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AN OPTIMIZATION METHODOLOGY FOR DESIGN AND EVALUATION
OF INTERCITY PASSENGER TRANSPORT SYSTEMS

By

Salah G. Hamzawi

B.Sc. (1st Hons.) (Civil Eng'g)

M.Sc. (Civil Eng'g)

M.Eng. (Civil Eng'g)

A Thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment of
the requirement for the degree of
Doctor of Philosophy

Faculty of Engineering
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Ottawa, Canada

March 1977

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The undersigned recommend to the Faculty of Graduate Studies and Research acceptance of the thesis, "An Optimization Methodology for Design and Evaluation of Intercity Passenger Transport Systems", submitted by Salah G. Hamzawi, B.Sc.(1st Hons.) (Civil Eng'g), M.Sc. (Civil Eng'g), M.Eng. (Civil Eng'g) in partial fulfillment of the requirement for the degree of Doctor of Philosophy.

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ABSTRACT

The research reported in this thesis is aimed at developing a methodology for optimizing the supply factors of a public transport network serving a number of major urban centers. The design optimization methodology involves modeling - in terms of a set of design variables - the travel demand for the system, the level of service and transport capacity to be provided, and the various system cost components and revenue. Determination of these measures is carried out over an analysis period rather than on the basis of a single target year.

The design optimization variables dealt with in the analysis include the vehicle speed and seating capacity as transport technology variables, and the frequency of service and fare structure as system operational variables. The focus of this research is on determining the optimal values of these variables. This is accomplished through maximization of an objective function which reflects the economic viability of the system. Although different objective functions representing different optimization criteria could be formulated and tested using this methodology, yet the optimization criterion emphasized in this research is the maximization of the present worth of the net revenue of the system (revenues less costs). Determination of the optimal values of the above design variables in turn determines the corresponding levels of the travel demands for the system, its supply and performance measures, and its economic consequences throughout the analysis period.

The methodology brings together, in the network context, both the demand and supply sides of the transport system and permits their interaction explicitly. Uncertainty in future travel market shares is also treated in designing the system. The method is flexible in its application as it can be applied directly to the design of air as well as ground transport systems.

In addition to being useful in analyzing the problem of introducing new travel modes or improving the level of service of an existing transport system, the reported optimization methodology can potentially be applied also to identify the optimal implementation strategy of system introduction (or improvement) along the various links of a given network. A meaningful process of selecting among a number of transport system alternatives can only be made through determining the optimal level of service that each alternative can provide. The optimization methodology can effectively be used in this regard as well.

Two case studies are analyzed in the thesis. The first deals with a Short Take Off and Landing (STOL) system. The second considers the improvement of an existing passenger railway system. Both applications involve the network linking the major Canadian cities of Toronto, Ottawa, and Montreal.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Problem and the Need for the Thesis Research

For the past several years, there has been a growing concern about future transportation needs between heavily populated urban areas. This concern is stimulated by the increasing demand for intercity travel by common carrier and the desire to provide improved level of transport service between cities. Intercity passenger transport studies^{1,2,3,4*} have frequently been undertaken to estimate the intercity transport needs and to suggest and evaluate alternative approaches to meet these needs. Two basic approaches, which may or may not be treated as mutually exclusive, are usually prescribed. The first approach is to improve the quality of service of the existing transport system through increasing the travel speeds, making the services more frequent, etc. The second approach involves the introduction into the service of a new mode of travel. Such a mode could be based on a conventional, an innovative conventional or a new transport technology.

Increased attention is presently being focused on this area of transport and particular emphasis is being placed on the common carrier modes, especially rail and air systems. Improved Rail and Short Take Off and Landing (STOL) air systems are among the alternatives considered as solutions to meet the growing demands for travel between major urban centers. High speed ground transportation modes other than the improved conventional railway mode, such as the magnetically levitated vehicles, are still at the development stage.

Substantial investments are required in the provision of considerably improved services. It would, therefore, appear highly desirable to plan and design the transport system in such a fashion

* Raised numbers refer to references listed at the end of the thesis.

that its economic viability* is maximized. That is, a major design goal is to optimize the level of service of the system so as to maximize its net return (e.g. gross revenue less total cost).

An essential element in the evaluation of and selection among a number of proposed transport system alternatives (e.g. rail, air, etc.) concerns the specification of the level of service provided by each alternative. The level of service best offered by any of the alternatives being compared is usually specified on an "ad hoc" basis within the present evaluation methods. Consequently, the economic viability of an alternative, which is a key factor in the selection process, may or may not be the best (optimal) that the system can produce. For example, the costs, revenues, and user benefits associated with an improved rail service of 120 miles per hour (mph), 300 seat trains operating at 2 hour intervals might be substantially different from another specification of 90 mph, 80 seats, and 1/2 hour interval. The economic viabilities of these two specifications might be quite different. Thus, when such a rail system is compared to another alternative system (e.g. STOL) without actually determining the best (optimal) specification of the level of service that each system could possibly offer, the conclusions drawn may not be regarded as reliable.

It would, therefore, be desirable to first optimize the level of service of each of the alternatives so as to maximize their economic viabilities (e.g. net revenues) and then carry out the comparison and selection process. Such a procedure, it is suggested, would lead to a more objective and reliable comparison of the relative merits of the analyzed set of alternatives.

The objective of maximizing the economic viability of the transport system can mostly be achieved through the design of the system by determining the optimal values of a basic set of variables which largely govern the design. Such variables may include vehicle

* The term "economic viability" is used here to reflect the system costs and revenues, although a proper terminology in this case might be "financial viability". System economic viability may account also for other system benefits (e.g. reduction in users' cost).

speed, vehicle-size(s), frequency of service, and fare structure. In addition to affecting directly and indirectly the system costs, such variables have a major impact on the system ridership and hence user benefits and fare revenues.

A systematic way of optimizing the design of a transport system can be structured into the sequential form shown in Figure (1.1). A sequence of operations is required to arrive at the optimal system design.

1. Statement of the design objectives and optimization criterion (e.g. maximum economic viability)
2. Selection of a set of design optimization variables together with initial specification of their values
3. Prediction of system travel demand between each city-pair in terms of these variables
4. Determination, in terms of these variables, of the required level of system supply and performance (travel times, frequencies of service (or vehicle size), departure times of vehicles, vehicle fleet size needed, maximum accumulation of passengers and of vehicles in the terminals, guideway capacity requirement, terminal space required for accommodating the passengers and vehicles)
5. Evaluation of the system economic consequences (system costs, fare revenues, users' cost) using cost models
6. Evaluation of an objective function based on the system economic consequences
7. Maximization (or minimization) of such function through altering the value specification of the design optimization variables.

There are many requirements that should be satisfied in designing an intercity passenger transport system. Firstly, the level of system supply depends on the demand for it while at the same time the demand is influenced by the quality of supply provided. The system design methodology should, therefore, treat the supply-demand interaction. Secondly, the capability of the design method to handle transport networks rather than analyzing only a single link (city-pair) is another requirement. A third requirement is the

FIGURE (1.1) - AN OVERVIEW OF THE SYSTEM DESIGN OPTIMIZATION PROCESS

recognition and treatment of uncertainty in future travel demand forecasts. Travel data typically available for use in demand modeling are not sufficient to reflect completely the travelers' tastes or perceptions of traveling by a given mode. As a result, it is not possible to forecast "exactly" the behavior of the traveling public with respect to trip making. Greater uncertainty is involved when predicting the demand for a new transport system. Evaluation of system demand, supply and performance measures, and cost and revenue streams throughout an analysis period (e.g. 15 years) rather than designing for a particular target year is a further requirement.

Present design methods are not capable of handling the system design requirements as outlined here, nor could they determine the best possible or "optimal" system design. At present, there is a need for developing a system design methodology that could be used for optimizing the system design within the requirements outlined above. Such a methodology would provide a rational answer to the fundamental design question of "what is the optimal level of transport service that can be provided?". Specifically, it involves determination of the optimal values of a set of supply and policy variables which largely govern the system design. And, accordingly, it answers a number of other important questions such as:

- (1) how far can the system penetrate in the travel market?,
- (2) what level of system supply (which includes vehicular and fixed facilities requirements) should be provided?,
- (3) what level of performance will the system have?, and
- (4) will the system be economically viable? and what magnitudes of costs and revenues are involved?

In addition to being useful in analyzing the problem of introducing new travel modes, (e.g. STOL) or the improvement of the level of service of an existing transport system (e.g. improved rail), the optimization methodology can also be applied to identify the optimal implementation strategy of system improvement (or introduction), such as the question of "along which links of a

given network and to what extent should a rail passenger service be upgraded?" Similarly, the methodology can be applied in choosing among a number of mutually-exclusive transport system alternatives or possible improvements of an existing system. In such a case, the methodology is applied to optimizing the design of each individual alternative, and the alternatives can then be compared on the basis of their "optimized" economic viability measures (or other selected criterion) in addition, of course, to their associated social-environmental impacts.

Furthermore, the proposed technique could also be used when the system to be designed is composed of a number of individual transport systems (or modes). In such a case, the design of the overall system could be optimized through maximization (or minimization) of one composite objective function over an aggregate set of decision variables. Such a set would be made up of subsets of design variables representing the individual systems.

1.2 Research Objectives

The objectives of the research reported in this thesis are twofold: the development of an optimization methodology for use in design and evaluation of intercity short-haul public transport systems, and the demonstration of it as a tool for designing new or improved intercity passenger transport systems. Specifically, the model should be capable of determining the optimal values of a selected set of basic system design variables so as to maximize (or minimize) an objective function reflecting the economic viability of the system (or any other selected optimization criterion). Examples of such variables include vehicle speed, vehicle size, frequency of service, and fare structure.

System measures relating to its demand, supply and performance, costs and revenues are to be treated as functions of the selected set of design variables, and as such, their values which correspond to the optimal design can be determined.

The methodology is to be developed in such a way that

- (1) it explicitly treats the interaction between the system supply and the demand for it. That is, the system supply should automatically adjust to the demand while at the same time the demand itself changes with the quality of supply,
- (2) it handles short-haul transport networks,
- (3) it considers uncertainty in travel demand forecasts,
- (4) it accounts for an analysis period rather than designing for a specific year,
- (5) it permits flexibility in using different vehicle sizes for different city-pair markets, and
- (6) it is flexible enough to be applied to air as well as ground public transport systems.

1.3 The Approach

A set of system design parameters are first selected to represent the design optimization variables. These include technological, operational, and policy variables such as: vehicle speed, vehicle size(s), frequency of service, and fare structure. Travel demand models based on a disaggregate behavioral approach are structured in terms of these variables and are calibrated using travel survey data gathered from the heavily traveled intercity network in Canada which extends from Quebec City to Windsor.

System supply and performance measures are determined throughout a specified study or analysis period and are expressed in terms of the system design optimization variables. Expressing both the system supply and demand in terms of the same set of design variables permits their interaction explicitly and ensures achievement of equilibrium between supply and demand.

System cost components are identified. Cost estimating relationships for both short-haul air (STOL) and rail modes are developed and the optimization variables are included as well. Through optimization of an objective function combining the system costs and revenues over the entire length of the analysis period, the optimal values of the design variables are obtained. Also,

the corresponding values of the system travel demands, supply and performance measures, system costs and revenues throughout the study period are determined.

Uncertainty in system travel demand estimates are treated through sampling a probability distribution of the system's travel market share.

The design and evaluation model reported in this thesis has the capability of handling short-haul transport networks* and it has been generalized to permit flexibility and applicability to different common carrier modes of travel.

The design optimization model is implemented in the form of a computerized method. Input data used in the computer program are maintained in parametric form to provide flexibility in input variation and to permit conducting sensitivity analyses. The different components of the model system are programmed in separate subprograms to allow for more flexibility in modifying or replacing any of these components, if desired, with minimal programming effort.

The workability and usefulness of the methodology are demonstrated by means of applying it to two case studies involving STOL and Improved Passenger Rail systems with reference to the network composed of the heavily traveled links connecting Toronto, Ottawa, and Montreal.

1.4 Thesis Organization

The thesis consists of ten chapters. In Chapter 2, existing design methods are reviewed and the framework of the system design optimization model is presented. In Chapter 3, travel demand models are structured, and their calibration is presented. In Chapter 4, the system supply and performance measures are derived. Chapter 5 discusses the various system cost components and system revenues, and presents cost estimating relationships for both air

* An example of the type of system network considered here is the one connecting the cities of Toronto, Ottawa, and Montreal; where the length of the network link ranges from about 100 miles to 335 miles.

(STOL) and rail systems. In Chapter 6, system design optimization criteria are discussed, and the objective function is formulated. A method of handling uncertainty in the system travel demand is described. The search technique used for optimization is also outlined. Chapter 7 contains description of the characteristics of future activity and available transport systems within the corridor used, as an example, in order to illustrate the application of the model. Chapter 8 presents a STOL system design optimization as a case study. Chapter 9 reports on another case study involving a high speed passenger rail system. Finally, in Chapter 10, the highlights of the investigation and some concluding remarks are presented.

CHAPTER 2

THE FRAMEWORK OF THE SYSTEM DESIGN OPTIMIZATION MODEL

2.1 Review of Existing Design Methods and Their Deficiencies

Present methods of designing or optimizing the design of passenger transport systems are simplified and suffer from a number of deficiencies. One such deficiency is the assumption that the demand for the system is independent of the quality of its supply (design). It would seem unrealistic to design the transport system under the assumption that its travel demand is guaranteed to be a certain quantity no matter how attractive or unattractive the supply is to travelers. Another shortcoming is the unaccountability for uncertainty in future demand forecasts. Prediction of demand for a transport system involves uncertainty because it is not possible to forecast exactly the behavior of the traveling public with respect to trip making. Treating the demand as uncertain is desirable. A third weakness is the limitation of current design methods to analyzing only single transport links (single city-pairs). Analysis of a network of city-pairs, which is the real-life case, has not been attempted before. A fourth limitation is that present design models are cross-sectional in the sense that the system design is performed for a specified year. Consideration of an analysis period (time horizon) is believed to be more practical and realistic. The present thesis research improves on these deficiencies.

Formal and rational methods do not exist for designing intercity public transportation systems in the context described here. Modeling the performance of a transportation system was originally pursued by Roberts and Soberman⁵ in the form of their development of a vehicle-performance model for highway transport. Inputs to the model include the physical characteristics of the highway route, the volume of goods being carried, and the number and characteristics of the different classes of the highway vehicles. Through volume-speed analysis of the traffic mix and use of a set of empirical operating cost functions, a number of

performance measures are determined. Such measures include travel speeds, delays, operation and maintenance expenses of the vehicles and maintenance expenses of the highway link.

Optimization of transport performance measures similar to those obtained by Roberts and Soberman was attempted by Lago⁶ through exhaustive investigation of possible values (specifications) of some of the input parameters. The cost functions he developed expanded over those used by Roberts and Soberman and covered more cost elements. For each parameter whose optimal value is sought, the cost elements that are likely to be affected by it are identified. The total cost of those elements is to be sequentially computed for a set of trial values of that particular parameter. The value which results in a minimum total cost of these elements is regarded as the optimal value of the parameter.

Although neither of these two highway models is directly related to the research topic explored in this thesis, the overall research goals are somewhat similar. These two models suffer from deficiencies pointed out earlier.

Few attempts have been made during the past few years to develop simplified models for determining the optimal value of one or two of the design variables of a public passenger transport system. Hoffman⁷ investigated, with hypothetical data, the effect of vehicle speed, as a single basic design variable, on part of the cost of a high-speed ground transport link. The optimal value of this variable was derived by setting equal to zero the first derivative of a simplified partial cost function with respect to the speed, and solving for that single unknown. The assumption was made that the demand is a "given annual deterministic quantity" that has nothing to do with the vehicle speed. Full account of the system cost components or revenues was not taken. Simplified empirical formulas were employed for estimating some cost components and rough estimates were used for some others. Because of the very simplified nature of this parametric study, it left out the analysis of the system supply and performance measures (such as travel times, frequencies of service, vehicle departure times, vehicle seating capacity, vehicle fleet size needed, accumulation of passengers and of vehicles in system terminals, etc.).

Snell⁸ developed a simple design optimization model which covered more aspects than did Hoffman's model. In particular, simple system operational measures and user time cost were incorporated in the analysis, and one more design variable, vehicle size, was introduced. The optimal values of the two design parameters were determined by setting equal to zero the first partial derivatives of a simplified total cost function with respect to these two variables and solving simultaneously the resulting two equations for the two unknowns. Snell's model suffers from many limitations, some of these are: 1) the model is only applicable to one pair of identical cities, 2) the unaccountability for the interaction between demand and supply (design); as no demand function was included in the analysis, 3) viewing the demand as a given deterministic quantity flowing uniformly over the entire servicing day, 4) vehicles are dispatched only when they become full and return empty; which is obviously an impractical operating policy, 5) some of the cost functions are highly simplified; and 6) as a result of limitation 2, the method views the single transport link system as being functioning in isolation of any other competing modes. Such a view does not reflect the real-life situation. Because of these limitations, most of which were realized by Snell, and also because of other assumptions made, the model appears to be so much simplified that its use for design or evaluation purposes is questionable.

A method heavily based on random sampling (Monte Carlo simulation) for evaluating new transportation systems was developed by Solomon⁹. It involves generating a huge number of possible departure times for a single transport link, based on a particular combination of vehicle seating capacity and fleet size. The departure times of each trial schedule were assumed to be regularly spaced in time of day. By using random sampling of an assumed independent demand profile and trying each of these generated optional schedules sequentially, the number of "potential" travelers using the system and the operator's revenues are computed. (Fares were assumed to be exogenously specified). No cost functions were, however, developed in the method. The set of departure times

which results in the largest net revenue is to be chosen. A kind of parametric analysis is then performed through varying the values of the above two parameters, vehicle capacity and fleet size, in hope of finding a combination that results in a maximum net revenue (gross revenue minus cost). No optimization methodology of the type explored in this thesis was presented, but rather an exhaustive random sampling and parameter-varying approach was employed.

To forecast the total number of travelers by all modes, a generalized gravity model was proposed in that method. Monte Carlo simulation was again used to estimate the travel market share of the designed mode out of the total demand. In the proposed gravity model, the level of service of the transport system, including the designed mode, was not shown to be a variable affecting the total travel demand between the pair of cities. This modeling approach does not permit the system supply and demand to interact with each other and the demand predicted was, therefore, regarded as "potential" demand which may or may not match what the mode actually carries. In addition to this drawback of non supply-demand interaction nor equilibrium, the use of "potential demand" is likely to impose an obstacle in calibrating such a demand model because calibration data relate in most cases to "observed" or "actual" demands carried by each mode and not to "potential" demands.

In addition to the above deficiencies in this method, the leaning heavily on random sampling for most of the method analyses necessitates furnishing massive amounts of input data to describe the large number of input probability distributions employed. It also makes model calibration difficult. Availability of this kind of data is likely to be a problem. The validity of the simulation approach to predict modal splits has not - at least behaviorally - been demonstrated.

A method for determining values of frequency of service and aircraft size which maximize the return to a STOL operator was developed by Simpson and Neuve-Eglise¹⁰. The method is developed for a single city-pair link with assumed market behavior in terms

of fares and travel times. It requires that STOL passengers have no knowledge of the departures time-table and, accordingly, an average waiting time of one-half the inter-departure time interval can be used to induce changes in the travel demand as the frequency of service is varied. A highly simplified demand function exogenously specified was used for that purpose. Demand predictions (output of the demand function) are not, however, in equilibrium with the actual traffic volumes carried (input to objective function evaluation). This is because the method requires the aircraft size be specified rather than computing it in terms of the predicted demand and the selected frequency of service along the link. The objective function optimized was the difference between fare revenues and the variable portion of the carrier's operating cost. Fares were assumed to be given and a simple two-term linear expression was hypothesized for the variable operating cost. The optimal aircraft size can, according to this method, be found by plotting the values of the objective function for a number of trial aircraft sizes.

The method appears to be suited for analyzing, in a simplified manner, the sensitivity of the return to a STOL operator to changes in frequency of service or aircraft size along a single city-pair air link. Because of its short-term scope, the method is not addressed to the task of sizing the system supply (e.g. fleet size(s) determination, accumulation of vehicles and of passengers in the system terminals, terminal space requirements, etc.). Nor does it take full or detailed account of the financial implications (particularly, the various system cost components) of the tested STOL frequency of service and/or seating capacity options. No demand models were developed in this method, nor was the relationship between demand and supply realistically treated. Furthermore, the method can only be used for analyzing one single transport link.

The author's previous work¹¹ in this area dealt with system design optimization for a single transportation link. It recognized the interdependence between supply and demand and treated the demand as an explicit function of the system design variables. Aspects of

intermodal competition and fluctuation over time of day of intercity traffic flow were considered. System cost estimation included all the relevant components of the system. The optimal system design was obtained by minimizing the total system cost (including users cost) per passenger-mile over the vehicle speed and seating capacity. Other optimization viewpoints were also tested. Part of the work involved application of the model to the design of a Montreal-Toronto STOL system. The model is yet limited to the analysis of one pair of cities, and the system design is cross-sectional (i.e., based on the conditions in a given target year). Deterministic travel demands were used in the analysis. Here, extensions were made to handling simple transport networks, to elaborate treatment of system supply-demand interaction, to development of more reliable demand functions, to accounting for uncertainty in demand forecasts, and to extending the system design to cover a time horizon (analysis period). These extensions are incorporated in the present thesis research.

2.2 The Framework of the System Design Optimization Model

The basic components of the system design optimization model are illustrated in Figure (2.1), and are briefly described below.

System Design Objectives:-

In designing a public transport system a major goal is to achieve the maximum possible economic efficiency of the system. That is, the main design objective is to optimize the level of transport service such that the economic viability of the system (e.g. present worth of fare revenue less total cost) is maximized.

The specific system cost components which are included in the objective function depend on whether the system is already in existence (i.e. to be improved) or is yet to be introduced. They also depend on the particular optimization criterion being adopted. For example, a transport carrier operating an existing system might be interested in knowing the economic

FIGURE (2.1) - FRAMEWORK OF THE SYSTEM DESIGN OPTIMIZATION MODEL

implications (primarily profit) of changing any or a combination of the system supply factors such as: introducing faster vehicles, using vehicles of different seating capacity, altering the frequency of service along a route or set of routes, or changing the fare structure, etc. In such a case the carrier's objective would be the maximization of the net profit (i.e. gross revenues less those cost elements incurred by the operator).

The methodology presented here for optimizing the system design is based on the broader viewpoint which implicitly includes that of the system operator. In other words, all the system costs, whether or not incurred by the system carrier, are considered.

