACTOR .50
$      OBTAIN ACCESSIBILITY DATA AND DEFINE ALTERNATIVE DATA,
$      TO BE USED IN COMPARE AND PREDICT DISTRICT DATA COMMANDS.
EVALUATE ACCESS, ALTERNATIVE 'BASE'
EJECT

```

5 EXAMPLE RUN 5 -- EQUILIBRIUM AND IMPACTS

TRANSET

6 RETRIEVE DATA PREVIOUSLY FILED

LOAD NETWORK '5X3.1765'

LOAD TRIPS 'BASE'

LOAD VOL/DELAY SET '3MODES.2'

LOAD GEN/RATE SET 'BASE'

GET DISTRICT DATA 'SCENTERS'

GET MODEL DATA '5X3 NO.1'

7 DEFINE VARIABLE INCREMENT

USE INCREMENT 50 PERCENT

8 SPECIFY NAME OF NETWORK WHICH WILL INCLUDE THE EQUILIBRIUM CONDITIONS

SAVE ASSIGNMENT RESULTS IN NETWORK 'BASE'

9 START THE INCREMENTAL APPROACH TO EQUILIBRIUM COMPUTATION

PREDICT ACTUAL TRIPS

THE NETWORK IS COMPLETELY ASSIGNED AFTER 420 ITERATIONS

TIME USED SINCE START OF RUN IS 1.65 MINUTES

ASSIGNMENT RESULTS HAVE BEEN STORED ON DISK IN NETWORK BASE

8 OUTPUT ACTUAL AND ESTIMATED TRIP DEMANDS

9 CONTRARY TO HEADING, TRIPS ARE IN PASSENGERS PER DAY

PRINT TRIP MATRIX 'BASE'

INTERZONAL TRIP STATUS

TRIP MATRIX NAME IS BASE

THIS IS THE TABLE TO CONVERT MACHINE ZONE NUMBERS TO USED ZONE NUMBERS

MACHINE NUMBERS	1	2	3	4	5	6	7	8	9	10
1001	1002	1003	1004	1005	1006	2001	2002	2003	2004	2005
3001	3002	3003	3004	3005	3006					

THE FOLLOWING MATRIX USES MACHINE ZONE NUMBERS.

002 002

002 002

002 002

002 002

002 002

002 002

YU JUNE
PRIME JUNE

15

14

13

12

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14	342	920	1	3	3
	338	1392	12564	0	8754
	3	3	14300	0	3334
			3	3	3
15	230	560	3308	8906	0
	216	624	3372	9510	0
	3	3	3	3	1

3 OBTAIN COST DATA BASED ON ACTUAL FLOW PATTERN
EVALUATE COSTS TIME VALUE 2.00 WAIT FACTOR .50

COST SHARES FOR NETWORK RASH
AND TRIP MATRIX BASE

DAILY USER DATA BY MODE AND ORIGIN

MODE	ORIGIN DISTRICT (PASS/DAY)	TOTAL TRIPS	USER FARE		USER TRAVEL TIME		USER WAIT TIME		WEIGHTED COSTS	
			TOTAL (\$)	AVERAGE (\$/TRIP)	TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL (\$)	AVERAGE (\$/TRIP)
AIR	1	1552	0.28861E 05	18.60	0.39947E 04	154.	0.99343E 03	38.41	0.39837E 05	25.02
	2	1618	0.24215E 05	14.97	0.36320E 04	135.	0.10535E 04	39.07	0.33586E 05	20.76
	3	3054	0.46437E 05	15.21	0.69182E 04	134.	0.17284E 04	33.96	0.43731E 05	20.87
	4	974	0.14885E 05	15.28	0.22902E 04	141.	0.11386E 04	30.14	0.21742E 05	22.32
	5	1844	0.31603E 05	17.14	0.44475E 04	145.	0.10327E 04	33.50	0.42554E 05	23.04
RAIL	1	1424	0.13982E 05	9.81	0.41999E 04	261.	0.45517E 03	35.94	0.24092E 05	19.70
	2	4674	0.31738E 05	6.79	0.13401E 05	172.	0.21759E 04	27.92	0.62891E 05	13.45
	3	5922	0.41682E 05	7.04	0.18018E 05	183.	0.31044E 04	31.45	0.43924E 05	14.17
	4	2020	0.15598E 05	7.72	0.65330E 04	194.	0.16744E 04	49.73	0.32013E 05	15.85
	5	672	0.71588E 04	10.65	0.34545E 04	304.	0.83411E 03	74.47	0.15736E 05	23.42
ROAD	1	7968	0.36145E 05	4.54	0.42515E 05	320.	0.99600E 03	7.50	0.12317E 04	15.46
	2	18470	0.58890E 05	3.19	0.90947E 05	295.	0.23087E 04	7.50	0.24541E 04	13.29
	3	29900	0.95604E 05	3.20	0.13415E 06	269.	0.37375E 04	7.50	0.37138E 04	17.42
	4	22980	0.63044E 05	2.79	0.84587E 05	225.	0.28225E 04	7.50	0.23936E 04	10.54
	5	13004	0.45721E 05	3.52	0.59450E 05	274.	0.16255E 04	7.50	0.16789E 04	12.91

DAILY USER DATA BY MODE

M O D E	TOTAL TRIPS (PASS/DAY)	USER CARDS		USER TRAVEL TIME		USER WAIT TIME		WEIGHTED COSTS	
		TOTAL (S)	AVERAGE (S/TRIP)	TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL (S)	AVERAGE (S/TRIP)
AIR	9042	0.1460E 06	16.15	0.21283E 05	141.	0.59466E 04	39.46	0.20044E 06	22.17
RAIL	14716	0.11016E 06	7.49	0.47506E 05	134.	0.86439E 04	35.24	0.22256E 05	15.13
ROAD	91922	0.79940E 06	3.26	0.41177E 06	753.	0.11490E 05	7.50	0.11459E 07	12.47
T O T A L S	115680	0.55556E 06	4.80	0.48066E 06	749.	0.26081E 05	13.53	0.15698E 07	13.56

YEARLY COSTS AND REVENUES BY MODE

M O D E	TOTAL TRIPS	USER CARDS	TOTAL USER COSTS	OPERATOR'S PROFIT	GOVERNMENT REVENUE	OPERATOR'S PROFIT PER PASSENGER	GOVT. REVENUE PER PASSENGER
AIR	3300330	0.53293E 08	0.40134E 08	-0.26871E 04	-3.72335E 04	-9.14	-21.92
RAIL	5371340	0.40207E 08	0.66797E 08	-0.55785E 04	0.0	-10.39	0.0
ROAD	33551520	0.10928E 09	0.34378E 09	0.15690E 08	0.0	0.47	0.0
TOTALS	42223200	0.20278E 09	0.57270E 09	-0.56966E 04	-0.72335E 04	-1.59	-1.71

- 5 OBTAIN ACCESSIBILITY DATA AND DEFINE ALTERNATIVE DATA TO BE
- 6 USED IN COMPARE AND PREDICT DISTRICT DATA COMMANDS.
- EVALUATE ACCESS, ALTERNATIVE 'BASE'

ACCESSIBILITY FOR ALTERNATIVE BASE

NETWORK BASE

TRIP MATRIX BASE

ORIGIN DISTRICT	AIR	RAIL	WDOF	ROAD	ALL WDOFS
1	0.15984E 04	0.14688E 04	0.42070E 04	0.11274E 05	0.23259E 05
2	0.15203E 04	0.43937E 04	0.17355E 05	0.19633E 05	0.34245E 05
3	0.15423E 04	0.29907E 04	0.15100E 05	0.12557E 05	0.14986E 05
4	0.13058E 04	0.27080E 04	0.12557E 05	0.12557E 05	0.14986E 05
5	0.17806E 04	0.64889E 03	0.12557E 05	0.12557E 05	0.14986E 05
ALL ORIGINS	0.15649E 04	0.26376E 04	0.15336E 05	0.19534E 05	

ALTERNATE FILE NUMBER BASE HAS BEEN STORED ON DISK

EJECT

```

$      EXAMPLE RUN 6 -- FLOW PATTERN SUMMARIES
TRANSET
$      CHECK FOR CONGESTION POINTS
$      CONTRARY TO HEADING, VOLUME IS IN PASSENGERS PER DAY
REQUEST FINAL PRINTOUT OF VOL CAPACITY RATIOS FROM NETWORK 'BASE' --
      FOR ALL LINKS
$      LIST ALL LINK-BASED FLOW PATTERN DATA
$      VOLUMES AGAIN IN PASSENGERS PER DAY
REQUEST FINAL PRINTOUT OF LINK VOLUMES, SPEEDS, AND TIMES FROM -
      NETWORK 'BASE' FOR ALL LINKS
$      INTERZONAL TRAVEL TIMES -- ALL ENTRIES CORRESPONDING TO -
$      ZERO TRIPS ARE MEANINGLESS - SEE TRIP MATRIX.
REQUEST FINAL PRINTOUT OF TRAVEL TIMES FROM NETWORK 'BASE' -
      FOR ALL ZONES
EJECT

```

5 SAMPLE RUN 5 -- FLOW PATTERN SUMMARIES

TRANSIT

5 CHECK FOR CONGESTION POINTS

5 CONTRARY TO HEADING, VOLUME IS IN PASSENGERS PER DAY

REQUEST FINAL PRINTOUT OF VOL CAPACITY RATIOS FROM NETWORK 'BASE' -
FOR ALL LINKS

FINAL OUTPUT

LINK	VOLUME (VEHICLES PER HOUR)	VOLUME-CAPACITY RATIO
1001 1101	1552	0.14
1001 2001	0	0.0
1002 1102	1618	0.15
1002 2002	0	0.0
1003 1103	3054	0.28
1003 2003	0	0.0
1004 1104	974	0.09
1004 2004	0	0.0
1005 1105	1844	0.17
1005 2005	0	0.0
2001 1101	1426	0.13
2001 2001	0	0.0
2002 1102	4676	0.43
2002 2002	0	0.0
2003 1103	5922	0.54
2003 2003	0	0.0
2004 1104	2021	0.19
2004 2004	0	0.0
2005 1105	672	0.06
2005 2005	0	0.0
3001 1101	7568	0.72
3001 2001	0	0.0
3002 1102	18470	1.59
3002 2002	0	0.0
3003 1103	29900	2.72
3003 2003	0	0.0
3004 1104	22580	2.05
3004 2004	0	0.0
3005 1105	13004	1.19
3005 2005	0	0.0
1101 1001	1570	0.14
1101 1001	1552	0.14
1102 1002	1546	0.14
1102 1002	1618	0.14
1103 1003	3022	0.27
1103 1003	3054	0.28

1305	1201	210	0.03
1305	1202	198	0.13
1305	1203	1077	0.18
1305	1204	366	0.35
1301	2201	1416	0.34
1301	2202	1426	0.04
2307	2202	4627	0.37
2302	2203	4618	0.37
2303	2203	2054	0.33
2303	2204	1998	0.33
2304	2204	672	0.02
2304	2205	680	0.02
3201	3101	8184	0.34
3201	3102	7968	0.50
3402	3201	8184	0.51
3402	3202	6910	0.63
3402	3202	1058	0.07
3202	3102	1058	0.07
3202	3402	1262	0.08
3302	3102	16862	1.35
3302	3402	17208	1.36
3402	3102	16867	1.35
3402	3102	16574	0.69
3402	3502	6922	0.43
3402	3402	6922	0.43
3502	3402	6780	0.43
3702	3402	16220	3.69
3702	3203	16574	3.69
3203	3702	16220	0.68
3203	3403	2036	0.09
3203	3103	14538	0.61
3403	3103	15072	0.66
3303	3503	15732	0.66
3403	3203	2052	0.39
3403	3503	2036	0.39
3503	3303	15072	0.54
3503	3403	2052	0.09
3503	3603	17768	0.74
3603	3503	17924	0.75
3603	3104	17768	0.74
3204	3104	13004	0.61
3204	3105	12498	0.78

8 LIST ALL LINK-BASED FLOW PATTERN DATA

8 VOLUMES AGAIN IN PASSENGERS PER DAY

REQUEST FINAL PRINTOUT OF LINK VOLUMES, SPEEDS, AND TIMES FROM NEARER 'BASE' -
FOR ALL LINKS

FINAL OUTPUT

LINK TABLE
THIS TABLE IS FOR ALL LINKS IN NETWORK BASE
THE FOLLOWING GIVES THE TRAFFIC VOLUME, SPEEDS, AND TRAVEL TIMES OVER THE NETWORK CONTAINING 139 LINKS.

LINK FROM TO	TRAFFIC VOLUME (VEHICLES PER HOUR)	SPEED (MILES PER HOUR)	TRAVEL TIME (MINUTES)
1001 1101	1552	48.1	33.20
1001 2001	0	60.7	800.00
1002 1102	1618	48.1	34.40
1002 2002	0	60.0	800.00
1003 1103	3054	48.2	26.70
1003 2003	0	60.0	800.00
1004 1104	974	48.3	38.00
1004 2004	0	60.9	800.00
1005 1105	1844	47.9	29.80
1005 2005	0	60.0	800.00
2001 2101	1426	36.0	30.00
2001 3001	0	50.0	800.00
2002 2102	4676	36.0	19.00
2002 3002	0	60.0	800.00
2003 2103	5922	36.0	28.00
2003 3003	0	60.0	800.00
2004 2104	2020	36.0	21.00
2004 3004	0	60.0	800.00
2005 2105	672	36.0	26.00
2005 3005	0	60.0	800.00
3001 3101	7968	36.0	30.00
3001 4001	0	60.0	800.00
3002 3102	18470	35.0	19.00
3002 4002	0	60.0	800.00
3003 3103	29900	36.0	29.00
3003 4003	0	60.0	800.00
3004 3104	22580	35.0	21.00
3004 4004	0	60.0	800.00
3005 3105	13004	36.0	24.00
3005 4005	0	60.0	800.00
1101 1001	1570	48.1	33.20
1101 1301	1552	2.0	29.60
1102 1002	1546	48.1	34.40
1102 1302	1618	2.1	29.00
1103 1003	3022	48.2	26.40
1103 1303	3054	2.1	29.00
1104 1004	1060	48.0	38.00
1104 1304	974	2.1	29.60
1105 1005	1844	47.9	29.80
1105 1305	1844	2.1	29.00
2101 2001	1416	36.0	30.00
2101 2201	1426	6.0	10.00
2102 2002	4690	36.0	12.00
2102 2202	4676	6.0	10.00
2103 2003	5974	36.0	28.00
2103 2203	5922	6.0	10.00
2104 2004	1956	36.0	21.00
2104 2204	2020	6.0	10.00
2105 2005	680	36.0	24.00
2105 2205	672	6.0	10.00

3101	3101	8184	36.0	30.00
3101	3101	7968	18.5	18.80
3102	3102	17900	35.0	19.00
3102	3102	17208	5.7	61.00
3103	3103	1262	19.4	72.20
3103	3103	30410	36.0	28.00
3103	3103	15732	17.1	7.00
3103	3103	14168	17.5	20.60
3104	3104	22930	36.0	21.00
3104	3104	12498	16.8	30.40
3104	3104	17924	50.5	121.80
3105	3105	12498	36.0	26.00
3105	3105	13004	48.0	124.60
3105	3105	1570	3.8	15.80
3105	3105	1546	3.8	15.60
3105	3105	3022	3.9	15.60
3105	3105	1080	3.9	15.40
3105	3105	1844	3.8	15.60
3105	3105	1416	6.0	10.00
3105	3105	1426	29.6	13.80
3105	3105	4690	6.0	10.00
3105	3105	4618	29.2	10.00
3105	3105	1416	63.9	7.40
3105	3105	5974	6.0	120.60
3105	3105	1998	29.6	10.00
3105	3105	4622	63.2	58.00
3105	3105	1956	6.0	83.20
3105	3105	680	29.7	10.00
3105	3105	2054	64.1	40.40
3105	3105	680	6.0	41.00
3105	3105	672	64.4	10.00
3105	3105	420	305.1	127.40
3105	3105	774	304.0	23.60
3105	3105	152	304.7	45.00
3105	3105	206	304.4	64.00
3105	3105	626	305.1	81.40
3105	3105	652	303.3	23.60
3105	3105	138	304.7	18.40
3105	3105	202	304.4	38.40
3105	3105	782	304.0	55.00
3105	3105	790	303.3	45.00
3105	3105	606	305.8	18.40
3105	3105	1076	304.9	20.80
3105	3105	152	304.7	36.60
3105	3105	138	304.7	64.00
3105	3105	324	305.8	38.40
3105	3105	360	303.3	20.80
3105	3105	210	304.4	18.00
3105	3105	198	304.4	81.40
3105	3105	1072	304.9	55.00
3105	3105	364	303.3	16.60
3105	3105	1416	29.6	18.00
3105	3105	1426	63.9	13.80
3105	3105	4622	29.2	120.60
3105	3105	4518	63.2	7.40
3105	3105	2054	29.6	83.20
3105	3105	1998	64.1	58.00
3105	3105	672	29.7	41.00
3105	3105	680	64.4	40.40
3105	3105	8184	18.5	127.40
3105	3105	7968	53.1	19.80
3105	3105			111.40

3402	3201	8184	53.2	111.60
3402	3502	6910	18.1	8.60
3402	3202	1058	59.1	13.40
3202	3102	1058	19.7	72.00
3202	3402	1267	59.1	13.40
3302	3102	16847	6.5	53.20
3302	3602	17208	17.1	45.40
3602	3302	16842	19.7	39.60
3602	3702	16574	17.1	19.20
3502	3502	6922	54.2	41.20
3502	3602	6910	18.1	8.60
3502	3602	16220	54.2	41.20
3702	3602	16220	17.1	18.20
3702	3203	15574	51.1	92.20
3703	3702	16220	51.4	91.80
3203	3403	2036	19.5	8.00
3203	3103	14538	17.3	20.80
3303	3103	15872	17.1	7.00
3303	3503	15732	51.4	7.00
3403	3203	2052	19.5	8.00
3403	3503	2036	58.5	8.00
3503	3303	15872	51.4	7.00
3503	3403	2052	58.5	8.00
3503	3603	17768	16.9	37.60
3603	3503	17924	16.8	37.80
3603	3104	17768	50.5	121.60
3204	3104	13004	16.0	32.20
3204	3105	12498	50.2	119.00

5 INTERZONAL TRAVEL TIMES -- ALL ENTRIES CORRESPONDING TO ZERO TRIPS ARE

5 MISSING (SEE TRIP MATRIX).

REQUEST FINAL PRINTOUT OF TRAVEL TIMES FROM NETWORK 'BASE' FOR ALL ZONES

FINAL OUTPUT

TRAVEL TIME OUTPUT FOR NETWORK BASE

THIS IS THE TABLE TO CONVERT MACHINE NODE NUMBERS TO USER NODE NUMBERS

MACHINE NUMBERS	1	2	3	4	5	5	7	8	9	10
C USER NUMBERS	1001	1002	1003	1004	1005	2001	2002	2003	2004	2005
10 USER NUMBERS	2001	2002	3003	3004	3005	1101	1102	1103	1104	1105
20 USER NUMBERS	2101	2102	2102	2104	2105	3101	3102	3103	3104	3105
30 USER NUMBERS	1201	1202	1203	1204	1205	2201	2202	2203	2204	2205
40 USER NUMBERS	1301	1302	1303	1304	1305	2301	2302	2303	2304	2305
50 USER NUMBERS	3402	3203	3302	3402	3402	3702	3702	3703	3403	3503
60 USER NUMBERS	3603	3704								

THE FOLLOWING MATRIX USES MACHINE NODE NUMBERS

THIS IS THE MATRIX FOR 15 ZONES WHICH GIVES THE TRAVEL TIMES
BETWEEN ALL ZONE PAIRS IN MINUTES.

TO ZONE FROM ZONE	1	2	3	4	5	6	7	8	9	10
1	0.0	136.40	149.80	180.20	189.60	807.20	936.40	949.80	980.20	999.60
2	136.40	0.0	173.80	155.20	163.80	935.20	803.00	923.80	945.20	963.80
3	149.80	173.80	0.0	129.60	137.40	943.40	923.80	900.00	928.60	937.40
4	180.20	155.20	129.60	0.0	130.00	979.60	955.00	929.40	900.00	930.00
5	189.60	163.80	137.40	130.00	0.0	989.20	953.80	937.40	930.20	800.00
6	807.20	935.20	943.40	979.60	989.20	0.0	207.40	303.00	395.20	567.80
7	936.40	803.00	923.80	955.00	953.80	207.40	0.0	157.50	249.60	422.40
8	949.80	923.80	900.00	929.40	937.40	303.00	157.50	0.0	148.00	340.80
9	980.20	945.20	928.60	900.00	930.20	395.20	249.60	148.00	0.0	234.80
10	999.60	963.80	937.40	930.00	800.00	567.80	422.40	340.80	234.80	0.0

TO ZONE FROM ZONE	11	12	13	14	15
1	1600.00	1736.40	1749.80	1780.20	1789.60
2	1736.40	1600.00	1773.80	1755.20	1753.80
3	1749.80	1773.80	1600.00	1729.60	1737.40
4	1779.60	1755.00	1729.40	1600.00	1730.00
5	1789.20	1763.80	1737.40	1730.20	1600.00
6	800.00	1003.40	1103.00	1195.00	1267.80
7	1003.40	800.00	957.60	1049.60	1222.40
8	1103.00	957.60	800.00	968.00	1140.80
9	1195.00	1049.60	968.00	800.00	996.80
10	1267.80	1222.40	1140.80	1003.40	800.00
11	0.0	264.60	369.20	516.60	671.40
12	264.60	0.0	284.80	437.20	587.00
13	369.20	284.80	0.0	222.20	377.00
14	516.60	437.20	222.20	0.0	196.80
15	671.40	587.00	377.00	196.80	0.0

EJECT

\$ EXAMPLE RUN 7 -- USE OF TWO ALTERNATIVES
 \$ BASE -- DEFINED IN RUN 5
 \$ NEWRAIL -- UPGRADING OF RAIL TO APPROXIMATELY
 \$ 90 MPH IN THE CORRIDOR
 TRANSET
 \$ OBTAIN DIFFERENCES BETWEEN THE TWO ALTERNATIVES
 \$ COMPARE ACCESSIBILITIES, TRIPS, SURPLUSES, ALTERNATIVES -
 \$ 'NEWRAIL' AND 'BASE', TIME VALUE 2.00 WAIT FACTOR .50
 \$ SHOW THE AFFECT THE NEW ALTERNATIVE WILL HAVE ON
 \$ POPULATION AND INCOME IN 1975
 \$ GET DISTRICT DATA 'SCENTERS'
 \$ PREDICT DISTRICT DATA, BASE ALTERNATIVE 'BASE' NEW ALTERNATIVE -
 \$ 'NEWRAIL' ACCESS WEIGHT 1.0, POPULATION GROWTH RATE .15, -
 \$ REGIONAL PRODUCT GROWTH RATE .35
 FINISH

```

5  EXAMPLE RUN 7 -- USE OF TWO ALTERNATIVES
5
5  WAST -- DEFINED IN MIN 5
5  CEMRAIL -- UPGRADEING OF RAIL TO APPROXIMATELY 30 MPH IN THE
5              CORRIDOR
5
5  TRANSF
5
5  OBTAIN DIFFERENCES BETWEEN THE TWO ALTERNATIVES
5  COMPARE ACCESSIBILITIES, TRIPS, SURPLUSES, ALTERNATIVE 'NEWRAIL' AND 'BASE',
5  TIME VALUE 2.00 WAIT FACTOR .5C

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COMPARISON OF ALTERNATIVES NEWRAIL AND BASE

NETWORK NEWRAIL AND BASE

TRIP MATRIX BASE AND BASE

VALUES SHOWN ARE (ALTERNATIVE NEWRAIL) - (ALTERNATIVE BASE)

CHANGE IN ACCESSIBILITIES

ORIGIN DISTRICT	AIR	RAIL	MODE	ROAD	ALL MODES
1	0.0	0.10733F 04		0.20625F 01	0.10753F 04
2	0.0	0.25050F 04		0.0	0.25050F 04
3	0.0	0.21402F 04		-0.20195F 01	0.21382F 04
4	0.0	0.10164F 04		0.26436F 01	0.30191F 04
5	0.0	0.75704F 04		0.0	0.75704F 04
ALL ORIGINS	0.0	0.19127F 04		-0.44219F 00	0.19122F 04

CHANGE IN TRIPS

ORIGIN DISTRICT	AIR	RAIL	ROAD	ALL MODES
1	0	1042	2	1044
2	0	2666	0	2666
3	0	4218	-4	4234
4	0	7250	2	2252
5	0	784	0	784
ALL ORIGINS	0	10980	0	10980

CHANGE IN CONSUMER TRAVEL TIME SURPLUS
(PASSENGER-HOURS PER DAY)

ORIGIN DISTRICT	AIR	RAIL	MODE	ROAD	ALL MODES
1	0.0	0.18086E 04	-0.11706E 02	0.26467E 04	
2	0.0	0.10723E 04	0.0	0.73694E 04	
3	0.0	0.52107E 04	-0.31387E 02	0.10462E 05	
4	0.0	0.29627E 04	-0.95156E 01	0.47622E 04	
5	0.0	0.15808E 04	-0.15520E 01	0.14969E 04	
ALL ORIGINS	0.0	0.14131E 05	-0.54409E 02	0.76404E 05	

CHANGE IN CONSUMER TRAVEL COST SURPLUS
(DOLLARS PER DAY)

ORIGIN DISTRICT	AIR	RAIL	MODE	ROAD	ALL MODES

1	0.0	-0.46951E 03	-0.12023E 02	-0.31485E 04
2	0.0	-0.12590E 04	0.0	-0.69179E 04
3	0.0	-0.12655E 04	0.72139E 01	-0.10939E 05
4	0.0	-0.11751E 03	-0.47377E 01	-0.89252E 04
5	0.0	-0.39656E 03	0.0	-0.45157E 04
ALL ORIGINS	0.0	-0.47940E 04	-0.11196E 02	-0.34025E 05

CHANGE IN CONSUMER WAITING TIME SURPLUS
(PASSENGER-HOURS PER DAY)

ORIGIN DISTRICT	AIR	RAIL	MODE	ROAD	ALL MODES
1	0.0	-0.14390E 02	0.0	0.0	-0.35589E 03
2	0.0	-0.65271E 02	0.0	0.0	-0.69993E 03
3	0.0	-0.21234E 03	0.95043E-03	0.0	-0.14796E 04
4	0.0	0.37081E 02	0.0	0.0	-0.12653E 04
5	0.0	0.27837E 02	0.0	0.0	-0.74038E 03
ALL ORIGINS	0.0	-0.59260E 03	0.80359E-02	0.0	-0.45228E 04

CHANGE IN CONSUMER WEIGHTED FRICTION SURPLUS
(WEIGHTED FRICTION = TRAVEL COST SURPLUS
+ 2.00 * TRAVEL TIME SURPLUS
+ 1.00 * WAITING TIME SURPLUS)

ORIGIN DISTRICT	AIR	RAIL	MODE	ROAD	ALL MODES
1	0.0	0.31248E 04	-0.35434E 02	0.14330E 04	0.14330E 04
2	0.0	0.27661E 04	0.0	0.64439E 04	0.64439E 04
3	0.0	0.87307E 04	-0.55558E 02	0.71264E 04	0.71264E 04
4	0.0	0.58872E 04	-0.23769E 02	-0.19313E 04	-0.19313E 04
5	0.0	0.28207E 04	-0.37039E 01	-0.30027E 04	-0.30027E 04
ALL ORIGINS	0.0	0.22284E 05	-0.12060E 03	0.10538E 05	0.10538E 05

5 SHOW THE AFFECT THE NEW ALTERNATIVE WILL HAVE ON POPULATION AND

5 INCREASE IN 1975

GET DISTRICT DATA *SCENTERS*

PREDICT DISTRICT DATA, BASE ALTERNATIVE *BASE* NEW ALTERNATIVE *NEWRAIL* -
ACCESS WEIGHT 1.0, POPULATION GROWTH RATE .15, REGIONAL PRODUCT GROWTH -
RATE .15

ACTIVITY SYSTEM PREDICTIONS

FOR ALTERNATIVE NEWRAIL

BASED ON BASE

ORIGIN DISTRICT	PAST YEAR POPULATION IN MILLIONS	PREDICTED POPULATION IN MILLIONS	PERCENT INCREASE	BASE YEAR PER CAPITA INCOME	PREDICTED PER CAPITA INCOME	PERCENT INCREASE
1	4.415	4.880	10.52	2135.	2415.	13.13
2	5.448	5.931	8.86	2079.	2610.	25.55
3	16.243	17.451	19.75	2414.	2825.	17.01
4	7.611	7.968	13.66	2131.	2530.	18.73
5	5.278	5.866	11.14	2032.	2254.	10.94

REGIONAL TOTALS

BASE YEAR	PREDICTION	PERCENT INCREASE

POPULATION IN MILLIONS 33.995 39.094 15.00

NET REGIONAL PRODUCT (BILLIONS OF DOLLARS) 76.752 102.940 35.20

FINISH

GOOD-BYE

4.0 Prototype Analysis Experiments

The prototype analysis system has been used to provide data for the analysis of a number of issues:

- 1) how the results of an equilibrium analysis can differ from "non-equilibrium" analyses;
- 2) how alternative transportation networks will impact on users; on transportation operators; on governmental costs and revenues; and on the regional pattern of population and income distribution;
- 3) how impacts vary for different combinations of capital investment in fixed facilities (the network), changes in fares, and changes in service frequency;
- 4) how different time staging strategies of investment in transportation can affect the growth of the region, including the variations due to timing of investment and due to changes in the sequence of investment in various links in the network;
- 5) how a transportation sensitivity analysis can be done in the network context, to determine the sensitivities of impacts with respect both to key data variables and to exogenous policy decisions.

The analysis of each of these five issues has been termed an "experiment." Complete descriptions of these experiments are given in Chapter V of the Prototype Analysis report.

For this summary report, two major themes arising from these experiments are significant:

- a. the errors introduced by "non-equilibrium" analyses;
- b. the systematic analysis of options and impacts.

These two themes will be discussed in the following sections.

For descriptions of the other experiments, especially those on time-staging of alternatives and sensitivity analyses, the reader is referred to the Prototype Analysis report.

5.0 Equilibrium vs. Non-Equilibrium Analysis

5.1 Purpose of the Experiment

An important conclusion of the research project is that transportation systems analysis in general is an equilibrium problem and that particular substantive analyses should be designed to determine transportation equilibria. It can therefore be asked whether equilibrium analysis is necessary, or whether more traditional non-equilibrium analyses are just as good. This experiment has been designed to show what can happen when non-equilibrium analyses are attempted in the Northeast Corridor. The differences between equilibrium and various non-equilibrium analyses, and the errors introduced by non-equilibrium analyses can then be shown.

5.2 Experimental Design

A set of five runs was devised to show various types of non-equilibrium analyses. The characteristics of the five runs are illustrated in Figure III-3 (V=volume, t=trip time). The runs progress from the fixed demand-fixed supply case to the varying demand-varying supply case which represents a true equilibrium analysis. This progression is described in the following paragraphs.