The objective of maximizing the system economic efficiency (or viability) can mostly be achieved through the design of the system by determining the optimal values of a basic set of variables which largely govern the design. In addition to affecting directly and indirectly the system costs, such variables have a major impact on the system ridership and hence the accrued benefits and revenues.

Optimization Criteria:

The design optimization methodology is developed with the intention that it would permit testing different optimization criteria which may include total (or partial) system cost, fare revenue, and users' cost. A measure of the economic viability of a transportation system is its ability to earn sufficient revenues to recover its total cost and return a profit (if possible). An optimization objective function based on the economic viability criterion can be formulated to be the maximization of the net present worth (revenues less total cost), computed over the entire study period. This criterion has been typically used in optimization and/or evaluation of public transport systems on the basis of their costs and revenues^{2,3,9,12}.

Other objective functions representing different optimization criteria could, of course, be formulated and tested using this design optimization methodology. An alternative criterion can be stated as the minimization of the system unit

cost (i.e. cost per revenue passenger-mile). Users' cost may also be included in this unit cost. Maximization of the (benefit/cost) ratio has also been employed in comparing transportation alternatives.¹

The results of the two example applications of the design optimization model which are documented in Chapters 8 and 9 are based on the economic viability criterion described above (i.e. maximization of the present worth of system net revenue). Sensitivity of the model to another optimization criterion (minimization of system unit cost) is also presented.

Selection and Value Specification of the System Design Optimization Variables:

Based on the stated design optimization objective, a set of system design variables are selected to be the optimization independent variables. The search for the optimal system design is carried out over such variables. Candidate system design variables include: vehicle-related parameters such as vehicle speed and seating capacity; supply and operational variables such as vehicle fleet size and frequency of service; and a pricing policy variable (fare structure). Such variables have significant influence (relative to other possible variables) on the system demand, supply, costs, and revenues. Some of these variables could, however, be expressed in terms of others and need not, therefore, be treated as optimization variables. For example, the number of unique (same seating capacity) vehicles needed (i.e. fleet size) can be determined by knowing the vehicle speed and frequency of service. Similarly, for a certain vehicle dispatching policy and demand profile, either the vehicle size or the frequency of service may be treated as an optimization variable, since one of them determines the other. The above list of system variables can thus be reduced to a smaller set of "basic" or "primary" system design variables.

The choice of a set of basic design optimization variables depends also on the transport system being considered. For example,

in designing a STOL system, the seating capacity of the aircraft is a significant design variable, whereas for passenger rail, the car size may not be since it is fairly standard. The number of cars in the train may, however, be considered instead as a design optimization variable. By the same token, in designing a rail system which involves improvement of existing tracks and use of high speed trains, a relevant design optimization variable may be taken as a discrete variable representing possible track improvement alternatives. In essence, this is a typical case where the design optimization methodology could be applied directly to evaluate different transport system alternatives.

In order to proceed with the system design, initial feasible values must be specified for the design optimization variables. Such specification could be based on experience. The function of the search algorithm is to keep on altering these values in an attempt to improve as much as possible the objective function. Improvement of the objective function means here maximizing the attainment of the design objective (e.g. maximizing the system economic viability). Upon successful termination of the search procedure the final or "optimal" value specifications of the design variables are obtained.

Prediction of System Travel Demands:

Upon selection of the set of design optimization variables and specification of their values, the passenger volumes expected to be flowing on each of the system links, throughout a specified analysis period, must be estimated in order to design the system. Demand models structured in terms of these design optimization variables are developed here for this purpose. The demand for travel between any pair of cities on a particular mode is based upon the level of service characteristics of that mode and all its competitors, as well as on the socio-economic characteristics of cities between which travel is being predicted. A common carrier demand model is structured and calibrated to estimate the total demand for travel by all the public modes between each two cities. A multinomial logit model is also developed and calibrated to

predict the percentage share of each of the system's service links out of each city-pair's total travel demand. The effect of user characteristics on demand for travel is accounted for through inclusion of user attributes as explicit variables in these demand models. Separate demand models are structured and calibrated for different trip purposes. In addition to the likelihood of providing a more accurate and more responsive travel forecasting procedure, inclusion of user attributes in predicting travel demand and stratifying the demand by trip purpose are made here for two other main reasons. Firstly, it is believed that the rate of making trips and the travel mode chosen for the trip are both affected by the characteristics of the user and by the purpose of his trip. Secondly, this disaggregation procedure allows more flexibility in formulating objective functions which include users' cost, since the cost to a user is likely to be affected by his attributes (e.g. income) as well as by the purpose of his trip.

Input information required to estimate the system demand as modeled here include:

- (1) the socio-economic characteristics within each city (population, employment, income)
- (2) level of service characteristics of the system and of all other travel alternatives between each two cities (total (door-to-door) travel times and costs and service frequencies), and
- (3) service network configuration of the system to be designed.

The total system travel time is computed in terms of the vehicle speed, which is a basic design optimization variable. Total system travel cost is also based on the fare structure which is another optimization variable. Average access and egress times and costs are determined exogenously for each city.

In the case of treating the vehicle size as a design optimization variable and leaving the frequency of service to be determined accordingly, an initial value of the latter is to be assumed in the demand functions. This is because of the dependence

of the required frequency of service on the "as yet undetermined" travel demand. The appropriate value of this variable is calculated within the next step of the methodology "Supply and Operational Measures" and is fed back into the present step of demand prediction. Such an iterative process continues until both the demand and supply are determined on the basis of the same value of frequency of service (supply-demand equilibrium). This iterative procedure is expected to converge rapidly to the equilibrium point because the demand-frequency relationship typically exhibits a diminishing marginal return property.

Determination of the Required Level of System Supply:

The above step of the design model yields estimates of the number of passengers flowing between each origin-destination via each of the system links during a given time period (e.g. day) and throughout the analysis period. The purpose of the current step is to determine the amount of system supply required to meet the above estimated demand and to compute the associated performance measures. Specifically, given the system's service network, the aim of this phase of the model analysis is to:

- (1) compute travel times along each link,
- (2) construct vehicle departure schedules,
- (3) determine the necessary vehicle seating capacity, if required, and train consist* for rail modes,
- (4) determine the number of vehicles required to service the network (i.e. fleet size), by type (size) of vehicles, and
- (5) compute maximum accumulations of passengers and of vehicles in the system terminals, and hence terminal space required for their accommodation.

All or some of the selected system design optimization variables are used here to determine the supply and operational measures. In addition, these measures are based on the previously estimated travel demands which are in turn based on the design optimization variables.

* number of cars and number of locomotives in the train.

Estimation of the System Economic Consequences:

In order to compare among different value specifications of the design optimization variables the economic consequences associated with each specification must be estimated. Such consequences involve here system costs, revenues, and users' cost.

The total cost of a passenger transport system involves capital investment in fixed facilities (terminals and guideways) and in vehicles, in addition to the cost of operating and maintaining the system which includes components such as: crew, fuel, vehicle maintenance, vehicle servicing, maintenance of fixed facilities, passenger servicing, marketing, insurance, and other general and administrative costs. Cost estimating relationships are developed in this thesis for the various system cost components in terms of the system design optimization variables and unit cost information. Some of these components are common to all modes while others are mode-specific. For those cost elements which are mode-dependent, the modeling effort is focused here on short-haul air and improved rail systems, which are of major concern at the present time.

System costs relating to social or environmental impacts are not discussed here because, in addition to being very difficult to monetize, they show very little, if any, correlation with the system design optimization variables. That is, such impacts are not expected to significantly alter the specification of the optimal design of the system being considered.

System revenues are assumed to be drawn from fare-paying passengers. Additional revenues which may be derived from other services such as mail or parcel services are not considered in the analysis.

Annual cost and revenue flows are evaluated throughout the selected analysis period and discounted back to a common base year. This procedure is believed to be realistic and desirable. Accounting for all the system costs and revenues over a study period rather than considering just one single year ensures a more reliable assessment of the economic viability of the system. A system operating in loss in its initial service years may show an overall net profit when a time profile of costs and revenues is analyzed.

Based on the criterion used for optimization, the overall worth of a particular system design (i.e. value specification of the design optimization variables) may also be assessed from the viewpoint of reducing users' cost. Users' cost could be expressed here in the form of travel time cost and out-of-pocket travel cost. (Other user impacts are not generally easy to quantify or express in dollar terms). A value of travel time is therefore required to monetize the time spent traveling. An imputed value of travel time is obtainable from the set of disaggregated demand models calibrated in this project. This value is expressed in terms of the user's income and the purpose of his trip.

Formulation of a measure to assess the system economic consequences is described in the next activity of the design optimization methodology.

Evaluation of Objective Function:

The objective function structured earlier on the basis of the stated design objective and optimization criterion can now be evaluated by estimating the system revenues and cost components included in it. All cash flows are inflated to the year in which they occur and then discounted back to a selected base year using assumed inflation and discount rates. This procedure (present worth method) reduces the flow of revenues and costs to an equivalent amount of money at the base year and permits proper comparison among candidate optimal values for the system design optimization variables.

Incorporation of Demand Uncertainty in Objective Function Evaluation:

The demand for travel by a transport mode depends upon the perception of travelers to its service characteristics. This perception cannot be modeled with certainty, particularly in situations involving new modes or improvement of existing transport systems. It is, therefore, desirable to treat the travel demand as uncertain.

Two approaches are proposed here to incorporate this feature into the model analysis. The first approach requires furnishing probability distributions for the perception coefficients involved in the set of demand functions used. These distributions are randomly sampled whereby a drawn set of values of such coefficients defines a probable demand state and an associated probability of occurrence. In the second approach a probable range of variation in the level of the system travel market share (as predicted by the demand model) is specified. The specification of this range could be based on previous experience or perhaps on the basis of the accuracies (confidence intervals) associated with the demand models employed. Associated with each possible market share value within this range (i.e. demand state) is a probability of occurrence. The distribution of probabilities over this range could be assumed bell-shaped (normally distributed) or, simply, triangular.

The first approach requires defining a rather large number of probability distributions especially if the demand models are of the disaggregate type. Data required to define these distributions are likely to be difficult to obtain, and one might inevitably assume arbitrary distributions. This approach is also time-consuming. The other approach, which is adopted in the design model, is, however, simpler, much less time-consuming, and requires no specific data.

The "expected" value of the objective function can thus be computed by evaluating it for a number of possible demand states, each of which is assigned a certain probability of occurrence defined by the above probability distribution. Symbolically, let $Z = f(d_i; x_1, x_2, \dots, x_n)$ represent the value of the objective function for a possible demand state d_i ($i=1, 2, \dots, m$) and a candidate value combination of the system design optimization variables $x_1, x_2, \dots, x_n$. Let also $p(d_i)$ denote the probability of occurrence of the demand state d_i . The expected value of the objective function corresponding to this combination can thus be written as:

$$E[Z|x] = \sum_{i=1}^m f(d_i; x_1, x_2, \dots, x_n) \cdot p(d_i) \quad \dots(2.1)$$

Expression (2.1) is evaluated over feasible or candidate combinations of $x_1, x_2, \dots, x_n$ to search for an optimum.

Optimization of Objective Function:

The search for the optimal values of the system design optimization variables is carried out over the "expected" values of the objective function, as determined above. A direct search method (e.g. Pattern Search technique) is best suited for the particular design optimization problem explored here because of its large size (a macro design model) whereby a large number of different kinds of relationships are involved. Also, it is very difficult, if not impossible, in this design methodology to provide analytical functions for the derivatives needed in a gradient or derivative optimization technique.

The direct search method deals directly with the objective function and does not require its regularity or continuity, nor the existence of its derivatives. The basic scheme is to evaluate the objective function at a series of points which form a carefully directed search pattern across the feasible region of the function. Detailed description of the method is presented in Chapter 6.

The Optimal System Design:

Upon successful termination of the optimization search procedure, the optimal values of the system design variables are determined together with the optimal value of the objective function. All other components of the system design are then specified as a result; as they have so far been expressed in terms of the system design optimization variables. These components are determined for every year (or number of years) throughout the study period (and for each probable system demand state) and include:

- (1) system travel demand, broken down by link and trip purpose
- (2) design traffic volumes on each of the system links
- (3) distribution of vehicle departures over the servicing day for each of the system links (routes)
- (4) required vehicle seating capacity* and train consist

* if not treated as a design optimization variable.

- (5) required number of vehicles (fleet size) by type (size)
- (6) vehicle loading factors and daily utilization
- (7) maximum passenger and vehicle accumulations in terminals, and hence terminal space required
- (8) system costs broken down by components, system revenue, net revenue (or deficit), and users cost
- (9) "expected" values of the system economic measures (and patronage), computed over the entire length of the analysis period and expressed in present worth. These include:

- (a) total capital recovery payments
- (b) total operating costs
- (c) total fare revenues
- (d) total users' cost
- (e) total passengers carried
- (f) total passenger-miles
- (g) overall system unit cost (cost/passenger-mile)
- (h) overall net revenue (or deficit)

Other outputs of the model include the travel market share of each of the competing systems in any given year. This information is provided on a city-pair basis and for each trip purpose.

Sensitivity Analyses:

Since exogenous data information as well as specific assumptions are to be specified as inputs to the design optimization model, it is desirable to test the outcome of the model, which is the optimal system design, to variations in these data and to making different assumptions. Chapters 8 and 9 contain sensitivity analyses with respect to some of the key factors involved in determining the optimal design of a STOL and an Improved Rail system.

2.3 Use of the Methodology

If the objective is to use this methodology for determining the optimal design of a given transport system (or set of systems combined), the methodology framework which has just been outlined

describes how this objective could be achieved. In situations where this method is used as a tool for selecting among a number of alternative systems, the same design optimization procedure is to be applied sequentially to each of the candidate systems. The alternatives could then be compared on the basis of their maximized economic viabilities in addition, of course, to their associated socio-environmental impacts. There will be no need to re-optimize the design of the "selected" system in this case as it has already been done within the process of selecting among the candidate alternatives.

The following five Chapters describe in detail the activities and operations involved in the basic analysis steps of the system design optimization methodology.

CHAPTER 3

MODELING THE SYSTEM TRAVEL DEMAND

The main purpose of this Chapter is to structure and calibrate a set of models for estimating the travel demand for the system whose optimal design is sought. A requirement for the model is that it predicts, with acceptable degree of accuracy, changes in the system demand due to selection of different values for the design optimization variables. In the following section present demand modeling capabilities are reviewed with the aim of identifying a modeling approach which leads to an accurate and responsive travel forecasting procedure.

3.1 Brief Review of Travel Demand Modeling Approaches

Historically, most of the work in demand modeling has been done in connection with urban travel. The traditional urban transportation planning process involves four phases of travel forecasting: trip generation, trip distribution, modal split, and network assignment. In intercity travel, the first three steps can, however, be combined into two: volume of trips generated between each pair of cities, and modal split. Present demand forecasting methodologies, particularly for intercity travel, can be classified into two main types: one-step (or direct) demand modeling and two-step demand modeling. Models of the first type attempt to forecast directly the number of trips between each pair of cities (or zones) by each travel mode through the use of one equation (model). In the second procedure, the total number of trips generated between a given pair of cities is modeled first, and then split among the available travel alternatives competing for that city-pair market.

Either of these two approaches is based on the hypothesis that the demand for travel by a given mode does not depend on the mode itself (e.g. air, rail, bus, auto) but rather on the set of level of service attributes (abstract characteristics) associated with this mode as well as with other competing modes. This postulate is

in effect an application of the Lancaster theory¹³ which states that consumer utility is derived from the properties or characteristics of the goods rather than from the goods themselves.

Direct (one-step) Demand Models:

In most of these models, the demand estimating equation typically has as a dependent variable, the number of trips made between two cities per unit time by a particular mode, and as independent variables the level of service attributes of that mode and of the other competing modes along with the socio-economic characteristics within the two cities, raised to certain powers and in product form. Examples of these models include those of Baumol-Quandt¹⁴, and Kraft-SARC¹⁵. Several other formulations based on these initial models have also been produced. The Baumol-Quandt and Kraft-SARC models were developed for predicting intercity travel in connection with the U.S. Northeast Corridor Transportation studies and are given below.

Kraft-SARC Model:

$$T_{ijm} = \alpha_{mo} \cdot (P_i P_j)^{\alpha_{m1}} \cdot (Y_i Y_j)^{\alpha_{m2}} \cdot (t_{ijm}^{\beta_{m1}} \cdot C_{ijm}^{\beta_{m2}}) \cdot \prod_{r \neq m} (t_{ijr}^{\beta_{r1}} \cdot C_{ijr}^{\beta_{r2}}) \dots (3.1)$$

Baumol-Quandt Model:

$$T_{ijm} = \alpha_o \cdot (P_i P_j)^{\alpha_1} \cdot (Y_i Y_j)^{\alpha_2} \cdot (t_{ij}^*)^{\beta_1} \cdot (C_{ij}^*)^{\beta_2} \cdot (F_{ij}^*)^{\beta_3} \cdot \left(\frac{t_{ijm}}{t_{ij}^*}\right)^{\beta_4} \cdot \left(\frac{C_{ijm}}{C_{ij}^*}\right)^{\beta_5} \cdot \left(\frac{F_{ijm}}{F_{ij}^*}\right)^{\beta_6} \dots (3.2)$$

where

T_{ijm} = number of round trips originating in city i and destined to city j via mode m, per unit time

P_i, P_j = populations of city i and city j, respectively

[†] SARC = Systems Analysis and Research Corporation (U.S.A.)

Y_i, Y_j = per capita income in city i and in city j, respectively

t_{ijm} = the one-way travel time between cities i and j via mode m

C_{ijm} = the one-way travel cost between cities i and j via mode m

F_{ijm} = the one-way departure frequency between cities i and j via mode m

t_{ijr}, C_{ijr} are similar to t_{ijm} and C_{ijm} except that they pertain to a competing mode r

t_{ij}^* = best (shortest) one-way travel time between cities i and j

C_{ij}^* = best (cheapest) one-way travel cost between cities i and j

F_{ij}^* = best (highest) one-way departure frequency between cities i and j

the α 's and β 's are constants to be estimated by calibration.

Calibration of these models is usually done by transforming the demand equation to a linear form through taking natural logarithms of both sides, and then applying a least squares regression using a sample set of data.

Because this approach attempts to circumvent the traditional sequential modeling procedure by combining the generation of trips between each pair of cities (zones) with the modal split in one step, too many independent variables are included in a single equation. Most of these variables, particularly the level of service variables, are highly intercorrelated. As a result, this form of model presents considerable problems in estimating the coefficients in the demand equation due to the severe multicollinearity that exists among the variables[†]. Quite often, magnitudes and/or signs of these coefficients that are obtained

[†] An example of a downtown work trips model developed by Talvitie¹⁶, which is essentially a modified version of the Kraft-SARC model, is shown to include some 35 coefficients to be estimated.

by calibration were not plausible. Attempts to overcome this drawback have been made through fixing the signs of the coefficients, and sometimes the magnitudes of some of them as well so that these appear in regression equations "as would be expected", and then performing least squares regression analysis. It should be noted, however, that this procedure of imposing constraints within the regression analysis detracts from the goodness-of-fit of the equation, and, hence, poor demand predictions are likely to be obtained by using such models. It has in fact been revealed that current applications of this type of model have not been conspicuously successful, and that the use of the Kraft-SARC and Baumol-Quandt models in the U.S. Northeast Corridor Transportation Project (NECTP) studies yielded forecasts that were considered to be implausible¹⁷. The Baumol-Quandt model given by equation (3.2) suffers from an additional drawback. A change in any of the level of service variables of a mode other than that of "best" mode is not allowed by that model to have any effect on the demand for any of the other systems. This cannot be regarded as realistic.

Two-step Demand Models:

The first step in the two-step modeling approach involves estimation of the number of trips generated per unit time between each pair of cities. An equation similar in form to that of the direct demand model is used except that the level of service variables of the individual modes are replaced here by a much smaller set of variables reflecting the combined level of service of all the modes serving a city-pair. The second step is concerned with splitting this total travel demand among the available travel alternatives (modes). The wealth of literature on travel demand modeling contains an enormous number of modal split models which vary quite considerably in structure and sophistication.

Examples of the two-step models include those of the Canadian Transport Commission (CTC)², and McLynn¹⁸ whose formulations are given by equations (3.3), (3.4), and (3.5). As can be seen from these formulations, the CTC modal split model is essentially of the same structure as that of McLynn.

McLynn Model:

$$\frac{T_{ijm}}{\sum_k T_{ijk}} = \frac{a_{mo} \cdot (t_{ijm}^{a_1} \cdot C_{ijm}^{a_2} \cdot F_{ijm}^{a_3})}{\sum_k a_{ko} \cdot (t_{ijk}^{a_1} \cdot C_{ijk}^{a_2} \cdot F_{ijk}^{a_3})} \quad m \in k \quad \dots (3.3)$$

CTC Model:

$$ms_m = \frac{w_{ijm}}{\sum_k w_{ijk}} = \frac{a_{mo} \cdot [t_{ijm}^{a_1} \cdot C_{ijm}^{a_2} \cdot \exp(a_3/F_{ijm})]}{\sum_k a_{ko} \cdot [t_{ijk}^{a_1} \cdot C_{ijk}^{a_2} \cdot \exp(a_3/F_{ijk})]} \quad m \in k \quad \dots (3.4)$$

$$T_{ij} = a_o \cdot P_i \cdot P_j^{a_1} \cdot \exp(a_2/r_i) \cdot g_{ij}^{a_3} \cdot \exp[a_4(D_{ij} - t_{ij})] \cdot (C_{ij} - P_{ij})^{a_5} \cdot (\sum_k w_{ijk})^{a_6} \quad \dots (3.5)$$

where

ms_m = modal split (market share) for mode m

w_{ijk} = a measure of the level of service offered by mode k between cities i and j

T_{ij} = number of trips from city i to city j by all common carrier modes per unit time

r_i = fraction of families in city i with annual income greater than \$12,000.

g_{ij} = index for language interaction between cities i and j ($0 \leq g_{ij} \leq 1$)

D_{ij} = highway driving time (center to center)

P_{ij} = perceived cost of automobile

t_{ij} and C_{ij} = average total trip time and trip cost by common carrier weighted according to the modal split, respectively

The rest of the notations are as defined for equations (3.1) and (3.2).

Application of this type of model has been successful. It was pointed by Stopher¹⁷ that the McLynn model, which is concerned with modal split alone, was more successful than the Kraft-SARC or Baumol-Quandt models and was adopted as the modal split model in the NECTP.

In view of the operational problems associated with the direct (one-step) demand approach and the structural flexibility and ease of operation of the two-step procedure, the latter approach is preferred. Present models of the two-step demand modeling approach are, however, deficient in terms of their behavioral basis and accuracy. For instance, two factors that have significant influence on travel demand are absent from the models presented above: the attributes of the user and the purpose of his trip.

In this preferred procedure, the basic approach of modeling the total travel demand in terms of the socio-economic characteristics within each city and an aggregate measure of the level of transport service, is plausible. Disaggregation with respect to trip purpose would seem, however, to be desirable in order to obtain more reliable demand forecasts.

With regards to the modal split (market share) modeling, it would seem desirable to make use of recent developments in this area. Most modal split models have been developed for urban travel with the typical objective of splitting traffic between automobile and transit. In the context of intercity travel, a number of model types exist and are outlined below.

One type of model¹⁹ uses attitudinal studies²⁰. One among a number of significant problems hindering the usefulness of the attitudinal data is the difference between what the consumers say they would like to do and what they actually do. Modern economic analysis is based on the concept of revealed preferences²¹. That is, the preferences of an individual are inferred from his actual choices when confronted with a number of alternatives in the market place²¹.

Another class of mode choice models uses Monte Carlo simulation to sample the travelers' attributes in order to simulate their choice of mode²². Each traveler is considered individually. A generalized cost function is computed for each mode available to a sampled traveler based on his randomly drawn attributes. The traveler is assumed to choose the mode offering the lowest generalized cost. Although the method is of an appealing disaggregate nature, yet, the use of the simulation approach to predict modal split is limited because of at least four reasons. Firstly, this modeling approach does not seem to have a sound behavioral basis. Secondly, a substantial amount of data is required to describe the input probability distributions employed in the simulation analysis. Such data are not likely to be available. Thirdly, calibration of these simulation models does not appear to be easy nor reliable. Lastly, simulation of all traveling individuals, particularly in a network context and if large passenger volumes are involved, is clearly computationally inefficient.

A third type of demand model^{23,24,25} employs the technique of linear graph theory, which is used to solve electrical networks, to model the traffic flows over the arcs of an intercity transport network. These models are founded on a doubtful hypothesis which requires the flow of passengers (or commodities) over the links of a network to follow the same pattern that would result from electric current flow in the arcs of an analogous electrical network. There is no practical evidence to support this postulate. Human behavior with regard to travel decisions need not follow the rigid physical laws of electricity. Some of the key variables in the method are not quite conceptually understood in the context of travel demand. This is an expected result of such a compelled analogy. In addition, computation times associated with models of this type appear to be quite substantial.

A recent approach to demand modeling has been directed towards development of what is being termed as "disaggregate behavioral" demand models. Most of the attempts that have been made are, however, concerned with predicting mode choice for urban travel. The models are termed "disaggregate" in the sense that they consider the individual traveler rather than the traffic zone, as in conventional urban transportation planning. They are, however,

of an "aggregate" nature because a single set of parameters is to be determined by calibration to describe a particular group of the population. They are also referred to as "behavioral" because they simulate the decision made by the individual traveler when confronted with alternative travel choices. A list of such models can be found elsewhere²⁶. It is being claimed²⁶ that this approach has the greatest likelihood of providing the basis for a more reliable and more policy-responsive travel forecasting procedure. It was also reported²⁶ that application of this approach in the United States in studies carried out by various State governments was successful.

3.2 A Preferred Approach to Modeling Intercity Travel Demand

In order to design the transport system, its market share should be predicted first. In reviewing the available approaches to demand modeling in the previous section, it was concluded that a two-step disaggregate approach is preferred. Once the attributes of a traveler (e.g. income) and the purpose of his trip are identified, one can identify the travel mode which he is likely to choose. For instance, experience shows that persons with high incomes attach less importance to travel fare, place more weight on travel time savings and, as a result, mostly travel by air. The advantage of air over ground modes is the shorter travel time. Experience also shows that business travelers choose to travel by air most of the time despite the higher fares of air relative to rail or bus. These observations are evident from Figures (3.2) and (3.3) which show results of an intercity travel survey. Details are discussed in a later part of this Chapter. The Figures also indicate a significant difference in the modal split pattern for business and non-business travel. Thus, if a Short Take Off and Landing air system, for example, is being considered here for design, most of its travelers are expected to be with high incomes and traveling on business. Consequently, model disaggregation with respect to user attributes and trip purpose is likely to lead to more reliable travel demand forecasts.

The implications of the above choice behavior to building a modal choice model to forecast the market share of the system being designed is to adopt a disaggregate behavioral approach. Such an approach allows the trip purpose as well as the system's and travelers' attributes to be considered in predicting the system's share out of the travel market. Changes in the travelers' attributes and/or the level of service characteristics of the travel modes are expected in this approach to realistically alter the split of traffic among them (modal split). This approach is believed to give realistic and more reliable estimates of travel demands. It has in fact been shown that the disaggregate behavioral approach is very much consistent with the theory of individual utility maximization²¹. To a large extent, this approach is also consistent with the system design methodology framework, and is, therefore, adopted here to structure an intercity modal choice model based on the theory of consumer choice.

A disaggregate total demand model is also structured here in which the total travel demand (by all modes) between each pair of cities is modeled as a function of a set of independent variables describing the socio-economic characteristics within the two cities and the composite level of service of all the modes (or routes) connecting them, each weighted by its market share (%). This modeling approach describes, therefore, the "causal" relationship between socio-economic and transport system characteristics, on the one hand, and trip making on the other. The share of the designed system out of an intercity total demand can thus be obtained by multiplying its market share (%) by the intercity total demand and summing up this product over all user groups and all trip purposes.

In order to simplify the modeling effort, the option of traveling by automobile and its effect on the common carrier

demand are not accounted for. Many reasons can be provided. Firstly, the type of service provided by the automobile is distinctly different from that of any of the common carrier modes: air, rail, or bus. The automobile user has instant accessibility to his car and enjoys a great deal of freedom of movement at the origin as well as the destination end of his journey. The privacy of the car and its convenience for family travel are other aspects of its unique service. Secondly, there is a significant lack of data on intercity volumes by car and on party size. Thirdly, trial calibration runs of the total demand model developed here showed that inclusion of the automobile results in poor statistical significance and distortions of the estimated parameters due to severe collinearities among the car and common carrier attributes. Finally, the concern here is, above all, on estimating the demand share for a particular public transport system as a first step in its design process.

It is recognized, however, that improving the level of service of an intercity common carrier mode (e.g. introducing a STOL system, or improving a passenger rail system) is likely to induce some of the intercity automobile travelers to switch to that mode. The motivations for this modal shift may include such factors as: reduction in intercity trip time, increased common carrier frequency of service, and/or relatively increasing cost of driving (e.g. fuel costs). Improvement or optimal specification of the level of transport service has, indeed, been defined here to include either or all of these three factors. Obviously, the automobile is much superior to any of the common carrier modes with regard to frequency of service as the car user enjoys instant accessibility to his car. As regards travel time, experience shows that the flexibility provided by the automobile within the urban centers can outweigh the lack of speed on the intercity part of the journey. The effect of the last factor, which concerns increases in fuel prices for motorists, is reflected in

current improvements in automobile fuel consumption and maintenance requirements on the part of the car manufacturers. National surveys carried out in the United States confirmed this trend and indicated also that people did not move away from relying on the car as a result of increased fuel prices, but rather adjusted their driving behavior (e.g. make less automobile trips) to conserve gasoline²⁷. It is therefore concluded that the above factors tend to balance out and that the simplification made here of leaving out the effect of the automobile in predicting the demand for the designed system does not appear to be at all unreasonable.

However, the system design optimization methodology is developed in such a way that the demand prediction portion of it can be easily modified to include alternate demand functions. It is in effect possible for the user of this optimization model to experiment with modal splits in which he could impose assumptions about marginal gains or losses of private cars to the common carrier system.

3.3 Development of a Multinomial Logit Model of Mode Choice

3.3.1 Conceptual and Analytical Structure of the Model

Because intercity travel by public modes commonly involves more than two modes, and because the design methodology is intended to analyze a network of cities, a choice among more than two travel alternatives is likely to exist. An examination of actual modal splits on a number of intercity links [as illustrated in Figures (3.2) and (3.3)] suggests that a multiple choice situation prevails*. A travel alternative is defined here as a modal service link or route between two cities. There may be more than one such alternative belonging to the same mode between the same city-pair.

* Long-distance intercity travel whereby modal competition is limited is not dealt with here.

The concept of "generalized travel cost" is derived from the notion that trip making has a number of characteristics which are unpleasant to the trip maker and that the perceived magnitude of this unpleasantness depends on his socio-economic characteristics as well as on the purpose of his trip²⁸. The generalized travel cost has sometimes been referred to in the literature as "travel disutility", "travel impedance", or "travel resistance". The generalized cost G_i of traveling by alternative i for a given trip purpose can be written as:

$$G_i = f(\underline{L}_i, \underline{U}) \quad \dots\dots (3.6)$$

where $\underline{L}_i$ and $\underline{U}$ are vectors representing the attributes of alternative i (service characteristics) and the attributes of the user (socio-economics), respectively.

The basic rationale of modal split is that travelers, either individually or in groups, make rational choices among the travel alternatives available to them on the basis of their perception of the generalized cost associated with each alternative for a given destination and purpose of their trip. One way of introducing the effect of the trip purpose on the choice of travel alternative is to estimate different choice models for different trip purposes (e.g. business and non-business).

The service characteristics used in modeling travel demands include factors such as: travel time, travel cost, service availability (service frequency), discomfort, etc., provided that these factors can be quantified. The user attributes may include such factors as income, age, occupation, etc. Disaggregation of the potential travelers into groups with homogeneous characteristics is expected to enhance the accuracy of the demand models.

It is commonly assumed that the generalized travel cost associated with an alternative is derived from its service attributes in a linear additive form. That is

$$G_i = a_1 L_{i1} + a_2 L_{i2} + \dots + a_n L_{in} + b_i \quad \dots (3.7)$$

where

- L_{ij} = level (magnitude) of a quantifiable attribute j (e.g. travel time, travel cost, service availability) of alternative i
- a_j = a perception coefficient which reflects the weight placed by the traveler on a quantifiable attribute j , for a given trip purpose
- b_i = a modal term which reflects the combined relative disutility of the non-quantifiable attributes (e.g. discomfort) of alternative i , for a given trip purpose. It is sometimes described as a reflection of users' attitude (bias) towards travel mode i relative to a particular mode.
- n = number of the quantifiable attributes used.

An assumption made in the above generalized cost formulation is that the perception coefficients of the travel attributes (the a_j 's) are assumed to be mode-independent (abstract) while the modal term b_i is treated as mode-specific and can thus account for any modal dependency in choosing among travel alternatives. This is believed to be consistent with the theory of consumer choice behavior as explained by Lancaster¹³. Complete abstractness is seen as not being desirable because there usually are mode-specific effects which cannot be captured by a full description of the quantifiable system attributes and which are likely to influence the traveler's choice of mode.

The linear form of equation (3.7) is based on the assumption that the various attributes (characteristics) of a travel alternative contribute in an additive manner to its generalized cost. This implies that differences in characteristics of alternatives are considered as the comparative mechanism in human choice decision making. A product form, if used instead, would lead to ratios of

characteristics rather than differences. However, the additivity (linearity) assumption is by far the most usual one²⁶.

As an illustration of using equation (3.7), Stopher's binary model²⁹ estimates the probability of choosing one travel mode (car) when another mode (transit) is available, as being equal to the difference in the generalized costs of the two modes, using only time and cost variables. That is

$$p_1 = G_2 - G_1$$

$$= (a_1 t_2 + a_2 c_2) - (a_1 t_1 + a_2 c_1) + b$$

or

$$p_1 = a_1(t_2 - t_1) + a_2(c_2 - c_1) + b \quad \dots (3.8)$$

where

p_1 = probability of choosing mode 1

t = travel time

c = travel cost

b = choice bias for (or against) mode 2 relative to mode 1

The subscripts 1 and 2 refer to mode 1 and mode 2, respectively.

In this linear form of mode choice probability, as given by the above equation, the bias term b represents the probability of choosing one of two modes when the travel time and cost of that mode are equal to those of the other. Accordingly, b must lie between 0 and 1. The b term reflects in such a case the dependence of choice of travel mode on factors other than time or cost, such as discomfort. If calibration of this kind of relationship results in a value of b outside the 0-1 range, the law of probability would be violated. Similarly, it is possible with this linear form that large positive or negative differences in travel times and/or costs could yield probabilities greater than one or less than zero. Again, this would be unacceptable. Although it may be possible to constrain the ends of such a linear relationship so that the

probabilities are confined to the 0-1 range, yet the question arises as to whether the simple linear form is satisfactory.

It may be argued that the rate of change of the choice probability need not be constant with respect to the generalized cost difference, as implied by Stopher's formulation. Rather, it could be postulated that as a certain threshold level of the difference in generalized costs is approached, a given change in the generalized cost difference will lead to a smaller change in the choice probability than it would at lower absolute levels of the cost difference³⁰. That is, the choice probability curve becomes flatter as it approaches the threshold levels of the generalized cost difference, and it will, consequently, be steeper in the regions where the difference in the generalized costs is close to zero. Such a relationship can be represented by an ogive (sigmoid) curve, similar to the one illustrated in Figure (3.1). The curve maps the linear choice probability relationship of equation (3.8) into a zero-one interval. In fact, in an attempt to overcome the problem of probability law violation associated with his initial formulation, Stopher later transformed his linear probability model into a simple logistic form.

The sigmoid form overcomes the problem of probability law violation and is based on a more realistic behavior in terms of its diminishing marginal return property, that is the rate at which the choice probability will change in response to changes in the generalized cost difference in different ranges of the curve. For instance, it appears behaviorally plausible to postulate that a change of 10 minutes in the difference between travel times of two modes is "less perceived" by the traveler when this difference is 2 hours than when it is, say, 20 minutes.

Two sigmoid curves have been commonly used: the cumulative normal curve and the logistic curve. When the normal distribution curve is used the analysis is known as "probit analysis". In this technique each individual is assumed to have a different critical value or "tolerance", with respect to the difference in generalized costs, at which he would switch from one alternative

to the other. The probit analysis is based on the assumption that this tolerance is normally distributed. When the logistic curve is used the analysis is termed "logit analysis". There are no distributional assumptions made in the logit analysis. The logit technique merely assumes that the relationship between the choice probability and the relative (e.g. difference, ratio) generalized cost is a logistic sigmoid.

Both probit and logit analyses are virtually indistinguishable except at probabilities very close to zero or one. Within the range of most data, both techniques provide almost equal probability figures and except for computational reasons, there is little to choose between them. Logit analysis is, however, computationally more convenient than probit and has been widely used for modeling mode choice, perhaps because it is apparently the only readily tractable mathematical form that can be derived.

The mathematical equation of the multinomial logit model of mode choice is derived in Appendix A and is given here by either of the following two alternative forms. A graphical representation of a 2-dimensional (binary) logistic curve is shown in Figure (3.1).

$$P_i = \frac{1}{1 + \sum_{\substack{r=1 \\ r \neq i}}^M e^{G_i - G_r}} \quad \dots (3.9)$$

or

$$P_i = \frac{e^{-G_i}}{\sum_{r=1}^M e^{-G_r}} \quad i \in r \quad \dots (3.10)$$

where p_i is the probability of choosing a particular travel alternative i out of M available alternatives, and G is as defined by equation (3.7).

FIGURE (3.1) - THE LOGISTIC CURVE FOR THE BINARY CHOICE

Elasticity Properties of the Logit Model of Mode Choice:

Elasticity with respect to a particular independent variable is defined as the percentage change in the dependent variable caused by 1% change in the independent variable. That is, for the choice probability defined by equations (3.7) and (3.10):

$$\eta_{ki} = \frac{\partial p_i}{\partial p_i} / \frac{\partial L_{ki}}{\partial L_{ki}} = \frac{\partial p_i}{\partial L_{ki}} \cdot \frac{L_{ki}}{p_i} \quad \dots\dots (3.11)$$

where

η_{ki} = elasticity of probability of choosing alternative i with respect to its k^{th} level of service variable, L_{ki}

p_i = dependent variable -- probability of choosing alternative i

Using the logit equation (3.10), the elasticity of the demand for alternative i with respect to any of its service variables (direct-elasticity) can be easily derived, as shown in Appendix A:

$$\eta_{ki} = a_k (-L_{ki}) (1-p_i) \quad \dots\dots (3.12)$$

where

a_k = the weighting coefficient associated with variable number k, L_{ki} , of alternative i, [see equation (3.7)].

That is, the elasticity of the market share of a travel alternative with respect to any of its service attributes is negatively proportional to:

the level (magnitude) of that particular attribute, L_{ki} , weighted by the importance, a_k , attached by the travelers to it, and further weighted by the remaining share of the market, $(1-p_i)$.

The first two parts of the statement above agree with a priori expectations. The negative sign is also expected, because all the system variables included in the generalized cost expression represent disutilities to the traveler, and thus demand should decrease with increasing (worsening) any of the generalized

cost elements. The latter part of the statement indicates that, all other things being equal, the larger the market share of a given travel alternative, the less elastic is its demand. In other words, the potential of a mode to gain (or lose) patronage is minimal when its share is already large (or small). This can be seen clearly in situations where one of the modes is dominating the travel market (e.g. air in long- or medium-haul travel). Again, this result is intuitively acceptable and is believed to be conformal with concepts of consumer behavior in economics²⁶.

Cross-elasticity measures can also be derived and interpreted in a similar manner.

Clearly, the logit model formulation is behaviorally and theoretically appealing. It has, furthermore, been shown that it also has the property of reducing measurement errors of the original variables used in the model²⁶. The logit formulation is, therefore, adopted here to structure the mode choice model.

3.3.2 Specification of the Generalized Travel Cost Function

It was postulated in the previous section that the generalized travel cost is the sole evaluation measure used in the mode choice process. It was also hypothesized that the generalized cost of traveling by a particular alternative is based in part upon the characteristics of that alternative, and in part upon the attributes of the travelers, whether individually or in groups. Furthermore, it was indicated that a desirable structure of the generalized cost function is one in which the system characteristics are inserted in an additive form. What remains to be specified in order to define fully the mathematical form of the generalized cost function is the manner in which the user attributes are to be included in it.

Most of the early behavioral mode choice models introduced the user attributes as additive linear terms along with the transport system characteristics in the generalized cost formulation. In a logit model of the type adopted here, the user attributes, if so included, will disappear from the expression of probability of

mode choice [equation (3.9)], because that probability is related to differences in generalized costs of the travel alternatives. This problem could be overcome by associating mode-dependent coefficients with the user attributes included in that way. Such a procedure requires that a set of different coefficients be determined for each alternative (mode) included in the multinomial choice set. This may limit the application of the calibrated model in situations involving new travel modes. Furthermore, the procedure implies that the estimated values of the coefficients (weights) associated with the transport system characteristics would be the same for all travelers regardless of differences in their socio-economic characteristics. For example, if a value of travel time is to be derived from such a model, all travelers will be credited with the same value of travel time, which is unrealistic.

An alternative procedure to reflect the user attributes in choosing a travel mode is to calibrate separate mode choice models in which the generalized cost function is formulated in terms of only the transport system characteristics for a number of different classes of user attributes (user groups). It is then hoped that associative relationships relating each of the coefficients being estimated [the a 's in equation (3.7)] to the user attributes be estimated using the values obtained by calibration for these coefficients and the corresponding values specified for the user attributes. It has been pointed out that this procedure has so far failed to produce such relationships²⁶. Additionally, the procedure requires a substantially large sample size to permit stratifying the population into a significant number of user groups (classes) and ensure a statistically acceptable sub-population size in each stratum. The problem becomes more acute when further disaggregation with respect to trip purpose is made.

A third, and preferred, procedure is to express the weights associated with the transport system characteristics (i.e. the a 's) in terms of the selected set of user attributes. In this case, only one mode choice model (of course, for each trip purpose)

is calibrated using the available data set. This procedure is believed to be consistent with the notion of "perception" of level of transport service. It is recommended, if this procedure is used, that the user attributes enter only one or two of the generalized cost functions, or else severe multicollinearity problems arise, and that the number of such attributes be likewise restricted²⁶. In this regard, the user income has been successfully employed in the literature as the primary user attribute. Other attributes such as age, sex, etc., may also be included. However, since the main purpose of structuring and calibrating a demand model is to use it in forecasting future travel demands, inclusion of such additional attributes is of little or no importance since their relative values in the population do not significantly change over the study or planning period. The income variable is, in this regard, significant. In addition to being a descriptor of the economic status of the traveler, user income may also be regarded as a proxy to other user attributes such as social status or occupational category, in as far as their effect on travel demand is concerned.

The particular generalized travel cost formulation given below is based on the latter procedure and is used here to calibrate the multinomial logit model of mode choice. The coefficients in that formulation are to be estimated separately for each trip purpose.

$$G_{iu} = c_i + a_1 I_u \cdot t_i + a_2 \cdot (1/F_i) + b_i \quad \dots (3.13)$$

where

- G_{iu} = generalized travel cost of alternative i as perceived by users of group u
- c_i = total cost of traveling by alternative i (the cost includes fare, and average access and egress costs)
- t_i = total time of traveling by alternative i. It includes:

- line-haul time (terminal-to-terminal),
- average access and egress times,
- average waiting time at origin terminal,
- average time to exit the destination terminal, and
- average schedule overrun time (schedule delay)

F_i = frequency of service of alternative i (dep./day/dir.)
 I_u = mean income value of income group u
 a_1, a_2 = mode-independent coefficients
 b_i = mode-specific coefficient -- bias for or against travel mode i relative to a selected mode.

System variables other than the three suggested in the above formulation could be included in the generalized cost function provided that measurable values for these are obtainable. Travel time, travel cost, and service frequency have, however, been shown by most travel demand studies to be the most important factors considered. Indeed, most, if not all, the travel demand models developed to date only consider these three variables, and quite often the list is even limited to only the time and cost variables.

In this formulation, the out-of-pocket travel cost is assumed to be perceived directly by travelers and, therefore, the cost term involves no calibration coefficient. The importance or weight attached to travel time is assumed to be proportional to the traveler's income. Previous demand modeling studies show that this assumption is valid. An implication of these two assumptions is that the value of time spent in travel is proportional to the user's income, which is consistent with empirical findings. The validity of this implication is also demonstrated by survey data presented later in Figures (3.2) and (3.3). The data show that travelers in high-income groups prefer to travel by air, although expensive, in order to save time.

The income variable used here is defined to be the family income. Although, other forms of income could be employed instead, yet, the travel survey data used for model calibration contained

only the family income. It seems reasonable, however, to assume that if the household has several sources of income all partial incomes will be pooled, and thus family income is the appropriate income variable to use.