Run 1: Fixed interdistrict demand by mode is predicted, based on the assumption that door-to-door travel will occur at the speed of the fastest links for a mode. When the term door-to-door is emphasized, the fallacy of this assumption is obvious; but it is the basis of such commonly-heard erroneous statements as the following:

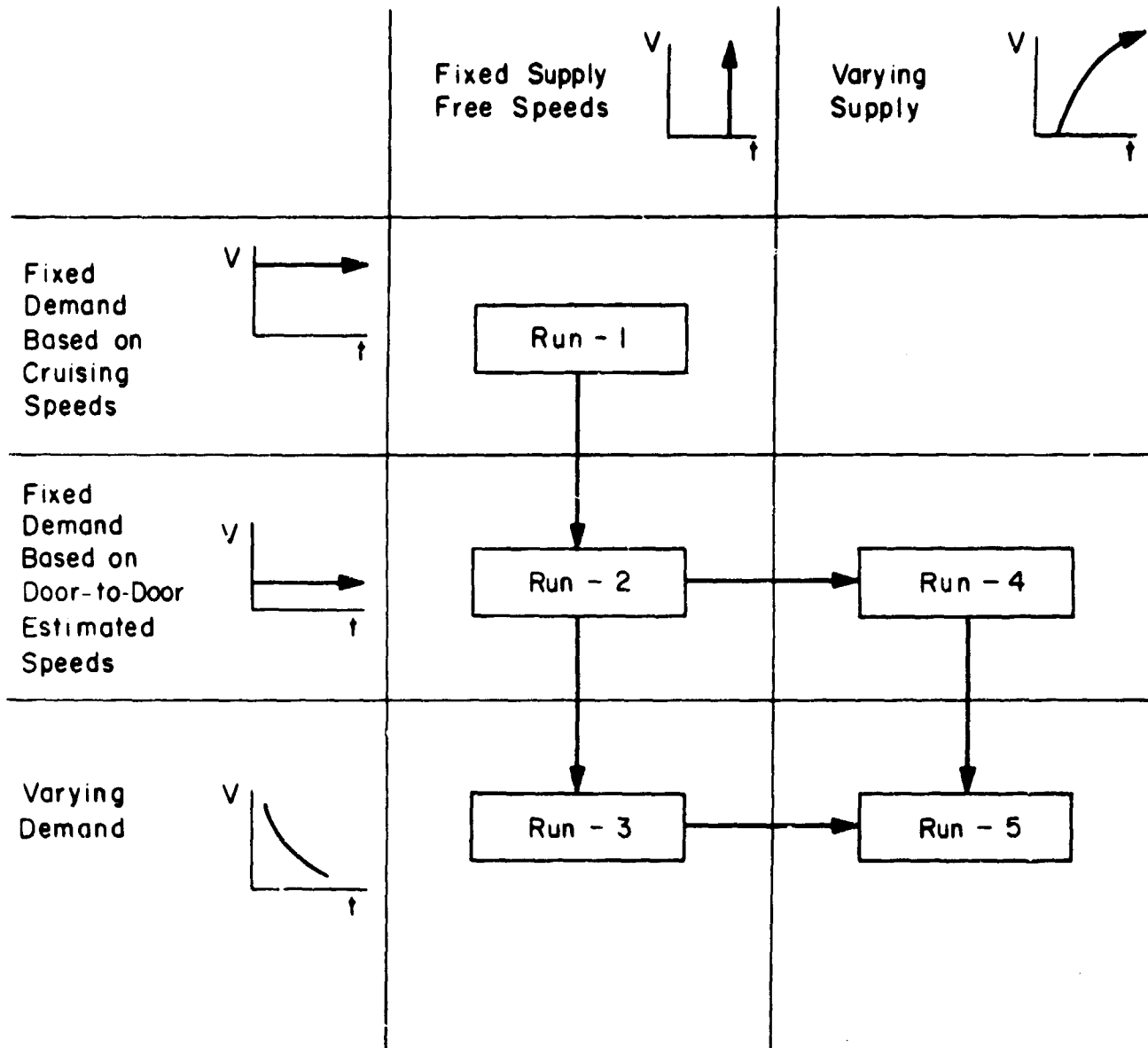


Figure III-3: Equilibrium vs. Non-Equilibrium Runs

- a. air travel is ten times faster than auto travel and eight times faster than train travel
- b. rail travel can never be as fast as air travel
- c. bus travel is just as fast as auto travel

Link travel times remain constant, equal to free flow conditions, in all portions of the network. No adjustments are made to link travel times as volumes increase.

Run 2: Fixed interdistrict demand by mode is predicted, based on estimated door-to-door travel times. This run corresponds to a common planning procedure in both urban and regional areas.

Run 3: A time-sensitive demand function is used, but the volume corresponding to free-speed travel time is chosen. This occurs because travel times on links remain constant, equal to free-flow conditions. This run resembles transportation "demand" studies which ignore the variation of travel times as demand levels and network usage vary.

Run 4: Fixed interdistrict demand by mode is predicted, based on estimated door-to-door travel times. Varying supply functions represent actual relationships between volumes and times. This run corresponds to the most common urban transportation planning procedures.

Run 5: Varying demand functions and varying supply functions are used. This run of the five runs therefore corresponds most closely to a true equilibrium analysis.

5.3 Hypotheses to be Tested

The results of the five runs discussed in the previous section can be hypothesized, based on knowledge of how each run approximates supply and demand functions:

Run 1 can be expected to consistently overestimate predicted trips and underestimate predicted trip times. Therefore, system measures which are directly proportional to trips -- such as total trips, total user fares, accessibility, and government revenues -- will be overestimated. Operators' profit will also be overestimated unless fares per mile are less than variable costs.

Measures inversely proportional to trips, such as operators' profit per passenger and government revenue per passenger, will be underestimated. Total user costs can be either over- or underestimated, depending on the relative errors in travel times and volumes.

Run 2 may either over- or underestimate trips, but can be expected to consistently underestimate travel times. The errors in travel time-related measures will tend to be low. However, in a measure such as total user cost, which depends on both trips and travel times, a large over-estimation of trips may outweigh the underestimated travel times.

Run 3 will always overestimate trips and underestimate travel times. The errors caused are as discussed for Run 1, although they are likely to have smaller magnitudes.

Run 4 will either over- or underestimate both volumes and travel times at the same time. It will therefore result in unpredictable errors

in all volume- /or time-related measures and in all measures directly related to both volumes and times.

Run 5 will estimate accurately both volumes and travel times. Any errors will be due to the approximations included in the incremental approach to determining network equilibrium.

5.4 Experiment Data

Nearly all of the data used in the equilibrium runs is the same as the data used to establish the Base Case, as described in the prototype analysis. The exceptions are the cruise speeds used to predict demand in Run 1, the estimated speeds used to predict demand in Runs 2 and 4, and the fixed supply functions used in Runs 1, 2, and 3.

Cruise speeds were set at the maximum speeds on line-haul links for each mode. These maxima are:

- 1) air mode: 300 miles per hour, based on 1960 to 1965 average schedules for piston-powered aircraft;
- 2) rail mode: 60 miles per hour, based on present schedules;
- 3) road mode: 55 miles per hour, based on present speed limits.

The estimated speeds used to predict demand on Runs 2 and 4 were obtained by determining, from Base Case output, the average predicted door-to-door speed (total passenger-miles divided by total passenger-hours) for each mode. These averages are:

- 1) air mode: 96 miles per hour
- 2) rail mode: 46 miles per hour
- 3) road mode: 38 miles per hour

By using these averages, the variations of speeds for different origin - destination district pairs is ignored in Runs 2 and 4.

The fixed supply functions used in Runs 1, 2, and 3 are formed by using the travel time at zero volume, from the standard functions, as the travel time at all volumes, as illustrated in Figure III-4.

5.5 Summary of Results - Equilibrium Experiments

General Characteristics -- Total Trips, Average Travel

Times: In this section, the results obtained are compared with Run 5, the Base Case discussed in Section 3.6.

As would be expected, Run 1 greatly overestimates trip-making by using line-haul speeds rather than door-to-door speeds. This is especially true for air travel, for which travel times assuming line haul speeds are only about 30% of actual travel times. Run 1 predicts about ten times too many air trips, and about two times too many road trips. In Runs 2 through 5, trip-making variations are much less pronounced. Run 3, with trips based on free speeds, predicts air and rail trips consistently higher, but within three per cent of Run 5. Road trips, however, are over 50 percent too high, indicating that highway congestion effects are significant. Runs 2 and 4, with trips based on estimated speeds, are within three percent of Run 5, for rail and road trips, indicating a good estimate of average speeds by these modes. Air trips in Runs 2 and 4 are high by 24 percent, indicating a poor estimate of the average speed by air.

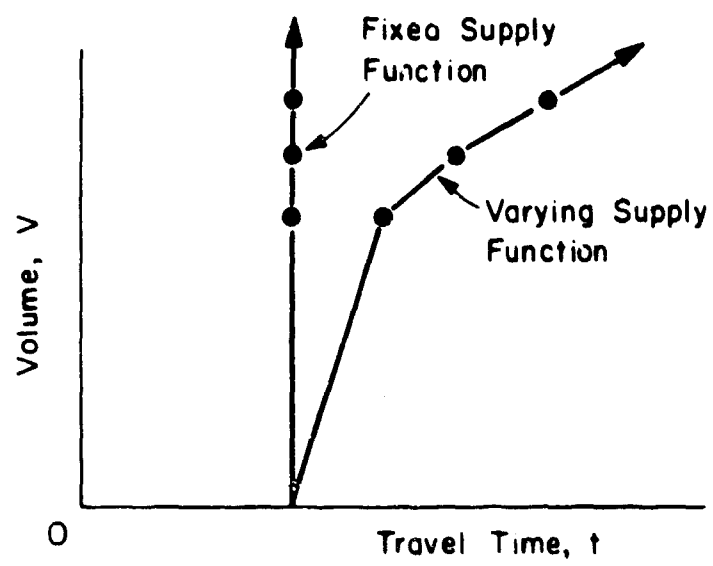


Figure III-4: Fixed and Varying Supply Functions

Interzonal travel times as predicted by the first three runs are all equal to free-speed travel times. Although the actual travel times which would result if the predicted number of trips used the network are not generated, they would undoubtedly be very high for Run 1, which has many trips, and significantly higher than predicted for Runs 2 and 3. Interzonal travel times for Run 4 are correct in the sense that they correspond to an intersection of actual flows and the supply functions, but incorrect in that they do not correspond to an intersection of actual flows and the demand functions.

Inconsistencies in Non-Equilibrium Results: The results obtained for the trips by a single mode -- road -- between a single zone pair -- New York and Hartford -- will be presented in detail to show the inconsistencies inherent in non-equilibrium analyses.

The results of the five runs for the specified trips are summarized in the following table:

New York to Hartford Road Trips

<u>Run</u>	<u>Trips (passengers/day)</u>	<u>Travel Time (minutes)</u>
1	21,352	195.4
2	10,566	195.4
3	16,648	195.4
4	10,566	218.0
5	12,612	222.0

These data and their relationships to the actual supply and demand functions are shown in Figure III-5.

The Run 1 and 2 results do not fall on either of the actual supply or demand functions because fixed supply and demand values were used. The Run 1 volume level is determined by the intersection of the cruise travel time and the demand function, point A. This volume level would result in a very high travel time, point B. The Run 2 volume level is determined by the intersection of the estimated travel time and the demand function, point C. This volume level would result in a travel time, point D, which is larger than the run results, but less than the estimated time.

The Run 3 results fall on the demand function, but not on the supply function, because the varying demand function and a fixed function were used. The volume level is determined by the intersection of the free travel time and the demand function. The travel time which would result at this volume, point E, is significantly higher than the predicted value.

The Run 4 results fall on the supply function, but not the demand function, because the varying supply function and a fixed demand function were used. The volume level is the same as for Run 2, but the travel time has been adjusted to reflect the effects of volume-varying demand.

The Run 5 results represent the true equilibrium point, the intersection of the supply and demand functions. Both volume and travel time are stable at the predicted point: no adjustments are necessary.

The results shown in Figure III-5 for a specific zone pair and mode substantiate the hypotheses discussed in Section 5.3. In this case, Runs 2 and 4 underestimate trips because the estimated time is too high. Run 4, therefore, also underestimates travel time.

These results demonstrate graphically the errors involved when non-equilibrium analyses are used instead of equilibrium approaches.

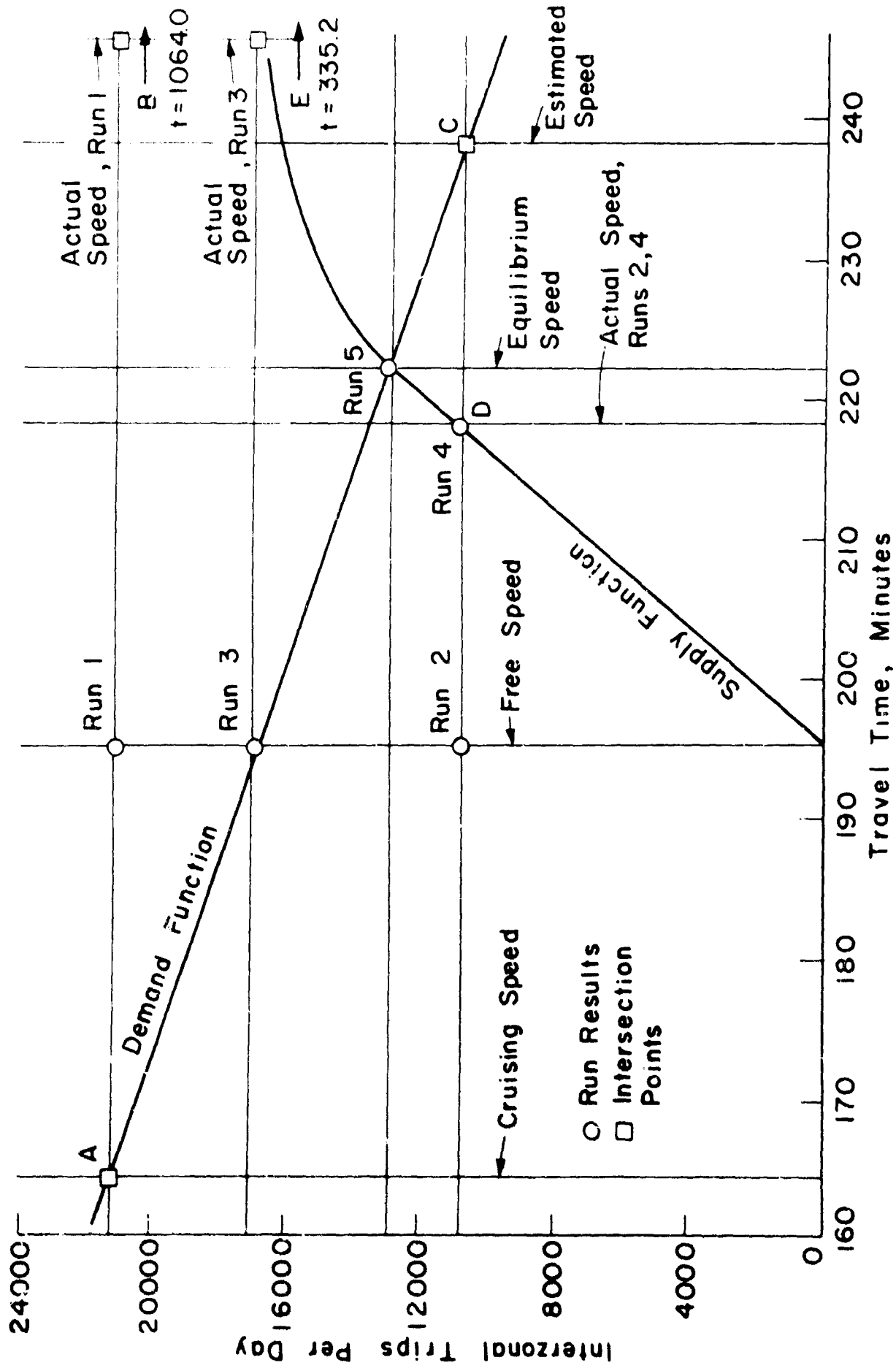


Figure III-5: Supply and Demand Relationships, New York to Hartford Round Trips

6.0 Systematic Exploration of Options and Impacts

Often, in using computers for problem-solving, far too much emphasis is placed upon getting the computer model running; not enough attention is given to how the model is to be used once it is running. A major objective of the prototype analysis was to demonstrate how prediction models should be used in transportation systems analysis.

The basic issues are these: what different combinations of options can achieve the same impacts; what different combinations of impacts (on different groups) can be achieved (by any combination of options). Using TRANSET II as a laboratory, a number of experiments were conducted to trace out such tradeoffs.¹ These are illustrated in Figures III-6 through III-9. The relationships in these figures were derived from data produced by a series of computer runs. In these runs, three levels of fare and three of frequency were explored, resulting in 9 combinations. This sample provided the basis for inferring the relationships shown in the figures (except Figure III-9, as noted below).

Figure III-6 shows how, as frequency of service between two points is increased, fare must also be increased to maintain the same volume of trips in the system (e.g. 1.10 = 1,100,000 trips per day). Thus, this figure shows how two options - fare and frequency over one single route - must be manipulated together to achieve a constant level of one impact - total trips. In Figure III-7, this same approach is extended to consideration of several different impacts simultaneously: total trips in

¹ Ruiter, loc. cit.

the system; total trips to or from Philadelphia; average trip time-all trips; average trip time-Philadelphia trips; operator profit; net benefit to the region as a whole.

In Figure III-8, the impacts are shown on the axes. Thus, the same data is now shown as tradeoffs between impacts - in this case, operator profit and average trip time (a user impact). All other things being equal (they are not), the point most to the upper left would be most desirable. Evaluation and choice deal with such tradeoffs among impacts; whereas for search, tradeoffs among options are needed.

In Figure III-9, a third option, in addition to fare and frequency, is added - level of investment in the network. There are now 27 data points: 3 different levels of network, and 9 combinations of fare and frequency for each. From this sample, we can now infer the locus of the most desirable alternatives, as indicated by the dotted line (again, everything else assumed equal!).

These examples illustrate how a number of "runs" of the computer models can be used to generate information. In this way, tradeoffs among options and among impacts can be systematically analyzed. As these tradeoffs are being developed in the analysis process, the information which is obtained can also be useful for search and choice. As systematic relations among the options are perceived, search procedures can concentrate on generating alternatives in the most interesting areas of the space of possible options. As achievable tradeoffs among impacts are identified,

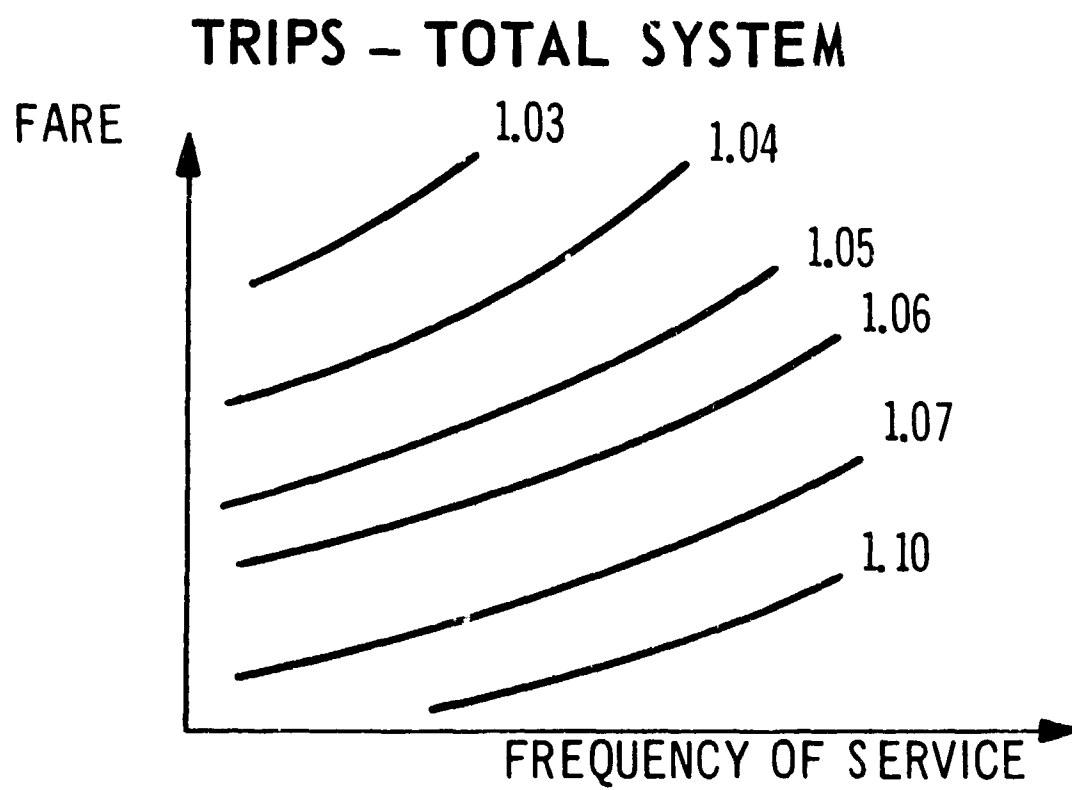


Figure III-6

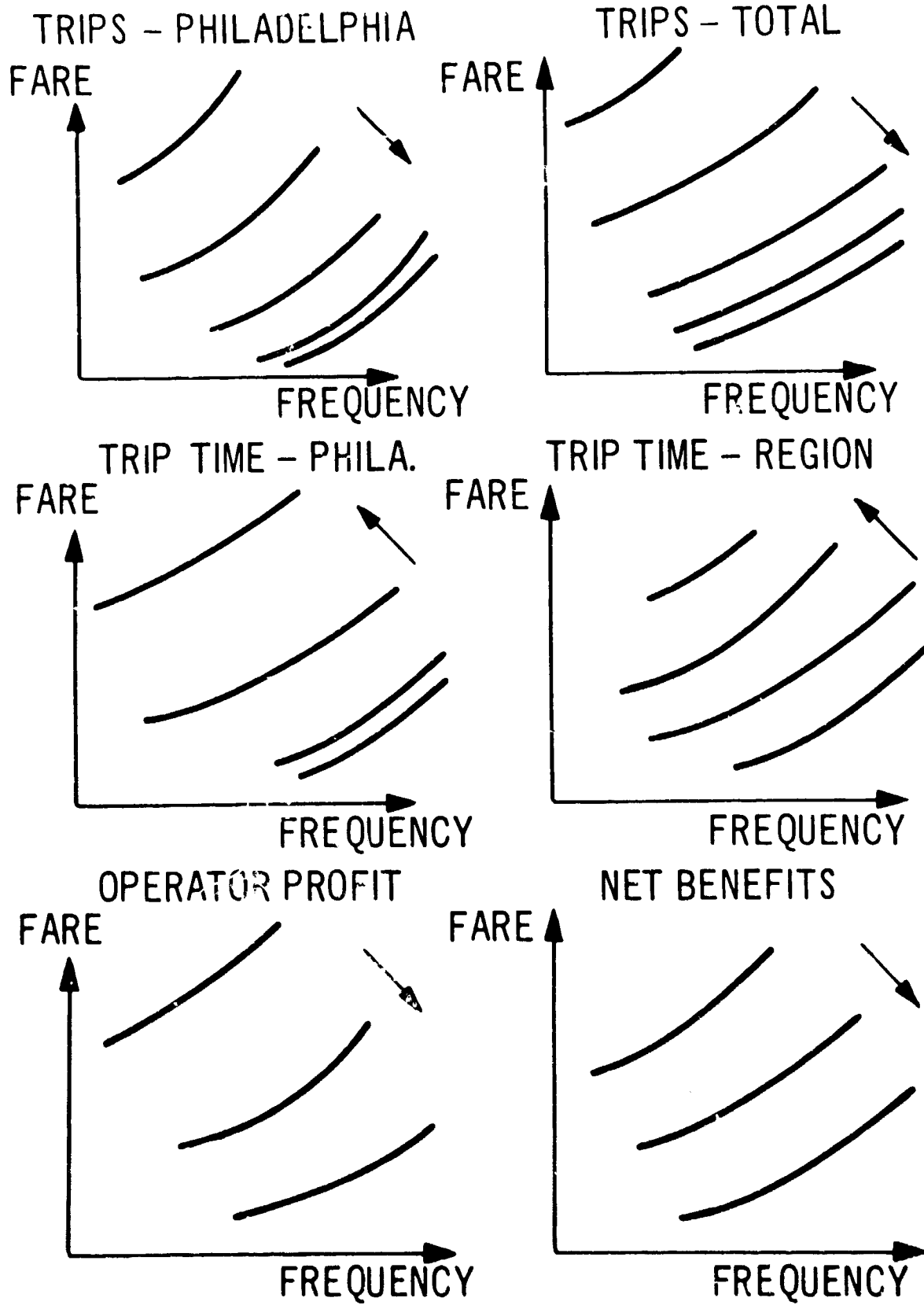


Figure III-7: Differential Impacts

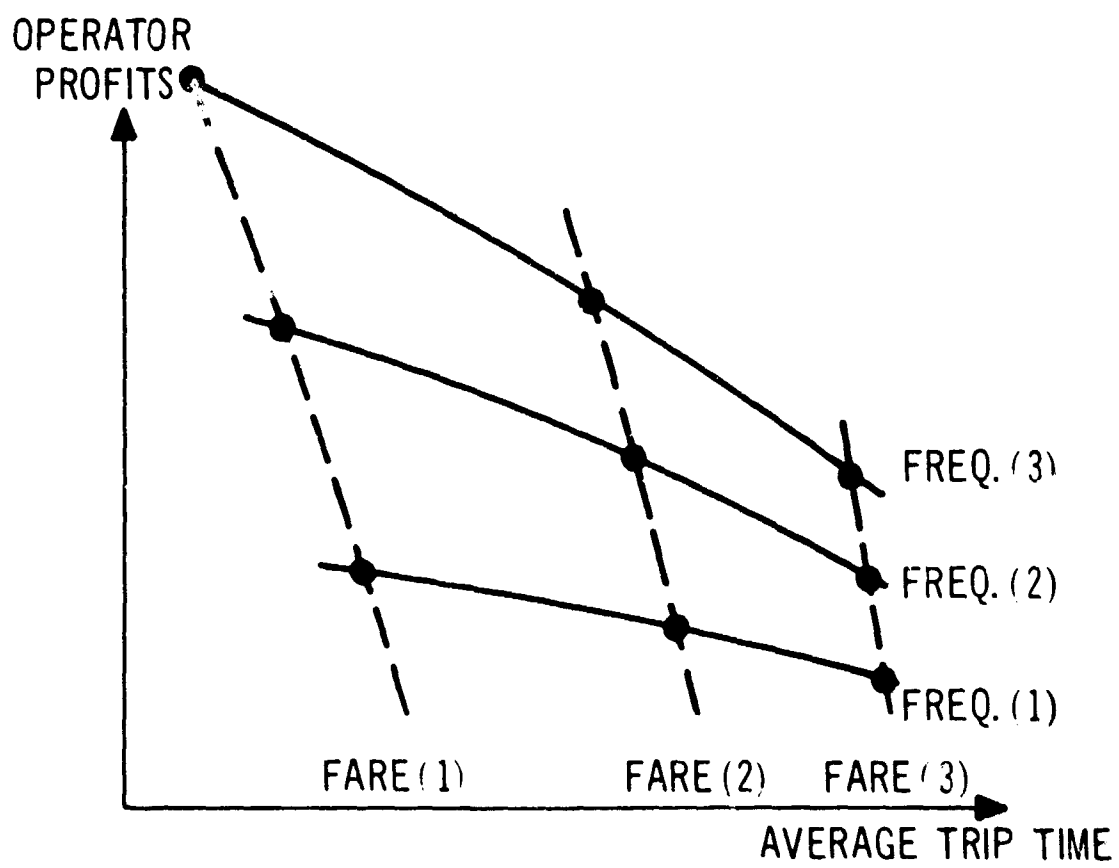


Figure III-8 : Tradeoffs among impacts

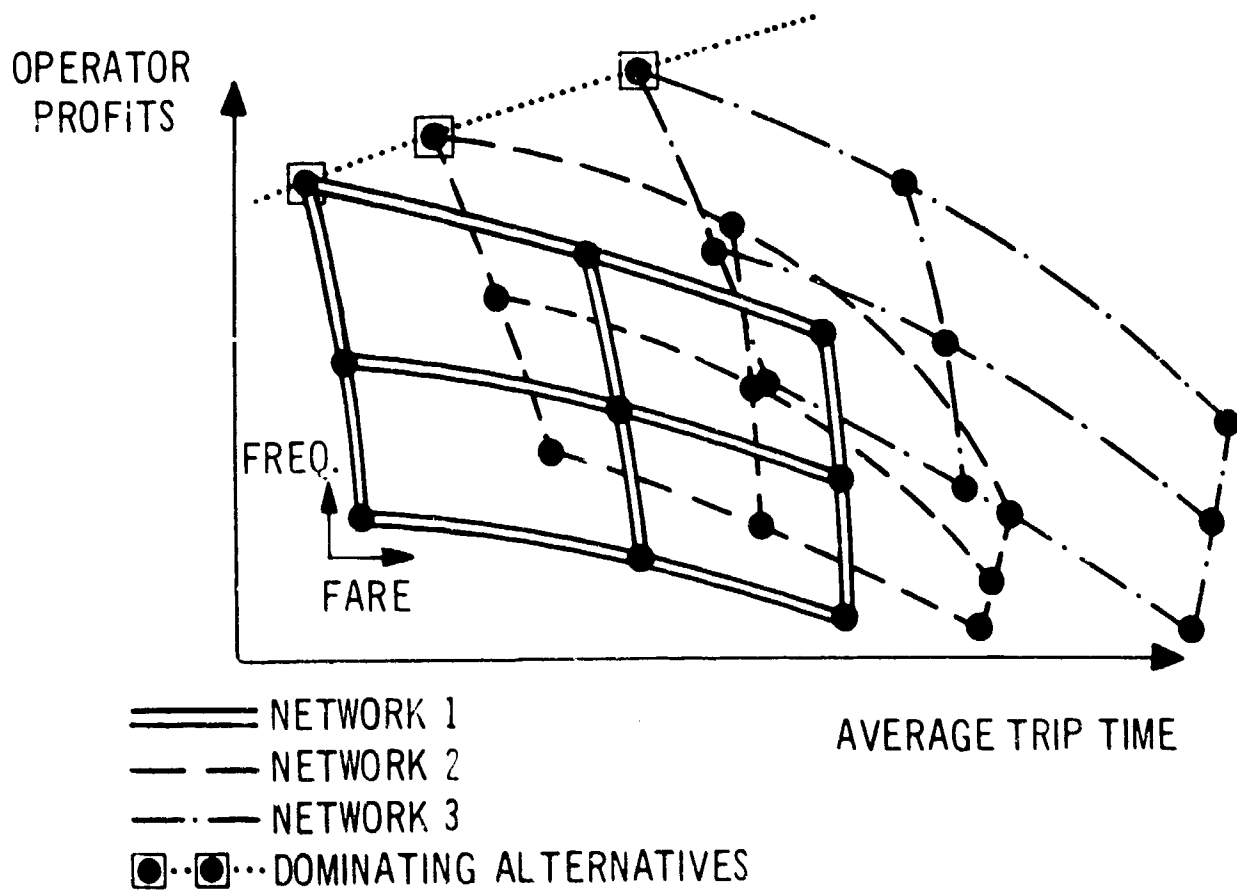


Figure III-9: Dominating tradeoffs

the key issues of choice become clearer. It may be relatively easy to find options which produce desirable impacts for each of one group of actors; but there may be unavoidable conflict in the impacts which are achievable between two other groups of actors - for example, decreased travel time for suburban residents can only be achieved by displacing families from central city homes by freeway construction. It is precisely these differential impacts which must be traced out.

7.0 Summary - Prototype Analysis

7.1 Conclusions

The prototype analysis system has been designed to demonstrate the applicability of the concepts and techniques developed in the Search and Choice research project for the analysis of transportation systems. The system has been used to analyze a simplified aggregation of the Northeast corridor passenger transportation system. Experience with the system and with analyses performed using the system have led to the conclusions presented in this section.

1. The Equilibrium Approach: The experiments demonstrate the feasibility of the equilibrium approach to transportation systems analysis, and the differences between the equilibrium and non-equilibrium approaches. Non-equilibrium approaches tend to produce inconsistent transportation flow pattern predictions and often cause critical impacts to be predicted erroneously.

2. The Prototypical Nature of the System: The emphasis in the prototype analysis system design has been on the general structure and on the relationships between the models in the system. Relatively little emphasis has been given to the models themselves. Although the emphasis on system design is sufficient to demonstrate the concepts developed in the project, it is not sufficient to provide a production-oriented, calibrated model system. Experience with the system has indicated the need for a number of model improvements:

- a. Supply and Resource Requirement Models: In the prototype analysis, these models are essentially the manual collection and processing of such aggregate data as total operator's revenues by mode and average

costs per passenger mile, and the conversion of these data to supply functions and cost parameters. More detailed procedures, such as the automatic aggregation of modal data by links and the simulation of vehicle operations would increase the accuracy of the supply and resource models and also make the entire prototype system easier to use. Detailed technology models which can be used to develop supply and resources functions must be developed.

b. Demand Models: The runs indicated that the Baumol-Quandt trip demand model exhibits counter-intuitive results for various sets of alternative policy options. In addition, calibration appears to be network-specific. For these reasons, it would be preferable to have as part of the system both a "library" of demand models, each useful for specific types of analyses; and model-calibration aids, such as multiple regression and iterative parameter-fitting programs.

c. Demand Shift Model: The population and income prediction model, more than any other within the prototype system, is tentative and simplistic. A more accurate model, responsive to many more transportation and activity system descriptors, is needed to provide accuracy for the analysis of the time-stream effects of transportation policies.

d. Representation of Policy Decisions: The prototype analysis system allows the policy maker to determine the effects of changes in fares and service frequencies specified by mode and by district pair, changes in subsidy and tax rates by mode, and changes in network geometry and link characteristics by mode. In addition, new modes can be added

into an analysis and previously tested modes removed. This range of policy options has proven to be adequate for the representation of many regional transportation alternatives. Desirable additions would be the optional specification of service frequencies by link as well as by mode, to specify a broader range of subsidy and taxing policies, such as an operating, rather than a fixed sum, subsidy; and property taxes as well as taxes on fares, as sources of government revenue.

e. Impacts: Many transportation system impacts can be predicted using the prototype analysis system. First-order effects of the transportation system on its users, on the transportation operators, and on government revenues are indicated in a large number of ways. Second-order impacts, such as changes in non-transportation business income; and hard-to-quantify impacts such as noise levels and air pollution, are not predicted, in the present set of models. Capabilities should be developed for predicting these impacts, too.

f. Systematic Analysis of Options and Impacts: The experiments have illustrated how the tradeoffs which exist among various policy options can be explored. The systematic analysis of options to explicitly trace out differential impacts was demonstrated. However, several issues were also raised by this analysis:

- a) systematic analysis generates - and requires - a large volume of information from a number of computer runs. How can the analyst deal with, and understand, this model-generated information? Particularly, to be able to infer such relationships as illustrated in the figures?

- b) if differential impacts among a variety of groups are to be considered explicitly, how can evaluation and choice be reasonably done, without aggregating all the impacts indiscriminately?
- c) what kinds of procedures can be developed to assist in search?
- d) each "run" of the computer models cost time, money, and other resources; must all search and selection cycles be at the same level of detail? If not, what errors are introduced?

These issues are significant, and will be explored in the following chapters.

3. Other Experiments:

Time-staging: One of the more difficult problems shown in the results of the experiments is the basic size of the problem, the dimensionality involved in considering the variety of options (vehicles, networks, fares, and frequency) open to the planner. The problem is by no means improved when the dimension of time is included.

The result of including time is a multi-dimensional inter-dependent investment decision tree. To investigate many alternatives, over multiple time periods, with prediction models such as those provided in the prototype analysis system has proven to be a very time-consuming and extremely inefficient way to search for alternative investments in networks. Research is needed to develop good staging strategies by

approximating procedures, such as mathematical programming techniques. Additional techniques are required for handling the problem of uncertainty and the resulting multidimensional decision tree.

Sensitivity Analyses: Mathematical investigations of the prototype analysis system and system runs have been used to determine the relative importance of the various model parameters and policy options. The results indicate those policy options and parameters which are most critical in the prediction of flows and impacts. Travel costs appear to be the most critical; travel time only slightly less critical. Service frequency has relatively less effect. With respect to the demand model parameters, the income parameter has the greatest effect, and the time, cost, and frequency ratio parameters have relatively minor effects.

7.2 Recommendations

It is recommended that the prototype analysis system be the subject of three general types of research:

- 1) Extension of the present system to improve its accuracy, the range of its applicability, and its ease of use.
- 2) Use of the present or extended system to study specific transportation analysis issues such as time-staging and sensitivity analyses of transportation networks.
- 3) Design of the next generation of transportation analysis systems, possibly encompassing such present-day packages as TRANSET, the urban transportation models, the full set of Northeast Corridor models, and the Harvard developing countries models.

The following task areas can be identified as specific steps on which work can begin immediately in these three types of research:

- 1) Extend the prototype analysis system by improving its demand models. The SARC trip demand model would be a valuable addition to the demand model library.
- 2) Develop more adequate transportation technology models to be used for predicting level of service and resource requirements.
- 3) Develop improved network equilibrium models; exploring alternative formulations for computing equilibrium. Extend present equilibrium models to incorporate supply-demand equilibrium over multiple time periods.
- 4) Design a single basic reference data base, from which working data bases would be extracted for input to TRANSET and to various optimization formulations. This reference data base should provide for the flexible description of links, modes, vehicles, etc. For example, the capability should exist to classify links by mode, by region, by capital and operating costs.
- 5) Develop an initial set of useful optimization formulations. Work out the interface between TRANSET and OPTECH (the linear programming subsystem of ICES) to implement these formulations to try to identify appropriate uses of mathematical optimization in a network context. In particular,

attempt to develop mathematical programming formulations which behave similar to traffic assignment predictive formulations.

- 6) Implement "goal-fabric" concepts in conjunction with TRANSET. Experiment with goal fabric analysis, in coordination with benefit-cost and other traditional choice techniques to evaluate the feasibility and utility of goal fabric procedures.
- 7) Develop a capability for understanding the results of a number of runs of the model system, such as the volumes of data generated by systematic analyses.
- 8) Continue experiments with real and hypothetical networks to try to identify how specific types of changes in the networks will impact on particular goal variables and consequences.
- 9) Formulate within TRANSET and test a variety of heuristic procedures as alternate search techniques.
- 10) Continue experiments in developing procedures for finding desirable time stagings of investments in transport facilities.
- 11) Continue to use the system to study the sensitivity analysis of transportation problems.
- 12) Continue development of remote processing interactive and batch computer environments for doing transportation search.

- 13) Continue development of graphic display techniques for visualizing the structure of the transportation problem, including development of alternative representations, as well as for actually producing graphic displays on scope and plotter.
- 14) Develop differential impact analysis techniques, for explicitly tracing out the potential impacts of transportation alternatives on different groups.

7.3 Summary

In summary, then, the prototype analysis has demonstrated:

- a. the feasibility of a network equilibrium analysis, and
- b. the differences between equilibrium and non-equilibrium formulations
- c. the feasibility of tracing out substitutability among options
- d. the feasibility of tracing out differential impacts
- e. the effects of time-staging
- f. the feasibility of sensitivity analyses.

The prototype analysis has also raised several issues. The most important issue is how to organize in a comprehensible way the volume of information generated in doing a systematic analysis.

Chapter IV

THE PROBLEM-SOLVING PROCESS IN TRANSPORTATION

SYSTEMS ANALYSIS

1.0 Introduction

In Chapter II, we sketched out the scope of the transportation systems analysis problem. This of course was a relatively comprehensive view of the problem; the crucial question was whether this approach can be made operational. In the chapter on Prototype Analysis, we demonstrated how this approach could be made operational in the context of analyzing passenger transportation in the Northeast Corridor of the United States. While the set of models and data was not highly refined, it was sufficient to illustrate some of the major issues in a systematic exploration of alternative transport systems policies in this region. As well as pointing out its feasibility, the Prototype Analysis also raised a number of issues about the difficulties in doing such a systematic analysis. In Chapter V, Search, we will explore in depth one of these issues: the problem of generating reasonably feasible alternative systems which are sufficiently promising to be worth testing in the complex set of supply-demand equilibrium prediction models.

Underlying all this discussion has been two themes: the scope of the substantive problem of transportation systems analysis; and a concern with how this substantive problem should be analyzed. It is very clear that it is not sufficient to have a set of computer models for predicting impacts of a given alternative; there are a variety of issues involved just in the problem of generating good alternatives to test. If we step back and look at the role of transportation systems analysis

In the context of the political process within which transportation planning inevitably takes place, then we see that there is an even greater order of magnitude and complexity involved. Thus, in order to understand how to conduct systematic analyses of transportation policy, we must turn from the problem of transportation to focus on the process of analysis.

This chapter discusses the analysis process in transportation. In the next section, some of the major issues are pointed out. Then, a conceptual model is outlined, stimulated by review of the characteristics of transportation systems analysis in the context of a political world. This conceptual model is illustrated by application to the prototype analysis, and serves as a basis for discussion of several specific operational techniques: DODO; goal fabric analysis; and network aggregation. These are described in succeeding sections.

2.0 The Rational Model and its Limitations

The essence of the rational model of decision-making is expressed in the very common prescription of "systems analysis:"¹

1. define objectives and formulate as utility function;
2. enumerate all the possible alternative actions;
3. identify the consequences of each action;
4. evaluate the consequences in terms of the objectives via the utility function;
5. choose that action which best achieves the objectives.

This "synoptic" model² is very limited in its application to complex public policy questions, such as transportation, for many reasons:

- a. we can never know completely all the alternatives;
- b. we can never define all the relevant objectives, consistently and completely. First, there are too many points of view - "actors" - to get agreement on objectives (though as Lindblom points out, we may get agreement on actions without agreement

¹See for example, Schoeffler, Sidney, "Toward a general theory of rational action," KYKLOS, VII:3 (1954), pp. 245-271; Hall, Arthur D., A METHODOLOGY FOR SYSTEMS ENGINEERING, Princeton, N.J.: D. Van Nostrand Co., Inc. (1962); Hitch, Charles J., and Roland N. McKean, THE ECONOMICS OF DEFENSE IN THE NUCLEAR AGE, New York: Atheneum (1965); Baumol, William J., ECONOMIC THEORY AND OPERATIONS ANALYSIS, Second Edition, Englewood Cliffs: Prentice-Hall (1965); Ackoff, Russell L., SCIENTIFIC METHOD, New York: John Wiley and Sons (1962).

²Braybrooke, David, and Charles E. Lindblom, A STRATEGY OF DECISION, New York: The Free Press of Glencoe (1963); Lindblom, Charles E., THE INTELLIGENCE OF DEMOCRACY, New York: The Free Press (1965); Although drawing heavily on their insights, I have modified them substantially. See also Steger, Wilbur A., and T. R. Lakshmanan, "Plan evaluation methodologies: some aspects of decision requirements and analytical response," in Hermens, George (ed.), URBAN DEVELOPMENT MODELS, Special Report 97, Washington D. C.: Highway Research Board (1968).

on objectives). Second, objectives are difficult to formulate in the abstract, and will be substantially revised and clarified through examination of the consequences of specific alternatives.¹

- c. We can never completely identify the relative values of all possible combinations of the various objectives - that is, we can never get a fully-defined utility function. Therefore evaluation of the consequences of an action is not so simple. Most naturally, we prefer to examine alternatives explicitly, and to evaluate the incremental differences between them.²
- d. There will always be uncertainty, in the prediction of consequences. Many relevant consequences will be left out; because of the open nature of the socio-economic system (i.e., not a closed system), consequences of actions such as transportation will "spill over" into other areas (e.g., functional and governmental impacts). Further, we can expect to find that actions which we have implemented do lead to "unanticipated" consequences.³
- e. The costliness of analysis is a severe constraint. Generation of alternative actions, formulation of objectives, anticipation of the consequences of actions (prediction), and determination of the most desired action (evaluation and choice) all take resources. The resources of analysis are dollars, time, manpower, computing capability (computer time), etc. Analysis

¹ Lindblom, op. cit., pp. 140, 142

² Ibid.

³ Neversen, Martin, and Edward C. Banfield, POLITICS, PLANNING AND THE PUBLIC INTEREST, Glencoe, Illinois: The Free Press (1955) p. 319

of policy alternatives generally suffers under very severe constraints on these resources, and so analysis is inevitably incomplete.

- f. Analysis is dynamic. Problems are never solved completely; massive changes in the system, such as transportation, generally take time for implementation. Within the analysis or problem-solving process itself, the conceptions of the problem held by analysts and decision-makers will evolve. Initial statements of objectives will be revised as successive alternative actions are generated and examined. Examination of previous alternatives will suggest new ones for analysis.

Perhaps the best way of summarizing the limitations of the rational model is that,

in the face of man's limited capacities, it offers simply a prescription: "Be comprehensive!"¹

The comprehensive ideal fails to accept the realities of policy analysis: the costs of analysis, and the inability for cost and cognitive reasons of ever being comprehensive.

This does not mean, as some would argue, that systematic analysis must be discarded altogether; rather, that the simple five-step model of the analysis process must be replaced by a more subtle structure.

¹Lindblom op. cit.; p. 119.

3.0 PSP: A dynamic model of decision-making

As a partial answer to the limitations of the rational model described above, a more complete model of decision-making is necessary. Such a model has been formulated, the PSP model (for "Problem-Solving Process").¹ Only a few of its major characteristics will be summarized here.

3.1 The Basic Model

The first important characteristic of the PSP model is the role of time. The analysis process itself takes place over real time - to develop, evaluate, and choose among alternatives takes time. Further, the analysis process is itself imbedded in the larger evolutionary process of the real world system of interest - the actions selected by analysis are implemented, their results observed, and new analyses lead to new, revised actions.

The second important characteristic of the PSP model is the distinction between generating and choosing among actions. We emphasize this distinction by defining Search and Selection as the procedures which perform these functions. Search designates any procedure used to produce one or more alternative actions. Search may be intuitive, as in the sense of "design," or may be formalized, as in a linear programming model. Selection designates the process of choosing among several alternative

¹Manheim, Marvin L., PROBLEM-SOLVING PROCESSES IN PLANNING AND DESIGN, Professional Paper P67-3, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1967), Volume XVI of a Series; abridged version in DESIGN QUARTERLY 6:267, Minneapolis: Walker Art Center, and in W. Krampen and P. Seitz (eds.) DESIGN AND PLANNING 2, New York: Hastings House, (1967). See also Manheim, Marvin L., Kenneth G. Tollansbee, and Ronald Walter, MODELLING THE EVOLUTIONARY NATURE OF PROBLEM-SOLVING, Research Report R68-43, Volume IV of a Series, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1966)

actions. The input to Selection is a set of alternative actions. The output of Selection is a "preference ordering", or ranking of the actions by desirability.

To actually accomplish Selection, three basically different kinds of procedures are required. Prediction models are used to anticipate the consequences which an action would have if implemented in the real world - for example, to predict volume of travel on a particular transportation link. Evaluation procedures operate upon the predicted consequences to yield statements of the valuations, or relative desirabilities of those consequences - for a particular actions - for example, the values of user costs and benefits associated with a particular flow volume on a link; or the relative desirability of a particular regional growth pattern. Since all predicted consequences cannot be represented adequately by a single measure of value, or valuation, we do not assume that evaluation summarizes all the valuations into such a single measure. For example, we do not assume that construction dollars, loss of recreation land and regional development patterns can all be lumped into a single measure of value, such as dollars or some overall utility measure. Therefore, after evaluation there must be choice. In Choice, two or more actions are compared on the basis of the set of valuations for each - dollar costs, recreation land acreages, quality of regional pattern, etc. - and a decision made about the rankings of the actions. Choice is difficult, but necessary.¹

¹At this point, we will not distinguish between choice executed by the analytical staff, and choice executed by a small group of decision-makers or the larger political process.

The third important characteristic is a distinction between the state of the analysis process at any particular time, and the procedures which may be used to change that state. The state of the process expresses the analyst's current view of the problem. The problem-solving system contains a variety of procedures, to be used in the problem-solving process when and as appropriate. Each time a procedure is used, it changes the state of the process in a way appropriate to the procedure: the use of a procedure changes the analyst's view of the problem.

From the point of view of our present discussion, the major variables describing the state of the process are the actions, A, the goals, G, and the current ranking of the actions, R. The major procedures for changing that state are search, selection, and goal formulation and revision.¹ All these procedures involve some reference to the current set of goals, G.

The basic view of the problem-solving process which this implies is shown in Figure IV-1, Basic Cycle. Alternative actions are generated, and then a preference ordering is established over those alternatives. If the most desirable alternative is sufficiently attractive, then the problem-solving process ceases and that most desirable action is implemented in the real world; if not, then search is repeated and new actions are generated. These new actions may or may not be related to the previous actions. The sequence is repeated again and again, until finally there is one action sufficiently attractive for implementation in the real world.

This image of a "trial-and-error" process, basic to the PSP concept, is completely contrary to the image of a problem for which the

¹ Additional state variables include: consequences; valuations; raw information; probability distributions over uncertain variables. Additional procedures include information analysis; model construction and revision; decomposition and restructuring procedures; and metaprocedures. Mannheim, PROBLEM-SOLVING PROCESSES IN PLANNING & DESIGN, *op. cit.*

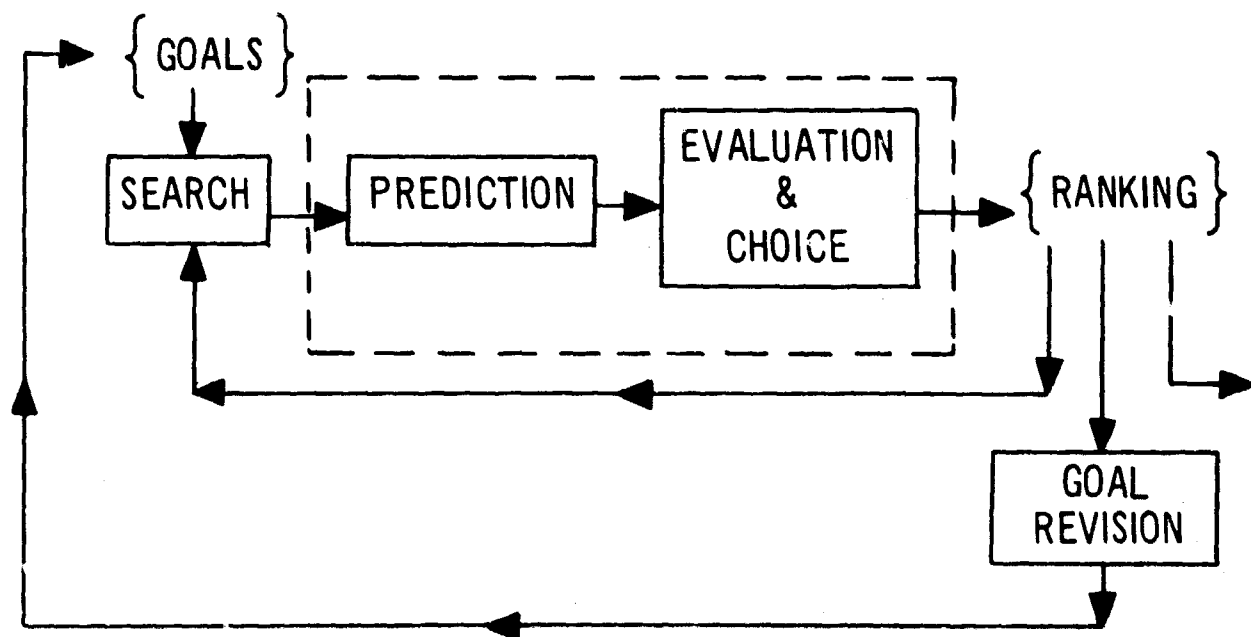


Figure IV-1: Basic Cycle

optimal solution is obtained directly by "solving" a mathematical (or other) model. Such "optimizing" methods do have an important role in the broader PSP, but such real problems as transport systems planning are too complex for such techniques to carry the whole burden. A particular optimizing method corresponds to one search-and-selection sequence; but many kinds of search and selection procedures are required in addressing the total problem.

3.2 Evolution of actions and goals

The focus of a PSP is on actions. Because Search and Selection procedures concern the basic processes of generation and selection of actions, these procedures are at the heart of the PSP. However, there are a variety of other activities which must occur in a PSP, to allow Search and Selection to operate, and to revise the context in which they operate.¹ Particularly important are goal formulation and revision procedures.

The purpose of these procedures is to formulate and revise the statement of goals G, as new actions are generated and their consequences are examined. That is, each cycle of search and selection potentially may trigger goal revision. For example:

1. An initial statement of goals is formulated.
2. The search procedures are executed, one or several times, producing one or more alternative actions.
3. The selection procedures are executed, identifying and evaluating the consequences of the actions, and their performance with respect to the goals. The result is a ranking of the alternatives.

¹ See Preceding footnote

4. In the basic cycle, steps (2) and (3) may be repeated a number of times, until an action sufficiently desirable for implementation has been found, or analysis resources have been exhausted.
5. The mutability of goals must be recognized, however, and so step (3) or even step (2) may be followed by goal revision.

Goal revision may follow search immediately particularly when the results of search are either very disappointing - it proves very difficult to generate actions which achieve the goals - or very successful - the goals are set so low it is not at all difficult to achieve them.

By this simple model, the analysis process is typified by continued and parallel evolution of the set of actions A, and the set of goals, G. The ranking of the alternative actions will change, not only by addition of new actions to the set, but also by revision of the goals G.

Search and choice interact heavily in the socio-political arena. To account for this interaction, a more subtle model of the analysis process than the static, "rational," model is required. The evolution of goals as well as actions is an important facet of the more complete model.

3.3 Implications of the Interactions of Search and Choice

In this brief exposition, we have touched only quickly upon the characteristics of a more general model of the problem-solving process. Let us now explore some of its implications. Once we shift from a static conception of the analysis process to an evolutionary one in which actions and goals change over time, our perception of the interaction of search and choice changes in fundamental ways.

For one thing, we need no longer search desperately for a utility, or social welfare, function. Such functions are used to reduce a multi-dimensional set of goals to a single dimension (for example, benefit-cost ratio). In an evolutionary process, we can accept a less well-structured set of goals, because all that we require at any time is sufficient information about goals to reach a choice over alternatives, not a function over all conceivable combinations. (In fact, we may not need to have a completely consistent goal structure to produce agreement over alternatives; as Lindblom points out, actors may reach agreement on actions even though they are striving for different objectives.) Thus, a much looser, more flexible structure of goals is appropriate and useful. The concept of a "goal fabric" has been proposed to serve this purpose, and is described in section 6.0.

A second important implication is that alternatives need not be single massive system proposals, but can and should be formulated as staged strategies over time. The typical urban transportation study chooses among a small number of alternative transportation system plans for a target year (1985, say). Instead, there should be a much richer number of smaller actions, each one being the building of a specific part of the network in a particular year (or other options, such as buying additional transit cars). Then the major alternative 1985 plans could be composites of a number of the specific time-staged facility actions. However, the whole approach to analysis would be different. Instead of choosing among single packages, the emphasis would be upon choosing among sequences of actions staged over time. In this way, there would be a great deal of

flexibility for revision of both actions and goals as each stage of the system selected is implemented. Furthermore, the decision about appropriate facilities to construct at each successive time period could be revised as changes in the real world are observed, or changes in the goals or the available actions as new technologies are developed. Models for searching out and choosing among sequential decisions in transportation planning are under development.¹

A third implication is more emphasis on the value of information. That is, instead of collecting all the information necessary for constructing demand models and the other analysis models in one single survey, there can be a much more efficient use of resources through continuous sampling over time, with a flexible readjustment of data acquisition as new issues are identified for study. This is an important consequence of the time-staged strategy approach. Further, this implies that there should be an economic analysis of the value of information in its relevance to the search and choice issues at hand; as the actions and goals change over time, the value of different types of information will also change. Models for optimal information collection strategies in networks are under development.²

Finally, and perhaps most importantly, the evolutionary image of the analysis process leads to a major new perspective on the relationship between the analysis team and the political environment.

¹

See Chapter V, Section 4.6.

²

Ibid., Also, William F. Johnson, DECISION THEORETIC TECHNIQUES FOR INFORMATION ACQUISITION IN TRANSPORTATION NETWORK PLANNING, ScD. Thesis, Department of Civil Engineering, M.I.T.

The evolution of actions and goals takes place at several different levels. First of all, consider the technical analysis team actually doing transportation systems and related studies for a particular area. Within this team, the sets of actions and goals will evolve fairly rapidly: the team is engaged in day-to-day development and testing of alternatives, and as it learns more about the problem, will be almost continuously revising its assumed goals.

At a second level, this analysis team will interact periodically with the political decision-makers or other responsible public or private officials for whom the analysis team is acting as staff. As a result of these (more or less frequent) interactions, the actions and particularly the goals will be further refined and revised. At a third level, these decision-makers will interact with the body politic: the variety of actors - individuals and interest groups - who comprise the full set of interests impacted by transportation systems alternatives. As a result of their interactions with the body politic, the decision-makers will revise their conceptions of actions and, more particularly, goals, and will pass these revised conceptions on to the analysis team. But also, the results of the analysis team, as communicated through the decision-makers, to the public at large, should help to change and broaden the perceptions of the decision-makers and of the body politic.

The interactions in search and choice among analysis team, decision-makers, and polity should be exploited explicitly. Perhaps the most important role of a technical analysis effort is to clarify public objectives, even more than the development and implementation of specific actions. For example, one of the major contributions of the highway transportation program may have been to create a public awareness of the

choice issues which need to be addressed in the core of the metropolitan area; by threatening highways through the centers of cities, the political forces set in motion have helped to raise serious discussion about the competing objectives of groups in the metropolitan area, and have stimulated the search for new transportation technologies, as well as new methods of highway planning.

Throughout this report, we have been suggesting ways in which transportation systems analysis interacts with the broader political process. We first broached this in the discussion of the substantive transportation systems problem, by pointing out the variety of impacts. Then, in the prototype analysis we showed how the options could be systematically explored to trace out the differential impacts. In this chapter, we have discussed the limitations of the static model of decision-making and proposed the PSP model as a more general formulation.

Perhaps the most critical attribute of the PSP model is that, in contrast with the "rational" model, the multiplicity of impacts and the iterative, exploratory nature of the analysis process are emphasized, not assumed away. What is required in transportation systems analysis is the recognition of the interactions of analysis with the political process, and the development of appropriately sensitive operational techniques, not perpetuation of the myth of the objectivity of analysis.

4.0 Example: The Prototype Analysis

To see the applicability of the PSP model to transportation systems analysis, we shall review the specific problem-oriented language capabilities of TRANSET II, described in Section 3.0 of Chapter IV, Prototype Analysis.

4.1 Search

No explicit search procedure is provided in TRANSET II at this time, although several are under development. The analyst must generate a policy alternative -- execute search -- through his own judgement. He may generate a completely new action, or use parts of one or more previously-generated actions as stored in the computer files (i.e., on disc). If he uses stored components of alternatives, he may modify them if he wishes.

One particularly powerful capability of TRANSET II is the ability to name data files. Thus, the analyst may store several transportation networks under such arbitrary names as '1956-1' 'RAIL-2' 'HWAY,' etc. This is particularly useful in search as the analyst may build up a new action out of components of other actions very easily.

To generate a completely new transportation system alternative, or new components of an alternative; to save portions or all of an alternative in computer storage; and/or to create a new alternative through modification of a previously-stored component, he uses these commands:

a. Transportation options

- (i) READ NETWORK - for general network characteristics
- (ii) LINKS - for network connectivity and link characteristics

- ### b. Activity System Options

- In addition to specifying a completely new alternative, it is also possible to generate an action by using portions of another action previously stored in the computer:

- (1) MODIFY NETWORK + name of network to be changed

DELETE LINK specification of changes

(11) REVISE MODAL DATA + name of data to be changed

specification of changes

(111) REVISE DISTRICT DATA + name of data to be changed

specification of changes

4.2 Selection - Prediction:

The prediction procedures of TRANSET II are based upon the supply-demand equilibrium concept. The commands to accomplish prediction of the consequences for a specific alternative are:

- a. PREDICT POTENTIAL TRIPS - generate estimated trip demands
- b. PREDICT ACTUAL TRIPS - predict actual network equilibrium flows
- c. PREDICT DISTRICT DATA - predict future population and income for each zone, based upon predicted network flows

4.3 Selection - Evaluation:

The evaluation components of TRANSET II are relatively simple. For any particular alternative action, its predicted consequences can be displayed in a variety of ways for intuitive evaluation by the analyst. User, operator, and government costs can be computed and aggregated in a variety of ways, through the EVALUATE COSTS commands. Accessibilities can also be evaluated, as measures of functional impacts (i.e., potential changes in the activity system). There are no capabilities at this stage for predicting physical impacts explicitly.

- a. Display flow pattern consequences:

REQUEST FINAL

LINK data

MINIMUM PATHS

TRAVEL TIMES

SYSTEM TRAVEL

DISTRIBUTION

INTERZONAL TRIPS

PRINT TRIP MATRIX

- b. EVALUATE COSTS - for user, operator, and governmental impacts
- c. EVALUATE ACCESSIBILITY - for functional impacts

4.4 Selection - Choice:

Choice involves the comparison of alternatives to determine a preference ordering. In TRANSET II, no automatic choice capability is provided. However, a very simple but powerful set of commands provides the analyst information which is extremely useful in his judgmental decision about preferences between alternatives. These commands do a pairwise comparison of two alternatives, displaying the differences between them. Then the analyst can examine the incremental differences between the two alternatives, as well as the absolute levels of the impacts.

- a. COMPARE TRIPS - for summary of the differences in flow volumes between two alternatives
- b. COMPARE SURPLUSES - for differences in user benefits, as provided by consumer surplus measures
- c. COMPARE ACCESSIBILITIES - for differences in functional impacts.

The problem-oriented language capability is particularly useful in these commands, as: COMPARE TRIPS, ALTERNATIVES 'AIR' AND 'RAIL'.

5.0 DODO: A PSP-oriented information system¹

The prototype analysis uses a simplified set of models, and a very simplified representation of the Northeast Corridor transportation system. Yet, even with this simplicity, the analyst finds it difficult to deal with the large volume of information produced in doing a systematic analysis of the alternatives. If only twenty different actions have been generated and compared, the analyst has real difficulty understanding the difference and similarities among the actions:

1. which actions are basically different in their impacts;
which are very similar.
2. what the feasible tradeoffs in impacts are, and which actions produce the most desirable combinations.

Even a single run of the model system results in large masses of data which are difficult for the analyst to comprehend. Given the results of analyses of a series of complex transportation systems alternatives, how can the analyst understand the differences between these alternatives in order to establish a preference ordering among them, and in order to identify fruitful areas to search for even more promising alternatives than those he has already examined?

What is needed is a way of storing all the relevant information generated in a series of model runs, such that questions meaningful to the decision problem can be asked of the data. Some of these questions can be identified a priori, and so built into the system; but many significant questions will occur to the analyst only as he is examining the specific

¹ Follansbee, Kenneth G., Marvin L. Manheim, and Ronald A. Walter, MODELLING THE EVOLUTIONARY NATURE OF PROBLEM-SOLVING, Research Report R68-43, Volume IV of a series, Cambridge, Mass: Dept. of Civil Engineering, M.I.T. (1968). Follansbee, Kenneth G., A PROTOTYPE INFORMATION SYSTEM FOR THE PROBLEM-SOLVING PROCESS MODEL, Unpublished M.S. Thesis, Dept. of Civil Engineering, M.I.T. (1968).

data of a series of runs. Therefore, the information system must be designed for interactive use with flexible query capabilities.

The concept of DODO was developed in response to this need. DODO is an information system intended to provide the decision-maker and analyst with the capability to analyze and structure the large amount of data that may be generated in the analysis of a complex problem. The name DODO reflects this objective: Decision-Oriented Data Organizer. An initial operational version of DODO has been developed in the context of the TRANSET II subsystem of ICES, as developed and modified for the prototype analysis. Later versions of DODO will be more general, applicable to many other design problems as well as transportation.

5.1 Design Concepts of DODO:

The design of DODO is based upon the module suggested by the PSP model. This "basic decision module" (BDM) consists of the quintuple (A/P/C/U/V) - action A, consequences C, valuations V; with consequences conditional upon a (data) parameter set P, and valuations conditional on a set of (partial) utilities U.

In an actual problem, each of these "files" may comprise large volumes of data. For example, in the "prototype analysis", each action A corresponds to specification of the options of technology mix, network, fares, frequency of service, and costs and subsidies. The consequences C and valuations V may also be large files of data; e.g., the file of travel time for system users by trip purpose by zone pair by mode, for 5 purposes, 4 modes, and 50 zones contains 50,000 items, which can be aggregated a number of ways.