In the above generalized cost function, the inverse of service frequency variable ($1/F_i$) is used to reflect the travel inconvenience due to infrequent service. High frequency permits travelers to fit the scheduled arrival times to their preferred or desired arrival times, thus the service becomes more convenient to users. This variable is, therefore, regarded as a measure of system flexibility and convenience. The effect of the frequency variable on the perceived generalized travel cost, as reflected in the above formulation, is consistent with the notion of "high frequency attracts more travelers but the extent of this attraction decreases as the service frequency increases -- a diminishing marginal return property". When a travel alternative between two cities is comprised of a number of successive links, the frequency of service on it can be defined to be equal to the lowest frequency on any of its links.

The frequency variable can be treated as responsive to the demand peaking phenomenon by assigning different weights to vehicle departures made during peak and off-peak periods, and taking the weighted sum of these departures as an "effective" service frequency measure to be used in the generalized cost formulation above.

Finally, the last term in expression (3.13) reflects the relative bias of travelers for or against the transport mode on grounds other than time, cost, or departure frequency; such as discomfort. This term is sometimes referred to as "mode penalty" or "acceptability factor". The generalized cost function is therefore "partially abstract" in the sense that it contains mode-independent as well as mode-specific coefficients. Complete abstractness may be appealing particularly for use of the model in forecasting the share of a new transport system. However, full

abstractness may be neither necessary nor desirable if one important feature of a mode (other than time, cost, or frequency) differs from its competitors in important but intangible ways. That is, to the extent that there are mode-specific characteristics which cannot be captured by a full description of the system quantifiable variables, one cannot hope to reliably forecast the demand for a new system without considering its mode-specific effects:

3.3.3 Statistical Estimation of the Multinomial Logit Model

Statistical estimation of the logit model is concerned here with outlining a method for determining the best values of the unknown coefficients included in the generalized cost formulation (i.e., the a's and b's) which, in turn, appear in the multinomial choice model given by equation (3.10). The calibration is carried out here for each trip purpose separately.

There are two statistical techniques that could be used in this regard: maximum likelihood method of estimation and simultaneous least squares analysis.

The Maximum Likelihood Method of Estimation:

Assume that out of N individuals who belong to the same user group and who are observed traveling for the same purpose between a given origin-destination pair, n_1 chose to travel by alternative 1, n_2 chose to travel by alternative 2, ..., and n_M chose to travel by alternative M , where M alternatives are available. The likelihood, $L=L(\theta)$, of the values of the parameters $\theta = (a_1, a_2, \dots, b_1, b_2, \dots)$ based on the observations $(n_1, n_2, \dots, n_M)$ can be written as:

$$L = \left(\frac{N!}{n_1! n_2! \dots n_M!} \right) (p_1^{n_1} \cdot p_2^{n_2} \dots p_M^{n_M}) \dots (3.14)$$

where

$p_i = p_i(\theta)$ = probability of choosing travel alternative i ($i = 1, 2, \dots, M$); as determined by equations (3.10) and (3.13), which is a function of the parameters θ involving the a's and b's.

$$\sum_{i=1}^M p_i = 1.0 \quad \text{as implied by equation (3.10)}$$

$$\sum_{i=1}^M n_i = N$$

The likelihood function, L , is thus a function of the unknown generalized cost coefficients (a's and b's).

Ignoring the constant term contained between brackets in equation (3.14) as it does not affect the maximization of L with respect to any of the coefficients, the logarithm of the sample likelihood may be written as:

$$\text{Log } L = \sum_{i=1}^M n_i \cdot \log p_i \quad \dots (3.15)$$

As the data sample is composed of a set of independent sub-samples; each representing a certain city-pair and user group, "pooled" estimates of the a's and b's can be obtained by expanding equation (3.15) as follows:

$$\text{Log } L = \sum_{i=1}^M \sum_{j=1}^K \sum_{k=1}^U n_{ijk} \cdot \log p_{ijk} \quad \dots (3.16)$$

where

- n_{ijk} = number of travelers in user group k traveling between a city-pair j by alternative i
- p_{ijk} = probability that an individual belonging to user group k who is traveling between city-pair j will choose alternative i , as given by equation (3.10)
- M = number of available travel alternatives between a city-pair
- U = number of user groups
- K = number of city-pairs sampled.

In the formulation above, n_{ijk} generally differs from one origin-destination pair to another. Also, the number (M) and type of travel alternatives may or may not be the same for each origin-destination pair. Expression (3.16) can handle such situations.

Maximization of the logarithm of the likelihood function given by equation (3.16) with respect to the unknown coefficients (a's and b's) yields their maximum likelihood estimates*. The maximum likelihood estimator possesses a number of extremely desirable properties such as³³:

- (i) The maximum likelihood estimator $\hat{\theta}_i$ is a consistent estimate of the true value of the parameter θ_i (i.e. $\hat{\theta}_i$ converges to θ_i with increasing the sample size)
- (ii) The maximum likelihood estimator is efficient (i.e. exhibits small variance for its sampling distribution)
- (iii) The maximum likelihood estimator $\hat{\theta}_i$ is asymptotically normally distributed with mean θ_i and covariance matrix given by $R^{-1}(\theta)$, where³³:

$$R(\theta) = -E\left[\frac{\partial^2 \text{Log} L}{\partial \theta \partial \theta'}\right] \dots (3.17)$$

where $E[]$ = expected value of

The method of maximum likelihood is also flexible as it allows establishing constraints among the coefficients being estimated, if so desired. These several properties clearly make the maximum likelihood method a highly desirable estimation technique -- at least for large samples.

The Likelihood Ratio Test:

To evaluate the goodness-of-fit of the logit model, a statistical measure termed "likelihood ratio" is commonly used. It is analogous to the coefficient of multiple correlation, R^2 , in regression analysis. It simply tests the null hypothesis that

* It has been indicated²¹ that the Log L function is proven to be concave in the unknown logit coefficients, thus implying the existence of a unique set of maximum likelihood estimators.

the dependent variable (choice probability) is independent of the values of the independent variables in the model. In other words, the null hypothesis to be tested for the logit model, for an alternative i , is:

$$p_i = \frac{e^{-k_i}}{\sum_r e^{-k_r}} \quad i \in r \quad \dots\dots (3.18)$$

where k_r is a constant term for alternative r .

If the maximum value of the Log L function corresponding to the null hypothesis of equation (3.18) is denoted by $\text{Log } L_0$, then twice the difference between this value and that of the no-independence case, $\text{Log } L^*$, can be written as:

$$-2 \text{Log } \lambda = 2 (\text{Log } L^* - \text{Log } L_0) \quad \dots\dots (3.19)$$

The measure " $-2 \text{Log } \lambda$ " has been shown³⁴ to be approximately distributed for large samples like chi-square with as many degrees of freedom as there are independent variables. Consequently, the larger the value of this measure the higher will be the confidence level with which this null hypothesis can be rejected.

Simultaneous Least Squares Analysis:

To employ this statistical technique in estimating the unknown coefficients of the logit model, a "base" alternative is arbitrarily chosen. The probability of choosing each of the other alternatives, as given by equation (3.10), is divided by the probability of choosing the base alternative; thus resulting in $(M-1)$ simultaneous equations, when there are M travel alternatives. This new set of equations can be linearized by taking the natural logarithms of both sides of each equation. The coefficients are estimated by minimization of the sum of square errors of all the $(M-1)$ equations rather than of one equation at a time. In other words, this estimation approach results in "pooled" estimates of the coefficients.

It is, however, not usually possible to subdivide a data set into a sufficient number of classes showing variation in values of the transport system characteristics. This problem is crucial and limits the use of this technique particularly in cases where the data sample covers a few origin-destination pairs. In such situations the estimates obtained are not likely to be reliable. Furthermore, it has been reported that many researchers have encountered difficulties in calibrating multinomial modal split models by relying on linear regression techniques and that the maximum likelihood method was helpful in alleviating these difficulties³⁵. Estimates obtained by using the maximum likelihood technique are found, however, to be the most satisfactory^{21,34}.

3.3.4 Calibration of the Mode Choice Model

The calibration of the multinomial choice logit model developed here is conducted using the maximum likelihood method of estimation. The data used to calibrate the logit model as well as the total demand model (to be structured later) were obtained from three sources: the 1969 Canadian Transport Commission (CTC) common carrier travel survey for the Windsor-Quebec City corridor, 1969 common carrier service schedules, and Statistics Canada publications. Appendix B contains a description and analysis results of the data base.

The CTC raw data were analyzed for the purpose of determining the observed modal splits as well as the total travel demands between the various city pairs. The available sample of trips was stratified according to travel link, travel mode, and user income group. It was also possible to sub-classify the sample according to trip purpose into business trips (e.g. trips made for meetings, planning sessions, sales, etc.) and non-business or personal trips (personal business, visiting friends and relatives, vacationing/sightseeing, and other personal purposes). This trip purpose classification is fairly typical in intercity travel

demand studies. Besides, disaggregation of the available data into more than two trip purposes was not statistically feasible. Table (3.1) presents the observed modal splits for business and non-business travel purposes over the four links (both ways) of Montreal-Toronto, Montreal-Ottawa, Toronto-Ottawa, and Montreal-Quebec, and for a number of user income groups. Portion of the data sample pertaining to other city-pairs was so small in size to be disaggregated by trip purpose, link, mode, and income group.

Figures (3.2) and (3.3) illustrate graphically the observed modal splits vs. the traveler's income level for both business and non-business trips and for two of the four city-pairs contained in Table (3.1): Montreal-Toronto and Montreal-Ottawa. The Figures demonstrate that as the user's income increases, it becomes more likely that he will travel by the more expensive air mode in order to save time. The Figures also suggest that time savings for business trips are more important than time savings for non-business trips. The Figures also indicate that the bus mode is not a desirable travel alternative on long travel links, particularly for business trips and that the air travel market is small on short links, especially for non-business trips.

Given the above information about the observed modal splits for the various user-income levels, an additional piece of information is further required in order to carry out the model calibration. This concerns the service characteristics of the three public modes on each of the four links. Generation of this information is described in Appendix B and the final results are presented here in Table (3.2).

The data presented in Tables (3.1) and (3.2) are assembled together to conduct the model calibration. Instead of using the "actual" number of same-income passengers (by all modes) observed on each link, this number was normalized to 100. Such a procedure ensures that the estimation of the coefficients is not dominated by links or user groups contributing more sample observations than others. The following values were used in connection with the logarithm of the likelihood function, $\text{Log } L$, given by equation (3.16):

TABLE (3.1) - 1969 OBSERVED MODAL SPLITS (%) FOR DIFFERENT LINKS AND INCOME GROUPS

TRAVEL LINK:	MONTREAL-TORONTO			MONTREAL-OTTAWA			TORONTO-OTTAWA			MONTREAL-QUEBEC		
	AIR	RAIL	BUS	AIR	RAIL	BUS	AIR	RAIL	BUS	AIR	RAIL	BUS
BUSINESS TRAVEL												
Income Group (\$)												
5001- 7000	64.1	33.8	2.2	10.2	57.3	32.5						
7001- 9000	74.1	24.1	1.9	24.0	55.1	21.0	91.2	8.0	0.7	28.9	46.6	24.5
9001-11000	83.1	16.9	0.1	23.3	56.6	20.0	94.4	3.1	2.5	45.6	39.6	14.7
11001-13000	88.1	11.7	0.3	24.9	56.1	19.0	97.4	2.6	0.0	65.4	25.8	8.8
13001-20000	89.0	11.0	0.0	31.9	50.5	17.6	96.5	2.5	1.0	70.8	22.7	6.5
>20000	94.1	5.6	0.3	56.0	37.4	6.6	98.5	1.5	0.0	80.0	16.0	4.0
NON-BUSINESS TRAVEL												
* Income Group (\$)												
<5000	10.2	60.2	29.6	0.6	34.3	65.2	9.4	28.8	61.8	1.8	45.0	53.2
5001- 9000	20.3	63.7	16.0	1.7	39.4	58.9	21.3	33.5	45.2	3.5	49.7	46.8
9001-13000	30.4	58.8	10.8	3.9	42.7	53.4	33.7	23.8	42.5	5.2	47.5	47.4
13001-15000	35.6	53.4	11.0	5.9	49.2	44.9	48.0	22.0	30.1	4.7	48.6	46.7
15001-20000	44.0	49.1	6.9	7.0	53.1	39.9	50.5	19.6	29.9	12.4	44.3	43.3
>20000	56.1	40.3	3.7	12.7	52.6	34.7	59.3	18.6	22.0	14.5	45.9	39.6

* 1968 incomes

FIGURE (3.2)- MODAL SPLIT VS. TRAVELERS INCOME (MONTREAL-TORONTO)

FIGURE-(3.3)- MODAL SPLIT VS. TRAVELERS INCOME (MONTREAL-OTTAWA)

TABLE (3.2) - 1969 CHARACTERISTICS OF TRAVEL MODES

TRAVEL LINK:		MONTREAL-TORONTO			MONTREAL-OTTAWA			TORONTO-OTTAWA			MONTREAL-QUEBEC		
TRAVEL MODE:		AIR	RAIL	BUS	AIR	RAIL	BUS	AIR	RAIL	BUS	AIR	RAIL	BUS
TOTAL TRAVEL TIME (HRS.)		2.83	6.61	7.45	2.12	3.38	3.50	2.57	6.45	6.47	2.33	4.40	4.08
TOTAL TRAVEL COST (\$)		30.53	13.83	13.76	19.91	6.24	5.96	26.22	11.21	11.23	20.12	8.32	7.99
EFFECTIVE* DAILY FREQUENCY		21.60	3.30	2.30	10.80	6.30	13.70	11.80	1.30	5.10	10.60	4.70	10.70
TOTAL TRAVEL TIME (HRS.)		3.05	6.98	7.72	2.25	3.52	3.57	2.75	6.73	6.50	2.62	4.65	4.22
TOTAL TRAVEL COST (\$)		29.13	13.52	13.63	18.49	5.57	5.85	24.46	10.43	10.95	19.11	7.92	7.29
EFFECTIVE* DAILY FREQUENCY		24.20	4.00	5.00	11.50	7.10	17.00	12.80	2.00	6.80	11.00	6.00	13.80

* Vehicle departures are weighted according to their weekly frequency and the manner in which they are spread over the time of day (peak and off-peak departures). Details are provided in Appendix B.

$M = 3$ (air, rail, and bus); $U = 6$; $K = 4$; and

$\sum_{i=1}^3 n_{ijk} = 100$ (e.g. n_{1jk} = number of persons out of 100 of income group k who chose to travel by air ($i=1$) on link j).

As can be seen from equation (3.9), the modal split depends on the differences in generalized costs of the travel alternatives (modes), which are determined by equation (3.13). As a result, only the "differences" in the bias terms associated with the travel modes are required to estimate the modal split. For this reason, and also to minimize the computational effort, the bias term b relating to one of the three modes (arbitrarily chosen to be the rail mode) was set equal to zero. Values of b estimated for the other two modes are thus regarded as "relative" to that of the reference mode. The coefficients to be estimated, for each trip purpose separately, are therefore: a_1 , a_2 , b_{air} , and b_{bus} .

Using the data contained in Table (3.2), the generalized travel costs of the modes serving the sampled city-pairs are expressed by means of equation (3.13) as functions of the four unknown coefficients. The logarithm of the likelihood function, $\text{Log } L$, given by equation (3.16) is then evaluated in terms of the observed modal splits reported in Table (3.1) and the modal split expression given by equation (3.10), in which these generalized cost functions are included. The $\text{Log } L$ expression consequently becomes a function of those coefficients, and was thus maximized using a non-linear optimization technique*. To test the statistical significance of the estimates obtained for the coefficients, their t -statistics were computed by calculating their variances as given by equation (3.17). The goodness-of-fit of the logit model was also tested by conducting the likelihood ratio test as well as by graphical comparison of the "observed" and "predicted" modal splits. Appendix C outlines the manipulations performed to arrive at the final specification of the $\text{Log } L$ function and the associated statistical measures. This calibration procedure was carried out twice - once for each trip purpose.

* The specific method used is due to Zangwill, W.I., "Minimizing a Function without Calculating Derivatives", The Computer Journal, pp.293-296, (Nov. 1967), and is documented in the Scientific Program Library of Carleton University Computing Centre.

The calibration results are given in Table (3.3) for both business and non-business travel. It should be noted that in order to use the shown estimates of the coefficients, the following units must be used for the time, cost, and income variables in the generalized cost function given by equation (3.13):

- travel time, t_i : in units of 10 hours,
- travel cost, c_i : in units of \$10, and
- family income I_u : in units of \$10,000, (per year).

It is seen from Table (3.3) that all the estimated coefficients are highly statistically significant and that their values are plausible. For example, the results confirm the observation made earlier about the higher importance of travel time to business travelers than to non-business travelers. This is reflected in the larger value of the a_1 coefficient obtained for business travel as compared to that for non-business travel.

As noted before, the probability of mode choice depends on the "relative" (difference in) values of the modal coefficients (the b 's) rather than their absolute values. These coefficients have been regarded earlier as reflections of modal inherent characteristics other than time, cost, or frequency of service that influence the choice of travel mode. The estimates obtained for these coefficients appear to be also plausible. For example, the value obtained for the bias term b of the air mode can be seen from Table (3.3) to be smaller, for business travel, than that of the bus mode (rail was treated as a basic or reference mode with $b=0$). This implies a personal preference to the air mode over the bus when traveling on business. The Table indicates that the opposite is true for non-business travel. Also, since the b values obtained for the air and bus modes are greater than zero for business as well as for non-business trips, the rail mode (although closely matched by air for business trips, as the Table shows) appears to be favored over the other two modes on grounds other than travel time, travel cost, or service frequency; such as in-vehicle relaxation or comfort.

The likelihood ratio test results for the business and non-business mode choice models indicate that the probability

TABLE (3.3) - CALIBRATION RESULTS OF THE
MULTINOMIAL CHOICE LOGIT MODEL

<u>COEFFICIENT</u>	<u>MAXIMUM LIKELIHOOD ESTIMATE</u>	<u>STANDARD ERROR OF ESTIMATE</u>	<u>t-STATISTIC</u> [†]	<u>LEVEL OF SIGNIFICANCE</u> [*]
<u>B U S I N E S S T R A V E L</u>				
a ₁	5.6266	.2123	26.5	< 0.1%
a ₂	4.4031	.3931	11.2	< 0.1%
b _{air}	0.4304	.0156	27.6	< 0.1%
b _{bus}	1.6162	.0537	30.1	< 0.1%
<u>N O N - B U S I N E S S T R A V E L</u>				
a ₁	3.2531	.1122	29.0	< 0.1%
a ₂	3.8634	.3116	12.4	< 0.1%
b _{air}	1.6682	.0420	39.7	< 0.1%
b _{bus}	0.6701	.0211	31.8	< 0.1%

LIKELIHOOD RATIO TEST:

BUSINESS TRAVEL MODEL: $(-2\text{Log}\lambda)=412 \rightarrow$ LEVEL OF SIGNIFICANCE <0.1%

NON-BUSINESS TRAVEL MODEL: $(-2\text{Log}\lambda)=286 \rightarrow$ LEVEL OF SIGNIFICANCE <0.1%

[†] = maximum likelihood estimate/standard error of estimate.

* Number of data groups equals 66 for business trips and 72 for non-business trips, with each group containing 100 travelers.

of choosing a travel alternative is very significantly dependent on the attributes of the user as well as of the available travel alternatives, as modeled by the multinomial logit equations (3.10) and (3.13).

The goodness-of-fit of the calibrated business and non-business modal split models is further demonstrated in Figure (3.4) where plots of "observed" vs. "predicted" modal splits are presented for both trip purposes. The Figure indicates that the models predict the actual mode choices with high degree of accuracy. The goodness-of-fit measures shown in the Figure were compared to those of the Canadian Transport Commission's² modal split model* which was calibrated by using the same original raw data base. The comparison revealed that the predictive accuracy of the present disaggregated logit models is much higher than that of the CTC model.

3.4 Modeling Intercity Total Travel Demand

A common carrier total demand model is structured and calibrated here. It predicts the total number of person trips generated in one city and destined to another, in a given time period, as a function of a set of variables describing the socio-economic characteristics within the two cities and the supply (level of service) of the overall transport system linking them. This general travel demand relationship is employed in transportation planning, and is shown to have a basis in consumer demand theory which postulates that the quantity of a good purchased by an individual or a group of individuals having same socio-economic characteristics (e.g. income), depends on their socio-economic attributes and the set of prices of that good and its substitutes³⁸. In a travel demand context, the good is regarded as the transport, and the price of good is considered as the level of service including the user out-of-pocket cost.

* The mathematical formulation of this model has been given earlier by equation (3.4).

FIGURE (3.4) - GOODNESS-OF-FIT OF THE MULTINOMIAL LOGIT MODELS

Demand for transportation is regarded as a "derived" demand. That is, travel is not demanded for its own sake, but rather for gaining utility associated with the activity to be carried out at the end of the trip. It is, therefore, desirable to disaggregate the trip making rate according to the purpose of the trip, which is considered as a proxy to the utility of destination activities. Other reasons for demand disaggregation with respect to trip purpose have also been discussed earlier in this Chapter.

A total demand function, for a given trip purpose, can be expressed as:

$$T_{ij} = f(SE_i, SE_j, LS_{ij}) \quad \dots (3.20)$$

where

T_{ij} = number of trips originated in city i and destined to city j , per unit time (e.g. day, week, year, etc.)

SE_i = a vector of socio-economic characteristics within city i

SE_j = a vector of socio-economic characteristics within city j

LS_{ij} = level of service of the transport system serving i and j .

Socio-economic variables that have usually been tried in the literature include population, employment, and average (or median) income in each city. As regards level of transport service, variables such as total travel time, total travel cost and frequency of service may enter in the demand equation either separately or in the form of a combined level of service measure. Collinearity problems are likely to arise should they enter the equation separately*. The variables to be included in expression (3.20) are usually raised to certain powers - which are to be estimated by model calibration - and are entered in a product form.

* For instance time and cost variables are usually intercorrelated since they explain the same thing: travel distance.

Additional variables which contribute to explaining the interaction (in terms of travel) between city-pairs may also be included. An example of such variables could be a language interaction factor which is believed to be significant in determining the pattern of interaction between cities within the Quebec-Windsor corridor where some of the cities are linguistically French-dominated while others are English-dominated.

Although it is desirable to include the effect of the automobile in the common carrier total demand model, yet in the models calibrated here the influence of automobile on common carrier demand was left out. The reasons for excluding the car have been given earlier in this Chapter. In fact, a number of prototype demand functions involving different ways of including the car variables (total travel time and perceived cost) were initially formulated and calibrated. None of the attempted models came out statistically significant and estimates obtained for model coefficients were distorted. Such a result is attributed to interdependence between the level of service variable(s) of the automobile and that of the common carrier (collinearity).

The final formulations of the common carrier total demand models given below are selected from a number of alternatives that were tested statistically.

For business trips:

$$T_{ij} = a_0 E_i^{a_1} E_j^{a_2} g_{ij}^{a_3} W_{ij}^{a_4} \dots (3.21)$$

For non-business trips:

$$T_{ij} = b_0 P_i^{b_1} P_j^{b_2} g_{ij}^{b_3} W_{ij}^{b_4} \dots (3.22)$$

where

- T_{ij} = number of common carrier person trips originated in city i and destined to city j , per unit time
 E_i = number of employed persons in city i
 P_i = population in city i
 E_j = number of employed persons in city j
 P_j = population in city j
 g_{ij} = linguistic-pairing index between cities i and j
 W_{ij} = composite (average) generalized travel cost between cities i and j (weighted according to the modal split)
 α 's and β 's = coefficients to be statistically estimated.

The structure of the two equations above assumes that the number of trips generated in or destined to a particular city increases with its size. The population and employment terms in the models are the generators of non-business and business trips, respectively. The same city-size-descriptors are used as measures of trip attractions. The effect of language spoken on potential communication (travel) between residents of one city and those of another is quantified by an index, termed the "linguistic-pairing index", which is defined over the range zero to one. It is equal to one if the two cities (i and j) are perfectly paired with respect to language (i.e. if the cities are both English, both French speaking or at least one of them is completely bilingual). It is equal to zero if the language patterns do not intersect.

The level of service of the overall transport system between a pair of cities is defined here as the weighted sum of individual levels of service of the travel modes (alternatives) comprising the common carrier system serving the two cities; each weighted by its market share. Specifically, the common carrier level of service is expressed here as a weighted sum of cost, time, and service availability variables of all the modes; each variable being weighted by its importance as a user-perceived disutility and further weighted by the modal market share (expressed as a fraction between 0 and 1). That is, the common carrier level of service, W_{ij} , is written for a given trip purpose, as:

$$W_{ij} = \sum_r p_r [w_1 C_r + w_2 t_r + w_3 (1/F_r)] \dots (3.23)$$

where

- p_r = market share of mode r , as defined by equation (3.10)
 C_r, t_r, F_r = total travel cost, total travel time, and effective frequency of service of mode r
 w_1, w_2, w_3 = "relative" weights associated with the above three modal variables. They are implicitly determined by the a_1 and a_2 coefficients in the calibrated modal split models. That is:

$$w_1 = 1/w, \quad w_2 = a_1 I/w, \quad w_3 = a_2/w$$

where

$$w = 1 + a_1 I + a_2$$

$$w_1 + w_2 + w_3 = 1.0$$

I = average income in city of trip origin.

The formulation of the common carrier level of service outlined above is believed to be appropriate and avoids collinearity problems that are likely to arise should the level of service variables be introduced separately in the demand model. Weighting the generalized cost variables of each mode by their relative importance to travelers as well as by the relative penetration of the mode in the travel market, suggests that the reasonability conditions for making reliable travel forecasts are more likely to hold than for other model formulations. In fact, initial calibration attempts were made using separate independent variables describing the common carrier level of service in the total demand equations, and revealed high degree of correlations among those variables.

The disadvantage of this manner of including the level of transport service in the total demand function is that direct-elasticities and cross-elasticities of travel demand with respect to time, cost, or frequency variables are not observed directly.

Explicit determination of elasticities is not, however, a necessity in designing the transport system here, because such elasticity or "responsiveness" measures are evaluated internally within the optimization process.

Calibration of the total demand models thus structured was carried out using the data sets obtained from the CTC travel survey and from other sources (as presented in Appendix B). The origin-destination trip matrix used for this purpose is shown in Table (3.4) for business and non-business trips. The statistical estimation technique employed is the multiple linear regression. The demand functions given by equations (3.21) and (3.22) were therefore transformed to the "linear log" form by taking the natural logarithms of both sides of each equation so as to be amenable to conducting linear regression analysis. The calibrated demand models are given by equations (3.24) and (3.25). Underneath each model are the statistical measures associated with its log-transformed form, which include for a sample of size n : t -statistic, level of statistical significance (l.o.s.) standard error of estimate, s_e , coefficient of variation, c_v , and the coefficient of determination, R^2 .

Business travel demand model:

$$T_{ij} = .000567 E_i^{.957} E_j^{.947} W_{ij}^{-2.330} \dots (3.24)$$

$$[t = \dots (7.7) \dots (7.7) \dots (-6.3), n=20 \text{ l.o.s.} < 0.1\%$$

$$s_e = 0.45 \quad c_v = 9.18 \quad R^2 = .94]$$

Non-Business travel demand model:

$$T_{ij} = .001926 P_i^{.807} P_j^{.945} g_{ij}^{.797} W_{ij}^{-1.525} \dots (3.25)$$

$$[t = \dots (7.0) \dots (8.2) \dots (2.3) \dots (-6.4), n=20 \text{ l.o.s.} < 0.1\%$$

$$s_e = 0.38 \quad c_v = 6.58 \quad R^2 = .95]$$

* except for the coefficient of the language variable g which has l.o.s. = 4%.

TABLE (3.4) - 1969 INTERCITY COMMON CARRIER PASSENGER TRIP GENERATION*
(AVERAGE WEEKLY VOLUMES)

	TO FROM	MONTREAL	TORONTO	OTTAWA	QUEBEC	LONDON	WINDSOR
BUSINESS	MONTREAL		2473.2	637.22	518.40	62.28	40.25
	TORONTO	2847.80		1020.50	121.69		
	OTTAWA	740.71	604.64		73.78	19.16	7.67
	QUEBEC	471.44	62.28	67.08			
	LONDON	61.33		39.29			
	WINDSOR	43.12		21.08			
NON-BUSINESS	MONTREAL		2746.30	1972.00	2590.10	112.11	102.53
	TORONTO	3259.90		1425.80	201.23		
	OTTAWA	3406.50	934.27		188.77	83.37	23.00
	QUEBEC	2360.10	151.40	130.32			
	LONDON	148.52		107.32			
	WINDSOR	206.02		82.41			

* Passengers originated in one city and destined to another.

The variables appearing in these two equations have been described earlier for expressions (3.21) and (3.22). To define fully these variables, the following specifications, which were used in calibrating those two models, must be followed:

- the number of trips, T_{ij} , is on a per week basis
- population P_k (or employment E_k) of a city k is in thousands of persons and refers to the total metropolitan area
- units used here for time, cost, frequency, and income variables are same as those defined for the modal split models (i.e. 10's of hours, 10's of dollars, effective number of vehicle departures per day per direction, and 10,000's of dollars, respectively).

The total demand models given by equations (3.24) and (3.25) were selected as best among a number of alternative formulations tried for both business and non-business trips. It is seen that the selected business demand model does not contain a language variable. In fact the model was initially calibrated with this variable included in it but the coefficient associated with it came out statistically insignificant ($t = 0.6$). The language coefficient in the non-business model was found, however, to be statistically significant at the 4% level. All other coefficients estimated for both models are significant at less than the 0.1% level. The signs as well as magnitudes of the coefficients are reasonable and agree with a-priori expectations. The models also suggest that the elasticity of travel demand to the level of transport service is higher for business travel than for non-business. The negative sign associated with the generalized travel cost variable in either model indicates that improving the level of transport service results, according to the models, in increases in travel demands. Values of the population and employment coefficients are close to unity (except for P_1); thus indicating nearly-direct-proportionality relationships. The relatively lower value (0.807) of the coefficient associated with the population of the city of origin P_1 implies that as the city grows the rate of increase in making

personal (non-business) trips to another city gets smaller (diminishing marginal return property). This is because most of the generated trips are likely, in this case, to be made within the origin city itself. This result is also consistent with past empirical observations.

In addition to the c_j and R^2 values associated with the above demand models, the goodness-of-fit of these models is also illustrated in Figure (3.5). A fairly high degree of predictive accuracy can be seen from the plots. This applies, however, to the models in their logarithmic transformations. Relatively lower accuracies are expected when reference is made to the original demand volumes. It should be noted, however, that the explanatory powers of the variables included in the demand models are sufficiently high to warrant the use of the models for forecasting future travel demands. To attain a high degree of predictive accuracy, the magnitude of travel demand in a future year relative to the "observed" demand in the base year (1969) can be expressed in terms of the relative values of the demand explanatory variables in the two years and the values of the elasticity coefficients[†]. The elasticity coefficients are estimated here with high degree of confidence. This procedure is further discussed in Chapter 7.

The income variable does not appear explicitly in the above total demand models. Actually, its effect is implicitly considered in computing the modal generalized travel costs. These costs are used in estimating the modal split and in evaluating the composite level of service variable W which appears in the total demand models. It is desirable, however, to classify the generated total demand by income group so as to be consistent with the modal split estimation procedure outlined earlier. An attempt was initially made to calibrate the total demand models based on disaggregation of the traveling population according to income so that the trip making rate* in each group is estimated directly. Poor results (high coefficients of variation and low t -values) were obtained.

[†] the α 's and β 's in equations (3.21) and (3.22) whose estimated values are given in equations (3.24) and (3.25).

* number of trips made per person per unit time.

FIGURE (3.5) - GOODNESS-OF-FIT OF THE TOTAL DEMAND MODELS

An alternative approach which was adopted was to express the ratio of trip making rate of individuals belonging to each income group to the overall trip making rate of the resident population as a function of the ratio of mean income of the group to the overall average income of the resident population. Such a relationship, when calibrated, can be used to apportion the total volume of trips generated among the various income groups. Figure (3.6) presents the observations obtained by analyzing the travel data sample (Appendix B) for determining - on a provincial basis - the business trip making rate vs. income relationship. The Figure indicates that businessmen with high incomes show a higher rate of making business trips than those with low incomes. The income variable may be regarded, in this case, as an indicator of the occupational category or seniority of the business traveler. The form of the fitting curve shown in the Figure was obtained by non-linear least squares analysis and its equation is given below:

$$RT = 14.254 \exp(-3.49/RI^{.923}) \quad \dots (3.26)$$

where

RT = ratio of the rate of making business trips by employed individuals of a given family income bracket to the average trip making rate of all the employed persons in the same area of origin

RI = ratio of the mean family income in that particular income group to the average family income in the area.

No statistically significant relationship between the rate of making non-business trips and income was obtainable from the data sample. Poor correlation between these two variables was observed. This may be attributed to the supposition that individuals belonging to low income groups are mostly young and single and are therefore more mobile; thus exhibiting a high rate of making non-business trips. This high trip making rate of those

FIGURE (3.6) - EFFECT OF INCOME ON BUSINESS TRIP MAKING RATE

at low income levels tends, therefore, to offset (in terms of correlation) the expected high rate of trip making of those individuals at the other end of the income scale; thus resulting in no statistically significant trip making-income relationship.

Of course, the volume of trips made by individuals in a given income group will depend on the actual number of such individuals in the resident population. That is, the volume

of business trips made by individuals in a given income group out of the "total" volume of business trips estimated by equation (3.24) is determined by applying two factors: a weighting factor reflecting the increase in trip making rate with income [as determined by equation (3.26)], and the proportion of employed persons in the city of origin who belong to this income group*. Similarly, the total volume of non-business trips predicted by equation (3.25) is apportioned among the various income groups in accordance with the ratio of the number of residents in each income group to the total population of the city. Such population (or employment) proportioning can be computed from analysis of the demographic characteristics within each city (as will be shown in Chapter 7).

CHAPTER 4

SYSTEM SUPPLY

The demand models developed in the previous chapter are used within the system design optimization methodology to estimate the number of passengers expected to be flowing on each of the system links during a given time period (e.g. a day) and throughout the analysis period (e.g. every year or every number of years). The purpose of the present chapter is to determine the level of system supply that is required to accommodate the predicted traffic volumes. Based on both the supply and demand, the system costs and revenues can be evaluated, as will be presented in the next chapter. Specifically, given the service network of the designed system together with its origin-destination traffic volumes, the aim of this phase of the system design methodology is to:

- (1) compute vehicle travel time along each link,
- (2) construct vehicle departure schedules,
- (3) determine the necessary vehicle seating capacity, if required, and train consist for railway mode,
- (4) determine the number of vehicles required to service the network (i.e. fleet size), and
- (5) compute maximum accumulations of passengers and of vehicles in the system terminals, and hence terminal space required for their accommodation.

Built into the scheduling program is the option of varying the vehicle size across the network links, since the volume of traffic may vary widely from one link to another.

4.1 Vehicle Transit Time

The time taken by a vehicle to overcome the distance between two given terminals depends on a number of factors such as: the characteristics of the route (horizontal and vertical alignments, speed restrictions along the route, interference from other

vehicles using the same route, etc.) and the vehicle design and motive power characteristics (horsepower, maximum speed, acceleration and deceleration rates, curve negotiating speed capability). The maximum speed of vehicles is treated in the system design optimization methodology as an optimization variable and the terminal-to-terminal transit time of a vehicle will, therefore, be expressed here in terms of this variable. Because the mission profile* of an air mode is different from that of a ground mode, transit times are determined separately for each of these two modes.* Dependence of travel times on route characteristics is intentionally left out because the system design optimization methodology is not developed in a location-specific context.

The following analysis specifically assumes that there are no enroute delays due to interference from other vehicles and that the vehicles do not have to wait in any queues while leaving or entering the terminal. An average schedule overrun time (late arrivals) is, however, used in computing total travel times for use in the demand estimating models.

Intercity Travel Time by Air:

As was pointed out earlier, Short Take Off and Landing (STOL) air systems are of particular interest in studying short-haul air transport in this thesis. Air traffic control systems designed for STOL operation are expected to permit STOL aircraft to fly a more efficient mission profile [Figure (4.1)] compared to conventional take off and landing operations². Part of the STOL mission profile represents a non-productive or fixed time as the aircraft is circuiting, taxiing, or landing whereby no contribution is actually made to trip distance.

* a movement trajectory which depicts the motion of vehicle between two terminals [see Figure (4.1)].

1. TAXI OUT*	5. DESCENT
2. TAKE OFF*	6. AIR MANOEUVRE*
3. CLIMB	7. LANDING*
4. CRUISE	8. TAXI IN*

* A non-productive or fixed time component

FIGURE (4.1) - MISSION PROFILE FOR A STOL AIRCRAFT (Ref.2)

Block performance data furnished by DeHavilland Aircraft of Canada³⁹ suggest that the block time (non-stop terminal-to-terminal travel time) by STOL as well as by other competing short-haul aircraft can be expressed in the following form:

$$t_{ij} = t_g + t_a + d_{ij} \cdot f(V) \quad \dots (4.1)$$

where

t_{ij} = gate-to-gate or block time between terminals i and j

t_g = fixed or non-productive time spent on the ground

t_a = fixed or non-productive time spent in the air

d_{ij} = air distance between terminal i and terminal j

$f(V)$ = average time taken by the aircraft per mile of distance; a function of the aircraft cruise speed.

The data indicate that the mean values of t_g and t_a are 5 and

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11 minutes, respectively, thus giving an average fixed time of 16 minutes which is flight distance-independent.

Block time data for a number of STOL and other competing aircraft are presented in Table (D.1) in Appendix D. The reported values of the unit-distance function $f(V)$ are plotted here in Figure (4.2) against the aircraft cruise speed. It is seen from the Figure that the time taken per unit distance by aircraft of cruise speeds below about 385 miles per hour (mph) is linearly related to the cruise speed. Similar but flatter linear relationship is also evident for cruise speeds above 385 mph.

Simple linear regression analysis was performed on the data plotted in the Figure for the purpose of determining the exact specification of the function $f(V)$ for short-haul air transport. The regression results are given below:

$$f(V) = .4330 - .7181 (V/1000) \quad \text{for } V \leq 385 \text{ mph} \quad \dots (4.2)$$

$$[t = \dots (-32), n=8 \quad 1.o.s. < 0.1\%$$

$$s_e = .0032 \quad c_v = 1.4\% \quad R^2 = .99 \quad]$$

and

$$f(V) = .2545 - .2547 (V/1000) \quad \text{for } V > 385 \text{ mph} \quad \dots (4.2)$$

$$[t = \dots (-19), n=5 \quad 1.o.s. < 0.1\%$$

$$s_e = .0014 \quad c_v = 1.0\% \quad R^2 = .99 \quad]$$

Thus, the average non-stop gate-to-gate or block time (in minutes) can be written for short-haul air transport in terms of the terminal-to-terminal distance and aircraft cruise speed as:

$$t_{ij} = \begin{cases} 16 + d_{ij} [.4330 - .7181(V/1000)] & \text{for } V \leq 385 \text{ mph} \\ 16 + d_{ij} [.2545 - .2547(V/1000)] & \text{for } V > 385 \text{ mph} \end{cases} \quad \dots (4.3)$$

FIGURE (4.2) - SHORT-HAUL FLIGHT DISTANCE-DEPENDENT BLOCK TIME

Obviously, further higher cruise speeds are expected to exhibit a much flatter additional straight line relationship. However, estimation of such additional time-speed relationship was not necessary for the range of speeds considered here in designing short-haul transport systems. In fact, in the example application presented in Chapter 8, the search for the optimal STOL aircraft cruise speed had no upper bound on the speed and showed to be confined to speeds within those shown in Figure (4.2).

Intercity Travel Time by Rail:

Terminal-to-terminal travel time by rail depends to a large extent on the characteristics of the traveled route (horizontal and vertical alignments, speed restrictions along the route, etc.) in addition to the rolling stock design and motive power. Railway agencies compute train travel times between railway stations by means of a "train performance calculator" program which takes account of such route-specific factors and train motive power characteristics.

An elementary train journey involves three distance phases: acceleration, cruising, and braking. Of course, a number of accelerations and decelerations are involved throughout the journey, depending on the particular alignment of the traveled route. The net tractive effort exerted by the locomotive(s) in accelerating the train at a given speed v is equal to the total tractive effort, $TE(v)$, available at the rail less the portion used up in overcoming the train resistance, $TR(v)$, (assuming a straight and level track). Thus

$$TE(v) - TR(v) = \frac{W}{g} \cdot \frac{dv}{dt} \cdot fac \quad \dots\dots (4.4)$$

where

W = train weight

g = gravitational acceleration

v = train speed

t = time

fac = factor to account for the inertia of the rotating parts of the train and the force required to produce

rotational acceleration in these parts (wheels, axles, gears, etc.). An empirical value of this factor in the order of 1.05 to 1.12 is common in the literature on train traction (e.g. Ref.40).

The time, t_a , taken in accelerating the train from a speed v_o to a speed V can, therefore, be found as

$$t_a = \frac{W}{g} \cdot \text{fac} \cdot \int_{v_o}^V \frac{dv}{TE(v) - TR(v)} \quad \dots\dots (4.5)$$

The distance, d_a , covered in acceleration is, therefore,

$$d_a = \frac{W}{g} \cdot \text{fac} \cdot \int_{v_o}^V \frac{v \cdot dv}{TE(v) - TR(v)} \quad \dots\dots (4.6)$$

Obviously, the effect of an adverse grade or curve resistance is to reduce the net tractive effort used in acceleration [i.e., $TE(v) - TR(v)$]; thus lengthening acceleration time and distance.

In carrying out the above integrations, the rate of train acceleration should not be allowed to exceed a recommended rate for passenger comfort (say about .1 g), that is

$$\left[\frac{TE(v) - TR(v)}{W \cdot \text{fac}} \right] \leq a_c \quad \dots\dots (4.7)$$

where a_c is a comfortable acceleration rate (in g's).

Otherwise, the horsepower output is reduced (by means of switching to a lower power setting).

Formulas describing the train tractive effort $TE(v)$ and resistance $TR(v)$ as functions of the train speed can be found in the railway literature (e.g. Ref.40). For example, analysis

of the tractive effort curve furnished for the Canadian LRC* train⁴¹ confirmed the general tractive effort-speed relationship for diesel-electric locomotives⁴⁰:

$$TE(v) = K[1 - \exp(-v/v')] / v \quad \dots (4.8)$$

where

v' = "basic speed" at which rail friction is just equal to the tractive effort that the engine can exert at the driving wheels⁴⁰

K = constant for a given locomotive

Non-linear regression analysis performed on the LRC tractive effort-speed relationship revealed that the values of v' and K are around 10 mph and 760,000 when the tractive effort is expressed in pounds and the speed in miles per hour.

Also, LRC train resistance equations were made available by its manufacturers and are given below⁴²

$$D_a = .283[.63 + .13(n_l + n_c - 2)] \cdot v^2 \quad \dots (\text{lbs}) \quad \dots (4.9)$$

$$D_{rl} = 70 + W_l(.8 + .0450v) \quad \dots (\text{lbs/locomotive}) \quad \dots (4.10)$$

$$D_{rc} = 70 + W_c(.8 + .0375v) \quad \dots (\text{lbs/coach}) \quad \dots (4.11)$$

and

$$TR(v) = D_a + D_{rl} \cdot n_l + D_{rc} \cdot n_c \quad \dots (4.12)$$

where

D_a = aerodynamic drag.....(lbs)

D_{rl} = rolling resistance of locomotives.....(lbs)

D_{rc} = rolling resistance of coaches.....(lbs)

n_l = number of locomotives in the train

n_c = number of coaches in the train

W_l = weight of locomotive.....(tons)

W_c = weight of coach.....(tons)

v = train speed.....(mph)

* stands for Light, Rapid and Comfortable.

The portion of train journey time spent while cruising can be easily found by dividing the cruising distance by the cruise speed. The time spent while braking can also be determined by integration for a variable deceleration rate, or by simply dividing the speed differential by the rate of deceleration if a uniform rate is to be applied.

It should be noted that the above procedure of computing rail travel times is intended to merely demonstrate the dependence of rail transit times on the motive power characteristics (in particular, the train speed which is a system design optimization variable). Actual travel times depend on the characteristics of the traveled route and their implications in altering the train speed profile throughout the journey.

4.2 Determination of Vehicle Size and Train Consist

In situations where the departure frequency of vehicles is included among the design optimization variables, the minimum size(s) of vehicles required to accommodate the predicted traffic volumes is to be determined. Conversely, if the size of vehicle is selected instead to be one of the design optimization variables, the required number of vehicle departures can simply be computed. In either situation, it is assumed, based on existing public transport scheduling practices, that vehicle departures are spread over the daily servicing period in accordance with the profile of demand for service which exhibits periods of peaks and lulls. (Such a profile can be obtained from present common carrier services). The following simple supply-demand relationship can be used to determine the minimum number of vehicle departures - or the minimum vehicle size (seating capacity); depending on the design situation being considered - which is required to meet the demand on a particular link of the system:

$$FRQ_{ij} \cdot S_{ij} \geq VOL_{ij} \quad \dots (4.13)$$

where

FRQ_{ij} = one-way vehicle departures per unit time on link (or service route) ij

S_{ij} = vehicle size (or total seating capacity if the vehicle is made up of more than one unit) which is assigned to link (or route) ij

VOL_{ij} = one-way design traffic volume on link (or route) ij (within the same unit of time).