In outline, the basic capabilities of DODO are:

- a. It is designed as a command-structured problem-oriented language, a subsystem of ICES.¹ Thus, the commands are easy for the non-technical analyst to use.
- b. The basic files of the system are organized in terms of the basic decision module (BDM); i.e., the basic record is the n-tuple (A/P/C/U/V).
- c. Each step in the analysis process either initiates a new cycle, through initiation of a new BDM, or adds information to a previously-initiated BDM. That is, a "log" of the analysis process is built up in the form of a sequence of BDM's. A new BDM is initiated each time a new action is produced, a new set of parameter values P or utility values U is used.
- d. The "genealogy" of the actions generated is recorded: for each action, inclusion, component/composite, and alternative relationships to other actions are explicitly recorded.
- e. Actions can be grouped into arbitrary subsets at will, through a capability for defining sets of BDM's according to very general criteria. This "set" capability allows a wide variety of relationships among actions to be established. In particular, actions can be grouped so as to isolate and display tradeoff relations, as demonstrated in the prototype analysis.

¹ Roos, op. cit.

- f. By explicitly separating the parameters P, sensitivity analysis is easy: simply designate a new P and repeat the prediction of consequences. Similarly, the sensitivity of the preference ranking to the statement of goals can be explored: designate a new goal statement (represented in DODO-I by a set of utilities U) and repeat the evaluation and choice procedures.¹
- g. The system is designed for browsing through the results of the analysis process. For example, the analyst may suddenly perceive a new issue and wish to define a new goal variable. He can do this, through the DEFINE GOAL VARIABLE command, at which time he also specifies how it is to be computed. The analyst may then "browse" the predicted impacts of actions previously examined with this new variable; if he decides it is a meaningful variable to use, he can add it to the system on a "permanent" basis, thus enlarging his set of goals.

5.2 A DODO Example

To present a picture of the DODO capabilities, this section contains an example of the use of DODO. The example illustrates the definition of one BDM that is generated in the "search and choice" process for determining an optimal solution.

In the following example, all lines beginning with a *** are printed as output by the system. Inputs include comments and commands. All lines beginning with a \$ are comments. All other lines are commands to be executed. All phrases within single quotation marks - 'THUS' - are arbitrary names assigned to a block of data by the user for easy reference.

¹ Work is in progress to incorporate explicit goal fabric capabilities, less restrictive than the use of utilities.

DODO

```

***          CES DODO I - PROBLEM SOLVING PROCESS MODEL
***          CIVIL ENGINEERING SYSTEMS LABORATORY
***          TRANSPORTATION SYSTEMS DIVISION
***          MASSACHUSETTS INSTITUTE OF TECHNOLOGY
***          CAMBRIDGE, MASSACHUSETTS
***
***          THE FILE STRUCTURE FOR THE PSP MODEL
***          CONSISTS OF 6 PRIMARY DICTIONARY FILES
***
***          THE ACTION   FILE
***          THE PARAMTER FILE
***          THE CONSONCE FILE
***          THE UTILITY  FILE
***          THE GOALS    FILE
***          THE PREFENCE FILE

```

OPERATION 'N.E.CORR'

\$ DEFINITION OF ACTION A - RESULTS OF SEARCH

ACTION 'A'

ALTERNATIVE TO 'AA' 'AAA' 'AAAA'

INCLUDED IN 'GROSS' 'HIGHER'

INCLUDES '3LOWER'

COMPONENT OF 'X'

COMPOSITE OF 'R' 'S' 'T'

STRATEGY '20YEARS' STAGE 10, STRATEGY '15YEARS' STAGE 7

TEXT 'ACTION A' 'MESSAGE'

DESCRIPTORS FOLLOW

NETWORK 'N.E.CORR'

DISTRICT DATA '5CITIES'

MODE DATA '4MODES'

FARE DATA 'EXISTING'

FREQ DATA 'PROPOSED'

V/D DATA '1968TECH'

END DESCRIPTORS

END ACTION DEFINITION

\$ DEFINITION OF PARAMETER P

PARAMETER 'P'

MODAL SPLIT PARAMETERS '1966'

DISTRICT GROWTH PARAMETERS '1967'

END PARAMETER DEFINITION

\$ PREDICTION OF CONSEQUENCES

PREDICT CONSEQUENCES 'C' OF ACTION 'A' AND PARAMETER 'P'

GENERATION RATE '1968A'

POTENTIAL TRIPS '1968'

ACTUAL TRIPS '1968LINK'

DISTRICT DATA '1970'

END OF PREDICTION

\$ DEFINE UTILITY FUNCTION

UTILITY FUNCTION 'U'

WAIT FACTOR 0.50

TIME COST 2.00

END UTILITY DEFINITION

\$ EVALUATE THE CONSEQUENCES

EVALUATE CONSEQUENCES 'C' WITH UTILITY FUNCTION 'U'

TO DETERMINE GOAL VARIABLES 'V'

\$ DETERMINE THE PREFERENCE ORDER

PREFERENCE ORDER 'R'

ACTION 'R' PREFERRED OVER 'B' 'C' 'D'

ACTION 'B' INDIFFERENT TO 'C'

ACTION 'R' BEST

ACTION 'E' WORST
 END PREFERENCE ORDER
 \$ EXAMPLES OF LIST AND PRINT COMMANDS

LIST ACTIONS

*** LIST OF ACTIONS
 *** AA
 *** AAA
 *** AAAA
 *** GROSS
 *** HIGHER
 *** 3LOWER
 *** X
 *** R
 *** S
 *** T
 *** A

LIST PARAMETERS

*** LIST OF PARAMETERS
 *** P

PRINT CURRENT BDM

*** BASIC DECISION MODULE 10
 *** ACTION A
 *** PARAMETER P
 *** CONSEQUENCE C
 *** UTILITY FUNCTION U
 *** GOAL VARIABLES V
 *** PREFERENCE ORDER R

\$ EXAMPLE OF CRITERION DEFINITION

DEFINE CRITERION 'COST'

FARE 'WASH' 'PHIL' LT 5.00

FARE 'WAS' 'PHIL' 'AIR' GT 10.00

POPULATION 'WASH' GT POPULATION 'PHIL'

END CRITERION DEFINITION

\$ EXAMPLE OF SET DEFINITION

CREATE SET 'FARE'

CRITERION 'COST'

ACTIONS ALTERNATIVE TO 'A'

END SET

\$ PRINT OUT SET ELEMENTS

PRINT SET 'FARE'

*** SET FARE HAS 2 ELEMENTS

*** ACTION AA

*** ACTION AAA

\$ ORDER SET FARE

ORDER SET 'FARE' BY INCREASING 'RAIL' SUBSIDY

*** SET FARE -- INCREASING 'RAIL' SUBSIDY

*** ACTION AAA 18000000

*** ACTION AA 20000000

\$ DEFINE GOAL VARIABLE

DEFINE GOAL VARIABLE 'AVE COST'

COMPUTED BY SUM(TRIP*FARE)/SUM(TRIP)

\$ EXAMPLE OF USE OF G.V.

'AVE COST' FROM 'WASH' to 'BOST' VIA 'AIR'

*** AVE COST EQUALS 18.69

\$ AGGREGATE OVER ALL DESTINATIONS

'AVE COST' FROM 'WASH' TO *** BY 'BUS'

*** AVE COST EQUALS 8.03

\$ ADD G.V. TO ALL SETS OF GOALS

EVALUATE 'AVE COST' FROM 'NEW YORK' TO 'BOSTON' -

BY *** FOR ALL BDM

\$ END OF DODO EXAMPLE

FINISH

6.0 The Goal Fabric Concept

The impacts of transportation alternatives are many. We can distinguish these impacts by their nature, the groups which are affected, and time at which they occur. Some of these impacts are relatively easy to evaluate in quantitative terms - such as travel time, out-of-pocket costs. Others are difficult or impossible to quantify - such as "quality of life", change in regional growth pattern, etc. Such impacts can only be ranked - i.e., placed in an ordinal scale - or perhaps only given nominal values such as the numbers on the shirts of football players. Some impacts occur quickly and cause only short-term effect; others will not occur until a long time into the future. The groups which are affected must potentially include a number of examples of the basic types outlined earlier - users, operators; non-users including physically-impacted, functionally impacted, and governmental actors.

6.1 The Problem

To define and operate upon goals, we must first formulate a list of "goal variables": we must have a variable for each facet of the problem which will be relevant to our decision among alternative actions. In light of the above discussion, we will have goal variables for different groups which may be affected, for different kinds of impacts, and for different points in time. For example, we may have goal variables corresponding to each of the following:

- a. noise impacts perceived by SST users (passengers) in 1980
- b. noise impacts perceived by SST users (passengers) in 1990
- c. noise impacts perceived by SST non-users, over whose property the SST flies, in 1980

d. trip times perceived by SST passengers in 1980, etc.

Once we have defined a list of goal variables, we may then attempt to use this list as a basis for choosing among alternative actions. The simplest way is to use the list as a checklist - if the level of every goal variable on the list is satisfactory, then that action is acceptable; it is unacceptable otherwise.

A more general approach is to establish some type of scoring scheme. Mathematically, this can be expressed as

$$U_i = \sum_j a_{ij} w_j$$

where:

- w_j = relative weight of the j^{th} goal variable
- a_{ij} = level on scale of j^{th} goal variable achieved by action i
- U_i = total weighted score for action i .

Standard economic criteria, such as total annual cost, net present worth, or benefit-cost ratio are variants on this scheme, as also utility theory.

The difficulties with such a scheme (as discussed in Section 2.0 of this chapter), include the following:

- a. we never have a full, complete list of goal variables;
- b. it is very difficult to get all the goal variables defined so as to be independent, mutually exclusive, and all at the same "scale" of relevance,
- c. we can never completely identify the relative values w_j of all possible combinations of the various objectives;

- d. we prefer to make decisions based upon the differences between alternatives, not the absolute levels; it is particularly important to us in making a decision to know how much of goal j we must give up to achieve goal k;
- e. particularly in a socio-political context such as transportation, it is essential to examine the differential incidence - one alternative may score high on the goal variables important to group A but low on those important to group B, and therefore, the total score U_i hides the essential issues of choice;
- f. objectives change over time - it is sometimes as important to clarify our objectives through examining a series of successive alternatives, as it is to develop new actions to implement.

6.2 Approach: The Goal Fabric¹

Recognizing the difficulties of the "scoring scheme" approach, an attempt was made to develop a looser, more subtle, more flexible approach to evaluating and choosing among alternatives. The concept developed is termed the "Goal Fabric". It does not solve the problem completely, but seems a fruitful direction for development.

The basic ideas of the Goal Fabric are:

- a. a list of goal variables can be generated, but this list is never complete nor fully consistent and independent;

¹ Manheim, Marvin L. and Fred L. Hall, ABSTRACT REPRESENTATION OF GOALS. Professional Paper P67-24, Cambridge, Mass., M.I.T., Dept. of Civil Engineering (1968), Volume XIV of a series. Also in TRANSPORTATION: A SERVICE, Proceedings of the New York Academy of Sciences - American Society of Mechanical Engineers Transportation Engineering Symposium (1968).

- b. a number of relations among goal variables can be identified and used to structure the list (means-ends, specification; value-wise dependence or independence);
- c. it is not necessary to get complete information on all possible combinations of values of the goal variables (e.g. by getting dollar equivalents, or by defining a utility function); the decision maker need supply only sufficient information to indicate his preferences between the alternatives with which he is confronted, not all possible alternatives.

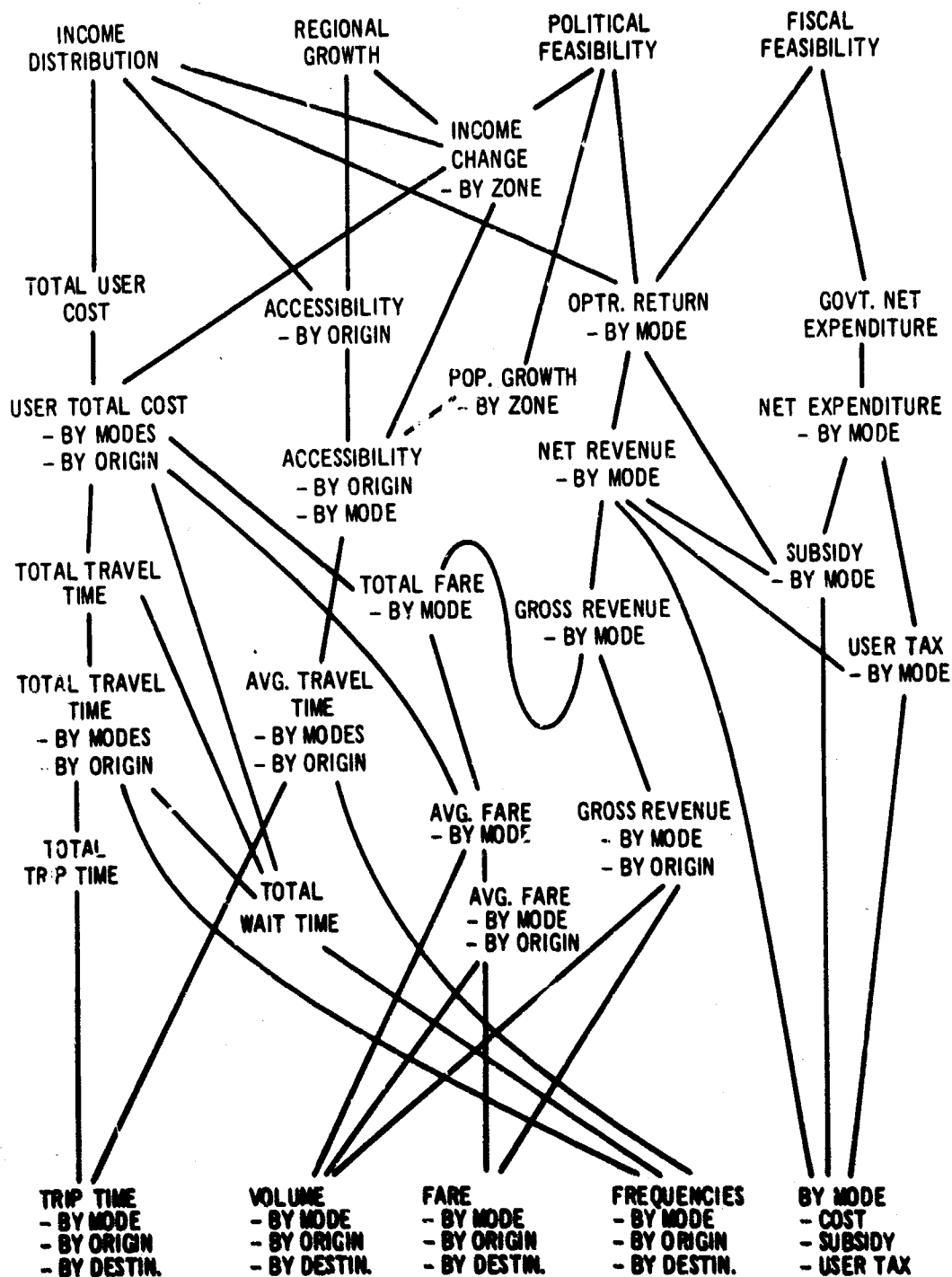
The resulting technique is described in detail in a related report.

6.3 Example: Prototype Analysis Goal Structure

The basic impacts and consequences which are treated in the prototype analysis were discussed in Chapter III. As indicated in that chapter, various aggregate measures of those impacts are constructed. For example, travel times are summed over origins, destinations, and/or modes, to various levels of aggregation. On such a summation, all the goal variables are weighted equally.

The general structure of the goal variables is shown in Figure IV-2. The figure indicates how many different goal variables the analyst may wish to examine, and the complex structure of their interrelations.

GOAL FABRIC



CONSEQUENCES

Figure IV-2

7.0 Multi-Level Problem Solving: Network Aggregation

In human problem-solving, we rarely analyze real problems at only one level. It is a natural approach to problem-solving to operate at several levels of analysis. In some contexts, this corresponds to first doing "preliminary analysis," then "detailed".

7.1 Hierarchical Structure

When an analysis process deals with several levels, we say it is "hierarchically-structured". A model of hierarchically-structured problem-solving processes has been developed,¹ revolving around the concept of inclusion among actions.

By inclusion we mean that one action may be a representation of a set of other actions. For example, a schematic diagram of a network and its associated regional development pattern ("linear system," "a polynucleated region") may represent a number of different detailed network and land use pattern alternatives. Conceptually, we can visualize the "gross" or "higher level" action, as a set of more detailed, or "lower level" actions; all the lower-level actions in the set differ in details but have the same basic characteristics, and so can be represented by a single higher-level action.

The concept of hierarchical structure is defined by this inclusion relation. Consider now the "basic operator," consisting of the sequence search-prediction-evaluation-choice (i.e., search followed by selection). Such a basic operator produces a characteristic kind of action. For example, in highway location, we might have three operators: one operator to produce bands of interest, a second to produce location bands, and a third to produce locations.

¹ Mannheim, Marvin L., HIERARCHICAL STRUCTURE: A MODEL OF DESIGN AND PLANNING PROCESSES, Cambridge, Mass: M.I.T. Press (1966)

The purpose of multi-level structure is to enable us to search more efficiently by generating and evaluating gross alternatives as well as detailed ones. The inclusion relationship implies that only for the most detailed alternatives is it possible to predict impacts precisely. Of course, since at higher levels we are working with approximate characteristics rather than precise detailed characteristics, there is higher uncertainty about the performance of alternatives. In other words, if we are dealing with performance attributes of a particular system then we can get a single-valued vector only at the most detailed level. At other levels we can only deal with the distribution of these attributes.¹ So what we gain in computational effort by dealing at the gross level, we lose in accuracy and certainty of results.

7.2 Multi-Level Transportation Analysis

The complexity of the transportation systems problem suggests we may find it efficient to structure it as a multi-level process. A possible multi-level structure was initially proposed by Bruck, Manheim, and Shuldiner for the Northeast Corridor study.² Related work is discussed in Chapter V, Search.

¹ Op. Cit.

² Bruck, N.H., Marvin L. Manheim, and Paul W. Shuldiner, TRANSPORT SYSTEMS PLANNING AS A PROCESS: THE NORTHEAST CORRIDOR EXAMPLE, Professional Paper P67-23, Cambridge, Mass., Dept. of Civil Engineering, M.I.T. (1967). Volume XIII of a series, also in 1967 PROCEEDINGS OF THE TRANSPORTATION RESEARCH FORUM.

7.3 Network Aggregation¹

To successfully use a multi-level framework, an understanding of the fundamental relationships among different levels is necessary. To develop this understanding in the particular context of network equilibrium, experiments were conducted in the area of network aggregation.

7.3.1 A Question of Detail

A basic problem in the analysis of transportation systems is that of the detail with which networks are modelled. Very rarely can the analyst expend sufficient resources to model a transport network in full detail, with a link in the model for every link in the real-world network. Rather, the analyst must be satisfied with an approximate representation of the real network.

For example:

- a. urban transportation - usually the rail transit and expressway systems are represented in complete detail, but the arterial and local streets, and bus lines, are more usually approximated in some way.
- b. megalopolitan or national transportation systems analysis - usually only the major intercity links can be modelled directly; the intra-urban networks, and secondary road systems, can be represented only approximately at this scale of interest.

¹Chan, Yupo, Kenneth G. Foliansber, Marvin L. Manheim, and John Mumford, AGGREGATION IN TRANSPORT NETWORKS: AN APPLICATION OF HIERARCHICAL STRUCTURE, Research Report R68-47, Cambridge, Mass.: Dept. of Civil Engineering, M.I.T. (1968), Volume VIII of a series.

When modelling in full detail is not possible, the analyst must explicitly account for the uncertainties introduced by the approximation by a less-than-fully detailed ("aggregate") network. The basic idea is that each link of an "aggregate" network corresponds to a set of links in the true network.¹ This simple notion implies that the aggregate link does not have a single value of travel time (length, capacity, or other parameters), but a probability distribution. The analyst should formulate and use this distribution; and thus avoid possible serious errors which may result from only using the point estimate of the aggregate link's travel time (length, capacity, etc.).

In general, many different levels of detail of network representations will be desirable. Each will have a corresponding uncertainty in analysis, consequent upon the degree of aggregation; but as aggregation and uncertainty increase, ease of computation for analysis should increase and computing cost (dollars, time) should decrease.

It is the task of the analyst to determine the desired level of detail for an aggregate network. To do so, he must estimate the relative benefits of increased accuracy associated with a detailed network versus the ease of computation and analysis effort permitted with an aggregate form. If a small number of alternative transport systems are being evaluated for a final decision of which alternative to implement, uncertainty in the network parameters should be minimized and the required aggregate network will retain a high level of detail. If preliminary studies are being performed on a large set of widely different transportation alternatives, then a higher level of uncertainty can be tolerated to permit many

¹ More precisely, a subset of links at the aggregate level correspond functionally to a subset at the "true" level. See further Marvin L. Manheim, HIERARCHICAL STRUCTURE, op. cit.

analyses so that possible alternatives can be reduced to a small number for detailed analysis. The usefulness of aggregation in a transportation planning environment is reflected in the ability to analyze a larger number of alternative transportation systems for a given set of analysis budget and time constraints than would be possible if aggregation techniques were not employed.

7.3.2 Forms of Aggregation

Network aggregation occurs in every transportation analysis. Every network model is an abstraction of the physical system of highways, streets, and other channels of transportation. It is not at all feasible to represent the actual detailed street system in its entirety. In spatial aggregation, we create an "aggregate" network as an approximation to some more detailed one.

We can also have temporal aggregation. Flow patterns in networks are subject to temporal variations. The traffic during the rush hours is entirely different from that during 3 a.m. in the morning. This variation is seen also in the seasonal fluctuations in regional networks. The number of inter-city travellers in August is different from that in February. In order to describe the traffic flow pattern accurately, it would be necessary to perform a large number of network equilibrium computations corresponding to the peak and off peak hours of the day and the summer and winter seasons of the year. However, usually the limited amount of analysis resources allows only a few network equilibrium analyses to be performed. The transportation analyst is therefore forced to represent the time varying flow pattern by a few temporally-aggregated equilibrium calculations. For economy reasons, he may attempt to extract information about peak hour and off peak hour traffic from an "average" equilibrium flow analysis.

7.3.3. Experiments

Experiments and analyses of network aggregation were conducted in a variety of ways. Alternative aggregation rules were formulated. Several idealized test networks were constructed, and using TRANSET, experiments were conducted to explore the properties of aggregation in these networks. Theoretical analyses were also conducted.

Particularly important conclusions were derived from a theoretical analysis of a simple aggregation approach. These results are summarized in the following section.

7.3.4. Aggregation in Space and Time

A simple case example was explored in detail to determine the validity of network equilibrium analyses made with aggregate parameters. Realizing that both the trip demand curve and supply curve are time varying functions throughout the day, this analysis explored the relationship of the equilibrium point of the aggregate analysis and the equilibrium points of the detailed analysis. It was found that under special conditions (e.g., special shapes of the supply and demand curves), the aggregate analysis is sufficiently accurate to approximate the detailed behavior of the equilibrium points throughout the day, while in other cases, the aggregate results are unrealistic.

The common assumption is that a network equilibrium computation, with average input parameters such as an average demand trip matrix and a set of volume delay curves which 'on the average' approximate the travel time characteristics on the link, gives equilibrium outputs which is also the average approximation of the detailed distribution. This assumption is not always true. For travel time output, this 'golden mean' concept is valid,

in that the aggregate travel time is bounded between the peak and off-peak travel times for all cases. But for volume, the 'golden mean' concept is valid only under special restrictions on the slopes (elasticities) of the supply and demand curves, and the peaking characteristics of the travel demand.

Thus, the common practice of computing network equilibrium using average parameters does not in general give flow volumes which are between the extreme values of the detailed equilibrium flow volumes.

These conclusions were obtained by an analytic investigation. An aggregation rule was formulated to collapse the spatially and temporally varying parameters of supply and demand. Network equilibrium based on the aggregated analysis is calculated by solving the supply-demand equations. Also, equilibria are calculated for the same link on a detailed level, in which we look into the peak and off-peak flow situations. A comparison of the equilibrium points obtained from both the aggregate and detailed analysis is made, leading to the above conclusions.

7.3.5. Aggregation Rules

A survey of alternative aggregation rules was developed. These aggregation rules suggest methodologies to aggregate zones, links and time-varying flow pattern. Many of these rules are based on weighted averages. In order to apply an aggregation rule, an initial estimate of the network equilibrium flow pattern is necessary. This fact can be seen very clearly in the "network reduction" link aggregation rule. The analyst must have an idea of the relative magnitude of the flow distributions before he can decide on the set of links that can be removed. The initial estimate of equilibrium is important because these estimated flows and service levels (e.g. travel time) are required to serve as "weights" in computing the aggregate, average parameters.

All the aggregation rules analyzed are designed to update the following 3 components of a network equilibrium analysis:

- (i) Zones - a set of zones are aggregated together to form an aggregate zone.
- (ii) Supply functions- a set of links are represented by an aggregate link with a level of service function derived from that of the set of detailed links, which may be time varying.
- (iii) Demand functions- the demand between zone pairs are collapsed together to form aggregate demand functions according to the way zones are collapsed together to form aggregate zones. The detailed demand functions can be time varying.

In general, it was found that zone aggregation is more difficult than aggregation of supply (link aggregation) and demand functions. The difference lies in dimensionality. The dimensionality associated with zone aggregation is an order of magnitude higher than supply and demand aggregation. Once zone aggregation has been performed, supply and demand aggregation follow in a relatively straight forward way.

It is recommended that more emphasis should be placed on link aggregation (as opposed to zone aggregation). Since the core of the problem of network aggregation lies in solving the complex interaction of supply and demand, it is felt that rearranging the zone patterns would further complicate the demand functions. Further, it has been pointed out that detailed interzonal transfers information is retained in a link-aggregated network better than a

zone-aggregated network. It is easier to handle the technologically controllable supply curves than the socio-economically determined demand functions. Thus, to replace a set of links by an equivalent composite link which renders the same level of service promises to be a more fruitful endeavor.

8.0 Computer Graphics in Transportation Analysis:¹

In a comprehensive PSP, the solved and current problems are used as the data base where they logically influence new decisions. We need to record and interpret a sequence of decisions and a large volume of information generated during the solution process to make it meaningful. A graphic capability can assimilate a proliferation of data for meaningful interpretation and use by bringing out the essentials.

Essentially, the issue is not the mechanics of generating computer displays, but what information is to be displayed and how it is to be displayed so as to be most useful in the transportation analysis process.

Input to the Computer

Increasing level of
ease and realism

1. Procedure Oriented Language
2. Problem Oriented Language (P.O.L.)
3. Graphic input with the help of
the screen, light pen and function
keys

Output from the Computer

Increasing level of
meaningfulness

1. Detailed numerical data
2. Aggregated numerical data, and
elementary plots of behavior
3. Detailed graphic representation of
aggregated data - network loadings,
dynamic flows, etc.

¹

Silverstone, Stuart M. and John Mumford. DEVELOPMENT OF COMPUTER GRAPHICS IN TRANSPORTATION ANALYSIS. Research Report R-50, Cambridge, Mass.: Dept of Civil Engineering, M.I.T. (1968) Volume XI in a Series.

A graphics capability enhances the transportation analysis process in two ways:

1. Better use of intuition of the analyst through quick visual comparisons.
2. Direct input/output procedures to establish closer communication between the analyst and computerized data; e.g., network loading displays showing steady state equilibrium flows, and dynamic flows showing the fluctuations.

The transportation planning process requires storage, and comparison of a series of complex alternatives. The recall may be along the dimensions of time, context or hierarchical scale. This implies the need for a very flexible and adaptable graphic capability, such as dynamic displays and window scaledown techniques for extraction, partitioning and aggregation of networks.

The basic issues are:

1. Dynamics of a proposed network should be analyzed at different scales to perceive macro and micro implications, and to identify strategy conflict and general alternative configuration.
2. User must be able to reference a large data base.
3. Difficulties of detail and routine of programming should be reduced.
4. Loose, and very flexible dialogue with the computer is needed.

The basic capabilities should include:

1. Ability to extract specific classes of information.
2. Ability to transform the information from one mode of representation to another.

3. Difficulties of detail and routine of programming should be reduced.
4. Ability to perturb the information by altering the value of the variable.

The following is a brief summary of where graphics might be used in each phase of the standard transportation planning process.

1. To illustrate the distribution of predominant land use over the entire study area. Existing population levels can also be represented to aid in zoning.
2. The level and distribution of future trip ends can be portrayed graphically to facilitate identification of areas with strong growth or where trip ends are decreasing.
3. The distribution of interzonal trips can be displayed graphically by desire line plots. These represent travel demand intensities over time. A quick sensitivity analysis is also possible to study changes in volume patterns with respect to link addition or speed increase in certain directions.
4. Modal split can also be displayed by the variable width line between all O-D pairs where the widths are proportional to the percentage of total trips.
5. Link volumes and velocities can be displayed. It is possible to monitor the assignment model at frequent intervals to study the gradual loading. This can help us identify the bottlenecks, and the effect of changing parameters of the assignment model, such as increment size or the assignment mode.
6. The evaluation of final results can be aided through use of graphics to show relationships between modes and distributions of LOS variables over the entire network.

7. Time Dimension: To study the micro fluctuations in loading which identify bottlenecks, and also to study fluctuations in long range time periods.
8. Availability of hard copy records for use in further studies and as means of communication with public policy officials or citizen groups.

9.0 Conclusion: Transportation Systems Planning as a Process

In earlier chapters, we defined the options and impacts with which transport systems analysis deals, and the basic core models of that analysis. In this and earlier chapters, we surveyed the issues of search and choice in the context of both "static" and more dynamic analysis.

"Search" is the task of finding a transportation system design which seems likely to achieve a particular stated set of goals. "Selection" is the task of determining whether in fact a particular system design does meet a set of goals. Because the impacts of transportation are numerous and differentiated in their incidence among groups in society, an important component of the selection task is "choice": balancing different types of impacts among various groups to reach a preference ordering over alternatives.

If one is willing to assume that the goals can be expressed as a single objective function to be maximized or minimized and a set of constraints, then various mathematical optimization approaches may be utilized. Selection, including choice, becomes trivial; search is in principle feasible, though perhaps at significant computational cost. As a practical matter, even for this case, search over the full set of options, ranging from trade-offs within the technology design to network structure and operating policies, is solvable only in an iterative series of successive approximations.

The "rational" ideal of systematic analysis has five basic components: formulate objectives, identify all possible alternatives, enumerate their consequences, evaluate the utility of the alternatives, and choose the alternative with the highest utility. In this ideal, the objectives are stated

as desired levels of impacts; the alternatives are described in terms of the various transportation and activity system options; and the utility of each alternative is expressed in terms of the impacts.

A number of objections to the static model were raised, and to counter these, a more subtle model of analysis was described. One of the key features of this model is recognition of the evolution of both actions and goals as analysis proceeds over time.

The recognition of the basic fact of evolution of actions and goals overcomes the problem of formulating objectives in the abstract. Initial objectives can be revised as soon as the first cycle of search and selection has produced some actions. The goal fabric construct, by replacing the requirement of a utility function, can accept the realities of policy analysis: inability to formulate a completely defined utility function. A sequential staged strategy approach recognizes that we cannot explore all the alternatives at one time, nor predict the future with certainty; and that flexibility is desired, not single massive alternatives. Furthermore, explicit analysis of the value of information, integrated into a sequential decision process, recognizes limitations in analysis resources.

Once we have accepted the role of analysis in helping to clarify both options and objectives among analysts, decision-makers, and the body politic, we see a most exciting and challenging prospect. At its core, transportation systems analysis deals with "hard" technology. But because of the multiplicity of impacts, and the imperfections of the analysis process, the role of analysis is seen very differently than in the past. The role of analysis is to clarify the issues of choice, not subsume them away; to identify explicitly areas of difficult choice because of conflicts among interest groups; to search out alternatives which can serve as a basis for compromise and

negotiation in the political process; and to involve the polity in choice through explorations they can understand.

To implement this philosophy, a number of specific operational techniques are under development: DODO; goal fabric analysis; network aggregation and multi-level structure; computer graphics; evolutionary staging and value-of-information techniques.

Research in the structure of transportation analysis as a process should continue.

CHAPTER V

SEARCH

1.0 Introduction¹

As a result of the discussions in the preceding chapters, we are now in a position to summarize the basic issues in the search problem. The discussion of the substantive nature of the transportation systems problem (Chapter II) indicated the variety of options which could be manipulated in trying to formulate a transportation plan or policy. This discussion also emphasized the variety of impacts on different groups which needed to be considered in analyzing alternative plans. In order to predict the impacts of a particular set of options, it is necessary to have a relatively complex system of models, organized around the concept of supply and demand equilibrium in the transportation network. In search, we are concerned with trying to trace out a full range of options and their impacts. In particular, we are concerned with tracing out the substitutabilities among options in achieving different impacts.