In fact, the design example application presented in Chapter 8 concerns a STOL system whereby the aircraft size is treated as a design optimization variable and the frequency of service is determined as a result. In Chapter 9 the design of a rail system is optimized using the frequency of service as one of the optimization variables and the required train consist (number of cars and locomotives per train) is computed accordingly. In the rail design problem, the question of train sizing is translated into determination of the number of cars (of a given seating capacity) per train.

The volume of traffic flowing per unit time on a particular link of the designed system network is determined by superposition of the origin-destination traffic volumes served by that link. Figure (4.3) shows a hypothetical short-haul service route composed of two links where traffic volume on either link is made up of the travel demands between the two city-pairs shown.

<u>LINK</u>	<u>O-D TRAFFIC CARRIED</u>
ij	$(i-j) + (i-k)$
jk	$(j-k) + (i-k)$

FIGURE (4.3) - A HYPOTHETICAL SYSTEM SERVICE ROUTE

The volume of trips in a peak day is usually used in designing transport systems, and can be computed by applying a peaking factor to the weekly or monthly volumes predicted by the demand models.

An objective of transport authorities is likely to be the uniformity of the vehicle fleet (in terms of vehicle size) so as to save on maintenance of vehicles and to permit more flexibility in switching the vehicles among the various service routes whenever desired. However, in generating the vehicle schedules each service route (which might be comprised of one or more links) can be assigned a different vehicle size. The scheduling program is developed here in such a way that this option is provided.

There may be situations where differences in traffic volumes on a set of connected links forming a route do not warrant the individual analysis of each link for the purpose of generating vehicle scheduling and vehicle sizing. In such cases, the set of links could be treated as one service route. The vehicle scheduling and sizing analysis would then be conducted for each of such routes as identified from the network. It is noted, however, that the design optimization methodology is developed for short-haul intercity passenger transport networks. In other words, the total length of the route should be consistent with the definition of short-haul transport.

This procedure, in addition to being conformal with common carrier service scheduling practice, reduces the size of the optimization problem since there would otherwise be a frequency of service (or vehicle size) optimization variable associated with each individual link. According to this procedure, the number of those optimization variables will instead be equal to only the number of service routes in the network. The procedure also implies that the vehicle scheduling and sizing for a given route should be based on the heaviest traveled link contained in the route. This in turn implies that the vehicle loading factors would be highest (close to 100%) on that particular link and

lower on the other links. The design vehicle loading factor, LF_{ij} , on a link ij is

$$LF_{ij} (\%) = \frac{VOL_{ij}}{FRQ_{ij} \cdot S_{ij}} \times 100 \quad \dots\dots (4.14)$$

Analysis of each link individually might, on the other hand, be desirable in situations where the designed network is small in size (i.e. small number of links) or has a special geographic layout [e.g. a set of radial links emanating from a focal central node (i.e. a set of shuttle services)]. Also, when the traffic volumes on the network links are significantly different from each other, analysis of the vehicle scheduling and sizing for each link separately is warranted.

Train Consist Determination:

Sizing the seating capacity of a train is assumed here to involve determination of the required number of cars and locomotives in the train -- i.e. train consist. (Train coaches have a fairly standardized seating capacity of about 70 to 80 seats per coach). The minimum number of cars per train, n_c^{ij} , for a given route* ij depends on the one-way daily passenger volume, VOL_{ij} , along the heaviest traveled link contained in the route, on the desired number of daily departures per direction, FRQ_{ij} , along that route, and on the car seating capacity, CAP. That is

$$n_c^{ij} = \frac{VOL_{ij}}{FRQ_{ij} \cdot CAP} \quad \dots\dots (4.15)$$

The number of locomotives required to pull this set of cars along that particular route ij and at a certain speed depends on the total power required to accomplish this performance and the power rating of each individual locomotive unit.

* According to the preceding discussion, the word "route" refers here to a sequence of links connected together to form a service route, or to just one single link; depending on the type of network and nature of service analyzed.

The power needed for propelling a train depends on the rate at which it is intended to pick up speeds, the resistance of the air it moves through at top speed, the mechanical resistance of the wheels and bearings (rolling resistance), the grade it is designed to climb at top speed, and whether it is to maintain speed in a head wind. Either the power to run at top speed, or the power to accelerate at lower speed may dominate the power requirement. That is, if a high acceleration rate is provided all the way up to the cruise speed, the train could run faster than cruise speed. Conversely, if just enough power is provided to overcome the total aerodynamic and rolling resistance at nominal top speed, the train acceleration will diminish asymptotically to zero as the speed approaches maximum. The power required may be determined on the latter basis and would then imply a reduction of speed on upward grades or curves which would, of course, be taken into account in computing travel times. That is, the rail horsepower, HP, required to just maintain a speed of V miles per hour on a straight and level track is

$$HP = \frac{TR(V) \cdot V}{375} \quad \dots (4.16)$$

where TR(V) is the train resistance (in pounds) at speed V.

The number of power units (locomotives) required to supply this horsepower can be determined by dividing the required horsepower determined above by the net horsepower (at the rail) of each locomotive, h_p , i.e.

$$N_l = \left\lceil \frac{HP}{h_p} \right\rceil \quad \dots (4.17)$$

where the brackets $\langle \dots \rangle$ denote the "largest integer", i.e., the quantity between brackets is rounded up to the next largest integer value.

It is noted here that an initial value for N_l has been previously assumed in computing the train resistance [equations (4.9) and (4.12)]. The N_l value should therefore be iteratively

modified according to equation (4.17). It is also noted that additional power is to be supplied by the locomotive(s) for auxiliary train services (such as electrical controls, blowers, lighting, heating and air conditioning, etc.) and should be accounted for in determining the horsepower requirement.

Since the system design is carried out in this optimization methodology over a study period, the passenger carrying capacity of the system provided in a certain year should be checked for sufficiency in a following year (or after a number of years; depending on the time period used in the analysis). Should deficiency in supply exist on a given service route, additional capacity (in the form of either more vehicle departures or more vehicle units (cars); depending on the particular design situation being analyzed) is provided on that route.

4.3 Diurnal Distribution of Demand and Vehicle Departures

Peaking is basically a demand phenomenon and an important dimension of trip generation particularly in urban transportation. Intercity travel, especially business trips, exhibits also a peaking pattern. Figure (4.4) presents a typical example of diurnal demand distribution which was observed during the Montreal-Ottawa STOL demonstration experiment (about 90% of the STOL passengers were business travelers)⁴³.

System operators are aware of the diurnal fluctuations in demand and respond to it by providing additional capacity during the peak periods. For the type of short-haul transport networks considered here a diurnal pattern similar to that shown in the Figure can be assumed for each of the system links or routes. The set of vehicle departures can, therefore, be distributed so as to match the diurnal distribution of demand. This is done below.

Whether the frequency of service or the vehicle size is selected as an optimization variable, a vehicle load (less or equal to the vehicle size) is to be determined and the pattern of vehicle departures throughout the servicing day is to be constructed for a given number of daily departures along each route. This is accomplished here through breaking up the diurnal

FIGURE (4.4) - DIURNAL DISTRIBUTION OF STOL DEMAND
(OTTAWA-MONTREAL DEMONSTRATION
PROJECT, REF.43)

distribution of demand into a finite number of time periods (slices) according to the passenger arrival rate. For example, the demand profile shown in Figure (4.4) suggests four time slices: two peak periods, and two off-peak periods. The number of vehicle loads dispatched within each time interval as well as their departure times are determined for a given route by knowing the portion of the route's design daily traffic in that period, the time length of the period, and the vehicle load which is, of course, based on the vehicle size assigned to that route. The average vehicle load, VL_{ij} , on a route ij , is

$$VL_{ij} = VOL_{ij} / FRQ_{ij} \quad (\leq S_{ij}) \quad \dots (4.18)$$

and the number of vehicle loads, NVL_{ij}^r , dispatched (at same headway time) within time interval r , is

$$NVL_{ij}^r = \text{INT} \{VOL_{ij}^r / VL_{ij}\} \quad \dots (4.19)$$

where

$\text{INT} \{ \}$ "smallest integer" i.e., the quantity between brackets is rounded down to the next smallest integer value

VOL_{ij}^r = portion of traffic volume, VOL_{ij} , occurring in time period r .

A fraction of vehicle load left over at the end of a time period (except for last period) is added up to the next time slice thereby augmenting its passenger demand which is to be translated in turn to a number of vehicle loads. The headway time differs from one time period to another depending on the passenger arrival rate within each period.

In general mathematical terms, the series of vehicle departures in either direction of a particular route can be analytically determined as follows. Let the cumulative* number of arriving passengers at time t for route ij be described by a function $P_{ij}(t)$, as shown in Figure (4.5). If d_{ij}^k denotes the time at which departure k is dispatched from i to j , then the next time at which a vehicle load, VL_{ij} , is accumulated (time of next departure) would be

$$d_{ij}^{k+1} = P_{ij}^{-1} [P_{ij}(d_{ij}^k) + VL_{ij}] \quad \dots (4.20)$$

where

$$k = 1, 2, 3, \dots, FRQ_{ij}$$

* The cumulative arrival curve can be constructed directly from the diurnal demand distribution.

FIGURE (4.5) - GENERATION OF VEHICLE DEPARTURE TIMES ALONG A ROUTE ij

Figure (4.5) illustrates graphically the foregoing scheduling algorithm.

It should be noted that the frequency of service is one of the demand variables. An initial value for it should, therefore, be assumed in order to predict the travel demand, if frequency is not among the optimization variables. The required frequencies of service which correspond to the predicted demands are determined as shown above and are fed back into the demand estimation models so as to adjust the demand estimates. This iterative process continues until the values used for frequency in these two phases of the system design model are the same (or close enough). Fortunately, this iterative process is guaranteed to converge very rapidly because of the "diminishing marginal return" property of the demand-frequency of service relationship.

The sequence of dispatch times, d_{ij}^k ($k = 1, 2, \dots, \text{FRQ}_{ij}$), for departures from i to j defines a cumulative departure function $D_{ij}(t)$, as shown in Figure (4.5), which defines in turn an arrival sequence a_{ij}^k ($k = 1, 2, \dots, \text{FRQ}_{ij}$) and, hence, a cumulative vehicle arrival function $A_{ij}(t)$ at the other node. That is, the time a_{ij}^k at which a vehicle dispatched from node i at time d_{ij}^k becomes available for a subsequent departure from node j after its arrival there can be written as:

$$a_{ij}^k = d_{ij}^k + t_{ij} + t_s \quad \dots (4.21)$$

where

t_{ij} = average one-way travel time along route ij
 t_s = average turn-around time; which is determined by the time required for passenger handling (unloading and loading) or vehicle servicing (e.g. inspection, fueling), whichever is larger.

4.4 Determination of the Minimum Vehicle Fleet Size Needed

The minimum number of unique vehicles (of same size) which are needed at an end node* (either end of a route) for assignment

* Intermediate nodes (or cities) along a route are excluded.

to the departures out of that node can be determined by arranging in order of time of day all the departures from and arrivals at that node, for this size of vehicle. The departure and arrival functions, $D_{ij}(t)$ and $A_{ij}(t)$, defined above are employed here in generating the overall departure and arrival functions, $D_i^r(t)$ and $A_i^r(t)$, at node i (and similar functions at j) for each set of routes assigned the same size r and having i as a terminal node. A difference $D_i^r(t) - A_i^r(t)$ represents additional vehicles that should be acquired to maintain the schedules at node i . The minimum fleet of such vehicles, NV_i^r , is the maximum difference $D_i^r(t) - A_i^r(t)$ that may occur at any time during the day. That is

$$NV_i^r = \max_t [D_i^r(t) - A_i^r(t)]^+ \quad \dots\dots (4.22)$$

Figure (4.6) is a graphical illustration of the fleet size determination procedure. The cumulative curves in the Figure are constructed for a hypothetical case of two "same-vehicle-size" routes emanating from one node, with sixteen departures being scheduled for one of them and twelve departures for the other.

The minimum fleet size of type (size) r needed for servicing the entire network, NV^r , is obtained by considering all the end nodes (i.e. both ends of each route) in the network. That is

$$NV^r = \sum_i NV_i^r \quad \dots\dots (4.23)$$

The vehicle fleet size thus determined is "minimum" in that it can just maintain the departure schedule. In practice, additional spare vehicles are needed to provide a "back-up" capacity should any of the active vehicles be delayed because of breakdowns, human errors, weather, etc., or be scheduled for maintenance. Present public transport practice is to procure a number of spare vehicles in the order of 20% of the active fleet (e.g. Ref.12). Also, implied average utilization* of the vehicle

* e.g. hours/day/vehicle.

FIGURE (4.6) - DETERMINATION OF MINIMUM FLEET SIZE OF VEHICLES TYPE r FOR DEPARTURES ALONG TWO ROUTES EMANATING FROM NODE i

fleet thus determined should not exceed a practical upper limit, otherwise the fleet size should be increased.

4.5 Passenger Accumulation in a Terminal

The instantaneous accumulation of passengers in any of the system terminals (or stations) depends on the vehicle schedules constructed above for all the services emanating from it and on the magnitude of travel demand for each of these services. The maximum possible accumulation is used to determine the space required for accommodating the passengers and their well-wishers (in particular the terminal space required for ticketing and waiting), and is determined below.

In Figure (4.7) assume that a vehicle departure k is scheduled for time t_k at a system terminal*. Passengers are expected to start arriving at the terminal, say $QSTART$ (minutes) prior to the departure time t_k and cease arriving, say $QEND$ (minutes) before the vehicle leaves the terminal. A uniform arrival rate is assumed. A curvilinear cumulative arrival curve (which corresponds to a variable arrival rate) may instead be observed. However, in recognition of the short-haul context of the transport design methodology and its much broader scope, and also due to lack of data to be used in describing a non-uniform arrival rate, a linear cumulative arrival diagram was considered adequate. The passenger accumulation diagram shown in the Figure does not include connecting (transferring) travelers who may arrive at that terminal from different destinations and will be waiting in it for the particular departure k . A more detailed analysis is required in this case as the volume of such travelers and the length of time during which they wait in the terminal depend on the origin-destination matrix, the set of links (or routes) connected to that node (terminal) and their schedules. The above simple triangular distribution can, however, be easily modified in such a case by adding a rectangular strip(s) along its base.

* All the system terminals (stations) are to be considered in a similar manner.

FIGURE (4.7)- ILLUSTRATION OF ACCUMULATION OF PASSENGERS IN A TERMINAL

FIGURE (4.8) - ASSUMED PASSENGER ACCUMULATION DIAGRAM WITH
CONNECTING PASSENGERS

with the height(s) representing the volume(s) of connecting passengers and the width(s) being equal to the length(s) of time they spent in the waiting area of the terminal, as determined by the departure and arrival schedules. Such a modified distribution is sketched in Figure (4.8).

As shown in Figure (4.7), the accumulated passenger volume represented by the ordinate VL_k is assumed to be discharged from the waiting area (to board the vehicle) at a uniform rate over an average time period of $QOUT$ (minutes). A passenger accumulation diagram typical to the one shown above is therefore associated with each departure from the terminal in question along the same route. Similar diagrams are also associated with departures along other routes except that the magnitudes of the cumulative passenger ordinates are generally different. The total number of passengers accumulated in a terminal facility at the time of maximum accumulation for departure k [Figure (4.7)] is therefore equal to its passenger load, VL_k , plus partial accumulations - at that time - for other close (in time) departures. The maximum possible accumulation, P_{max} , is found by searching over all possible departures from that terminal (i.e. over all the k 's). The procedure of determining the overall passenger accumulation in the terminal is diagrammatically illustrated in Figure (4.7) and is analytically outlined below.

$$P_{max} = \max_k \{ VL_k + \sum_r VL'_r \} \quad k \neq r \quad \dots (4.24)$$

where

r = an index for all departures from the terminal

$$VL'_r = \begin{cases} VL_r \cdot \frac{\Delta_r}{QOUT} & \text{if } \Delta_r \leq QOUT \\ VL_r \cdot \frac{(QSTART - QEND + QOUT - \Delta_r)}{(QSTART - QEND)} & \text{if } \Delta_r > QOUT \end{cases} \dots (4.25)$$

$$\Delta_r = t_r - t_k + QOUT \quad \dots (4.26)$$

$$0 < \Delta_r \leq (QSTART - QEND + QOUT) \quad \forall r \quad \dots (4.27)$$

4.6 Terminal Space Requirement

Terminal Space Required for Vehicle Storage:

The number of vehicles required to service the routes emanating from each end terminal has been determined in the preceding section for each type (size) of vehicles. Part of the space provided for vehicle accommodation is for storage and possibly maintenance of the vehicles. The minimum floor space required for sheltering a vehicle depends on its dimensions (length and width) which in turn depend on its seating capacity.

An example of how to relate the vehicle dimensions to its seating capacity is provided here for aircraft, and is used in the STOL design application presented in Chapter 8. Aircraft length-seating capacity data were compiled and are presented in Table (D.2) in Appendix D. Analysis of the data sample using linear regression yielded the following results:

$$L = 25.6 + .1265 \left(\frac{S \cdot P}{A} \right) \quad \dots (4.28)$$

$$[t = \dots (59), n = 35 \quad \text{l.o.s.} < 0.1\%$$

$$s_e = 4.4 \quad c_v = 4.6\% \quad R^2 = .99 \quad]$$

where

L = aircraft length (feet)

S = aircraft size (number of seats)

P = seat pitch (inches)

A = number of seats abreast

The goodness-of-fit of the above empirical formula is shown in Figure (4.9). This formula together with an assumed wing span and an appropriate minimum clearance measure can be used to compute the space required for an aircraft of a given seating capacity and arrangement.

The number of storage or repair tracks required for accommodating passenger trains can be determined in a similar manner. No analysis similar to that performed above for aircraft

FIGURE (4.9) - GOODNESS-OF-FIT OF THE AIRCRAFT LENGTH-SEATING CAPACITY RELATIONSHIP

was done here for trains under the assumption that a rail system design problem concerns, in most cases, service improvements and is, unlike a STOL system, of an evolutionary nature. In other words, it was assumed that existing track facilities at rail terminals will, in most design cases, be adequate for train storage.

Terminal Space Required for Passenger Accommodation:

The space required for accommodating passengers in the terminal includes the floor area required for ticketing and waiting. The waiting area should be capable of accommodating passengers and their well-wishers. Sizing of other terminal areas (such as crew rooms, management and administration offices, eating facilities and other concessions) is outside the scope of the design optimization methodology as the interest is in only those areas which are mostly affected by variation in the system design optimization variables.

The terminal space required for passenger accommodation can be easily computed by determining the maximum accumulation of passengers, as was done in the preceding section, knowing the terminal occupancy standards (e.g. square feet per person) for ticketing and waiting areas, and using empirically determined well-wisher per originating traveler factors. As will be seen in the next Chapter, the terminal space required for accommodating the vehicles and the passengers is translated into capital cost, which in turn is considered in evaluating the economic viability of the system being designed.

CHAPTER 5

SYSTEM COSTS AND REVENUES

In order to evaluate the economic consequences of selecting a given set of values of the system design optimization variables, the system costs, fare revenues, and users' cost must be measured. The total cost of a passenger transport system includes capital investment in fixed facilities (terminals and guideways) and in vehicles, in addition to the cost of operating and maintaining the system. The major part of this chapter is devoted to developing cost estimating relationships for the various system cost components in terms of the system design optimization variables defined earlier. Some of the cost components are common to all intercity public transport systems while others are mode-specific. For those cost elements which are mode-dependent, the modeling effort is focused here on short-haul air and improved rail systems. The reason for focusing on these two modes was discussed in Chapter 1. Measurement of the system revenues and users' cost is also presented here.

System costs relating to social or environmental impacts are not considered in the analysis because in addition to being very difficult to monetize, they show very little, if any, correlation with the system design optimization variables.

An attempt is made here to structure and calibrate, as far as possible, system cost estimating relationships for both STOL and passenger rail, so that they could be applied directly in the system design optimization examples presented in Chapters 8 and 9. Structuring and estimating the system cost functions in this chapter would also help appreciate the relative magnitudes of the various system cost components and the extent to which they are influenced by the system design optimization variables. Cost estimates provided here are the best available at the present time.

5.1 Terminal Cost

Part of the cost of a terminal is for providing a space sufficient enough to accommodate maximum possible accumulation of passengers (and well-wishers). Another part of the cost is for providing a vehicle storage (and repair) area for the active vehicle fleet (and spare vehicles) which service the routes, emanating from that terminal. Both the passenger accumulation and vehicle fleet size depend on the magnitude and distribution over time of day of the daily vehicle departures and arrivals at the terminal, which in turn depend, as determined in Chapter 4, on the values assigned to the system design optimization variables. A third and major portion of a terminal cost can be regarded as relating to other terminal facilities which are relatively much less dependent on the system design optimization variables. Examples of such terminal elements are: vehicle loading and unloading areas; runways and taxiways (for air transport systems); traffic control center and facilities; internal roads; terminal spaces provided for carrier operations, administration and management offices, concessions, storage lockers, security, restrooms, maintenance facilities, utilities, power equipment, and emergency services; car parking; landscaping; and fencing. Some of these terminal facilities such as concessions, lockers, and car parking may, however, be considered self-supporting in as far as their cost is concerned. A last portion of the capital investment in a terminal is the cost (or opportunity cost) of the land on which it is built. The capital investment in the system terminals could therefore be written as:

$$TINV = \sum_i [cp_i ps_i + \sum_j (cv_i \cdot sv_{ji}) + Cf_i + Cl_i] \quad \dots (5.1)$$

where

TINV = capital investment in system terminals.....(\$)

cp_i = construction cost per unit floor space
in the passenger accommodation area of
terminal i (\$/ft²)

* including ground-based navigational aids for an air system.

- ps_i = terminal space required to accommodate maximum accumulation of passengers (and well-wishers) in terminal i , as determined in Chapter 4 (ft²)
 cv_i = construction cost per unit floor space in the vehicle storage area of terminal i ... (\$/ft²)
 sv_{ji} = terminal space required to store a fleet of vehicles type j (including spares) in terminal i , as determined in Chapter 4 (ft²)
 Cf_i = "fixed" construction cost of terminal i (\$)
 = total terminal construction cost less construction cost pertinent to passenger and vehicle accommodations
 Cl_i = cost of land on which terminal i is provided (\$)

In calculating annual capital recovery of terminals investment, the land cost, Cl , should be isolated from equation (5.1) and be discounted separately because its economic life span is longer than that of the terminal, normally considered infinite.

5.2 Guideway Cost

This system cost component applies only to ground transport systems. Way link construction cost depends, among other factors, on its traffic volume, which is a function of the system design variables, and on the vehicle speed. The strength of the guideway structure and of the foundation or support for it (including the sub-soil) depend on the vehicle load, and hence its seating capacity; the number of load repetitions, and hence frequency of service and fare structure (as it affects traffic volumes); and on the vehicle speed. The guideway structural requirements, and thus its cost, are therefore related to the system design optimization variables. In rail transport, for example, the stresses developed in the rails were found to be directly proportional to train speed and daily number of train trips⁴⁴.

In terms of guideway geometrics, vehicle speed is a decisive factor in determining the horizontal and vertical alignments and has, therefore, an influence on guideway construction cost including engineering structures. Speed also has an effect on the traffic control and safety installations provided along each link and on guideway spacing.

Aggregate costs of upgrading or constructing railway lines in Canada and the United States have been shown to be significantly influenced by the design speed^{2,45,46}. Detailed relative increases in the construction cost of European railway lines due to incremental increases in design speed were also outlined for the various segments of the trackway such as track bed, track panel, signaling equipment, safety devices for level crossings and, with electric traction, the catenary⁴⁷.

Capital investments in railway tracks for the Toronto-Ottawa-Montreal network, on which the system design optimization example application is based are detailed in Chapter 9 for a number of track speed and capacity options.

5.3. Vehicle Cost

The cost of a vehicle depends, among other factors, on the transport technology-based system design optimization variables defined earlier. Although there is a host of quality of service considerations and other vehicle design factors which partially influence the cost of the vehicle, the main modeling concern here is to structure a vehicle cost estimating relationship in terms of the vehicle-related design optimization variables such as the speed and seating capacity of the vehicle.

Part of the cost of a vehicle can be attributed to building its body and is thus proportional to its seating capacity. Another part of the vehicle cost relates to its power requirement. For a vehicle of given size (seating capacity) whose power requirement is governed by its cruise speed capability, the power required is cubic in cruise speed since the resistance to its motion is generally quadratic in speed. The portion of the cost of a vehicle attributable to its power requirement can

thus be regarded as cubic in its cruise speed. A third part of the cost of a vehicle may represent its base cost and can thus be regarded as "fixed" in as far as either the speed or seating capacity is concerned. The cost of a vehicle may thus be modeled by a generalized relationship of this form:

$$VPRICE = a \cdot S + b \cdot V^3 + c \quad \dots (5.2)$$

where

VPRICE = price of one vehicle (\$)

S = vehicle seating capacity

V = vehicle cruise speed (mph)

a, b, and c are constants to be estimated, for a given mode, by statistical calibration.

Equation (5.2) may take different forms, particularly for different transport modes, or vehicle types, as they have different power requirements and the physical laws involved are not the same for each of them. However, the reasoning behind each of the vehicle cost components in that equation appears plausible, and in the absence of sufficient "modal" data to determine which of many forms is best for a given "mode", the above form is considered satisfactory if statistically estimated for each vehicle type separately..

5.3.1. Vehicle Research and Development Cost

Before a "new" transport vehicle can be put into operation, its performance, safety, and reliability must be thoroughly proven. This implies a research program, an engineering development program, and a vehicle test program. For relatively slight state-of-the-art advances, the test program will be the major cost item. But for more advanced systems such as Tracked Air Cushioned or Magnetically Levitated vehicles, research and engineering become more important.

The research costs are very much mode-specific. The essential research projects are to be identified and the resource requirements in terms of engineering man-hours are to be determined and translated to dollar costs.

The development costs include all scientific and engineering activities, development fabrication and tooling, and development testing within the contractor's facilities. Equation (5.3) below was statistically developed for estimating development costs for aircraft and high-speed trains (Turbo trains) in the Northeast Corridor Project, NECTP, of the United States^{48,49}:

$$VD = k \cdot V^{1.4} \cdot WE \quad \text{..... (5.3)}$$

where

VD = vehicle development cost (\$)
 V = vehicle cruise speed (mph)
 WE = vehicle empty weight (lbs)
 k = vehicle development cost factor whose value depends on the transport mode and the extent of development involved.

The test vehicles cost includes the production and assembly of the test vehicles required, test facility and actual test and evaluation expenses.

5.3.2 Development of a STOL Aircraft Cost Estimating Relationship

To illustrate numerically the foregoing vehicle cost concepts and assumptions, the calibration of an aircraft price estimating relationship is attempted here. In section 5.3.3, estimation of the cost of train sets will be also discussed.

In Table (D.3), Appendix D, prices of a number of existing aircraft are presented together with the corresponding aircraft cruise speeds and number of seats. Since the seat pitch is variable from one airplane to another, a desirable seating capacity measure for all airplanes was taken as the product of

the number of seats and the seat pitch. The vehicle cost estimating relationship given by equation (5.2) was statistically estimated by regression analysis using the data of Table (D.3) and the aircraft price, VPRICE (in millions of 1974 dollars), was found to be:

$$\text{VPRICE} = .6089 \frac{S \cdot P}{1000} + .0184 \left(\frac{V}{100} \right)^3 + 0.404 \quad \dots (5.4)$$

$$[t=(5.7) \dots (9.5), n=13 \quad \text{l.o.s.} < 0.1\%,$$

$$s_e = 0.221 \quad c_v = 7.2\% \quad R^2 = .99]$$

where

V = cruise speed of airplane (miles per hour)

S = number of seats

P = seat pitch (inches)

The goodness-of-fit of this equation is further illustrated graphically in Figure (5.1).

Since equation (5.4) was estimated using existing aircraft data, it may only be used to predict the price of an existing conventional aircraft of given speed-seating capacity combination. STOL passenger aircraft, while being in the prototype stage, have some unique features as compared to conventional airplanes, such as the capability to fly steep approaches and rapid climb-outs, which are direct consequence of their short field performance, and significantly reduced noise levels. Development of North American STOL passenger aircraft is underway in Canada (DeHavilland's Dash 7 and Augmentor Wing) and in the United States (NASA's MD 188, 210 E, 210 G, 210 M). STOL aircraft prices are, therefore, expected to be higher than those of comparable* conventional airplanes due to STOL development costs. This is confirmed by comparing the price of the Dash 7 to that of a comparable* conventional airplane.

* in terms of speed and seating capacity.

FIGURE (5.1) - GOODNESS-OF-FIT OF THE AIRCRAFT PRICE ESTIMATING RELATIONSHIP

A 1974 price of \$2.8 millions was quoted for the Dash 7 airplane⁵⁰ (also, a reported⁵¹ 1975 price is \$3.0 millions). This STOL airplane has 50 seats at 32 inches pitch, a maximum cruise speed of 281 mph, and an empty weight of 25,520 pounds⁵². These data suggest that the above price of the Dash 7 is higher than that of a comparable* conventional aircraft, as predicted by equation (5.4). Attributing the difference in price to STOL development cost and, hence, using equations (5.3) and (5.4), the k-factor in equation (5.3) was estimated to be 0.0148. An approximate 1974-price estimating relationship for STOL airplanes may thus be written as:

$$VPRICE = .6089 \left(\frac{S \cdot P}{1000} \right) + .0184 \left(\frac{V}{100} \right)^3 + .404 + (.0148 V^{1.4} \cdot WE) / 10^6 \quad \dots (5.5)$$

Assuming a price escalation rate of 10% from 1974 to 1975, equation (5.5)' can be written in terms of 1975 dollars as follows:

$$VPRICE = .6698 \left(\frac{S \cdot P}{1000} \right) + .02024 \left(\frac{V}{100} \right)^3 + .4444 + (.0163 V^{1.4} \cdot WE) / 10^6 \quad \dots (5.5)$$

Since it is desired to relate the vehicle cost to its cruise speed and seating capacity variables, the empty weight of the STOL airplane, WE, which appears in the equation above, should be expressed in terms of its seating capacity. A direct relationship is expected to exist between these two variables because the larger the size of a vehicle, the heavier is its own weight. Aircraft data were compiled for estimating this relationship and are presented in Table (D.4), Appendix D. Linear regression analysis was performed on the data sample and the least-squares fitting equation is given below.

$$WE = 13.91 S \cdot P + 4113 \quad (\text{pounds}) \quad \dots (5.6)$$

$$\begin{aligned} [t = (38.3), n=24, & \quad 1.o.s. < 0.1\% \\ s_e = 2254 & \quad c_v = 6.6\% \quad R^2 = .99] \end{aligned}$$

* in terms of speed and seating capacity.

The goodness-of-fit of this equation is illustrated graphically in Figure (5.2).

5.3.3 Estimating the Cost of a Train Set

Since the system design optimization methodology could be applied to air as well as to ground transport modes, estimation of the cost of a train set is also discussed.

Depending upon the train speed and the number of cars per train, the horsepower - and hence the number of locomotives (of given horsepower rating) - required to move the train at that particular speed on a given alignment can be determined. Following the same argument of looking at the vehicle cost as being comprised of mainly power cost and seating capacity cost, the train power cost would be represented here by the cost of the required number of locomotives while the seating capacity cost would be represented by the cost of the set of cars (of given seating capacity) in the train.

Rail data exist which relate the cost of a train locomotive to its horsepower capability. Equations (5.7) and (5.8) below were developed for estimating diesel-electric locomotive cost in the NECTP⁵³:

$$\text{CLOC} = 1235 (\text{HP})^{.67} \quad \dots (5.7)$$

$$[n=24 \quad s_e=25,100 \quad c_v=10.3\% \quad R^2=.97]$$

or

$$\text{CLOC} = 2580 (\text{HP})^{.48} (\text{NA})^{.45} \quad \dots (5.8)$$

$$[n=24 \quad s_e=11,000 \quad c_v=4.5\% \quad R^2=.99]$$

where

CLOC = cost of a diesel-electric locomotive ... (1970 Dollars)

HP = locomotive horsepower

NA = number of locomotive axles.

Average locomotive cost per horsepower is also reported in the literature^{54,55} for all-electric and diesel-electric locomotives.

FIGURE (5.2)- GOODNESS-OF-FIT OF THE AIRCRAFT EMPTY WEIGHT ESTIMATING RELATIONSHIP

The cost of a train car depends, in addition to the car seating capacity (or empty weight), on a host of other factors such as train type (electric, diesel-electric, turbo), car interior design, suspension system, capability of banking along curves, ride comfort, and other quality of service considerations. For a given car design and number and type of options specified by the purchaser, an average cost per car can be estimated⁵⁵.

In the rail example application presented in Chapter 9, use of the Canadian LRC train was assumed. This train is presently at the marketing phase and its price (per locomotive and per car) was made available⁴⁵. No additional costs for Research or Development were therefore considered in the analysis.

5.4 System Operating Cost -- Air Transport Mode

Because the system operating costs are, to a large extent, mode-specific, an attempt is made here to define operating cost estimating relationships for both air and ground (rail) transport modes, separately. In this section the operating cost functions for air (particularly STOL) will be presented while those for rail will be described in the following section.

The STOL operating costs are developed here within the framework of the Air Transport Association, ATA, and the Research Analysis Corporation, RAC, methods^{56,57}, which are widely used in estimating air carriers operating costs. The cost equations reported in these two methods were obtained by regression analyses using actual carriers operating costs.

The STOL operating costs can be broken down into the following components:

- Flight Personnel:
 - Flight Crew
 - Cabin Attendants
- Aircraft Maintenance:
 - Maintenance Materials and Labour
 - Maintenance Burden
- Aircraft Servicing:
 - Aircraft Inspection, Fueling, and Cabin Cleaning
 - Aircraft Control

- Passenger Servicing*
 - Ticket Sales and Service Promotion
 - In-Flight Passenger Food
- Aircraft Fuel and Oil Consumption
- Aircraft Insurance
- Depreciation and Maintenance of Ground Property and Equipment
- Maintenance and Administration of STOL Ports
- General and Administrative Costs.

No grouping of the above system operating cost elements into "Direct" and "Indirect" operating costs is made here, since the system design optimization is to be based on its "Total" cost. If the system design optimization is operator-based, the operating costs incurred by the operator (system carrier) are the same as those listed above but with the STOL port maintenance and administration cost replaced by landing fees and other terminal charges borne by the carrier.

The cost associated with each of the above operating cost components will be expressed below in an equation form with its variables being directly or indirectly related to the system design optimization variables. The ATA and RAC formulas will be made use of in deriving these equations. Costs realized in operating the Montreal-Ottawa STOL experiment will also be used to estimate some of the coefficients which appear in the operating cost equations.

Flight Crew Cost:

This cost was estimated by ATA through reviewing crew contracts and accounting for welfare, training, travel expenses, and crew utilization factors. The crew cost estimating relationship derived by ATA treats part of this cost as being related to the airplane's cruise speed and maximum take-off gross weight³⁹.

* Baggage handling costs are not included here under the assumption that the majority of STOL passengers will require little or no assistance with their baggage.

Equation (5.9)' below gives the crew cost per block hour for domestic subsonic two-man crew airplanes, as derived by ATA and later updated to 1974 by Boeing³⁹.

$$FCREW = 3.587 (V \cdot TOGW)^{.3} + 32.664 \quad \dots (5.9)'$$

where

FCREW = flight crew (two-man) cost....(1974 \$/block hr.)

V = cruise speed(mph)

TOGW = maximum take-off gross weight(1000's lbs)

The maximum take-off gross weight is indirectly related to the seating capacity of the airplane as it is equal to its empty weight plus the weight of its crews, passengers, and fuel, which are all functions of the seating capacity. Calculation of the take-off gross weight is described later in this section.

Assuming a 10% wage escalation rate* from 1974 to 1975, the above flight crew pay when expressed in terms of 1975 dollars would be:

$$FCREW = 3.945 (V \cdot TOGW)^{.3} + 35.93 \quad \dots (5.9)$$

Cabin Attendants Cost:

This cost component is attributed to passenger services related to passenger comfort, safety, and convenience while being in flight. It includes all costs associated with stewardesses or other cabin crews. A 1967 rate of \$10 per block hour per attendant was reported⁵⁸. A STOL flight attendant requirement of one attendant for every 50 seats⁵⁹ was also suggested. Thus, in terms of constant 1975 dollars*, the cabin attendants cost can be estimated by equation (5.10) below:

$$CABIN = 20.60 <S/50> \quad \dots (5.10)$$

where

* Price and wage indices are contained in Appendix E.

CABIN = cabin attendants cost(\$/block hr.)
 S = number of seats
 <...> = quantity between brackets is rounded up to
 next highest integer

Aircraft Maintenance -- Materials and Labor:

The term "maintenance" as presented in the ATA method includes material and labor costs for inspection, servicing, and overhaul of the airframe and its accessories, engines, propellers, instruments, radio, etc. Equations (5.11) and (5.12) below present the ATA maintenance formulations relevant to a STOL system.

Airframe Maintenance Cost:

$$AMC = [6.24 \times C_a \times N_f + 3.08 \times C_a \times N_{fh}] + \\ [R_l \times (0.05 \times W_a + 6 - \frac{630}{W_a + 120}) \times (N_f + .59 N_{fh})] \dots (5.11)$$

Engines Maintenance Cost:

$$= [20 \times C_e \times N_f + 25 \times C_e \times N_{fh}] + \\ [R_l \times (0.3 N_e + 0.03 \frac{T}{1000}) N_f + R_l \times (0.65 N_e + 0.03 \frac{T}{1000}) N_{fh}] \dots (5.12)$$

where

AMC = average airframe daily maintenance cost(\$)
 EMC = average engines daily maintenance cost(\$)
 C_a = airframe cost(\$ millions)
 = cost of complete airplane less engines
 C_e = engines cost(\$ millions)
 = cost of complete airplane less airframe
 W_a = airframe weight(1000's lbs)
 = empty weight of airplane less engines
 N_e = number of engines per airplane

- T = total airplane sea-level static thrust - lbs
 (or total sea-level shaft horsepower for
 turboprops - hp)
 N_f = number of daily flights
 N_{fh} = number of daily flight-hours
 R_l = rate of maintenance labor (\$/man-hour)

The first square-bracketed quantity in each of the above two equations represents the maintenance portion attributable to materials cost while the second quantity reflects the labor cost involved.

Again, in order to express the above aircraft maintenance cost relationship in terms of variables directly related to the system design optimization variables, airframe weight and cost data furnished by DeHavilland Aircraft³⁹ for ten airplanes including STOL aircraft were analyzed and resulted in the following two simple relationships:

- ratio of airframe weight to the airplane empty weight ranged from 0.767 to 0.847 with a mean value of 0.813, and
- ratio of airframe price to airplane price ranged from 0.761 to 0.859 with a mean value of 0.808.

Data were also compiled for relating the aircraft horsepower to its total weight and are presented in Table (D.5), Appendix D. As indicated in the Table, the ratio of shaft horsepower to maximum take-off gross weight for turboprops ranges from 0.096 to 0.107 with a mean value of 0.102.

Thus, combining these three mean values with equations (5.11) and (5.12) and assuming a 4-engine STOL airplane, the maintenance cost relationships given by these two equations can be rewritten, for a given aircraft type (size), as follows:

$$AMAINM = APRICE[8.88 N_f + 7.29 N_{fh}] \quad \dots (5.13)$$

$$AMAINL = R_L [(7.2 + .0031 \text{ TOGW} + c)N_f + (6.14 + .0031 \text{ TOGW} + .59c)N_{fh}],$$

.... (5.14)

$$\text{where } c = 0.041 \text{ WE} - \frac{775}{\text{WE} + 148}$$

where

AMAINM = aircraft maintenance material cost (\$/day)

AMAINL = aircraft maintenance labor cost (\$/day)

APRICE = aircraft price (\$ millions)

TOGW = maximum take-off gross weight (1000's lbs)

WE = aircraft empty weight (1000's lbs)

A 1974 maintenance labor rate, R_L , of \$7.90 per man-hour is reported by DeHavilland³⁹. A 1975 value of \$8.70 per man-hour is used in the STOL example application presented in Chapter 8.

Aircraft Maintenance Burden:

Maintenance burden is defined by the Civil Aeronautics Board as "including all overhead or general expenses which are specifically identified with activities involved in periodic maintenance operations and the maintenance and repair of property and equipment, including the cost of direct labor, materials and outside services. It also includes expenses specifically related to the administration of maintenance stocks and stores, and the keeping of pertinent maintenance operations records, and the scheduling, controlling, planning and supervision of maintenance operations"⁶⁰.

The cost attributable to maintenance burden is taken in practice as a ratio of the aircraft maintenance cost estimated above. The ATA method⁵⁶ suggests that the maintenance burden be calculated at 1.8 times the aircraft maintenance labor cost.

Aircraft Servicing:

This cost item accounts for aircraft visual inspection, routine checking, fueling and servicing, and cabin cleaning. The formula used in practice to estimate this cost is that of RAC⁵⁷ which relates the aircraft servicing cost to its maximum take-off

gross weight which is, in turn, related to the seating capacity of the aircraft. The daily servicing cost, ACSERV, of all flights of a given type (size) of aircraft is:

$$\text{ACSERV} = c \cdot \text{TOGW} \cdot N_f \quad \dots (5.15)'$$

where

TOGW = maximum take-off gross weight (1000's lbs)

N_f = daily number of flights

c = unit servicing cost (\$/1000 lbs/flight)

= 0.64 (\$/1000 lbs/flight)⁵⁷ (in 1967 dollars)

Servicing cost experienced for the DHC-6 aircraft* used in the Montreal-Ottawa STOL demonstration project amounted to an average of \$17,700 per month over 1200 flights⁴³; thus resulting in an average value for the unit servicing cost, c , equal to \$1.18 in 1974 dollars, or about \$1.30 in terms of 1975 dollars**. The 1967-value of c which was estimated by the RAC method would, upon escalation to 1975 using the appropriate indices in Appendix E, be about \$1.32; thus indicating a very close agreement between extrapolated RAC values and data obtained from present STOL demonstration. In terms of 1975 dollars, equation (5.15)' can be written as:

$$\text{ACSERV} = 1.30 \text{ TOGW} \cdot N_f \quad \dots (5.15)$$

Aircraft Control:

This cost component involves communications, flight planning, meteorology, crew scheduling and related activities and administration costs. A constant cost of \$16.13 per flight is given in the RAC method⁵⁷ for 1967. Upon escalation** to 1975 the aircraft control cost becomes:

$$\text{ACCONT} = 33.23 \times N_f \quad \dots (5.16)$$

* has a maximum take-off gross weight of 12,500 lbs³⁹.

** Price and wage indices are contained in Appendix E.

where

ACCONT = aircraft control cost (\$/day).

N_f = number of flights per day

Passenger Servicing -- Ticket Sales and Service Promotion:

It reflects the cost of processing passengers at airports, reservations & sales, and advertizing & publicity of passenger services. The cost of such activities can be assumed porportional to the number of passengers handled per unit time. This cost component amounted to \$26,000 per month for the Montreal-Ottawa STOL demonstration, where an average of 7200 passengers were carried each month⁴³. A 1974 average unit cost of \$3.61 per revenue passenger therefore results. The daily passenger servicing cost, PXSERV, expressed in terms of 1975 dollars* can thus be written as:

$$PXSERV = 4.00 PAX \quad \dots (5.17)$$

where

PAX = number of passengers carried per day

Passenger Servicing -- In-Flight Food:

STOL passenger food may be assumed to include only the cost of a snack⁵⁹. In the STOL system design application presented in Chapter 8, a 1975 food cost of 70¢ per passenger was arbitrarily assumed.

Aircraft Fuel and Oil Consumption:

The oil consumed by an airplane may be left out of account since its magnitude is very small** relative to the amount of fuel consumed, and also in recognition of uncertainties in fuel prices.

Although the rate of fuel consumed by an airplane depends on its particular design, there are common variables which affect

* Price and wage indices are contained in Appendix E.

** about 0.135 pounds of oil/hour/engine⁵⁶.

this rate for aircraft in general. Among these variables are the total weight and speed of the airplane. The higher the aircraft speed the greater is the rate of fuel consumption. The same trend applies to increases in the weight of the aircraft. The aircraft fuel consumption can therefore be modeled by the following relationship:

$$RF = a \cdot V^b \cdot (TWT)^c \quad \dots (5.18)$$

where

- RF = rate of fuel consumption -- weight of fuel consumed per hour
 V = aircraft speed
 TWT = aircraft total weight
 a, b, c = constants to be estimated.

Actual aircraft fuel consumption data were compiled for twenty different* airplanes to estimate statistically the above relationship. Only fuel consumed per hour while cruising at a certain speed and for a given aircraft take-off gross weight was reported. The data appear in Table (D.5), Appendix D. Multiple linear regression analysis of these data yielded the following fuel consumption equation together with its associated statistical measures.

$$RF = .11184 V^{1.282} \cdot (TOGW)^{.636} \quad \dots (5.19)$$

$$[t = \dots (8.6) \dots (10.0), n=20 \quad 1.o.s. < 0.1\%$$

$$s_e = .129 \quad c_v = 1.6\% \quad R^2 = .98$$

in the transformed linear (log) form]

where

- RF = rate of fuel consumption (pounds per hour)
 V = aircraft cruise speed (miles per hour)
 TOGW = aircraft take-off gross weight (1000's lbs)

* in terms of speed and total weight.