The Prototype Analysis described in Chapter III indicated several things. First, it showed that it was in fact feasible to represent the basic options and impacts in a transportation systems analysis in a set of models of the supply-demand equilibrium type. Second, the experiments indicated what some of the problems and issues would be in tracing out the substitutabilities and tradeoffs among options and impacts. Even though this is a difficult problem, it still is feasible as an objective to try to do systematic exploration of the alternatives.

We have seen that the basic set of prediction models will be used to

¹This chapter was written with Kiran C. Bhatt, and draws heavily from material by Felipe Ochoa.

evaluate a number of well defined alternative systems. This is however only the basis for testing the alternatives; the problem of search is to develop inputs to the system of models used for predicting impacts.

In general, as indicated by the Prototype Analysis, the range of possibilities for any particular problem is immense. In practice, of course, we can sample only a very small percentage of the large number of possible alternatives. In doing this we use a variety of short-cuts:

We consider the existing transportation system, and explore possible small changes to that system;

we focus on a component of the system - we decompose the system into sub-systems, and work only on a piece of it - for example, we design a better vehicle and ignore the terminal, the access links or land use impacts;

we abstract and simplify from the detail of the real problem, constructing a model which we can manipulate to get an approximate idea of the characteristics of the desirable alternative.

Each of these approaches has its value, and its limitations.

In actuality, we want to build up our search strategy out of all of these approaches. Because of the massive fixed existing investment in transportation systems, most often we shall actually implement only strategies which involve a series of small changes to the existing system. However, we want to make this series of steps part of an incremental path toward some target end-state; this end-state objective may be radically different from the present system. We shall often take a piece of the system and focus on some component if only to understand its properties better in relationship to the overall system. And, we shall definitely attempt to abstract and simplify from

the problem.

This suggests the general flavor which underlies our discussion of search. There is no single, all-powerful, procedure to use for searching out transportation systems alternatives. Rather, what is needed is a variety of tools used flexibly by the transportation systems analyst as he explores the shape of the problem.

In this exploration, we assume that the analyst uses a complex system of models for predicting the impacts associated with each alternative action. This model system, of course involves network equilibrium prediction. Because of the variety of options and impacts, and the complexity of their interactions as represented by the system of models, the analyst will attempt to systematically trace out variations of the options and impacts, as was illustrated in the Prototype Analysis.

Every model abstracts from reality and imposes its own biases on the problem. We need to be careful about the limitations and biases imposed by the system of models being used. Thus, we can conclude that systematic analysis using the predictive model system is only a guide to the search process of the analyst.

The analyst uses predictive models and search techniques to stimulate his perception and understanding of the problem. Neither the predictive model system nor the "kit" of search techniques will specify the solution to a transportation systems problem. The systematic analysis of alternatives, and the results of search procedures, serve to build up the analyst's image of the issues in a problem. This understanding, conscious and unconscious, provides an experience base from which he will create intuitively¹ that

Hadamard, Jacques, THE PSYCHOLOGY OF INVENTION IN THE MATHEMATICAL FIELD, New York: Dover Publications (1954; original edition 1945).

synthesis of technical and political elements with which he will try to "solve" a real-world problem. The solution comes from the analyst's understanding and imagination, not the models; but the models are an important aid.

In this chapter, we discuss some of the issues and techniques of search. We first describe search as an abstract issue, in Section 2. In the following section, we discuss some of the specific issues of search in transportation and some general approaches. In Section 4, we enumerate a variety of specific search techniques, which can be viewed as modules of a larger process. In Section 5, we discuss how these modules may be strung together in flexible, more powerful strategies. Finally, the last section indicates our conclusions, including specification of an ideal environment for search.

2.0 The Issues of Search

2.1 The General Search Problem

We are at some point in the analysis process. Assume that we have some current statement of goals $\underline{G}^*$ - a statement of desirable levels or ranges of impacts. We also have a list of all the actions which have been previously generated and examined, $A_1 \dots A_m$. Each of these actions corresponds to a particular set of transportation systems options. For each action, we have the results of previous selection cycles, in that we have the predicted impacts for each of these actions. We also have the preference ordering, or ranking of the actions, in terms of their relative achievement of the goals $\underline{G}^*$. Assume that none of these actions has been fully satisfactory in its impacts.

The general search problem is this:

Given: a list of previously generated actions and their impacts, and a statement of the desired levels or ranges of impacts;

Find: what values of the decision options will achieve the desired levels or ranges of impacts? That is, find new actions A_n which will come closer to achieving the goals $\underline{G}^*$.

To see the central issue, define two functions ψ and ϕ as follows:

$$(a) \text{ Search function: } A_i = \psi(G^*)$$

$$(b) \text{ Selection function } G_i = \phi(A_i)$$

If we have a selection procedure - i.e., we know ϕ - then for any A_i we can determine G_i , its performance with respect to the goals G^* . If we know ψ , on the other hand, then search is in principle trivial: given a statement of desired goals G^* , we can find via ψ the specifications of the action A^* which achieves those goals. Obviously, ψ is an inverse function of ϕ .

The reason why search is a problem, of course, is that the inverse function, ψ , is either unknown or intractable or both. This is not hard to understand: if it takes a complex set of models to predict the impacts of a set of options (i.e., execute ϕ), then going in the reverse direction may indeed be very difficult.

So far, we have ignored the difficulties of selection. That is, we assumed that given a particular set of transportation and activity system options - a particular action A_i - we can predict its impacts, via supply, demand, equilibrium, resource requirements, and demand shift models; evaluate those impacts, and decide on that basis whether A_i is preferred to any previous actions A_j . In terms of our symbols, we know ϕ with certainty.

In actuality, ϕ is not well-defined either. If nothing else, we have difficulty with choice, deciding which action is preferred after the consequences have been predicted. Thus, the reasons why "search and choice" is a problem are:

- (1) We can never know either ψ or ϕ with certainty over the relevant ranges of A and G;
- (2) We need to find both a G and an A which are 'satisfactory', in the sense that the statement of goals G is acceptable to all the relevant decision-makers; and the particular action alternative A is, within the limits of our predictive capability, anticipated to yield G.

In order to find such an A-G pair, we must work at two levels of problem-solving. At one level, we generate particular A's and G's, trying to find A's which achieve specified G's, and modifying G's as we learn more about the available A's and their characteristics. At the second, more

"prodecural" level, we try to find better estimates of the functions ψ and ϕ , as a means of getting better A's and G's¹.

2.2 The Search Problem in Transportation

The search problem in transportation systems analysis is difficult for several reasons: the large number of types of options and combinations; the variety of impacts which must be considered, and the consequent subtlety of the goals; the complexity of interactions between options and impacts; and the need to consider staging over time. The Prototype Analysis, as simplified as it is, illustrates this complexity.

¹CF. "Goal Formulation and Revision", and "Model Construction" Procedures in the PSP Model, Chapter IV.

3.0 Approaches to Search

There are a number of general ways we can try to reduce the complexity of the search problem. These include the following: decomposition into subproblems, reduction of dimensionality through identification of substitutabilities, use of previously developed solutions, and abstraction into more tractable problems through multilevel structuring and "slicing" the time dimension.

3.1 Decomposition into Subproblems

One of the obvious ways of reducing the search problem is to refrain from manipulating all of the options simultaneously. For example, one might partition the options very naturally into the groups indicated in Chapter II: technology, network configuration, link and node characteristics, physical operating policies such as schedules, other operating policies such as pricing, and vehicle size and characteristics. At first glance, this would seem to be a reasonable partitioning of the set of options. For example, the problem of manipulating the operating options is that of the typical transportation operator: the questions of what services he should offer. The question of pricing policy is often that of a state or federal regulatory agency. The problem of new technology is that of the planner of research and development activities; while the planner dealing with networks and link characteristics generally will assume the mix of technologies as given. That, in any event, is the natural way we might tend to partition the options. Yet it is not at all clear that this is, in fact, a reasonable and efficient way to do so.¹

¹ For a discussion of arbitrary partitioning, see Alexander, Christopher, NOTES ON THE SYNTHESIS OF FORM, Cambridge, Mass.: Harvard Univ. Press (1964); Alexander, Christopher and Manheim, Marvin L., THE DESIGN OF HIGHWAY INTERCHANGES: AN EXAMPLE OF A GENERAL METHOD FOR ANALYSIS OF ENGINEERING DESIGN PROBLEMS, Highway Research Record 148, Washington, D. C.: Highway Research Board (1964).

Perhaps one simple example will help to highlight the issue. Consider that we are trying to design a new transportation technology, and are exploring all the various trade-offs between propulsion system, suspension system, vehicle shape and internal characteristics, and passenger services to be provided, as well as station spacing, maximum speed, acceleration rates, and the degree of smoothness of the supporting way (for example, roadway or track). Now, we might be inclined to establish certain performance levels as constraints: for example establish maximum acceleration and deceleration rates, maximum rates of oscillation of the vehicle, minimum seat spacing of people in the vehicle, and so forth. These design standards will ordinarily be established as "engineering judgments". Then, the technology design will search out various subsystem and system configurations which will be within these constraints. When the technology has thus been optimized for cost and physical performance within these constraints, we would represent the result of this research and development effort as a specific technology design with its corresponding supply function. In putting this supply function into the network equilibrium model, we will then attempt to predict ridership, and other effects on flow patterns, revenues to operators, etc.

Yet, some of the characteristics which we have assumed as design standards may well be very significant service variables with respect to their effect on demand. For example, it might turn out that within a fairly broad range of trip times, attractiveness of a new technology for passengers is far more sensitive to the rate of oscillation of the vehicle up and down - the physical comfort of the ride - than to the perceived psychological comfort of the spacing of passengers and the degree of privacy in the vehicle; which may not be very closely correlated with the physical density of passengers in the vehicle.

Thus, a key service variable which should have been varied in the context of the network equilibrium formulation, has been fixed prematurely in the design of the technology. The search process should have included at the network level variation of the service characteristics, instead of subsuming them into the detailed technology design at the technology level. Or, to put it another way, the wrong partitioning of the transportation options has been implemented.

The problem of partitioning the search space of options into subspaces is a very real one. The only sound theoretical work on this is Alexander's model for decomposition of complex problems into subproblems, via a linear graph model of the problem.¹

3.2 Substitutabilities:

Another useful approach is to search within the bundle of options for combinations which are substitutable in respect to some, if not all, impacts. For example, different combinations of vehicle size, vehicle speed, and station spacing can yield the same level of travel time for a particular volume. In a sense, the link supply functions already represent the results of such trade-off analyses. In developing a particular technological alternative which is then characterized by a link supply function, many of the components of the technology, such as suspension system, roadway, propulsion, system, etc., have already been partially optimized with respect to cost and service characteristics.

Even more important is the exploration of parametric relationships among the goal variables (the impacts). For example, one might attempt to

loc. cit.

determine whether it is possible to decrease travel time for one user group, while not increasing travel time for any other user group and also not decreasing net revenue for the transportation operators.

The prototype analysis experiments (Chapter IID) illustrate some of the substitutability explorations which might be undertaken. Under limited conditions, analysis of the demand and supply models alone may potentially be very useful in studying substitutability of one attribute for another. Plourde¹ illustrates the concept of trade-off-ratios in the context of the Baumol-Quandt demand model. For any particular origin-destination pair, the tradeoff ratios show how the travel attributes can be varied without altering the volume of travel. Of course, this is valid only over a range of volumes where network effects do not occur—that is, flows over other routes and/or flows between other origin-destination pairs are not affected. Such tradeoff ratios, together with information about the costs of providing different levels of service, can suggest directions for system improvement. These relationships also indicate the characteristics that a new mode would need in order to be competitive with an existing one.

Explorations of tradeoffs among the different goal variables are also important in order to identify areas of potential conflict and negotiation in the political arena.

3.3 Use of Previously Developed Solutions

One way to reduce the space to be searched is to use previously-determined solutions. "Design standards", representing engineering judgment through experience, play this role, as well as other standard "patterns." A design standard is the specification of the level of

¹ Plourde, CONSUMER PREFERENCES AND THE ABSTRACT MODE MODEL, Research Report R68-51, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1968), Vol. XII of a series.

some option - for example, standards which have been extensively used in transportation design include speeds, number of lanes, and grades for highways. A pattern is the specification of a more complex set of relationships - the patterns for optimum spacing of expressways in a highway system, developed at CATS, and for the optimum spacing of interchanges, developed by Berry and Satterley, are good examples.¹

This is a good method in situations similar to those used in establishing the standard. Of course, the objection to design standards raised above must be kept in mind, as well. The highway grade standard illustrates the issue. The maximum grade represents, in principle, a compromise between the capital costs of construction, which tend to decrease with increasing grade, and vehicle operating costs, which tend to increase with increasing grade. Ideally, one would like to find the optimum grade for each particular highway location by a detailed economic analysis of construction and operating costs for various grades. However, the assumption is that such detailed analysis is not economically justified, and that adherence to the design standard (say, 6%) will average out reasonably close: the costs of additional detailed analysis to find the true optimum grade for a particular situation would not be justified by the margin of savings.

When one uses such patterns as those reviewed by Bhatt, in general, these must be subjected to the same kind of analysis. These patterns may represent good starting points for the basic alternative, but as in the highway grade case, details of the special circumstances may require

¹ Kiran U. Bhatt, SEARCH IN TRANSPORTATION PLANNING: A CRITICAL BIBLIOGRAPHY, Research Report R68-46, Cambridge, Mass.: Dept. of Civil Engineering, MIT (1968), Vol VII in a series. See especially articles by Creighton et al and by Berry and Satterly.

that variants from the specified norms be evaluated explicitly. It is very important to determine if applying design standards for a critical variable would be premature fixing of that variable.

3.4 Multilevel Structure

Transportation planning can be structured as a hierarchical process, where search takes place at several levels. Decisions about subsidy levels, network changes and operating policies may be most relevant at different levels of detail, and may address different levels of detail among the goals.¹

Multilevel planning provides a logical way of partitioning the search space, to avoid manipulating all options simultaneously. At each level, the actions and goals are defined with appropriate degrees of detail. At the highest level the actions and goals are relatively abstract, and the descriptive parameters may be few. Search can be simpler, selecting a few potential alternatives which seem attractive enough to be explored further at a more detailed level. As we go down the multilevel structure, we introduce more and more detail, but we consistently reduce the search area.

The idea of multilevel planning has been used implicitly in most planning projects. For example, the urban transportation studies develop transportation plans at the network level; options such as toll policies, scheduling of transit and other operating policies are dealt with separately, at later stages or by other agencies. This multilevel structure is ad hoc, however, and not explicitly analyzed to identify clearly the relationships

Nanheim, Marvin L., HIERARCHICAL STRUCTURE: A MODEL OF DESIGN AND PLANNING PROCESSES, Cambridge, Mass.: MIT Press (1964); Bruck, Henry W., Nanheim, Marvin L., and Shuldiner, Paul W., "Transport Systems Planning as a Process: The Northeast Corridor Example", in PAPERS OF THE TRANSPORTATION RESEARCH FORUM, Volume 8, Chicago, Ill.: Transportation Research Forum (1967).

among the goals and actions at the different levels. Serious errors may be induced by such relatively arbitrary hierarchical structure.

When planning is structured hierarchically, different search procedures can be applied at various levels of analysis. The nature and sophistication required of a search procedure will depend on the detail and explicitness of impacts considered at that level. For example, the objectives and service characteristics may be very well defined at a detailed level, so that a formal and well-structured technique such as mathematical programming may be well suited - e.g. to optimize schedules over a fixed route. At a gross level where we are trying to manipulate general network structure and policies, less formal search procedures have greater relevance, because the impacts are more general and often not quantifiable.

In summary, we need search procedures at each level, and procedures to relate the different levels.

3.5 Time-slices

The implementation of changes to a transportation system takes time. The effects of those changes in the activity system - for example, changes in land use - also occur relatively slowly. In a sense, the transportation and activity system possess an inertial momentum; any proposed changes to the system operate generally as impulses which alter the trajectory of this inertial system. In general, the inertia is so great that the impulses can only modify the trajectory, not change it dramatically (at least in the short run).

Two basically different philosophies of planning exist, often seen in contradiction to each other. In "end-state" planning, one identifies some target year (say, 1985), and tries to find the optimum system for that end-state year. Most urban transportation studies have done "end-state" planning. In "incremental planning," one considers the existing system, and tries to find a series of changes to make to that system which will modify it progressively over time. Many transportation operators view the problem this way.

These two philosophies do not really have to conflict; rather, they should be seen as two different ways of handling the larger problem of planning for a system with large inertia. End-state planning is useful to try to identify objectives: toward what state should the system be guided. However, to actually get there requires consideration of incremental planning: the sequence of steps which, over time, will so modify the trajectory of the system that it does arrive at the desired end-state. These considerations are particularly important when uncertainty is considered.

The prototype analyses demonstrated some of the implications of variation in time staging of alternatives. (See Chapter III.)

Thus, considering time, the general search problem is to find the optimal sequence of changes to the inertial system over the planning period which results in the optimal end-state, in the face of uncertainty. This problem is not solved at the present state of the art. What can be done is to "slice" at the problem in different ways:

- a. focus on "optimal" end-state
- b. focus on optimal stagings, under certainty,
- c. treat staging in the face of uncertainty explicitly:

As will be discussed in the following sections, search techniques exist for "solving" these slices of the problem. All of these techniques, however, beside involving slices, usually also require simplifying the demand and/or the supply sides of the problem significantly. Thus, the actions developed by these formulations must be tested in detail in the selection process, using the network equilibrium set of prediction models.

4.0 Search Techniques: basic modules

In the preceding section, we identified several basic approaches to search: decomposition into subproblems, substitutabilities, use of previously-developed solutions, multi-level structure, and time-slices. Within each of these genres, there are many specific search techniques which may be useful under particular conditions. Each technique has potential relevance and utility at some point in the overall planning process, but none of them is itself sufficient.

In this section, a number of very specific operational techniques will be described.

These techniques can be visualized as "modules." As discussed in section 5, using these modules as "building blocks," more complex search strategies can be formulated.

4.1 Mathematical Optimization:¹

If we make some fairly drastic simplifications in the problem, we can apply fairly powerful techniques. For example, if we are willing to weigh all the impacts comparably, in a single dimension, we can formulate the goals as an objective function to be maximized (or minimized), plus a set of constraints. Then, the problem can be formulated as a mathematical optimization problem.

In optimization theory, it is assumed that the degree to which the

¹ This section draws heavily upon:

Ochoa-Rosso, Felipe, APPLICATIONS OF DISCRETE OPTIMIZATION TECHNIQUES TO CAPITAL INVESTMENT AND NETWORK SYNTHESIS PROBLEMS, Research Report R68-42, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume III of a series; Ochoa-Rosso, Felipe and Angel (7) Silva, OPTIMUM PROJECT ADDITION IN URBAN TRANSPORTATION NETWORKS VIA DESCRIPTIVE TRAFFIC ASSIGNMENT MODELS, Research Report R68-44, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume V of a Series.

goal or objective of the problem is reached for each alternative course of action can be evaluated by a quantitative method. In other words, a measure of the utility of each course of action may be obtained, allowing the decision maker to select the alternative yielding the maximum utility. The degree to which the goal is obtained is the figure of merit for a particular solution.

DEFINITION. An optimization problem is defined as the selection from among a set of various alternatives (possibly infinite) of a certain problem, the one for which a given figure of merit is optimized (e.e., maximized or minimized).

Optimization theory in its widest sense is the unified branch of mathematical analysis that provides a formal approach to the solution of optimization problems. Specific techniques include mathematical programming, game theory, statistical decision theory, dynamic programming, control theory, calculus of variations, etc.

Optimization models can be classified conveniently by distinguishing three main components: i) the set of problem variables (the variables which specify a solution - the "options"); ii) the figure of merit to be optimized; iii) the domain of definition of the problem variables (determined by the constraints of the problem). The optimal solution for certain classes of optimization problems consists of numerical values taken by the problem variables, satisfying the constraints and simultaneously optimizing the figure of merit. Other classes of optimization problems seek to find a curve or function (variational problems), that satisfies a set of constraints and renders optimal a certain functional expression of the set of feasible solution curves.

For certain problems the objective will be amenable to a closed-form

mathematical representation as a function of the control variables. For other problems this closed representation might not be obtainable and the figure of merit for a given set of values of the control variables may only be known after a complex process has been completed (such as a simulation process, an engineering analysis, the solution of an elaborate computer program, or a table look-up).

Furthermore, the problem may be constrained or unconstrained. For constrained problems capable of formulation in a closed-form mathematical representation, the nature of the constraint expressions may be quite diverse. For instance, they may be algebraic or transcendent expressions, equalities or inequalities, linear or nonlinear with the domain of the variables being a discrete set or the continuum. Also some of the constraints may be differential equations or definite integrals.

Ochoa indicates a tree-structured classification of optimization models.¹ For certain specific classes of models, the solution procedures form a well-established mathematical development. For instance, models in the constrained optimization branch for which both the constraints and objective may be represented in closed algebraic form constitute that part of optimization theory generally known as mathematical programming. The class of problems for which the explicit objective function is expressed by a definite integral (functional objective) with or without subsidiary conditions, is the scope of the classical calculus of variations. Those models with constraints and/or objective lacking a closed mathematical representation, may be approached by the techniques falling under the general name of direct search methods.

Solution techniques are the procedures and algorithms devised for the solution of optimization problems. The actual solution usually

¹ Ochoa, Op. Cit.

entails determination of numerical values of the control variables and the optimum value of the figure of merit. Solution techniques for optimization problems are usually broken down into two major categories:

¹
indirect and direct methods. With direct methods, the optimum solution is sought by directly calculating values of the objective function at different points of the feasible domain. The values thus obtained are compared and, by means of an auxiliary criterion, a new point is next analyzed which hopefully will improve the value of the objective function.

Alternatively, indirect methods look for a set of values of the control variables that satisfy known necessary conditions for optimality. The classical method of the differential calculus is an example of the indirect type. In effect, values of the variables are sought for which the first derivatives of the objective function vanish, provided that continuity of the function and existence of **derivatives** in the region of interest are guaranteed. In this way, the optimization problem has been transformed into a root-finding problem.

The Simplex algorithm of linear programming exhibits features of both the direct and indirect methods. It performs a direct search over extreme points of the feasible domain only (points satisfying the necessary condition for an optimum) in such a way that the objective function is at least as good as in the previous step. Finally, the optimum among the set of extreme points is detected when the indirect criterion of feasibility of the complementary solution to the associated dual problem is satisfied.

For certain mathematical models of optimization, a solution method

1. Wilde, Douglas, J., OPTIMUM SEEKING METHODS, Englewood Cliffs: Prentice-Hall (1964)

may include transforming the original model into an equivalent one that¹ promises to be more tractable than the former. In the methodology of geometric programming,² the polynomial optimization is formulated in terms of its dual problem and this is the model that is actually solved. Another example is the transformation of a separable nonlinear program into a linear programming problem.

Direct techniques may be subdivided into two major groups: simultaneous and sequential methods. Simultaneous search techniques calculate values of the objective function at a set of points determined a priori by a certain search strategy. The experiments in the prototype analysis explorations of fares and frequency of service are examples. Sequential search methods, on the other hand, deal with sequential examination of trial solutions, basing the location of subsequent trials on the results of earlier ones.

Representative solution techniques for each of the classes of methods discussed are given in Ochoa.³ The selection of a convenient solution method for a given problem depends on the type of model employed, the existing solution techniques for that particular model, and the computation facilities available. In the selection process one may consider such factors as linearities of the model, number of variables, number of constraints, special structures, separability or weak-coupling of variables in constraints and/or objective, objective or constraint surfaces of readily interpreted geometric character, etc.

¹ Ochoa Op. Cit., Cf. Chapters III and IV.

² Duffin, R. L., E. L. Peterson, and C. T. Zener, GEOMETRIC PROGRAMMING New York: Wiley (1967)

³ Ochoa Op. cit.

The final selection of a well-suited method for a particular problem depends then on the detailed properties of the model as well as the solution techniques that form part of a software package of an available computer installation.

4.2 Transportation Applications of Optimization

A number of examples can be given of the use of optimization formulations for components of the overall transportation systems problem. For example, a scheduling problem can be formulated as a dynamic¹ or linear program with an objective to minimize a combination of operating costs (which may include direct operating costs, indirect operating costs, maintenance, labor, etc.) and user costs (waiting time, travel time, etc.). The design parameters, or options, may consist of speeds, vehicle size, fleet size, etc. The formulation usually idealizes the conditions and one must assign dollar-values on waiting time and other non-dollar impacts.

Direct calculus methods have also been used for optimization of a sub-problem. Optimum layout of road systems, spacings of highways, etc., can be obtained under very restrictive assumptions.² These procedures use such drastic assumptions that their utility is only to guide the planner in the right direction. However, we can use these to get a general idea of the patterns best suited for the particular areas.

A number of mathematical programming formulations have been developed for variations of the problem of network synthesis: to determine the additions of new links and/or additions of capacity to existing links

¹ Devanney, J. W., III, "Transportation Scheduling under Multidimensional Levels", Unpublished Sc.D. Thesis, M.I.T., Sept. 1967; Simpson, R. W., "Computerized Schedule Construction for an Airline Transportation System", T-66-3, M.I.T., November 1966.

²

Bhatt, op. cit.

in a network. A number of these formulations are surveyed by Schwartz¹ and by Ochoa.²

To understand the limitations of these formulations, it is necessary to review briefly the distinctions between two basically different approaches to predicting network equilibrium. These approaches are generally given the titles of descriptive (i.e. predictive) and normative (i.e. prescriptive). The distinctions are based upon two different criteria, enunciated by Wardrop³ and formalized in mathematical form by Beckman et al.⁴ and Charnes and Cooper.⁵ Each Wardrop postulate suggests that the flow distributes itself over the network according to one of two contrasting extremal principles:

- i) postulate of equal travel times: For a flow assignment, the travel time between any two points in the network will be the same on all routes used and less than the travel time on any other path joining the same two points.
- ii) Postulate of overall minimization: For an optimal flow assignment, the average travel time for all users of the network attains its minimum value.

Descriptive traffic assignment models are based on Wardrop's principle of equal travel times. The computer implementation of such models has acquired great momentum as a result of their use in transportation studies of major metropolitan areas during the early 1960's. These programs implicitly use the game theory model of Charnes and Cooper, where all travelers seek to minimize their own travel time. In the

¹ Schwartz, Jesse, NETWORK FLOW AND SYNTHESIS MODELS FOR TRANSPORTATION PLANNING: A SURVEY, Research Report P68-52, Cambridge, Mass., Dept. of Civil Engineering, MIT, (1968).

² Ochoa, loc. cit.; Ochoa and Silva, loc. cit.

³ Wardrop, J. G., "Some Theoretical Aspects of Road Traffic Research", INSTITUTE OF CIVIL ENGINEERING, Road Paper #36, London (1952).

⁴ Beckman, M., C. B. McGuire, and C. Winsten, STUDIES IN THE ECONOMICS OF TRANSPORTATION, New Haven, Connecticut: Yale University Press (1956)

⁵ Charnes, A. and W. W. Cooper, "Multi-Copy Traffic Network Models", In R. Herman (ed) PROC. SYMPOSIUM ON THE THEORY OF TRAFFIC FLOW, New York: Elsevier (1961), pp. 85-96.

incremental assignment method for example, the flow distribution is achieved by iteratively assigning traffic from each origin node to all destinations according to current shortest path routes. After completion of each iteration, the resultant travel times on links are updated according to their current loads and the origins will again take turns assigning portions of their flows. The descriptive models used in different transportation studies present variations in their actual calculation, but they are all based on the principles indicated above.¹

Normative traffic assignment models are based on Wardrop's postulate of overall minimization and on the traffic flow analysis of Beckman et al. and Charnes and Cooper: flows distribute themselves so as to minimize the total travel time in the system, as opposed to individual travel times. This optimization problem has been formulated by Charnes and Cooper,² for congested networks, as a non-linear programming problem; the nonlinearity results from the fact that link travel times increase nonlinearly with flow volumes. They simplify their model by suggesting a piece-wise linearization of the volume-delay relationship, accomplished by introducing multiple capacitated arcs with increasing travel times. The resulting model is a linear program known as the multicopy cost-minimization network flow problem. This problem has been thoroughly analyzed and exploited by Pinnell and Satterly³ and by Hershdorfer⁴ and Tomlin.⁵

¹ Martin, B.V., F.W. Memmott, III, and A.J. Bone, PRINCIPLES AND TECHNIQUES OF PREDICTING FUTURE DEMAND FOR URBAN AREA TRANSPORTATION, Cambridge, Mass.: M.I.T. Press (June 1961). Martin, B.V., A COMPUTER PROGRAM FOR TRAFFIC ASSIGNMENT RESEARCH, Research Report R64-41, Cambridge, Mass., M.I.T.: Department of Civil Engineering, (December 1964).

² Charnes, A. and W.W. Cooper, op. cit.

³ Pinnell, C., and G.T. Satterly, Jr., "Analytical Methods in Transportation: Systems Analysis for Arterial Street Operation", A.S.C.E. JOURNAL OF THE ENGINEERING MECHANICS DIVISION (December 1963) pp.63-95.

⁴ Hershdorfer, A.M., OPTIMAL ROUTING OF URBAN TRAFFIC, Ph.D. Thesis, M.I.T., Cambridge, Mass. (June 1955).

⁵ Tomlin, J.A., "Minimum Cost Multi-commodity Network Flow," OPERATIONS RESEARCH, Vol. 14, No.1 (1966) pp.45-51.

The actual computer implementation of normative models requires a linear programming routine capable of handling a potentially large number of constraints; or alternatively, it must have the capability of exploiting the highly-structured form of the model by decomposing the problem into more tractable subprograms.

Jorgensen¹ has studied both classes of network equilibrium models, and shows that for the uncongested case (rural networks), both the descriptive and normative solutions give the same flow distribution pattern.

The important advantage of normative models lies in their flexible handling of synthesis problems, since the intrinsic nature of the optimization problem is such that a convenient solution technique takes care of the combinatorial aspects, and provides the best project combination. A substantial amount of research has been done in this area in recent years and various models have evolved from the study of several types of network improvements.

The technique of continuous augmentation of capacity on existing links has been formulated by Garrison and Marble² and by Quandt.³ In the latter model, the construction cost appears as a budgetary constraint, rather than as part of the objective function as treated by Garrison and Marble.

A substantial body of research on highly combinatorial improvement

¹ Jorgensen, N.O., SOME ASPECTS OF THE URBAN TRAFFIC ASSIGNMENT PROBLEM, Graduate Report, Institute of Transportation and Traffic Engineering, University of Calif Berkeley, June 1963.

² Garrison, E.L., and D.F. Marble, "Analysis of Highway Networks: A Linear Programming Formulation", HIGHWAY RESEARCH BOARD, Vol 37, (1958) pp. 1-17.

³ Quandt, R.E., "Models of Transportation and Optimal Network Construction", JOURNAL OF REGIONAL SCIENCE, Vol. 2, (1960, pp.27-45.

problems has been developed at MIT by Roberts and Funk, Hershendorfer, Roberts, Taborga, Ichbia and Ochoa.¹ Hershendorfer studied the optimal one-way and two-way street configuration problem by extending Charnes and Cooper's multicopy network model by an ad hoc introduction of decision variables into the model. The link addition problem has been suitably formulated by Roberts and Funk and also by Hershendorfer by employing Dantzig's scheme of introducing decision variables in the upper-bounding constraints on certain links. These authors treat construction costs as part of the objective function. Roberts and Funk consider rural network improvement subject to a budgetary constraint, as opposed to Hershendorfer, who assumes an unlimited budget and considers congested networks. The authors use the Land and Doig branch-and-bound algorithm² as a solution method for the link addition problem.

Roberts, P.O., and M.L. Funk, TOWARD OPTIMUM METHODS OF LINK ADDITION IN TRANSPORTATION NETWORKS, Cambridge, Mass., MIT, Department of Civil Engineering, (September 1964).

Hershendorfer, A.M., op. cit.

Roberts P.O., TRANSPORT PLANNING: MODELS FOR DEVELOPING COUNTRIES, Ph.D. thesis, Department of Civil Engineering, Northwestern University, 1966.

Taborga, P.N., A MODEL TO STUDY AN OPTIMAL TRANSPORTATION POLICY IN CHILE, Research Report R66-8, Cambridge, Mass., Dept. of Civil Eng., MIT., (March 1966).

Ochoa, op. cit.

² The branch and bound algorithm developed by Ochoa and Silva (op. cit.) for descriptive models is equally applicable to the new link addition synthesis problem when normative models are employed. In this case the subprograms A_i correspond to multicopy network flow problems, which can be solved by means of a decomposition-form linear programming code.

Taborga¹ extended the link addition problem for multimode distribution of many commodities over a general transportation network. He considers production as well as commodity distribution.

Recently Ridley² has developed a combinatorial procedure of the branch and bound type, to select a subset of links in which a fixed integer budget B should be invested in order to minimize the total travel time in the network. He assumes that the total travel time on each link is decreasing function of the investment in the link. His method determines the subset of links in which one unit of investment should be made.

The simultaneous optimal node and link selection for an urban public transportation network, subject to a budgetary constraint, has been solved by Ichbiah³ by means of a parametric branch and bound technique. His method does not directly consider flow volumes on the proposed network.

¹Taborga, P. N., A MODEL TO STUDY AN OPTIMAL TRANSPORTATION POLICY IN CHILE, Research Report R66-8, Cambridge, Mass: Department of Civil Engineering, M.I.T. (March 1966).

²Ridley, T.M., AN INVESTMENT POLICY TO REDUCE THE TRAVEL TIME IN A TRANSPORTATION NETWORK, Operations Research Center, ORC 65-34, University of California, Berkeley, December, 1965.

³Ichbiah, J.D., CONNECTIVITY ANALYSIS AND BRANCH AND BOUND METHODS, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, August 1967.

The set of models described above study network improvements for a single time period (base year to target year); however, in a more realistic situation the budget available for transportation investments is commonly appropriated in a multi-stage manner. Roberts¹ studied the problem of optimum link addition for the last time period and then presented a way to determine a feasible sequence of improvements over time to achieve optimality of the last time period.

Ochoa² developed a multistage or intertemporal model to determine the optimum plan, namely the sequence of improvements of the traffic network which minimizes the total users' cost over all planning periods. He thoroughly exploits the structure of the model, proposing a partitioning technique for the solution of the problem.

¹Roberts, P.O., TRANSPORT PLANNING: MODELS FOR DEVELOPING COUNTRIES, Ph.D. Thesis, Department of Civil Engineering, Northwestern University, 1966

²Ochoa-Rosso, op. cit.

The multistage problem seeking to minimize total users' cost plus construction cost in the absence of budgetary constraints has been studied by Bergendahl¹. He determines user cost for a given network configuration by means of a normative model (i.e., minimum cost multi-commodity problem), and the best investment, as a recursive process by dynamic programming.

There are several major liabilities to these mathematical programming formulations. The linearity assumptions, although modifiable, may be restrictive. Second, the normative flow distribution assumptions may be unacceptable as predictors of "true" flows. Third, all the existing formulations treat demand as fixed; incorporating variable demand (depending upon the actual levels of service in the network) may not be feasible. Fourth, mathematical programming techniques for search have a value only when we are prepared to collapse the goal fabric into a simple statement of objective function plus constraints. Fifth, the methods become computationally expensive for problems of realistic size.

These liabilities all mean that mathematical programming may never be appropriate as the general search tool, but may be very useful for suboptimization, to partition the general search space. For example, for a particular mode, we could select from a large number of speed, vehicle size, and fleet size possibilities those which are efficient combinations using a programming formulation (even though a suboptimization), and consider these as potential candidates for further testing in selection.

¹Bergendahl, G., "A Combined Linear and Dynamic Programming Model for Interdependent Road Investment Planning", MEMORANDUM #58, Stanford, California: Stanford University, (February 1968).

Similarly, options such as pricing, highway link capacities, etc., can be compacted into a small set of desirable alternatives by programming formulations. Mathematical programming can also give an idea of the equitable tolls and/or priority schemes¹, because these models are prescriptive rather than descriptive. One advantage of the mathematical programming formulations is, of course, the relative ease with which the objective functions can be varied to explore the tradeoffs among the different goal variables.²

One important way in which mathematical programming formulations may become more useful is through network aggregation.³ With appropriate aggregation rules, the basic detailed network can be collapsed into an approximate, "aggregate" network. Then, an optimization formulation would be used within this aggregate representation of the network to find an optimum. The result would then be translated back to the detailed level, and guide a more detailed search procedure at that level.

To summarize: mathematical optimization techniques are seen as useful for suboptimization over part of the set of transportation options. A variety of optimization formulations may be useful in this way. However, the solutions provided by optimization models will only be starting points for more detailed exploration of the alternatives.

¹ Bivins, David, "Use of a Normative Model in Urban Highway Network Operation and Network Improvement," op. cit.

² Schwartz, Jesse, "Production and Transport Models for Regional Planning", in EQUILIBRIUM MODELS, Research Report R68-48, Cambridge, Mass.: Dept. of Civil Engineering, MIT, (June 1968).

³ See Chapter IV.

4.3 Search with Descriptive Flow Models

The normative flow models are more amenable to algorithmic search techniques; that is why there is relatively more work in this area than in techniques for descriptive flow models. The essence of the problem seems to be that, with descriptive flow models, it is more difficult to estimate a priori which change in the particular network is most likely to result in an improvement. Until recently, the only approach available was simply to try a number of changes to the network explicitly. Two recent areas of work - Ochoa's branch and bound methods, and Loubal's sensitivity analysis approach - suggest fruitful directions.

Branch and bound methods operate by dividing the search area into mutually exclusive and collectively exhaustive regions, step by step, introducing a bound on the objective function for each subregion. As we proceed down the tree of successive partitions the constraints of the problem will help us eliminate certain regions as infeasible, thus allowing us to prune the tree. For example, the link addition problem can be structured as a branch and bound problem where the user cost is the objective function and capital cost is used as the constraint. Certain branches of the tree corresponding to certain combinations of links will be infeasible because the capital cost constraint is exceeded. Ochoa and Silva¹ demonstrate the applicability of this approach for a descriptive network flow model.

This technique also requires that the designer collapse his multivalued goal structure into two independent components, one of which describes infeasibility. Thus, as other optimization formulations, it is limited in applicability. This technique uses the logic of "direct search" where steps are taken semirandomly, and the search can be stopped at any stage before reaching the optimum, leaving us with the best answer so far and the knowledge about its "goodness". (See following). Thus, branch and bound also suggests a search strategy, which is why we choose to treat this approach separately from other optimization formulations.

One of the limitations of using the descriptive network flow models is the computation involved in predicting the change in flows resulting from each change in the network. A change in one part of the network, for example, link addition, may potentially change the flow characteristics over a large part of the network; a network flow equilibrium prediction must be carried out for each change in the transportation system. Existing descriptive flow models (such as traffic assignment models) do not give sensitivity information explicitly, whereas from a normative flow model - e.g. a linear program - information is obtained from the dual variables.

Loubal's link augmentation scheme¹ makes sensitivity analysis computationally feasible in a descriptive flow model context. By considering only the first-order impact of a link change (addition or deletion), Loubal presents a simple model to estimate changes in the flow characteristics of the network, without going through a complete reassignment of flows.

¹Loubal, P. S., "A Network Evaluation Procedure", Highway Research Record 205, Washington, D. C.: Highway Research Board (1967). See also Bhatt, K. U., SEARCH IN TRANSPORTATION PLANNING: A CRITICAL BIBLIOGRAPHY, Research Report R68-46, Cambridge, Mass.: Dept. of Civil Engineering, MIT, (June 1968)

Briefly, the algorithm works in the following way. For a proposed link addition (or deletion), the process develops two new minimum path trees from the end points of the project link, and determines which of the original minimum paths will change. Then the evaluation module uses the new minimum path trees to calculate changes in flow characteristics over the whole network. This appears to be a good estimate of the characteristics of each proposed change.

Loubal's technique may be very useful as a method for quick evaluation of small changes in the system, using the realistic descriptive flow models. A combination of Branch and Bound and Loubal's procedure may prove especially useful.

Another fruitful direction for search with descriptive flow models is the general family of "direct search" techniques. The basic logic of direct-search is "hill climbing".¹ Beginning with any arbitrarily chosen starting point, small changes are made in the control variables, until the best set of small changes is found. This becomes a new "starting point", and another cycle of explorations of small changes is begun. This repeats until a starting point is reached from which no further improvements can be made. This is the optimum - which may be local, not global. The "hill-climbing" image arises if the criterion function is visualized as describing a surface in a space defined by the control variables; the sequence of successive starting points traces out a path to the top of a "hill" corresponding to the local optimum of the criterion function.

Most of the direct-search techniques are variants on this logic; the real insights and power come with the design of the exploratory "small steps", and techniques of shifting the starting point, in the context of particular classes of problems.

¹ Wilde, op. cit.

The value of this "direct search" model is that it suggests a very general set of operations for search. Let x be the (vector) set of options (control variables), and y the (vector) set of impacts (goal variables):

1. Basic selection operation: Given x^i , find $y^i = f(x^i)$ and compare with $y^j(x^j)$ to determine which is preferred, conditioned on a goal statement G .
2. Generate a starting point: Generate some x^0 - may be at random, or may be related to some goal statement or past set of actions.
3. Generate an exploratory move: Generate some possible "small" changes: Δx^j .
4. Generate a pattern move: Based upon past successful exploratory moves, make a major move - a number of small changes simultaneously, for example; or a large move in a direction indicated by a successful small change.
5. Shift base point: Accomplish necessary bookkeeping to actually shift base point to a new x^j .
6. Strategy Decision: Decide whether to make an exploratory move, make a pattern move, generate a new starting point or terminate; if options within these classes are available, select which exploratory move, pattern move, or starting point generation to execute.

In the simplest versions of this logic, there are no pattern moves. If x is a Euclidean space, the small changes Δx^j considered may be unit changes in the separate components: $\Delta x^j = (\Delta x_1 = 0, \Delta x_2 = 0, \dots, \Delta x_j = 1, \dots, \Delta x_n = 0)$. If the set of goals G is simply some utility function such that $u(y)$ is a scalar, then the image is that of "hill-climbing"; from a starting point, generate small steps to work the way up the "hill" of $u[y(x)]$ until the "peak" - maximum u - is found.

In contrast to the usual discussions of direct search techniques, note these points about the preceding description:

1. we did not make any assumptions about the space x , or the nature of the "small changes" Δx^j ;
2. we did not assume the goals G collapsed into an objective function and set of constraints on y ; only that the comparison of two y 's could be made and a preference ranking R established.

Thus, this same logic can apply in principle, to problems in which the space x is not a series of orthogonal real axes; and/or in which the goals G may be a loosely-structured set, not collapsible into a utility function. In particular, it can apply to search with descriptive flow models, and with multiple goals, not just user cost and construction cost. Of course, the utility of this approach depends on how it is done: the specific structuring of the problem, the types of small changes and pattern moves, the goal variables, etc: the art is in the doing.

4.4 Heuristic Search¹

Many examples of heuristic search techniques are found in the literature. In practice, for example, in urban transportation studies network location and design have been mostly intuitive. The papers in the bibliography² show how various abstract patterns, such as crystal patterns (Mital), and grid patterns (Creighton et al., and Satterly and Berry) can be used as good solutions for starting points in further exploration of

¹ See articles by Marvin Minsky and Arthur Samuels in Feigenbaum, Edward A., and Julian Feldman, COMPUTERS AND THOUGHT, New York: McGraw-Hill (1963).

² Bhatt, op. cit.

alternatives. All the papers in Part I of the bibliography discuss heuristic search procedures which partition the space of alternatives for further detailed exploration. Because it is infeasible to consider and analyze all possible alternatives, such patterns as these may be reasonable as starting points.

The term "heuristic" indicates the price that is paid. With a mathematical programming formulation, the probability is one that an optimum will be found - within the problem as defined. With direct search techniques, the probability is significantly less than unity that even a local optimum is found. For example, when we select a particular street pattern, we might be rejecting the one that may have proved the best. With heuristic techniques, we do not even hope, necessarily, for local optima, but simply for improvements over what we otherwise might do:

- a. The probability of finding the "best" solution is much less than one; but,
- b. we attempt them because they seem likely to work or have worked well in the past - and we do not have anything better.

The first characteristic implies that we want to build up a large repertory of heuristics. Since no single one is liable to work outstandingly by itself, we want to have a number. Thus, we try a heuristic; if it gives an improvement, fine; if not, we try another.

The second characteristic implies that we do want to try to keep track of the success of particular heuristics. This requires that we learn how to characterize the problems that we are trying to solve and then try to correlate the characteristics of the problem with the success of different heuristics. Another implication is that we can try

to formulate good heuristics a priori, but we should expect to get insights into really effective heuristics only by "playing with the problem" and varying options, tracing out impacts, and trying to infer relationships among them.

Heuristics should be developed to address each of these types of questions:

- (a) Given a particular set of options and their impacts, what are some small changes to the system which might result in some improvement?
- (b) How can the effect of a particular change be estimated approximately?
- (c) If a series of small changes have been relatively successful, what major changes along the same lines might be successful also?

As seen by our discussion of "direct search", these questions bear strong relation to the ideas of "exploratory" moves and pattern moves.

One aid to developing good heuristics for use in searching out transportation systems alternatives would be to actually systematically explore various combinations of options. In this way, the most significant relationships can be identified, and "rules of thumb" developed. For example, in the prototype analysis experiments the relative roles of changes in fares and frequency of service were identified, for a single link. Based upon the relationship uncovered, a heuristic routine might be designed to vary fares and frequency in a certain proportion on various links in the network. Using the approach of direct search, the following logic might be tested:

- (1) One by one, scan all the origin-destination pairs in the network, for each mode.

- (2) Exploratory moves: for each, using an approximate form of the demand and resource requirements (cost) models, compute the net return to operator revenue of a 10% (plus or minus) increment in frequency of service together with a corresponding change in fare (to keep ridership constant - as indicated by demand model parameters and/or prototype analysis-like runs).
- (3) Pattern move: select the best of these small changes - implement several simultaneously as a pattern move; do a complete network equilibrium prediction and check to see if improvement.
- (4) Decision logic: recycle if necessary.

A wide variety of specific heuristics can be proposed; they must be tested in the context of a particular transportation systems problem.

4.5 Network Aggregation

One particularly promising direction of work is that of "network aggregation". This is an application of the concept of hierarchical structure¹. The basic transportation problem being studied may involve a large detailed network. To do an equilibrium computation and evaluation of the impacts for one particular set of options in such a network may be a computationally expensive proposition. Thus, exploration of a large number of sets of options may be uneconomical. However, it may be possible to construct a gross representation of the network, which although

¹ Chan, Follanbee, Manheim and Mumford, AGGREGATION IN TRANSPORT NETWORKS: AN APPLICATION OF HIERARCHICAL STRUCTURE, Research Report R68-47, Cambridge, Mass.: Civil Engineering Department, M.I.T., (June 1968). See also Chapter IV of this report.

imprecise, is sufficiently accurate for exploration of a broad range of transportation system options.

In other words, in constructing a gross representation of the problem, we sacrifice accuracy for increased economy and feasibility of analysis. Of course, the essential issue is the quality of the gross representation of the detailed system.

In order to aggregate, an initial estimate of the equilibrium point is required. The initial estimate of equilibrium can be obtained in two ways:

- (i) by estimating by the transportation analyst;
- (ii) by performing an actual equilibrium flow prediction on the detailed network.

The more accurate the initial estimate, the better the aggregation, because one needs to use the initial estimate of equilibrium to get an aggregate network.

An aggregation rule is a procedure for constructing a gross network from a detailed one. Given an aggregation rule, the following approach to search may be fruitful:

- a. Construct a model of the detailed network (probably the existing system with a rich family of possible additions).
- b. Apply a particular aggregation rule to obtain a gross representation of the network.
- c. Conduct search in the gross network until one or several desirable systems are identified.
- d. Using the desirable gross networks as a guide, develop corresponding detailed networks; test these at the detailed level.

Such an approach might be particularly fruitful in conjunction with mathematical programming or branch and bound techniques.

4.6 Search in the Face of Uncertainty

In general, the decision - maker not only has the option of immediate actions - particular transportation system changes - but also of deferring implementation of an action in order to acquire more information about the problem. For example, if there is a great deal of uncertainty about demand, it might be more efficient in the long run to delay construction of a new system for a period in order to collect sufficient information to reduce this uncertainty. There usually are several alternative ways of collecting information, too - for example, traffic counts, origin-destination surveys, etc. Thus the more general problem has two basic sets of alternatives: immediate actions (such as highways), or actions which involve first collecting additional data, and then making a choice among "immediate" actions.

Statistical decision theory is particularly appropriate for this more general problem.¹ Such data collection programs as origin and destination surveys or traffic count programs can be evaluated not only in terms of cost but also in terms of their role in reducing uncertainty. Then, the decision as to which kinds of data collection programs to conduct can be based upon a careful economic calculation. In such a calculation, the costs of deferring action and of data collection are balanced against the "costs" of uncertainty if action were taken immediately. Pioneering work in applying statistical decision theory to transportation

¹ Raiffa, Howard, DECISION ANALYSIS - INTRODUCTORY LECTURES ON CHOICES UNDER UNCERTAINTY, Reading, Mass: Addison-Wesley, (1968); Schlaifer, Robert, PROBABILITY AND STATISTICS FOR BUSINESS DECISIONS, New York: McGraw-Hill (1959); Raiffa, Howard and Robert Schlaifer, APPLIED STATISTICAL DECISION THEORY, Boston: Division of Research, Graduate School of Business, Harvard University (1961).

data collection has been done by William F. Johnson.¹

An even more general formulation is that of a sequential decision process. There are significant time lags in implementation of transportation systems alternatives. It takes at least seven years to plan, design, and construct a new highway. The "comprehensive mass transit and expressway plan" for 1985 is not implemented instantaneously, but as a series of stages. Meanwhile, the world continues to change: transportation planning takes place in a context of continuous change in demand, in technology and in goals.

Transportation planners need to deal with strategies; each alternative strategy is composed of a sequence of actions staged over time. For example, consider a twenty-year comprehensive metropolitan plan. Such a transportation plan might be divided into five four-year stages. Each stage might consist of several actions - particular highway links, transit extensions, data collection activities, community decision points, etc. We can expect that by the end of the first four-year period, things will have changed. Demand patterns will have changed; new technologies will have been developed, or problems or advantages in existing technologies will have been uncovered; goals and aspirations will have changed; data collection activities will have produced new information. We will have learned more. Conditions will have changed and therefore, at the end of the first stage, the strategy consisting of a sequence of stages should be reviewed and possibly revised. If change has been relatively minor, the actions to be implemented in the following stages of the strategy may stay the same; more likely, however, the

¹ Johnson, William F., DECISION THEORETIC TECHNIQUES FOR INFORMATION ACQUISITION IN TRANSPORTATION NETWORK PLANNING, Sc.D. Thesis, Research Report R69-1, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1969), Volume XVII of a Series.

later stages of the plan will be revised because of the changing world. To have an effective continuous planning process, we need to conceive of our transportation systems plan as a sequence of staged actions; at the conclusion of each stage, we must open the door again to review and analysis of what the succeeding stages must be, based upon new information and the results of the preceding stages.

A formal basis for this "continuous planning process" is provided by the sequential decision model. At each stage, the set of actions includes not only "immediate" actions (e.g. highways) but also information-collection actions (e.g. traffic survey). The optimal strategy, or sequence of actions can then be determined. In principle, the logic of this calculation is straightforward, but in practice, in transportation, it is complicated by a number of factors.¹ First, there is generally a large number of combinations of actions and events. Second, the probabilities at different stages of the decision tree are different, because information is acquired at different stages, and the information depends upon which actions were taken at earlier stages. Third, the utilities at future periods are different from the utilities at the initial stage. Fourth, and perhaps most significant, to evaluate the utility at any point in the decision tree may require running a complex simulation model, such as the urban transportation package (or other network equilibrium prediction models). Clearly, this is impractical for several hundred points in the tree. Therefore, in order to apply the sequential decision process model to transportation planning, it is necessary to develop special

¹ Relatively tractable techniques exist for standard statistical processes such as often occur in standard sampling approaches, c.f. Raiffa and Schlaifer, Op. Cit.

techniques adapted to the transportation problem. Research¹ has begun, to develop practical techniques for treating transportation planning as a sequential decision process in the face of uncertainty.

One of the advantages of this sequential decision process formulation is that it places the role of experimentation in the transportation planning process in perspective. There is a variety of information-gathering experiments possible. For example, demonstration programs such as in mass transit or high speed rail transportation are experiments to get information about demand as well as technology performance.

It is essential² to analyze such experiments explicitly; they are as important a part of the set of transportation planning options as the construction of new highways, or new transit lines or other "physical" facilities. The sequential decision process model of transportation planning emphasizes this perspective by including explicitly such information gathering activities, as well as "physical" actions, in the context of staged strategies.

¹ Pecknold, Wayne M., THE EVALUATION OF TRANSPORT SYSTEMS: AN ANALYSIS OF TIME-STAGED INVESTMENT STRATEGIES, Ph.D. dissertation in process.

² See further William L. Hooper "Transportation: burden or blessing to the urban environment," TRANSPORTATION RESEARCH 2:2 (June, 1968).

5.0 Search Techniques: Strategies

In the preceding section, we identified a rich, but far from exhaustive, family of specific operational techniques for searching out partial improvements in the alternative transportation systems previously generated. These techniques represent "building blocks." Dramatic advances in search procedures will probably be achieved, not so much by the design of building blocks, but by the way several such modules are related to form flexible search strategies.

Two basically different approaches to developing search techniques could be followed:

- (a) attempt to develop a single search procedure which would explore all the options to find the "best" system alternative;
- (b) develop a series of relatively specialized search procedures which explore subsets of options, and develop techniques for using these in a coordinated way.

The essence of the problem is this:

- (1) there are a large number of options to be manipulated, and a large number of impacts to be evaluated;
- (2) detailed evaluation of the impacts requires the full set of network equilibrium prediction models;
- (3) no search technique now exists for exploring all options simultaneously with prediction of all impacts via network equilibrium;

- (4) if all options except a relatively few are held fixed, and all impacts are either treated as constraints, ignored temporarily, or collapsed into a single objective function, then the relatively powerful techniques surveyed above can be used to search out alternatives: for example a variety of mathematical programming formulations can be used for various problem formulations.

Therefore, approach (a) - development of a single general search technique - seems far less promising than approach (b) - development of a specialized search procedures and techniques for their use.

We will define a search strategy as a set of one or more specific search modules (e.g. a particular linear programming formulation), plus procedures for using the modules. These procedures may be simply "rules of thumb," suggesting when the technique in a particular module may be useful: or may be so carefully structured a logic as to be implemented in a computer program.

The general method of "direct search," as described above in section 4.3 suggests a family of search strategies. Each such strategy would have specific modules for generating a starting point; for generating and evaluating exploratory moves; for generating pattern moves; for shifting the base point and determining the strategy decision.

Other search strategies have been proposed by Simpson¹ and Nutter.² Each of these strategies consists of a mixture of modules. Some modules

¹ Simpson, R. W., COMPUTERIZED SCHEDULE CONSTRUCTION FOR AN AIRLINE TRANSPORTATION SYSTEM. Technical Report FT-66-3, Cambridge, Mass: Flight Transportation Laboratory, M.I.T. (November 1966)

² Nutter, Robert D., "An Alternative generation procedure for the NECTP Model System." Unpublished Working Paper WP-1568, the MITRE Corpor. (on May 10, 1968).

are optimization routines; others are heuristic. The strategies themselves begin by holding some options constant, then exploring others - for example, estimate demands (trip matrix) based upon future land use and optimistic levels of service; then holding demands fixed proceed to manipulate networks and vehicle assignments to routes and schedules, to minimize measures of transportation system cost.

A third type of strategy was proposed by Bruck, Manheim, and Shuldiner¹: the use of explicit multi-level (hierarchical) structure. In this approach the space of alternatives would be progressively narrowed down through doing search and selection at several different levels of abstraction. The work in network aggregation (see Chapter IV, Section 6.0) was begun to explore this approach.

A wide variety of such strategies can be suggested. However, it is not possible at this stage to indicate which are the most fruitful approaches. Rather, what is required is a broad program of research and experimentation to:

- (1) develop specific techniques, as search modules;
- (2) design and implement specific search strategies, and test
in the context of prototype problems.

Since it is not clear which specific modules or strategies will be most useful, or even most promising,

- (1) the research should be exploratory
- (2) a basic "search environment" should be developed in which a
variety of techniques can be operated in comparable manner.

¹ Bruck, Henry W., Marvin L. Manheim and Paul Shuldiner, TRANSPORT SYSTEMS PLANNING AS A PROCESS: THE NORTHEAST CORRIDOR EXAMPLE, Professional Paper P67-23, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1967) Volume 2111 of a series.

Such a "search" environment might be a single computer software system, or simply a standard specification of input and output formats.

The general characteristics of such a search environment are suggested in section 6.3.

In closing this discussion, it is useful to emphasize the human role in the search process,¹ by describing a hypothetical sequence of planner interactions with computerized procedures. The following might be a typical sequence in an on-line computer environment in which the transportation planner can sketch his networks on a television-screen type graphic display:

- (a) The planner sketches one or several basically different network configurations;
- (b) The computer generates with a semi-random search model a small number of minor variants on each of the major themes;
- (c) The planner eliminates some of these variants as probably unrealistic;
- (d) The computer then uses a mathematical optimization routine to identify relatively optimal link capacities and service schedules and prices for each of the network configurations,
- (e) The planner then selects a relatively small number of the proposed system designs and inputs them to a detailed simulation model (predicting network equilibrium); based upon the results of the simulation, he may modify or eliminate the alternative examined; and recycle or terminate.

¹Stairs, Sonia, "Selecting a traffic network," J. TRANSPORT ECONOMICS AND POLICY 11:2 (May 1968)

Thus, a rich variety of search techniques of different types may prove more efficient as a system than any single technique used alone. Furthermore, the judgment of the analyst can and should play a strong role throughout the search process.

6.0 Conclusions and recommendations - Search:

6.1 General Conclusions

The search problem is the following: given a number of previously generated actions and their consequences, and a statement of goals or desirable directions to go in improving the impacts of these actions, what values of the decision options will achieve the desired levels or directions of change? For example, if we want to decrease travel time without decreasing operator revenue how do we change the system?

There are a variety of search techniques available. If we make some fairly drastic simplifications in the problem, we can apply such powerful techniques as mathematical optimization, including linear programming, dynamic programming, and other techniques based on calculus. Alternatively, direct search or other hill climbing approaches may be used, as well as heuristic search techniques such as branch and bound, Loubal's sensitivity procedure and network aggregation.

There does not seem to be any specific search technique which will be the technique to use in all transportation systems problems. None of the analytical search techniques, such as mathematical optimization, are yet computationally feasible for large real-world transportation systems. However, it should be fruitful to use these techniques as modules in larger search strategies.

Network aggregation may be particularly useful in making effective use of optimization techniques. In this approach, an aggregate representation of the particular detailed transportation system under study would be constructed using a particular aggregation rule. The result of applying this aggregation rule would be a formulation of the problem appropriate for

some mathematical optimization technique. This mathematical optimization technique would then be used within the context of the gross representation of the problem to find an optimum (as narrowly defined). The results of this process would then be translated back to the detailed level. Thus, mathematical optimization formulations and other analytical search techniques may be useful in the context of a broader search strategy via the concept of network aggregation.

We conclude that a rich variety of search techniques of different types may prove more efficient as a system, as modules of search strategies, than any single technique used alone. Development of both specific techniques and search strategies is important.

The judgement of the analyst can and should play a strong role throughout the search process. Therefore, it is appropriate to develop a variety of different search techniques, as well as a flexible environment in which they can be used, such as an on-line computer environment with graphic display. Our conclusions about the desired capabilities of such an analysis environment are summarized in the next section.

6.2 Recommendations: Search Techniques:

A comprehensive balanced program of research should be conducted to develop and test a variety of specific search techniques. Research should continue in the development of various mathematical programming formulations, with the objective of increasing computational efficiency of present algorithms as well as development of new algorithms. Research should be conducted to exploit the ideas of direct search techniques and

their applicability to transportation analysis. A wide variety of opportunities exist for development of heuristic search techniques, such as network aggregation, pattern recognition and other approaches. This may be an extremely fruitful area in the short-run and the experiments necessary to develop and test heuristic techniques should provide powerful insights for avenues of development of efficient direct search and mathematical optimization techniques.

While research in a variety of specific search techniques is important, it is also important to try to develop overall strategies for using a number of search techniques in concert, in the context of particular substantive transportation systems problems. Research should continue in the area of developing such search strategies, for example: alternative multi-level approaches; and approaches that utilize network aggregation and approximations for evaluating and discriminating among alternatives in the initial stages.

6.3 Recommendations: Specification of a Transportation Search Environment

The discussions in the preceding sections can be viewed in part in terms of the implications for a single analysis "environment" for searching out and choosing among transportation systems alternatives. Such an analysis environment should have the following capabilities:

1. Repertory of prediction models: A basic set of prediction models should be provided in which there is at least one model for accomplishing each of the basic functions: supply ("technology"), demand, network equilibrium, resource requirements, and demand shifts; and evaluation.
2. Technology models: There should be at least one model capable of representing transportation technologies in general, as well as specific models for particular technologies ("modes"). These models should take

as input specification of options such as station spacing, stop time, vehicle size, number of vehicles, link characteristics, cruise speed, acceleration-deceleration rates, and other critical variables. The models should be so designed as to allow parametric variations to trace out supply and resources functions. Such models should be provided for mode interfaces (terminals) as well as for line-haul and access links. Where possible, corresponding search procedures should be provided, which would take as input specification of desired service and resource requirements levels, and produce as output values of the options.

3. Network equilibrium models: Alternative procedures for predicting network equilibrium should be provided. In particular, there should be at least one which is "descriptive," such as the traffic assignment approach; as well as one which is prescriptive, and thus useful as a search procedure, such as a network synthesis formulation. Network data management capabilities should be provided for extracting from the primary data base data appropriate for input to the predictive model(s), and to alternative mathematical optimization formulations. (Initially, TRANSET II or a modified version could be assumed as the basic predictive model. Several alternative optimization formulations could be specified for execution by OPTECH (the optimization subsystem of ICES), and the interface between TRANSET and OPTECH worked out to accomplish this).

4. Interface between technology and network equilibrium models: The network models (whether predictive or prescriptive) require specification of cost and service characteristics in a variety of particular forms.

These characteristics are produced by the technology (services and resource requirements) models. Procedures should be provided for interpreting the results of technology models to produce service and resource requirements relationships (as functions of volumes) for input to alternative network equilibrium models. (Initially, these interfaces should be worked out for a particular set of models, such as TRANSET II and CPTECH formulations. Later, more general capabilities can be provided.)

5. Reference data base: There should be one basic reference data base, consisting of all transportation and activity system data, including network and other options. Where parts of this data are required in different form for use in a particular search, prediction and/or evaluation model, an appropriate "working" data base should be constructed as needed.

6. Data management capabilities: Basic data management capabilities, such as file manipulation (editing, deletion, extraction, split, sort, merge, print, list, etc.) should be provided. Specific transportation-oriented capabilities are also required. Appropriate techniques should be provided for constructing working data bases from the reference data base with minimal user intervention - for example, techniques for going from the basic data base to several alternative programming formulations. As another example, the following capabilities for managing network data should be provided:

- (a) extraction of one or more sub-networks from within the network for specific analyses;
- (b) construction of approximate or aggregate networks with less detail but approximately the same characteristics as the reference network;

- (c) merging of two or more networks into a single network (with appropriate consistency and completeness checks);
- (d) partitioning of networks into subnetworks by geographic area, by functional classification, and by other criteria; as well as to increase computational efficiency.

7. Evaluation: A variety of evaluation procedures should be provided, such as benefit-cost and goal-fabric techniques. At an early stage, a basic goal fabric structure should be provided, with appropriate evaluation routines, so that outputs from TRANSET II and from the various OPTECH formulations will produce valuation information in the goal fabric.

8. Search: A variety of search procedures should be provided. A variety of heuristics should be programmed as modules; some of these heuristics should generate small system changes, while others may be used to infer direction for major changes from past small changes. Alternative search strategies should also be programmed, such as direct search, multi-level and time-staging approaches. These strategies should be so designed that alternative heuristics can be "plugged into" the broader strategy.

9. Data Organization: A basic data organization capability should be provided for keeping track of a large number of "runs" of the models. The capability would enable the analyst to look at the full history of runs and organize the information produced in ways meaningful to his decision issues. For example, as envisioned in DODO, there should be a capability to subset or partition the set of runs into classes according

to various criteria. This would allow construction of isoquants or isocontours for various quantities.

6.4 Recommendations: Next Steps (Priority Tasks)

A number of specific tasks can be identified which are important to begin immediately. Some of these constitute continuation of developments initiated by the present research project.

- (1) Develop more adequate transportation technology models to be used for predicting level of service and resource requirements.
- (2) Develop improved network equilibrium models, exploring alternative formulations for computing equilibrium. Extend present equilibrium models to incorporate supply-demand equilibrium over multiple time periods.
- (3) Design a single basic reference data base, from which working data bases would be extracted for input to TRANSET and to various optimization formulations.
- (4) Develop an initial set of useful optimization formulations. Work out the interface between TRANSET and OPTECH to implement these formulations to try to identify appropriate uses of mathematical optimization in a network context. In particular, attempt to develop mathematical programming formulations which behave similar to descriptive flow (e.g. traffic assignment) models.
- (5) Continue experiments with network aggregation techniques. Program a number of network aggregation procedures, and test these on the Northeast Corridor network and other networks, to determine their properties.
- (6) Develop and test one or several explicit multi-level structures of

the transportation process. Initially, develop a three-level model, and as experience is acquired, proceed to develop a variety of alternative multi-level structures.

- (7) Implement "goal-fabric" concepts in conjunction with TRANSET. Experiment with goal fabric analysis, in coordination with benefit-cost and other traditional choice techniques to evaluate the feasibility and utility of goal fabric procedures.
- (8) Develop differential impact analysis techniques, for explicitly tracing out the potential impacts of transportation alternatives on different groups.
- (9) Develop a capability for understanding the results of a number of runs of the model system, along the lines of DODO (Decision Oriented Data Organizer).
- (10) Conduct experiments with real and hypothetical networks to try to identify how specific types of systematic changes in the systems will impact on particular goal variables and consequences.
- (11) Develop techniques for making inferences about desirable search directions. Formulate and test "pattern recognition" approaches to try to identify appropriate directions for modifying a particular transportation system alternative in order to improve on it in respect to some subset of goal variables.
- (12) Formulate and test a variety of heuristic search procedures as search techniques.
- (13) Continue experiments in developing procedures for finding desirable time stagings of investments in transport facilities; in particular, emphasize the flexibility of initial decisions in

their ability to achieve many good target year plans while accounting for basic uncertainties in demand and technology.

- (14) Continue development of remote processing interactive and batch computer environments for doing transportation search.
- (15) Continue development of graphic display techniques (scope and plotter) for visualizing the structure of the transportation problem, including development of alternative forms of representing systems and their impacts.
- (16) Develop the use of demand models as guides to search, such as through the use of tradeoff ratios based upon demand parameters.
- (17) Implement the Loubal algorithm in conjunction with Branch and Bound as a link addition technique.

CHAPTER VI

SUMMARY OF CONCLUSIONS, RECOMMENDATIONS AND OTHER RESULTS

1.0 Introduction

The results of this research project fall into three major groups:

1. Conclusions - about the nature of the transportation systems analysis problem in general, and about the issues of searching out and choosing among transportation systems alternatives in particular. As part of the development of these conclusions, a prototype analysis was conducted.
2. Recommendations - for a program of methodological research in searching out and choosing among transportation systems alternatives, including specific recommendations for next steps to be undertaken as high priority research tasks with immediate payoffs;
3. Models and analysis techniques - developed or under development, for utilization in transportation systems analysis.

These results are discussed in this chapter in three corresponding sections.

2.0 Conclusions

2.1 General Conclusions - Transportation Systems Analysis

Our review of the substantive issues in transportation systems analysis leads us to the following conclusions.

Transportation systems analysis is an equilibrium problem. The alternative options and transportation technologies can be represented in terms of supply and resource functions. The pattern of social and economic activities can be expressed in terms of demand functions. The core of the transportation systems analysis problem is to predict the equilibrium pattern of flows in a network resulting from a particular set of options with regard to the transportation system and the activity system.

There are a wide variety of options which can be manipulated as instruments of public or private policy in any particular transportation systems context. An analysis of the alternative policies open to a single decision maker should include explicit exploration of a variety of these options, and should explicitly examine the use of a variety of options in concert. For example, one should explore the substitutability of such options as changes in fixed facilities, changes in vehicles or schedules, and/or changes in fares, subsidies, taxes, etc.

Models should be developed for analyzing alternative transportation policies in which tradeoffs among the various options can be considered explicitly. This does not mean, however, that a single model including all options is necessarily the best approach; it may be feasible only to have a connected series of models.

Transportation has a variety of impacts on different groups: users, operators, physically-impacted, functionally-impacted, and politically affected actors. In exploring alternative transportation policies it is important to trace out explicitly the differential impacts of the transportation options on different groups. Aggregate measures, such as "total benefits to whomsoever they accrue" and benefit-cost ratios, may be useful but only under certain conditions. However, it is most important to be able to distinguish carefully the discriminatory and differential impacts of those policies on various groups.

In order to predict the impacts associated with a particular set of options, it is necessary to predict the pattern of flows in the transportation network. By this is meant the volumes of passengers and goods moving between pairs of origins and destinations, and over specific network links; together with the levels of service (time, costs, etc.) each increment of flow incurs. The basic concept for prediction of these flows is that of equilibrium between supply and demand within the containing channels of the transportation network.

To accomplish this prediction of equilibrium flows a number of types of models are required: supply models, resource requirements models, demand models, network equilibrium models, and demand shift models. To put it another way, it appears useful to subdivide the flow prediction problem into these components.

There are many interactions among these component models, and several concepts have been advanced to assist in understanding these:

- a. Transportation technology: the modeling of transportation technology is proposed to be represented by two different models, resource requirements and supply prediction.

- b. Level of service vector: it is assumed that the interaction between transportation technology and the demand for transportation can be adequately separated by the concept of a vector of level of service variables, replacing the single "price" variable of basic economic theory. This is equivalent to the assumption made by Baumol and Quandt and others, that transportation demand can be predicted in a mode-independent way.

There are significant uncertainties in transportation systems analysis in spite of the tremendous progress that has been made in data collection and analysis and model construction and validation. Uncertainties exist as to the behavioral parameters of demand, the characteristics of transportation technologies, the consequences associated with different alternatives, and the goals of society. Furthermore, there is a long lead time from the planning stage to the actual implementation of most transportation systems investments. Therefore it is necessary that an evolutionary planning approach be adopted in transportation analysis. In particular, explicit consideration should be given to the value of information obtained by various sources and the design of experiments and demonstration programs explicitly for the information value they provide in a step by step sequential decision strategy. Furthermore, techniques should be developed for optimal allocation of information acquisition resources among alternative demonstrations, experiments, data collection and other information acquisition activities.

Transportation systems analysis requires use of an extensive and complex set of prediction models. In analyzing transportation policy alternatives,

it is very unlikely that there will be enough understanding of the significant issues in the particular substantive problem that a single run of the model system will be adequate for analyzing the issues. To determine the impacts corresponding to a single transportation system alternative requires fairly extensive analysis using all the model types described above. Therefore, it is difficult to identify precisely which action or transportation systems policy will most effectively achieve a particular set of impacts. Furthermore, it is a difficult task to trace out the substitutability among various options, to identify how alternative impacts may be achieved through manipulation of the options.

Thus, a systematic analysis of policy options will require a number of runs of the system of analysis models. Therefore, it is necessary to design the analysis strategy and the analysis environment with full consideration of the nature of transportation systems analysis as a problem-solving process, which is iterative, and evolving. In particular, it would be necessary to have flexible capabilities for analyzing and organizing the results of a large number of runs of a complex model system. Furthermore, a variety of graphic display, data manipulation, and other capabilities need to be provided for effective analyst use of a complex model system in the exploration of policy options.

2.2 Specific Conclusions - Search and Choice in Transport Systems Analysis

2.2.1 Transportation Planning as a Problem Solving Process

Because the system of models to be used in analyzing a transportation alternative is complex, transportation systems problems cannot

be solved as a single optimization problem. Rather, an iterative approach must be followed. This iterative approach consists of generating an alternative (search), predicting its consequences, evaluating those consequences, and then comparing that alternative with all others previously examined in order to make a choice. This cycle of search-prediction-evaluation-choice is repeated many times, as the technical analysis team endeavors to search out and choose among meaningful action alternatives.

In general, it is desirable to have a multilevel approach to the transportation planning process. In this multilevel approach, there are several different search-prediction-evaluation-choice cycles. Some of these cycles take place at a very detailed level of analysis, such as with a well-defined forward-seeking model system. Other cycles take place at a very gross or approximate level of analysis. The main value of these gross analyses is primarily in helping to trace out the general structure of the problem. A problem-solving process in transportation analysis which is "efficient" in an overall sense would probably have several different levels of analysis, with flexible interaction among them.

2.2.2 Search

The search problem is the following: given a number of previously generated actions and their consequences, and a statement of goals or desirable directions to go in improving the impacts of these actions, what values of the decision options will achieve the desired levels or directions of change? For example, if we want to decrease travel time without decreasing operator revenue how do we change the system?

There are a variety of search techniques available. If we make some fairly drastic simplifications in the problem, we can apply such powerful techniques as mathematical optimization, including linear programming, dynamic programming, and other techniques based on calculus. Alternatively, direct search or other hill climbing approaches may be used, as well as heuristic search techniques such as branch and bound, Loubal's sensitivity procedure and network aggregation.

There does not seem to be any specific search techniques which will be the technique to use in all transportation systems problems. None of the analytical search techniques, such as mathematical optimization, are yet computationally feasible for large real-world transportation systems. However, it should be fruitful to use these techniques as modules in larger search strategies.

Network aggregation may be particularly useful in making effective use of optimization techniques. In this approach, an aggregate representation of the particular detailed transportation system under study would be constructed using a particular aggregation rule. The result of applying this aggregation rule would be a formulation of the problem appropriate for some mathematical optimization technique. This mathematical optimization technique would then be used within the context of the gross representation of the problem to find an optimum (as narrowly defined). The results of this process would then be translated back to the detailed level. Thus, mathematical optimization formulations and other analytical search techniques may be useful in the context of a broader search strategy via the concept of network aggregation.

We conclude that a rich variety of search techniques of different types may prove more efficient as a system, as modules of search strategies, than any single technique used alone. Development of both specific techniques and search strategies is important.

The judgement of the analyst can and should play a strong role throughout the search process. Therefore, it is appropriate to develop a variety of different search techniques, as well as a flexible environment in which they can be used, such as an on-line computer environment with graphic display. Our conclusions about the desired capabilities of such an analysis environment are summarized in the next section.

3.0 Recommendations for a Program of Methodological Research in Searching Out and Choosing Among Transportation Systems Alternatives

3.1. General Recommendations

3.1.1. Prototype Analyses

In order to develop understanding of the substantive issues as well as of the characteristics of alternative search techniques, analyses of one or more prototype transportation systems problems (such as the current Northeast Corridor Prototype Analysis) should be contained. In these analyses, the objective should be to experiment with a variety of search techniques, to obtain computational insights into the capabilities of these techniques, in relation to the substantive issues of the problem and of alternative models and the way they might fit together.

3.1.2. Interactive Problem Solving Environment

Effective systematic analysis of transportation alternatives will require the use of computer-based models. Since in general, no single research technique or transportation model will be sufficient to adequately analyze a specific substantive transportation problem, it is important to maximize the efficient use of the analyst's judgements. This implies that the computer models be available in a flexible, interactive, on-line environment. Such a computer environment should have capabilities for graphic display (plotter, cathode ray tube, with input as well as output); for card and magnetic tape input of large volumes of information; for typewriter, console, or other type of on-line input of small amounts of information; and several levels of secondary storage, providing different combinations

of access time and storage capacity (such as the hierarchy of disk, data cell, tape, microfiche, or other hard copy record). The computer environment should have available a problem oriented language capability, such that the analyst can use the various models available in this environment through English language-like commands. Further, the computer environment should allow the flexible use of a multitude of models by allowing modular models to be used in an interchangeable way. Finally, there should be available powerful problem-oriented data organizing techniques, such as the proposed DODO system, which can allow the analyst to efficiently access the data generated in a large number of previous computer runs, and extract from this data information relevant to his decision-oriented transportation analysis.

3.1.3. Transportation Models

There is no single best transportation systems model. However, it should prove feasible to develop a flexible set of transportation models, in one system environment. In such a set of transportation models, there should be a variety of network equilibrium models, demand models, models for representing transportation technologies (both specific modes and general models), and other component functions of the transportation analysis process.

This system of transportation models should be so designed as to allow the analyst to specify a particular subset of models to be used at any point in the transportation analysis process. This is, the models should be designed as modules which can be sequenced in a variety of ways. For example, the analyst should be able to experiment with alternative demand and network equilibrium models at different points in the transportation analysis process.

Another important aspect of the design of such a system of transportation models would be the exploitation of a flexible computer environment to provide functional capabilities particularly appropriate for transportation analysis. For example, one capability which is very critical is a flexible system for management of network data. Such a system would allow a wide variety of sub-networks or versions of networks to be extracted from a single basic network data base, so that the analyst would be able to effectively apply various transportation models and search techniques to particular parts of the network as he desired.

3.1.4 Specific Search Techniques:

A comprehensive balanced program of research should be conducted to develop and test a variety of specific search techniques. Research should continue in the development of various mathematical programming formulations, with the objective of increasing computational efficiency of present algorithms as well as development of new algorithms. Research should be conducted to exploit the ideas of direct search techniques and their applicability to transportation analysis. A wide variety of opportunities exist for development of heuristic search techniques, such as network aggregation, pattern recognition and other approaches. This may be an extremely fruitful area in the short-run and the experiments necessary to develop and test heuristic techniques should provide powerful insights for avenues of development of efficient direct search and mathematical optimization techniques.

While research in a variety of specific search techniques is important, it is also important to try to develop overall strategies

for using a number of search techniques in concert, in the context of particular substantive transportation systems problems. Research should continue in the area of developing such search strategies, for example: alternative multi-level approaches; and approaches that utilize network aggregation and approximations for evaluating and discriminating among alternatives in the initial stages.

3.1.5 Interaction with the Political Process

One of the important roles of transportation systems analysis is to help clarify in the minds of political decision makers as well as the body politic the range of options which are open to them, as well as their implications. There are a number of fruitful directions for development of more effective interaction between the technical process of transportation systems analysis and the real-world political process. Research should be conducted to develop specific operational techniques for promoting this effective interaction. In particular, research should continue on further development and testing of the goal fabric concept, on various models for obtaining expressions of preferences from political decision makers and other non-technical persons, development of gaming techniques, and for development of political simulation models, in the context of transport systems analysis.

3.2 Implications: Specification of a Transportation Search Environment

The discussions in the preceding sections can be viewed in part in terms of the implications for a single analysis "environment" for searching out and choosing among transportation systems alternatives. Such

an analysis environment should have the following capabilities:

1. Repertory of prediction models: A basic set of prediction models should be provided in which there is at least one model for accomplishing each of the basic functions: supply ("technology"), demand, network equilibrium, resource requirements, and demand shifts; and evaluation.
2. Technology models: There should be at least one model capable of representing transportation technologies in general, as well as specific models for particular technologies ("modes"). These models should take as input specification of options such as station spacing, stop time, vehicle size, number of vehicles, link characteristics, cruise speed, acceleration-deceleration rates, and other critical variables. The models should be so designed as to allow parametric variations to trace out supply and resources functions. Such models should be provided for mode interfaces (terminals) as well as for line-haul and access links. Where possible, corresponding search procedures should be provided, which would take as input specification of desired service and resource requirement levels, and produce as output values of the options.
3. Network equilibrium models: Alternative procedures for predicting network equilibrium should be provided. In particular, there should be at least one which is "descriptive," such as the traffic assignment approach; as well as one which is prescriptive, and thus, useful as a search procedure, such as a network synthesis formulation. Network data management capabilities should be provided for extracting from the primary data base data appropriate for input to the predictive

model(s), and to alternative mathematical optimization formulations. (Initially, TRANSET II or a modified version could be assumed as the basic predictive model. Several alternative optimization formulations could be specified for execution by OPTECH (the optimization subsystem of ICES). and the interface between TRANSET and OPTECH worked out to accomplish this).

4. Interface between technology and network equilibrium models:

The network models (whether predictive or prescriptive) require specification of cost and service characteristics in a variety of particular forms. These characteristics are produced by the technology (services and resource requirements) models. Procedures should be provided for interpreting the results of technology models to produce service and resource requirements relationships (as functions of volumes) for input to alternative network equilibrium models.

(Initially, these interfaces should be worked out for a particular set of models, such as TRANSET II and OPTECH formulations. Later, more general capabilities can be provided.

5. Reference data base:

There should be one basic reference data base, consisting of all transportation and activity system data, including network and other options. Where parts of this data are required in different form for use in a particular search, prediction and/or evaluation model, an appropriate "working" data base should be constructed as needed.

6. Data management capabilities:

Basic data management capabilities, such as file manipulation (editing, deletion, extraction, split, sort, merge,

print, list, etc.) should be provided. Specific transportation-oriented capabilities are also required. Appropriate techniques should be provided for constructing working data bases from the reference data base with minimal user intervention - for example, techniques for going from the basic data base to several alternative programming formulations. As another example, the following capabilities for managing network data should be provided:

- (a) extraction of one or more sub-networks from within the network for specific analyses;
- (b) construction of approximate or aggregate networks with less detail but approximately the same characteristics as the reference network;
- (c) merging of two or more networks into a single network (with appropriate consistency and completeness checks);
- (d) partitioning of networks into subnetworks by geographic area, by functional classification, and by other criteria; as well as to increase computational efficiency.

7. Evaluation: A variety of evaluation procedures should be provided, such as benefit-cost and goal-fabric techniques. At an early stage, a basic goal fabric structure should be provided, with appropriate evaluation routines, so that outputs from TRANSET II and from the various OPTECH formulations will produce valuation information in the goal fabric.

8. Search: A variety of search procedures should be provided. A variety of heuristics should be programmed as modules; some of these heuristics should generate small system changes, while others may be used to infer directions for major changes from past small changes. Alternative search strategies should also be programmed, such as direct search, multi-level and time-staging approaches. These strategies should be so designed that alternative heuristics can be "plugged into" the broader

strategy.

9. Data Organization: A basic data organization capability should be provided for keeping track of a large number of "runs" of the models. The capability would enable the analyst to look at the full history of runs and organize the information produced in ways meaningful to his decision issues. For example, as envisioned in DODO, there should be a capability to subset or partition the set of runs into classes according to various criteria. This would allow construction of isoquants or isocontours for various quantities.

3.3 Recommendations: Next Steps (Priority Tasks)

A number of specific tasks can be identified which are important to begin immediately. Some of these constitute continuation of developments initiated by the present research project.

- (1) Develop more adequate transportation technology models to be used for predicting level of service and resource requirements.
- (2) Develop improved network equilibrium models, exploring alternative formulations for computing equilibrium. Extend present equilibrium models to incorporate supply-demand equilibrium over multiple time periods.
- (3) Design a single basic reference data base, from which working data bases would be extracted for input to TRANSET and to various optimization formulations.
- (4) Develop an initial set of useful optimization formulations. Work out the interface between TRANSET and OPTECH to implement these formulations to try to identify appropriate uses of mathematical optimization in a network context. In particular, attempt to develop mathematical programming formulations which behave similar to descriptive flow (e.g. traffic assignment) techniques.

- (5) Continue experiments with network aggregation procedures, and test these on the Northeast Corridor network and other networks, to determine their properties.
- (6) Develop and test one or several explicit multi-level structures of the transportation process. Initially, develop a three-level model, and as experience is acquired, proceed to develop a variety of alternative multi-level structures.
- (7) Implement "goal-fabric" concepts in conjunction with TRANSET. Experiment with goal fabric analysis, in coordination with benefit-cost and other traditional choice techniques to evaluate the feasibility and utility of goal fabric procedures.
- (8) Develop differential impact analysis techniques, for explicitly tracing out the potential impacts of transportation alternatives on different groups.
- (9) Develop a capability for understanding the results of a number of runs of the model system, along the lines of DODO (Decision Oriented Data Organizer).
- (10) Conduct experiments with real and hypothetical networks to try to identify how specific types of systematic changes in the systems will impact on particular goal variables and consequences.
- (11) Develop techniques for making inferences about desirable search directions. Formulate and test "pattern recognition" approaches to try to identify appropriate directions for modifying a particular transportation system alternative in order to improve on it in respect to some subset of goal variables.
- (12) Formulate and test a variety of heuristic search procedures as search techniques.

- (13) Continue experiments in developing procedures for finding desirable time stagings of investments in transport facilities; in particular, emphasize the flexibility of initial decisions in their ability to achieve many good target year plans while accounting for basic uncertainties in demand and technology.
- (14) Continue development of remote processing interactive and batch computer environments for doing transportation search.
- (15) Continue development of graphic display techniques (scope and plotter) for visualizing the structure of the transportation problem, including development of alternative forms of representing systems and their impacts.
- (16) Develop the use of demand models as guides to search, such as through the use of tradeoff ratios, based upon demand parameters.
- (17) Implement the Loubal algorithm in conjunction with Branch and Bound as a link addition technique.

4.0 Models, Analysis Techniques, and Other Results

Although the primary objective of this research was exploratory, in the course of this effort a number of specific models, analysis techniques, and other results were developed. Most are still undergoing development and refinement.

4.1 Prototype Analysis System

In order to accomplish the prototype analysis, a computer-based system of models was developed and a data base established and tested. The system of models, designated TRANSET II, is in the form of a command-structured problem-oriented language, and is a subsystem of ICES, the Integrated Civil Engineering System. TRANSET II was developed through adding capabilities to, and modifying, TRANSET I, an ICES subsystem for analysis of urban transportation networks.

(a) Specific capabilities incorporated include:

- 1) Computation of equilibrium between supply and demand in a network context consistent with Baumol-Quandt demand models;
- 2) Development of a variable increment technique for computing network equilibrium;
- 3) Representation of a multi-mode network for the Northeast Corridor, including access, terminal, and line-haul links;
- 4) Simplified model for simulating the effects of transportation on regional growth;
- 5) Evaluation routines for computing various goal variables of interest, including travel time, waiting time, fare, user costs, operator costs and revenues, government costs and revenues, and accessibilities;

- 6) Capability to compare alternatives by examining the incremental differences between alternatives;
 - 7) Graphic display, including the capability to plot flows, travel times, and speeds on a multi-mode network.
 - 8) Problem-oriented command-structured computer language, allowing easy use of system.
- (b) A data base was developed for prototype analysis of passenger travel in the Northeast Corridor:
- 1) District population and income data were developed
 - 2) The multi-mode network was modelled at the five-node and twenty-nine-node levels
 - 3) Supply functions were developed for air, rail, and auto modes
 - 4) The data base was tested and debugged
 - 5) A variety of alternative transportation systems were developed and tested, producing data showing tradeoff relationships among options and impacts.

4.2 DODO

The DODO system (Decision Oriented Data Organizer) has been designed and is in process of development. DODO is a command-structured problem-oriented language for storing data from a large number of computer runs in a way which is meaningful for analysis of those outputs. The design of DODO is based upon the PSP conceptual model. DODO should be useful for manipulating and exploring the outputs of the model system.

4.3 Goal Fabric

The goal fabric concept was developed as an extension of the PSP model. The concept was demonstrated in the Northeast Corridor Prototype Analysis, and is undergoing further testing and refinement.

4.4 Demand Models

The Baumol-Quandt abstract mode model, originally proposed for intercity travel, was tested and calibrated as a demand model for metropolitan area transportation.

4.5 Technology Models

Basic research was conducted into the structure of transportation technology in order to identify the kinds of issues which should be modelled in the form of supply and resource requirements functions for network level analyses. The concept of production functions in transportation was further developed. Tradeoff analyses for certain ground transportation forms were accomplished. Simple models were developed.

4.6 Branch and Bound Techniques

Techniques for searching for optimal investments in a transportation network have been developed and tested.

4.7 Value of Information

Procedures are under development for determining the optimal information acquisition policy in the context of transport investment planning.

4.8. Evolutionary Planning of Evolutionary Transportation Facilities

Computational procedures are being developed to determine the optimal staged investment strategy in the face of uncertainty.

EPILOGUE

EPILOGUE: Why Search and Choice?

This is a time of major shocks to our national consciousness. The assassinations of John F. Kennedy, of Robert Kennedy, and of Martin Luther King, have had deep impacts - individuals and even institutions have felt a profound loss of communication with, and control over, their environment. The sense of anomie is upon us.

The application of the techniques of systematic analysis to public policy issues is just beginning. The creation of new federal and state institutions, together with the development of new analytical tools, promises a rapid growth in the systematic analysis of public issues. In transportation, the new Department of Transportation and the metropolitan and megalopolitan transportation studies are particular examples.

This growth in analysis holds danger as well as promise. In some instances, analysis may succeed well in clarifying complicated issues in meaningful, relevant ways. In other cases, however, analysis may be used to justify predetermined courses of action or to hide the issues instead of clarifying them. Perhaps the most significant danger of all is that, by cloaking the issues of substance in a cloth of techniques, the development of more powerful analysis methods may remove the individual even further from any influence over the decision to be reached.

The objective of systematic analysis must be to destroy anomie, not accentuate it. At the scale of the room or the dwelling, architects talk about environments which people can change and shape by themselves - movable walls and modular furniture are proposed as examples. But transportation systems are massive investments, involving large commitments of resources. How can individuals affected by such decisions be involved in the decision-making in a meaningful way? How can the significant issues be presented to the man in the street in such a way that he can grasp them, relate them to his own intimate world, and thus become involved in the process of reaching a decision?

Systematic analysis must serve to illuminate the issues, not hide them. Analysis results should display to people, in an understandable way, the choices open to them; analysis should not make those choices for them. The idea that a "social optimum" can be determined by "objective" analysis is a dangerous myth.

The development of analysis techniques must seek to bring back to all men the relevance and meaning of control over their environments. This is the real challenge of research in search and choice.

APPENDIX

RESEARCH REPORTS

SEARCH AND CHOICE IN TRANSPORT SYSTEMS ANALYSIS

Manheim, Marvin L. with Earl R. Ruiter, and Kiran U. Bhatt, SEARCH AND CHOICE IN TRANSPORT SYSTEMS PLANNING: SUMMARY REPORT, Research Report 68-40, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume II of a Series.

Ruiter, Earl R., A PROTOTYPE ANALYSIS, Research Report R68-41, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume II of a Series.

Ochoa-Rosso, Felipe, APPLICATIONS OF DISCRETE OPTIMIZATION TECHNIQUES TO CAPITAL INVESTMENT AND NETWORK SYNTHESIS PROBLEMS, Research Report R68-42, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume III of a Series.

MODELLING THE EVOLUTIONARY NATURE OF PROBLEM-SOLVING:

Manheim, Marvin, PART I. CONCEPTUAL FRAMEWORK, Follansbee, Kenneth G., Marvin L. Manheim, and Donald A. Walter, PART II. DODO-AN INFORMATION SYSTEM FOR THE PSP MODEL, Research Report R68-43, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume IV of a Series.

Ochoa-Rosso, Felipe and Angel (17) Silva, OPTIMUM PROJECT ADDITION IN URBAN TRANSPORTATION NETWORKS VIA DESCRIPTIVE TRAFFIC ASSIGNMENT MODELS, Research Report R68-44, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume V of a Series.

Stafford, Joseph H., J.C. Prokopy, and V. Aivazian, PRODUCTION FUNCTIONS: MODELS OF TRANSPORT TECHNOLOGY, Research Report R68-45, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968), Volume VI of a Series.

Bhatt, Kiran U., SEARCH IN TRANSPORTATION PLANNING: A CRITICAL BIBLIOGRAPHY, Research Report R68-46, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968) Volume VII of a Series.

Chan, Yupo, Kenneth G. Follansbee, Marvin L. Manheim, and John Mumford, AGGREGATION IN TRANSPORT NETWORKS: AN APPLICATION OF HIERARCHICAL STRUCTURE, Research Report R68-47, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968). Volume VIII of A Series.

EQUILIBRIUM MODELS:

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Schwartz, Jesse G., NETWORK FLOW AND SYNTHESIS MODELS FOR TRANSPORTATION PLANNING: A SURVEY, Research Report R68-49, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968) Volume X in a Series.

Silverstone, Stuart M. and John Mumford, DEVELOPMENT OF GRAPHIC COMMUNICATION IN A COMPUTER-BASED TRANSPORTATION PLANNING PROCESS, Research Report R68-50, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968) Volume XI in a series.

Plourde, Rodney, CONSUMER PREFERENCES AND THE ABSTRACT MODE MODEL, Research Report R68-51, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968) Volume XII in a Series.

Bruck, Henry W., Marvin L. Manheim, and Paul Schuldiner, TRANSPORT SYSTEMS PLANNING AS A PROCESS: THE NORTHEAST CORRIDOR EXAMPLE, Professional Paper P67-23, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1967) Volume XIII in a Series.

Manheim, Marvin L., and Frederick Hall, ABSTRACT REPRESENTATION OF GOALS: A METHOD FOR MAKING DECISIONS IN COMPLEX PROBLEMS, Professional Paper P67-24, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1967) Volume XIV in a Series.

Manheim, Marvin L., PROBLEM-SOLVING PROCESSES IN PLANNING AND DESIGN, Professional Paper P67-1, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1967) Volume XVI of a Series.

Johnson, William F., DECISION THEORETIC TECHNIQUES FOR INFORMATION ACQUISITION IN TRANSPORTATION NETWORK PLANNING, Research Report R69-1, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1969), Volume XVII of a Series.

Guenther, Karl W., PREDICTIVE MODELS FOR VEHICLE OPERATING CONSEQUENCES, Research Report R69-2, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1969), Volume XVIII of a Series.

COMPLETED THESES (not published as reports)

Friedlander, Alex E., A METHOD OF SCHEDULE AND ROUTE PLANNING IN URBAN MASS TRANSIT; Ph.D. thesis, Department of City and Regional Planning, M.I.T., October 1968.

Hall, Frederick, A METHOD FOR DEALING WITH COMPLEX GOALS AND INDEFINITE UTILITIES IN DECISION PROBLEMS; S.M. thesis, Alfred Sloan School of Management, M.I.T., May 1967.

Hall, Gunnar, GENERATION OF IMPROVEMENTS IN URBAN TRANSPORTATION SYSTEMS: A MULTI-MODAL APPROACH WITH IDENTIFICATION OF IMPACTS ON DIFFERENT USER GROUPS; C.E. thesis, Department of Civil Engineering, M.I.T., June 1968.

Ichikawa, Yoshihiro, ECONOMIC CONDITIONS FOR ADOPTING SERIAL PARKING SYSTEM, S.M. thesis, Department of Civil Engineering, M.I.T., July 1968.

Mori, Y., A HIGHWAY INVESTMENT PLANNING MODEL: AN APPLICATION OF DYNAMIC PROGRAMMING; S.M. thesis, Department of Civil Engineering, M.I.T., June 1968.

Ruiter, Earl R., A PROTOTYPE ANALYSIS, Research Report R68-41, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

A prototype system designed for the equilibrium analysis of regional multimodal transportation systems is described, and the system is used to analyze an aggregated representation of air, rail and private automobile travel in the Northeast Corridor.

The system has been designed to illustrate the importance and usefulness of applying the equilibrium approach to transportation systems analysis. The theoretical framework of this approach is, therefore, presented as an introduction. Many concepts arising from urban transportation planning methodology have been incorporated into the prototype system. Urban transportation is therefore presented as a particular approximation of the equilibrium approach.

Based on the background of the equilibrium approach and of urban transportation planning, the prototype analysis system is presented as an alternate approximation of the equilibrium approach, with a structure better suited to multimodal regional transportation issues. The models comprising the system, although of secondary importance to the structure of the system, are described. Also, a problem-oriented computer language providing the prototype analysis system capabilities, TRANSET II, is described.

The system is demonstrated by showing its use to model the existing Northeast Corridor intercity air, rail and private auto systems. Five experiments, representing the use of the system, are described and results are presented.

The five experiments are:

- 1) Equilibrium vs. non-equilibrium analysis
- 2) Impacts of alternative networks
- 3) Effects of varying networks, fares and frequencies
- 4) Effects of time staging strategies
- 5) Sensitivity analyses of the system.

Ochoa-Rosso, F., APPLICATIONS OF DISCRETE OPTIMIZATION TECHNIQUES TO CAPITAL INVESTMENT AND NETWORK SYNTHESIS PROBLEMS, R68-42, M. I. T., Department of Civil Engineering, January 1968.

The purpose of this work is to formulate and solve certain optimization problems arising in the fields of engineering economics, scarce resource allocation, and transportation systems planning.

The scope and structure of optimization theory is presented in order to place subsequent work in proper perspective. A branch and bound algorithm is rigorously developed which can be applied to the optimization problems of interest. A rounding operation is defined, which provides a powerful rejection rule and permits the calculation, at each stage of the solution process, of an upper bound and a feasible solution in addition to the usual lower bound. This double bounding technique implies little or no extra computational effort.

Subsequent chapters are devoted to the study of various cases of capital investment problems. Investment in sets of independent projects is considered first. For the (0-1) multi-dimensional knapsack problem a new formulation, interpreted as a network synthesis problem on a bipartite graph, is given. This formulation permits the straightforward application of the branch and bound algorithm, and allows the solution of the linear program associated with each node of the solution tree to be obtained by inspection.

This study is pursued by considering capital investment in a single time period as a special case of the previous problem. Certain economic interpretations are derived by investigating the dual program of the discrete knapsack problem. A parametric branch and bound method is developed

which permits the solution of the knapsack problem for a range of values of the budget ceiling.

Two formulations are proposed for a special case of deferred capital investments, referred to as the multi-knapsack problem. The first formulation, after a transformation by means of a model equivalent, leads to a branch and bound algorithm which requires the solution of a standard transportation problem with surplus and deficits and certain routes prohibited at each step of the algorithm. The second model, although it may require a larger tree before optimality is reached, permits the solution by inspection of the linear program associated with each node of the solution tree.

The final part of this thesis studies capital investment for dependent proposals in the context of urban transportation planning. The branch and bound algorithm is adapted to the link addition network design problem, where a descriptive traffic assignment model is employed.

Finally, for the multistage link-addition network synthesis problem, a normative model is formulated as a block-angular mixed-integer linear program. A partitioning technique is employed to take advantage of the highly-structured form of the model.

We conclude with a detailed presentation of the partitioning technique of Benders, as applied to both continuous and mixed-integer programming problems presenting a block-angular structure.

Manheim, Marvin L., "Modelling the Evolutionary Nature of Problem Solving." PART I: CONCEPTUAL FRAMEWORK, R68-43, Department of Civil Engineering, M. I. T., June 1968.

Part I develops a conceptual vocabulary of the procedural models to guide and structure the use of transportation system planning models. The evolution of the analysis process is represented by the development of relations which describe the actions and goals in the Problem Solving environment. The first section briefly describes the PSP model. The next section develops a "snap-shot" view of the states of the PSP by defining the relationships among the set of actions, A, and the set of Goals, G.

The relationships among the actions are defined as:

- a. alternatives
- b. component/composite
- c. inclusions

The image of the goals is described with the idea of the goal fabric and goal statements, and the relations among the goals are:

- a. particularization - combination
- b. means - ends
- c. valuewise dependence
- d. indifference - preference

The paper also identifies several possible relations between A and G such as:

- (1) Goal performance of a specific action
- (2) Preference structure over A, and
- (3) Search directions.

Finally, we enumerate the ways in which the evolution of the analyst's view of the problem can be represented by changes to A and G.

Follansbee, K. G., Manheim, M. L., and Walter, R. A., PART II. DODO-AN INFORMATION SYSTEM FOR THE PSP MODEL, Research Report R68-43, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

Part II discusses the initial development of an information system for transportation systems analysis. It is intended to provide the decision-maker and analyst with the capability to structure and analyze the large amount of data which may be generated in the development, prediction, evaluation, and choice among the many alternatives in the search for an optimal solution to a transportation planning problem.

The system is structured in the PSP (Problem-Solving Process) model framework:

1. Strategies for solving the problem are generated.
2. These strategies are run through a predictive model which generates a set of consequences for each action.
3. The positive results of the prediction are transformed into normative goal performance terms.

This paper presents the basic ideas of the Files System, a basic decision element and proposed command specification. TRANSET-II will be used as the prediction model and also as part of the evaluation model. The analyst will be able to refer to all the data generated in the analysis during the evaluation. A search procedure to determine optimal link improvement will be implemented using a branch-and-bound optimization technique.

Ochoa-Rosso, Felipe and Angel (7) Silva, OPTIMUM PROJECT ADDITION IN URBAN TRANSPORTATION NETWORKS VIA DESCRIPTIVE TRAFFIC ASSIGNMENT MODELS, Research Report R68-44, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

The work reported here describes optimization techniques applicable to the solution of the project addition network synthesis problem when descriptive traffic assignment models for establishing flow distribution patterns are employed.

Chapter I describes the classes of models available for traffic assignment on transportation networks and outlines the types of improvements that may be considered. A survey of recent synthesis models and the solution methods employed for various types of improvements via descriptive traffic assignment becomes evident.

In Chapter II project addition to an existing transportation network under a budgetary constraint is formulated as a discrete optimization problem which seeks to minimize the total users' cost. Two optimization techniques are then developed to solve the synthesis problem, which use descriptive traffic assignments throughout the solution procedures.

The first algorithm, given by Ochoa , is a branch and bound procedure which provides a better lower bound on the problem at each iteration of the algorithm. When the procedure is carried out to completion, it permits the determination of the range of variation of the budget ceiling that will not alter the optimal solution. The second technique is a branch and backtrack (implicit enumeration) method which provides a feasible solution and an upper bound on the users' cost that decreases with the number of iterations. In both methods the solution of traffic assign-

ments is required for certain nodes of the solution tree.

In Chapter III, the use of both solution procedures is illustrated by means of a case-study on a simplified network of the San Juan Metropolitan Area of Puerto Rico. The required traffic assignments were made off-line using the TRANSET subsystem of ICES, developed by the Massachusetts Institute of Technology, Department of Civil Engineering.

Stafford, Joseph H., J. C. Prokopy, and V. Atvazian, PRODUCTION FUNCTIONS: MODELS OF TRANSPORT TECHNOLOGY, Research Report, R68-45, Cambridge, Mass.: Department of Civil Engineering, M. I. T., June 1968.

In order to analyze alternative future transportation systems it is necessary to estimate future costs of building and operating the components. This report discusses an approach to cost estimation which explicitly incorporates technology descriptors and the unit costs of separately identified resources or system inputs. The approach is based the economist's concept of a production function and especially as it has been expressed in activity analysis. This approach was taken to facilitate an explicit examination of the impact of government policies on transportation operators' choices of technology and of the impact of those choices on the cost of transportation under a range of different relative factor costs.

The report is divided into two principal sections. The first section describes the theoretical constructs to be used and illustrates the primary relationships to be considered. The second section presents some estimated costs for present-day U.S. passenger transport technologies and suggests some implications for policy based on these crude estimates of costs.

The conceptual model presented in Section I is a general model for all modes of transportation. For each technology the amount of equipment, time, crew labor, fuel, equipment maintenance, and fixed facility capacity required per unit of output are identified and expressed as function of such technology descriptors as vehicle operating speed and payload. The

effects of changing relative factor prices and changing technology descriptors is shown in a theoretical text. The high fixed costs for rights of way and the effects of vehicle size are shown to produce significant economies of scale while congestion and hence reduced operating speeds are shown to result in increasing average costs.

Section II describes the specific functions used in the Northeast Corridor prototype analysis. These functions are derived from the more general model of Section I. Two different functions are used in the prototype analysis. One, a volume/delay function, is used to estimate link travel time as a function of the volume of movement on the link. The other is used to estimate the cost of transportation on a link.

Bhatt, Kiran U., SEARCH IN TRANSPORTATION PLANNING: A CRITICAL BIBLIOGRAPHY, Research Report, R68-46, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

A survey is presented of the existing methods in the search for transportation alternatives available in highway and traffic flow literature. Some of the major papers and methodological ideas are described in detail to bring out important trends in the design of transportation systems.

Part I reviews the source of the papers which present comprehensive transportation design methodologies at the network planning level. These are the planning processes rather than the optimization modules. Part II reviews the micro-design models and optimization techniques which do not address the overall plan, but some specific detailed aspects. These are formal analytical modules which may constitute only a sub-problem in the comprehensive design.

The major limitations of the existing methodologies are described and a short discussion leads to the hypothesis that the absence of normative, comprehensive search methods has led to the generation of alternatives which are often biased toward existing and committed systems, and that a large number of impacts and their differential incidence are not explicitly considered. This leads to the evaluation and selection of schemes which do not always provide a rational choice.

Chan, Yupo, Kenneth G. Follansbee, Marvin L. Manheim, and John Mumford, AGGREGATION IN TRANSPORT NETWORKS: AN APPLICATION OF HEIRARCHICAL STRUCTURE, Research Report R68-47, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

This report studies the implications of different levels of detail with which networks are modelled. The analytical and computational resources are seldom sufficient to model a transport network in full detail and test vast numbers of detailed alternatives that are available. This paper studies the implications of different types of network aggregation, different rules of aggregation and how these can be structured for use in multi-level transportation analysis.

The first part of the report discusses the use of network aggregation in "Search and Choice" of transport alternatives. A general two level heirarchical framework is developed which enables the analyst to test a large number of actions on a gross level in terms of broadly based objectives and grossly defined attributes and to select a small set to be tested at the lower and detailed level. This approach uses two models for analysis at different levels. A case example is used to discuss how the partitioning of action space can be achieved by defining a heirarchical process.

The framework for network aggregation in space is developed which studies rules (methodologies) of link and zone aggregations and elements of uncertainty introduced in performance characteristics because of abstraction. An experiment was carried out to study the link aggregation based on "parallel link rule" in hypothetical networks and the measures of effectiveness and results are discussed.

The last section introduces the idea of aggregation in time with the

help of a case example which considers time dependent flows on
a line-haul link.

Jackson, L. F., "General Models of Urban Travel;" PART I, R68-48, Department of Civil Engineering, M. I. T., June 1968.

This paper extends the model of Beckman which gives a general equilibrium formulation to the study of the demand for travel on particular network links. The formulation here considers two major problems associated with the Beckman model and attempts to solve them while retaining the flow homogeneity assumption. The first problem is that in the model of Beckman, it is difficult to estimate the structure of the model, and to include important exogeneous variables which play a role in the supply and demand functions of the model. Second, the structure postulated for demands for travel from a particular origin to destination is independent of the demand to any other destination, and this inadequate if we wish to use the model for studying the changes in impact due to changes in route structure and capacities.

The paper develops a model of travel behavior considering transportation as a production activity which must operate at a certain level to consume other services, and not as an item for consumption. This model postulates uniform and homogeneous time flows and considers macro stability of flows. It is essentially a short term equilibrium model. The model is structured in three steps: discussion of transportation as a production activity, development of basic equations representing demand behavior, and general supply behavior equations.

Schwartz, Jesse, " Production and Transportation Models for Regional Planning," PART II, 168-48, Department of Civil Engineering, M. I. T., June, 1968

This report describes a class of models designed to assist the planning of transportation taking into account the other sectors of an economy and overall development goals. Emphasis is placed on the highly integrative role of transport in manufacturing and industrial activities. In this way the flow of commodities on the network, simulated in the models, is related to levels of productive activity throughout the regionally distributed economy.

Three models are presented. Two are static or single period in nature and allocate investment funds into network link capacity and plant production capacity on the basis of cost minimization. A series of numerical experiments are performed to demonstrate the effects of differing transport investment policies on consumers, manufacturers, and shippers. The third model is designed to deal with the relation of transport and production investment to economic growth. It attempts to simulate the essential intertemporal aspects of the problem of allocating investment between transport and production so as to meet the general social goal of increasing consumer goods. It can thus be used to explicitly relate the goal of economic growth to the efficient allocation and utilization of resources in both the transport and production sectors.

Bivins, Dave, "Use of a Normative Model in Urban Highway Network Operation and Network Improvement," PART III, r68-48, Department of Civil Engineering, M. I. T., June 1968.

This paper discusses the use of a linear programming model of networks with steady-state flows in the problem of urban highway network operation and improvement.

The multi-copy network model - a linear programming formulation - is compared and contrasted with the incremental traffic assignment model which is a predictive technique. The former is "prescriptive" while the latter is a "descriptive" model.

The second part discusses the application of the programming model to network flow control and improvement problems which would require careful validation of L.P. model to make it behave realistically. Three possible techniques of improving the correlation of the normative and predictive (realistic) flow patterns are discussed:

- (1) Levying of congestion tolls on links
- (2) Use of priorities on the network
- (3) Modification in the L.P. model itself

The first two techniques attempt to perturb the predicted individual flow behavior toward system optimal behavior, while the last one uses the traffic assignment model as a benchmark, and seeks to make the L.P. model a better "predictor."

Schwartz, Jesse G., NETWORK FLOW AND SYNTHESIS MODELS FOR TRANSPORTATION PLANNING: A SURVEY, Research Report R68-49, Cambridge, Mass.:Department of Civil Engineering, M. I. T. (1968).

This survey outlines some of the recent research advances in network equilibrium and programming models. The introduction traces their evolution starting with Wardrop's first and second principles, through the development of programming and traffic assignment procedures, decomposition, and network synthesis. The next section presents abstracts of some prominent network equilibrium models, namely, those of Beckman, Jackson, Lynn, and Tomlin. This is followed by abstracts of the network synthesis models of Quandt, Carter, and Stowers, Hershdorfer, Hay, Morlok and Charnes, Tabora, and Ochoa-Rosso. A summary section presents the models in common notation to facilitate structural comparisons. The final section outlines suggested directions for further research. An extensive bibliography is included.

Silverstone, Stuart M. and John Mumford, "Development of Graphic Communication in a Computer-Based Transportation Planning Process, Research Report R68-50, Cambridge, Mass: Department of Civil Engineering, M.I.T. (1968)

Comprehension of the information which is handled during a computer-based network assignment model requires the use of computer-graphic display techniques. Experiments are described which lead to the development of a man/machine interactive display software package for an existing traffic assignment model. The cathode-ray tube screen is organized to include traditional node and link data and network oriented displays such as the desire-line plot, in addition to alphameric and analogue graphic representations, such as two-dimensional line graphs. User manipulation of the network alternatives and dynamic flow displays increase the communication that could be afforded through band-copy or batch processing techniques. Through the sequence of search and choice in the planning process, comparisons can be made between alternative solutions or between data for different aspects of the same solution. The experiments are evaluated in the light of future research which can be undertaken for graphic communications in problem-solving processes.

Plourde, Rodney, CONSUMER PREFERENCES AND THE ABSTRACT MODE MODEL, Research Report, R68-51, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1968).

This research tests the Abstract Mode Model, developed by Quandt and Baumol of MATHEMATICA, as a predictor of trip generation and modal choice in urban areas. A travel mode - existing or as yet undetermined - is represented in terms of the mode's service attributes, such as travel, time, cost, comfort, convenience, etc., in this model. Only some of these attributes are directly measurable. This research is directed towards obtaining statistical fits of measurable attributes of a mode with respect to travel volume, which in turn would determine how successful each travel parameter is in explaining trip making and consumer preference patterns.

The analysis presented develops the concept of one independent travel attribute relative to other independent travel attributes. This concept is very useful in using estimated regression coefficients of measurable attributes, obtained from statistical fits, to analyze consumer preferences in travel. The transportation planner can use these trade-off ratios to predict consumer response to each attribute.

The analysis presented here fits the survey data in linear and log-linear forms, and for peak-hour and off peak-hour travel, by multiple regression techniques. Attention is focused on three directly measurable modal performance attributes, line-haul travel time, walk times to and from a travel mode (as a measure of comfort and convenience), and out-of-pocket travel cost. Environmental descriptors of the traveller and of the

O-D nodes, such as income, age, auto ownership, and population are also included in the trip generation-modal split equations.

The fitted equations tend to indicate that either the particular travel parameters chosen do not by themselves completely explain variations in consumer travel behavior, or that consumer preferences in urban travel are random, and cannot be described by the measurable attributes of a travel mode. However, general design implications, such as the value of time spent in travel etc., are significant and useful.

Bruck, Henry W., Marvin L. Manheim, and Paul Shuldiner, TRANSPORT SYSTEMS PLANNING AS A PROGRESS: THE NORTHEAST CORRIDOR EXAMPLE, Professional Paper P67-23, Cambridge, Mass.: Department of Civil Engineering, M.I.T. (1967).

Transport systems planning is a complex public investment process, because there are a variety of impacts to be considered, there are a multitude of actors and a large number of options available. It is unreasonable to try and construct one grand optimization model. The design process must consider a variety of procedures and evolution of the process.

The next section of this report defines the analysis problem by enumerating the range and variety of alternative transport systems policies and range of impacts and issues to be considered in choosing among them.

The third section summarizes a proposed model of the analysis - the "Problem-Solving Process" or "PSP" model, which is a general framework of design rather than a fixed model. This model develops a hierarchical tree of the process and makes explicit use of goal fabric analysis recognizing explicitly that there is no single criterion for choosing the best action and that generation of alternative actions is difficult. The basic idea is that one can talk about optimal process and not an optimal action.

The fourth section describes the anticipated process of analysis in the Northeast Corridor Transport Systems Planning and various models and procedures under development, and their interrelationships. The NECTP is modelled as a seven level hierarchical structure. Some issues and problems of the actual analysis process are discussed at the end.

Manheim, Marvin L., and Frederick Hall, ABSTRACT REPRESENTATION OF GOALS: A METHOD FOR MAKING DECISIONS IN COMPLEX PROBLEMS, Professional Paper P67-24, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1967).

This report presents a method for choosing among alternatives in complex, multi-goal problems. The method consists of four principal steps. First, list all the known goals. Second, determine how the various goals are related - specification, means - end, value-wise independent or dependent. Third, determine for which goals consequences can be predicted, and obtain predictions of those consequences. Fourth, use any of five techniques to condense this predicted data through several stages into a final choice. The method operates on paired alternatives to produce a preference; it can be applied sequentially to all the alternatives to produce a complete preference ranking.

Manheim, Marvin L., PRINCIPLES OF TRANSPORT SYSTEMS ANALYSIS, Professional Paper P67-1, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1967).

Nine principles for the analysis of transportation systems are presented. The primary purpose of these principles is to identify the common threads underlying a great variety of seemingly disparate transportation problems, and so to stimulate the development of a "transportation science." The principles are equally applicable to urban transportation, megalopolitan transportation, developing country transportation, and strategic mobility.

The first five principles pertain to the scope of the system: The components of a transportation system, the modes and movements in a system which must be considered, and the nature of a transportation system as a particular form of "market." The second group of four principles pertain to the problems of analysis; The spectrum of potentially available transportation and non-transportation options, the objectives of transportation, and the relevant impacts.

To illustrate these principles, the paper concludes with a discussion of their application to two specific problems - urban transportation and strategic mobility.

Manheim, Marvin L., PROBLEM-SOLVING PROCESSES IN PLANNING AND DESIGN, Professional Paper P67-3, Cambridge, Mass.: Department of Civil Engineering, M. I. T. (1967).

This paper develops a general theory of problem-solving processes, particularly applicable to planning and design, to attack complex problems where the coordination between the decision maker and the computer is necessary.

A "Problem-Solving Process" (PSP) is defined as a man/machine system interacting with a problem to develop, select, implement, monitor, and revise actions in the real world which can be applied to complex problems in architecture, transportation, urban planning and economic development planning. The basic activity of PSP is to generate and choose among actions.

The basic PSP model consists of a sequence of Search, Prediction, Evaluation and Choice procedures. The basic conceptual principles are:

- (1) A PSP uses a variety of different procedures.
- (2) The roles of man and machine are, generally, different for each process in a PSP.
- (3) The procedures are both specific and general.
- (4) PSP is a flexible process and the sequence of use of the procedures is determined and adjusted as the problem evolves.
- (5) There is an optimal process; not an optimal action.
- (6) Parallel and sequential applications of procedures is possible.

The idea of hierarchical structure is developed to identify different levels of planning and goal formulations.

Johnson, William F., DECISION THEORETIC TECHNIQUES FOR INFORMATION ACQUISITION IN TRANSPORTATION NETWORK PLANNING, Research Report R69-1, Cambridge, Mass.: Department of Civil Engineering, M. I. T. January 1969.

The problem is defined in terms of the need for a rational procedure to allocate resources to information acquisition activities in the uncertain environment of transportation decision making. Models are formulated for selecting an optimal information acquisition activity to estimate the current state of travel demand.

A general model is postulated based on concepts of statistical decision theory. This model is characterized by an explicit recognition of uncertainty over the true state of the real world system, explicit inclusion of the decision makers' judgments on the true state in the form of a prior probability density, and the facility to compare the costs and benefits of information acquisition activities with the costs and benefits of the investment decision before the information is acquired. Two specific models are formulated and examined.

A model for independent projects is described and demonstrated with a simple application and a simulation analysis of the most important model parameters. The model is sensitive to the travel cost savings and investment costs of project alternatives and to the specification of the decision maker's prior probabilities over the true state of the system.

A network model is formulated with a global demand function. Either observed flow counts on network links or origin-destination survey results can be used to revise the decision makers prior probabilities over the states of the model parameters. A variety of small scale link counting activities are simulated to determine their characteristics.

The development and simulation analyses have demonstrated the feasibility of the approach for prescribing optimal information acquisition activities. Extensions are discussed for both the specific models.

Guenther, Karl W., PREDICTIVE MODELS FOR VEHICLE OPERATING CONSEQUENCES, Research Report, R69-2, Cambridge, Mass.: Department of Civil Engineering, M. I. T. 1969.

Assessment of technological variables, and their ultimate impact on the system, is an important but difficult task in evaluating new transportation proposals. The models presented here give the analyst, planner, or engineer capability to predict vehicle operating consequences. Relevant technological variables are transformed into useful output - travel time, fuel consumption, and maintenance cost. This output may then be used in evaluating cost and service performance measures, eventually relating technology properly to the broader questions raised in transportation systems analysis.

Travel time prediction is based on the controlling velocity concept. Average speed on any link segment will be determined by the most constraining of several possible limits. These include arbitrary exogenous speed limits, vehicle limitations, route characteristics, traffic, and random delays. Inclusion of surface roughness as a velocity control is noteworthy, particularly for secondary roads and off-road operations. The speed change method employed for estimating traffic delays is also unique.

The fuel consumption model builds on the travel time model. Actual power expended is the independent predictive variable, and thus a true causal relationship is used for estimation.

Maintenance costs are predicted by a third model. Because of the number of individual variables influencing maintenance, their possible correlation, and general intractability, a commutative variable has been

used for estimation. With fuel consumption as the independent variable, good results have been obtained with linear regression analysis.

The contribution of this work is the assembly of a complete package for vehicle performance analysis which is concise, logical, easy to use, and computationally consistent. Cross modal capability is included - rail, highway and off-road vehicles may be evaluated using the same models. Readily available basic vehicle and link characteristics are the only required input data. Output is generated in physical resource units, which may be costed for any monetary system or economic environment.

Friedlander, Alex Efrem, "A Method of Schedule and Route Planning in Urban Mass Transit", Ph.D. Thesis, Department of City and Regional Planning, M.I.T., September 1968.

Continued arbitrary reductions in service are not a panacea for the financially stricken urban public transportation industry. In seeking to reduce costs, "it is not always realized by management that a cut in mileage during a period of fall-off in revenue will result in a reduction in patronage much beyond the normal or average fall-off." (Robert T. Pollock, former head of the Department of Schedules, Cleveland Transit System, chapter 2 footnote 35).

More attention must be paid to making urban mass transit service more attractive in such a way that the cost of doing so will be equal to or less than the additional revenue encouraged. To do this, new methods of data collection and analysis, and new approaches to service decisions, based on a better understanding of the costs of such decisions and of why the urban traveler chooses to make (or not make) his trips as he does, must be developed.

This thesis develops such new methods and approaches. The proposed method of Schedule and Route Planning is:

- 1) Market oriented, focusing on the sensitivity of demand as well as cost to changes in service, and on the potentially profitable demand for new or improved transit service. Relationships are found to exist between level of service and transit usage (chapter 5). These relationships can be measured, and applied to decisions on level of

service in manner that will enable the determination of an "optimum," or at least better, level of service for the desired objectives (maximum profit, maximum number of passengers, etc.).

2) Based on incremental analysis, making use of marginal cost analysis (chapter 6). The marginal (added) cost of a service increment is found to vary from route to route and change of change, depending on a number of factors; it is always less than the average accounted cost.

3) Systematic (as defined in chapter 3), drawing on the discipline of Systems Analysis to make what is now an essentially disorganized, inconsistent art (chapter 2) into a systematic, consistent science capable of being programmed for the computer.

It is hoped that the new approaches and findings in this thesis will inspire further efforts along similar lines in and out of the transit industry. In particular, the effect of service changes on demand; the adaptation of the model to the computer; and the improvement of data collection procedures in the industry are suggested as fruitful areas for research.

Hall, Frederick L., "A Method for Dealing with Complex Goals and Indefinite Utilities in Decision Problems", S.M. thesis, Alfred I. Sloan School of Management, M.I.T., May 1967.

The problem undertaken in this study is to determine a practical method for choosing among alternatives in complex decision problems in which the decision maker can not formulate a comprehensive, well-defined utility function over the entire set of goals, nor can he produce a concise, well-defined utility function over each one of the goals separately. The method produced involves pairwise comparison of alternatives, and relies on two things: the goal fabric, defined by a detailed analysis of the goals and the relations between them; and utility functions of various orders over each goal or group of goals. At any given time the state of the method is defined by these two things plus the ranking of the previously evaluated alternatives. The entire state of the method is subject to revision every time the method is used: when a new alternative is entered into the method, the output is a revised ranking of alternatives to include this one: in addition, it is possible that the data gathered while evaluating this alternative will indicate changes to be made in the goal fabric or in the utility functions.

To construct the goal fabric, we determine the relations between goals, and use these to place the goals in a hierarchical ordering. There are four possible types of relations. (1) Means-end, and (2) particularization-inclusion are used to define the hierarchical ordering; (3) value-wise dependence or independence and (4) direct connection or vector connection are defined between goals that have been placed on the same hierarchical level.

To assist in placing a utility function on each goal, we specify seven orders of utility measures. These are based on either the ordinal or the interval scale, and ordered according to the precision of estimate each measure involves.

The basic procedure in the method is to obtain predicted consequences for one alternative, and then map these consequences onto the goal fabric. Each consequence will map onto one or several goals; the set of consequences will map onto goals on several levels of the hierarchy.

Call these the active goals. Using the utility functions, calculate the valuations for each of the active goals. Check for dominance (i.e., A preferred to B, B to A, or A is indifferent to B) between this alternative and a previously evaluated one, with respect to these active goals. If there is no dominance, combine the valuations on the lowest level active goals to determine the valuations of the new alternative on the next level goals composed of these. If low orders of utility measures are used in the valuations, it may not be possible to combine them. It will then be necessary to increase the order of utility measure by one or several orders. Check again for dominance after moving up a level. If there is none, repeat the combining step to go up one more level in the goal fabric. This is continued until dominance of one alternative over the other is found. The method will then have produced a ranking of these two alternatives. This can be repeated, if necessary, with other alternatives to produce a definite ranking of all the alternatives.

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Hall, Gunnar, "Generation of Improvements in Urban Transportation Systems: A Multi-modal Approach with Identification of Impacts on Different User Groups." C.E. Thesis, Department of Civil Engineering, M.I.T., June 1968.

A framework is developed and implanted for urban transportation planning incorporating the multidimensional nature of objectives. The model developed for network analysis and design generates the investment plan for the highway system. This plan is a selective subset of a large set of pre-specified, feasible link improvement projects. System benefits are determined successively in more refined form and provide the basis for selection of potential improvements for the plan. A near maximum reduction in total user costs over the multimodal system is obtained for the given set of constraints.

The trip generation rates to be inputted in the multi-modal analysis model are assumed available from existing models, and may be specified as a function of zone accessibility measure developed. The travel demand model is not, at present, integrated into the framework. The general framework uses submodels developed for the determination of minimum paths through public transportation (multimode), for the determination of value of time to different user groups for modal split and assignment and heuristic sources for potential project.

The analysis of the network determines the user costs consisting of out-of-pocket and time costs. The incidence of costs and benefits on users from different zones and income groups is explicitly identified.

The nonquantifiables like social, political, aesthetic impacts are considered at an early stage in the planning process to identify their

influence of the selection of projects. The differential incidence of benefits on different user groups (income groups) has been considered as a major concern. The framework develops this impact for a given network and provides the planner with the capability to generate alternative plans of investment with any (feasible) desired distribution of benefits which are "near optimum."

Ichikawa, Yoshihiro, "Economic Conditions for Adopting Serial Parking System", S.M. Thesis, Department of Civil Engineering, M.I.T., July 1968.

Parking is still a big problem in the cities, although more than forty years have passed since it became one of the biggest public concerns in the United States in 1920's. The increasing tendency of parking demand will continue as far as the city goes on growing.

In order to relieve the parking problem, many proposals have been made. As a possible method, this study proposes the serial parking based on standardized leased cars, by which each downtown garage can accommodate twice to three times as many as cars by the conventional random parking based mainly on privately owned cars, and determines the economic conditions for the serial parking to be preferable to the random parking.

When a car is used primarily for commuting to the CBD--most downtown parkers belong to this type of users--the total annual cost which the user will spend consists of the vehicle operating cost and the parking cost, of which the latter, in some cases, may be paid by the organization which the user belongs to.

In order for the serial parking system, which is based upon standardized leased cars, to be economically preferable to the conventional random parking system, which is based mainly upon privately owned cars, the total annual cost of the former has to be lower than that of the latter. The vehicle cost of a leased car is generally higher than that

of a privately owned car and the cost difference is almost fixed, and the parking cost of the serial parking is lower than that of the random parking and the cost difference depends upon such factors as land cost, interest rate, and number of levels of a garage. Therefore, the parking cost under the various conditions determines the economic preferability of the serial parking system with standardized leased cars.

Both the parking cost and the vehicle cost vary depending upon the vehicle size, so four types--smaller foreign car, compact car, intermediate car, full-sized car--are examined individually. In case of a privately owned car, the vehicle use types--whether the car is bought new or used and how long the car is used--are also taken into consideration. The parking cost also depends upon the garage type--commercially operated garage or privately operated garage, so the two types are examined individually.

The detailed examination of each item which constitutes the parking and vehicle costs is made, and it is tried to use the average or standard values for the decision of each cost item as much as possible. Therefore, the results will be able to be applied all over the United States.

The results show that when smaller cars are used as standardized leased cars the serial parking system is economically preferable to the random parking system even in the case where both the land cost and the interest rate are comparatively low (land cost lower than about \$20 per square foot, interest rate lower than about 8%), and when compact or intermediate cars are used as standardized leased cars the system is economically preferable only in the case where both the land cost and the interest rate are comparatively high (land cost higher than about \$40 per square foot, interest rate higher than about 12%), but the serial parking system with leased full-sized cars is in general economically infeasible.

Mori, Yasuo, "A Highway Investment Planning Model: An Application of Dynamic Programming." S.M. Thesis, Department of Civil Engineering, M.I.T., June 1968.

Dynamic programming technique is applied to highway investment planning incorporating the three basic characteristics often not considered exhaustively in existing allocation models. These characteristics are:

- (1) Dynamic treatment of planning
- (2) Divisibility of project
- (3) Discreteness of investment level.

The paper develops a method which will search for the optimal allocation policies which maximize the total utility of highway investments. When a set of proposed projects and available funds in each period are given the order of priority on construction among the projects, and the more exact investment plan which determines the investment schedule in time are both treated in this model.

One-dimensional and two-dimensional dynamic programming modules are developed which implement all of the requirements mentioned earlier. The model also enables the designer to introduce stage construction as an alternative to the construction planning of each project.