Although the rate of fuel consumption during the climbing portion of the aircraft mission may be higher than that experienced during other segments of the mission profile, yet extra fuel used up while climbing could be offset by fuel savings while descending. Thus an overall average rate of fuel consumption (or block fuel consumption rate) is approximately equal to the rate during the cruising segment of the mission. The calibration data, and hence the estimates obtained by using the above equation are therefore regarded as representative of block fuel consumption.

Data on "block" fuel consumption were available⁶¹ for only a limited number (five) of airplanes including DeHavilland STOL and other similar (competitive) aircraft. The variation within and size of this sample did not permit estimating a statistically reliable expression for block fuel consumption. However, an attempt was made here to apply the above equation to reproduce and then compare the reported block fuel consumption rates of those five airplanes. The values computed and those reported are presented in Table (D.6), Appendix D. As the Table shows, the two sets of Figures are in close agreement.

This rather limited test strengthens the structural accuracy* of the above equation and suggests its appropriateness for predicting block fuel consumption rates for different values of aircraft speed and take-off gross weights. The predictive accuracy** of the equation can be judged by assessing its associated statistical measures which were given earlier. In addition to these measures, the goodness-of-fit of the equation is illustrated in Figure (5.3).

The take-off gross weight, TOGW, which appears in the preceding equations, can be considered here as composed of:

* "Structural accuracy" of an equation refers to the particular form it takes and the values estimated for the coefficients it contains.

** "Predictive accuracy" of an equation relates to its ability to produce answers significantly close to those observed under the same set of conditions.

FIGURE (5.3) - GOODNESS-OF-FIT OF THE FUEL CONSUMPTION ESTIMATING RELATIONSHIP

- empty weight of the airplane, as expressed by equation (5.6)
- weight of the flight crew: $(2 \times @ 170 \text{ lbs})^{61}$
- weight of the cabin attendants: $(@ 130 \text{ lbs per attendant})^{61}$
- weight of passengers aboard: $(@ 190 \text{ lbs per passenger, including baggage})^{61}$
- weight of fuel carried: block fuel plus fuel reserve. The block fuel required is estimated by equation (5.20). The ATA method⁵⁶ recommends that the fuel reserve for domestic flying be enough to fly for one additional hour as well as to fly and land at an alternate airport 200 nautical miles distant.
- additional weights (e.g. newspapers, magazines, food, beverages, etc.)

Additional fuel consumed due to any cargo carried in the airplane is left out of account under the assumption that the cost of the extra fuel consumed is recovered from cargo shipping revenues.

The fuel consumed per day in servicing any of the network links can be determined by first calculating the consumption rate, RF , for the type of aircraft servicing this particular link, and then multiplying this rate by the block time and daily flights along the link. That is

$$BFUEL_i = RF_i \cdot t_i \cdot N_{f_i} \quad \dots (5.20)$$

where

- $BFUEL_i$ = daily block fuel for link i (lbs/day)
- RF_i = rate of fuel consumption by aircraft assigned to link i (lbs/hr.)
- t_i = block time (one-way) along link i ... (hours)
- N_{f_i} = number of daily flights (two-ways) on link i

The ATA method⁵⁶ suggests augmenting the block fuel requirement thus estimated by a factor of 1.02 to account for non-revenue flying fuel consumption.

The total amount of fuel consumed in servicing the entire network in a given day can be determined by adding up the daily fuel consumed in servicing each of its links. The fuel cost can then be estimated by multiplying this fuel requirement by the unit price of fuel. Future estimates of the unit price of fuel are uncertain. The results obtained in Chapters 8 and 9 are based on a reported⁵¹ 1975 fuel price of 50¢/imperial gallon*.

$$CFUEL = PFUEL \sum_i BFUEL_i \dots\dots (5.21)$$

where

CFUEL = fuel cost per day (\$/day)

PFUEL = unit price of fuel (\$/lb)

BFUEL_i = daily fuel requirement for link i,
as given by equation (5.20) (lbs/day)

Aircraft Insurance:

The yearly hull insurance cost is taken in practice as a percentage of the initial aircraft price. The percentage suggested by ATA⁵⁶ is 2%, which is commonly applied in practice.

Ground Property and Equipment:

This cost item involves direct maintenance, maintenance burden, and depreciation of ground property and equipment, and is expressed in practice as a ratio of the aircraft direct maintenance expense. The value given in the RAC method⁵⁷ is 59.7% of the aircraft direct maintenance labor cost.

General and Administrative Costs:

This cost component includes a host of expenses incurred in performing activities which contribute to more than a single operating function. It is a common practice to express this

* One imperial gallon = 7.7 pounds of JP-4 aviation fuel⁵⁶.

cost as a percentage of the total operating costs presented so far. A percentage of 4.75 was furnished in the RAC method⁵⁷, while a close value of 5.65% was also reported by the Planning Research Corporation⁵⁸. Canadian regional air carrier experience⁵¹ shows an in-between value of 5%. The STOL system design results presented in Chapter 8 are based on the latter percentage.

Maintenance and Administration of STOL Ports:

This cost component involves:

- maintenance of the terminal building
- allocated expenses which include systems such as the electrical, water, heating and air conditioning, sanitary sewers and service equipment
- airport management and administration and general expenses
- custodial services
- guard services.

Maintenance and administration cost of STOL ports was estimated in a McDonnell Douglas V/STOL study⁶² for different terminal sizes. For a typical 4-gate positions terminal, this cost would amount, according to that study, to about \$700,000 per year per terminal when expressed in terms of 1975 dollars*.

5.5 System Operating Cost -- Rail Transport Mode

In a manner similar to the STOL system operating cost break-down and estimation, the rail system operating cost components will be individually discussed and costed in this section based on recent railway experience in North America. The cost functions discussed here are developed in the context of improving the level of service of existing railway systems. For cost elements which are train-specific, a diesel-electric technology (e.g. the Canadian LRC advanced trains) is assumed, mainly because of cost data availability for this type of trains.

* Price and wage indices are contained in Appendix E.

Train Crew Cost:

The question of the number of men in the train and engine crew is of current debate among railway management, labor, and others who are interested in the economics of improved passenger rail systems⁴⁶. Sizing of the train crew is outside the scope of this Chapter. Crew cost is based here on the traditional North American 5-man crew size, although most European railways operate passenger trains with a much less crew size⁴⁶.

Passenger rail crew cost is expressed in practice on a per train-mile basis, and it should therefore be possible to calculate the cost of manning trains on any route by merely knowing the mileage involved. Average train crew cost based on five main routes in the United States amounted to \$1.45 per train-mile in 1971⁴⁶. Recent Canadian passenger rail experience indicates an average 1974 crew cost of about \$1.80 per train-mile⁴⁵, and a 1975* estimate could thus be taken as \$2.00/train-mile. These estimates do not include passenger service crew costs under the assumption that such costs are recovered by service revenues.

Locomotive Maintenance Cost:

The maintenance cost of a locomotive expressed in terms of its horsepower and the mileage performed was estimated by the Canadian Institute of Guided Ground Transport⁶³ (CIGGT) at 15¢/1000HP-mile, in 1974 dollars. A 1975 value* of 16.5¢ can thus be estimated.

Locomotive Servicing Cost:

Locomotive servicing includes lubrication, water and other supplies, and engine house expenses, and is related to the number of times a locomotive is dispatched or serviced enroute. A 1971 unit cost of 7.1¢/locomotive-mile was reported in a recent United States Improved Rail Study⁴⁶, while a corresponding 1973 figure of 8.5¢/locomotive-mile was furnished in the Newfoundland Corridor

* Price and wage indices are contained in Appendix E.

Transportation Study⁶⁴. A 1975* estimate may thus be taken as 10.5¢/locomotive-mile.

Car Maintenance Cost:

Car maintenance is higher when operating at higher speeds due to the increased shock-absorbing requirements on the truck and draft gear mechanisms. In terms of 1971 dollars, car maintenance cost was estimated in the U.S. Improved Rail Study⁴⁶ at 9.8 and 20.5¢/car-mile at speeds of 80 and 120 miles per hour, respectively. The corresponding estimates furnished in the Newfoundland Study⁶⁴ are 11.7 and 24.4¢/car-miles, in 1973 dollars. In the rail system design example application presented in Chapter 9, two speeds are considered: 95 and 120 miles per hour. Based on the above estimates and the cost indices given in Appendix E, car maintenance cost at these two speeds expressed in 1975 dollars were taken as: 20 and 30¢/car-mile.

Car Servicing and Train Supplies:

This expense category involves cleaning cars, car inspection, lubricating cars; provision of supplies and laundry, etc. Estimates available for this cost element are furnished on a per car-mile basis and are as follows: 5.5¢ (1971)⁴⁶, 6.6¢ (1973)⁶⁴, and 7.0¢ (1974)⁶³ per car-mile. A 1975 estimate can thus be taken as 8¢/car-mile.

Train Dispatching Cost:

The dispatching workload is a function of the number of trains, relative speeds, and the resulting number of meets, overtakes, and other situations requiring activity by the dispatchers. The speed differential among trains creates more overtakes, and the time cost of a crossover movement or slowing for a restricting signal becomes much more critical. Thus the planning burden on the dispatcher increases significantly, and dispatching cost attains a stronger variability relationship to the number of trains⁴⁶. A 1975 cost of about 16¢/train-mile was calculated based on a reported 1971 value of 10.7¢/train-mile⁴⁶ and the cost indices furnished in Appendix E.

* Price and wage indices are contained in Appendix E.

Train Fuel Consumption:

Ideally, fuel consumption under various operating conditions, for each route segment, can be calculated for a specific locomotive using the "train performance calculator". In the absence of such capability an average specific fuel consumption rate (lbs/hp-hour) can be used⁴⁶. Specific fuel consumption of diesel-electric locomotives averages about 0.4 lbs/hp-hr whereas the turbo trains consume around 0.78 lbs/hp-hr under similar train seating capacity conditions⁵⁵. LRC fuel consumption data furnished by its manufacturers⁴¹, and confirmed during its test in Pueblo, Colorado⁶⁵, were best fit ($R^2 = .99$) by the following relationship which illustrates the improvement in fuel consumption at larger horsepower outputs as a result of higher diesel engine efficiency.

$$FH = .907(HP)^{.886} \quad \dots (5.22)$$

$$[t = \dots (218), n=14 \quad \text{l.o.s.} < 0.1\%,$$

$$s_e = 0.012 \quad c_v = 0.21\% \quad R^2 = .9998$$

in the transformed linear (log) form]

where

FH = fuel consumed by the LRC locomotive per hour(lbs)

HP = locomotive horsepower output(gross horsepower)

Fuel consumed by an LRC locomotive while idling is shown to be about 70 lbs/hr⁴¹.

The fuel consumed by a train in one trip can thus be computed from the horsepower developed by each locomotive in the train, the running time corresponding to each horsepower level, and the time spent idling. That is:

$$F = .907 \sum_j [(HP)_j]^{.886} \cdot T_j + 70 T_{id} \quad \dots (5.23)$$

where

F = fuel consumed per locomotive per trip(lbs)

$(HP)_j$ = horsepower developed by the locomotive during running time interval j of duration T_j hours

T_{id} = time spent idling per trip(hours)

Trackway Maintenance Cost:

Maintenance of a rail trackway involves the track itself (rails, fasteners, ties, and ballast), the signalling system, and the routeway. In terms of the system design optimization variables, the maintenance costs of the tracks increase as the speed, weight, and frequency of trains increase. Increased track maintenance costs at high speeds are due to the adherence to the much more stringent track geometry tolerance requirements for safe and comfortable operation at high speeds. Heavy trains cause higher stresses and wear and tear in the tracks. This effect is further amplified by the number of times the train passes over the tracks (i.e. frequency of service). In the U.S. Northeast Corridor Transportation Studies⁶⁶, the track maintenance cost was developed for different guideway concepts, of which equation (5.24) is for continuously welded rail on concrete ties and in terms of 1970 dollars:

$$C = 1303 (MGT)^{.585} \cdot (.59 + .0022 v^{1.3}) \quad \dots (5.24)$$

where

C = annual track maintenance cost ..(dollars/track-mile)

MGT = annual millions of gross tons carried on the track

v = average train speed(miles per hour)

An absolute value for the cost of maintaining a rail signalling system was not available. Incremental signal maintenance cost was estimated, however, for rail service improvement to speeds of up to 120 mph along a number of main corridors* in the United States⁴⁶. The estimated increased signal maintenance cost is primarily for the added circuits for additional signal aspects, grade crossing protection, and automatic cab signals, and was shown to average about \$620/track-mile/year (1971 dollars). Although this estimate represents the "incremental" cost of signal maintenance, yet, it could be used in this optimization model since the rail design problem involves, in most cases, improvement of an existing railway system.

* Present maximum speed is 75 miles per hour⁴⁶.

To get the total right-of-way maintenance cost, the routeway related costs must be added to the track and signal maintenance costs. Routeway maintenance involves drainage and erosion control, vegetation control, litter removal and ditching clean-up. The annual routeway maintenance cost was estimated at \$1500/track-mile (1970 dollars) for the high speed rail alternatives considered in the U.S. Northeast Corridor⁶⁷.

An annual total trackway maintenance cost per track-mile can thus be written in terms of 1975 dollars (using the appropriate cost (materials and labor) indices provided in Appendix E) as follows:

$$TKMAIN = 2000 (MGT)^{.585} \cdot (.59 + .0022 v^{1.3}) + 3350 \dots (5.25)$$

where

TKMAIN = annual total trackway maintenance
cost (\$/track-mile)

MGT and v are as defined for equation (5.24)

Switching Costs:

Train switching activities include moving the trains to and from storage or repair tracks, turning the trains, and changing the consists. These are performed at the main (or end) terminals by switching crews and switch engines. Reliable switching cost data were not available for use in the present investigation. In the railway example application presented in Chapter 9, trains are assumed to be provided with front and rear locomotives. Train switching was not, therefore, considered. Provision of a locomotive at each end of the train alleviates the need for turning the trains or using switch engines to pull them to or from the loading tracks. The train consist was not assumed to be changed on a day-to-day basis of operation.

Station Costs:

This cost category comprises those personnel providing the information, reservations, ticketing, and baggage handling, as well as station management. It also includes the cost of station maintenance and utilities.

The most basic determinant of the number of station employees for each work shift is the peak period boarding passenger volume. The number of employees required on each trick is dependent on the processing time per passenger, the percentage of passengers arriving with tickets, and the percentage of passengers to be processed within a critical time period before the train departure. The following equation was developed for estimating the number of station ticketing personnel in the U.S. Improved Rail Study⁴⁶.

$$NE = (t_p/t_{cr}) (p_{cr}) (1-p_t) (P_m) \quad \dots (5.26)$$

where

- NE = number of ticketing employees required for processing passengers
- t_p = average time to process one passenger(minutes)
- t_{cr} = critical time period before train departure .(minutes)
- p_{cr} = fraction of passengers arriving within the critical time period, t_{cr}
- p_t = fraction of passengers arriving with tickets
- P_m = maximum number of departing passengers for which manning level is being planned.

For example, if 50% of departing passengers arrive within 20 minutes, all requiring tickets, and that an average processing time per passenger is 2 minutes, the required number of employees would, according to the above equation, be $.05 P_m$. Practically, there should not be less than two employees⁴⁶, so that processing of all passengers is not unreasonably delayed when ticketing of a single passenger involves some special problem that might take a substantial amount of time.

A station master position is usually required. It may also be desirable to have a gateman to control access to the trains, display train information, and direct passengers.

In terms of 1971 dollars, the pay rate for the station employees and gatemen was estimated at \$40 per person/shift, while

the station master's rate was \$54/day/shift⁴⁶. Assuming two shifts per day and using the wage rate indices given in Appendix E, the daily cost of station personnel, CSTN, in a rail terminal, indexed to 1975, would thus be:

$$\text{CSTN} = 280 + 120 \text{ NE } \dots (\$/\text{terminal}/\text{day}) \dots (5.27)$$

Baggage handling in the station involves two basic categories: one is that of assistance to the passenger in movement of his baggage within the station facility, the other is checked baggage system for movement between terminals. No data were available to estimate a meaningful baggage cost estimating relationship. Assuming the adequacy of the existing baggage handling facilities of the rail system to-be-improved, this cost component was left out of account in optimizing the design of the improved rail system presented in Chapter 9.

Similarly, the cost of station maintenance and utilities (heating and air conditioning, lighting, and other utilities, and cleaning) may be assumed insignificantly affected by improvement to the rail system service, especially if existing station facilities are adequate for the new service. This is expected to be the case for the railway stations in Toronto, Ottawa, and Montreal which are involved in the rail system design optimization example presented in Chapter 9.

Marketing Cost:

The cost of advertizing and publicity of passenger services may be estimated, as was discussed in the STOL costing methodology, as a function of the system passenger volume. This cost was estimated for the U.S. Improved Rail Study⁴⁶ at 5% of the ticket revenues.

Liability:

This item includes the cost of insurance and liability for property damage and personal injuries. The AMTRAK contract of 4% of the sum of all above rail operating cost components was used in both the U.S. Improved Rail Study⁴⁶ and the Newfoundland Corridor Transportation Study⁶⁴.

System Overhead Costs:

These are expenses for management, administration, and support functions which do not vary immediately with the level of service provided. In transportation costing studies the system overhead costs are usually expressed as percentages of the system operating costs. The estimates given in the U.S. Improved Rail Study⁴⁶ suggest the following expression for a rail system overhead cost:

$$\begin{aligned} \text{overhead cost} = & [.062 \times (\text{train crew cost} + \text{fuel cost} + \text{train} \\ & \text{dispatching cost} + \text{switching costs} \\ & + \text{stations cost}) \\ & + .186 \times \text{rolling stock maintenance and servicing cost} \\ & + .406 \times \text{trackway maintenance cost}] \quad \dots (5.28) \end{aligned}$$

General and Administrative Costs:

This cost category includes expenses that are not directly assignable to transportation, maintenance, or traffic functions, such as general administration and accounting, finance, law, real estate, etc. In railroad practice, this cost component is expressed as a percentage of all above operating costs. A percentage of 7% was used in the U.S. Improved Rail Study⁴⁶.

5.6 System Revenues

System revenues are assumed to be drawn from fare-paying passengers. Additional revenues which may be drawn from other services such as mail or parcel services are not considered here. Fare revenues in a given year can be calculated directly as given by equation (5.29):

$$REV_k = \sum_i x_k \cdot d_i \cdot PAX_{ik} \quad \dots (5.29)$$

where

- REV_k = system annual fare revenues in year k (\$)
- x_k = fare structure* in year k (\$/person/mile)
- d_i = travel distance between city-pair i (miles)
- PAX_{ik} = two-way annual passenger volume between city-pair i in year k.

* treated as a design optimization variable.

The above equation calculates the system annual fare revenues in terms of year k dollars (not discounted).

5.7 System Users' Cost

The cost to a transport system user is commonly measured by the time he spends traveling and the out-of-pocket costs he pays. To convert travel time to dollars, a value of time is needed. An imputed value of travel time is obtainable from the calibrated modal split models. From equation (3.13) and Table (3.3) presented in Chapter 3, it is seen that the imputed value of travel time, VT (dollars per hour), in a given year, is as follows:

For business trips: $VT = 5.6266 \times \text{user's income} \dots (5.30)$
 For non-business trips: $VT = 3.2531 \times \text{user's income}$
 (user's income is in 10,000's of dollars in that year).

The users' cost depends therefore on the total (door-to-door) travel times and costs. Determination of the travel time has been presented in Chapter 4. Travel cost is evaluated in terms of the candidate value of the fare structure, as an optimization variable, and the intercity distance being traveled. Total users' cost in a given year can then be computed by aggregation over all the user groups (income brackets), the two trip purposes, and all the city-pairs.

CHAPTER 6

FORMULATION AND OPTIMIZATION OF THE OBJECTIVE FUNCTION

Part of the system design optimization methodology which has been outlined in Chapter 2 [Figure (2.1)] concerns the selection of an optimization criterion and, accordingly, the formulation and evaluation of the objective function. These as well as the particular technique used for optimization are discussed in this Chapter.

6.1 The Optimization Criterion

The choice of an optimization criterion is important because it affects the outcome of the optimization. The relative merits of a certain combination of values for the system design optimization variables may appear different from different viewpoints. A standard criterion for evaluation or optimization of transport systems does not however exist. One criterion that has been widely used is the assessment of the economic viability of a system on the basis of its net revenue (gross revenue less total cost) ^{2,9,12,68}.

Optimization of the system design is based primarily here on the criterion of maximization of the present worth of the net revenue. To assess the suitability of this criterion, one needs to review the basic objectives of introducing (or improving) the system and to identify the interest groups involved. One such objective is to meet the rising demands for travel where existing systems are not physically capable of meeting present or future demands*. Another objective is to promote the use of a transportation system that is more efficient in its use of energy and land.

* For example, an intercity STOL system and improved passenger railway service have been proposed as effective means to take away most of the short-haul travelers from the congested international airport in Toronto. This is believed to ease the load on the airport and obviates the need for construction of another major airport which was not met with success.

A third objective could be the improvement of the financial viability of existing unprofitable services[†]. The system operator or the government, the system users, and the non-users constitute the parties affected directly, or indirectly, by the system.

It may then be argued that for any of these objectives, maximization of the system net revenue appears to be a desirable criterion. It reflects, at least partially, the viewpoints of the three parties identified above. In addition to the users' enjoyment of the expected improvement of the quality of service being optimized, maximization of the system net revenue implies minimization of government subsidies required to keep the system functioning. The burden of such subsidies lies eventually on the public which includes those three parties. This criterion implies also improvement of the system operator's financial situation.

Use of the net revenue as a measure of effectiveness of a public transport system means that in order for the system to be economically viable, it must draw sufficient revenue to offset its cost and (possibly) return a profit. Practically, this criterion is the most stringent and has been applied in almost every passenger transportation study². de Neufville and Stafford⁶⁹ point out that the feasibility of a public transport system is measured by its ability to draw revenue, and that the size of revenue generated is an important measure of the system effectiveness.

The design optimization methodology lends itself, however, to different optimization criteria. An alternative criterion is one in which the difference between the users' benefits and the total system cost is maximized. That is, the system revenue in the previous criterion is replaced here by the users' benefits.

[†] Current initiatives taken by the Canadian government to improve the existing rail passenger services in the Windsor-Quebec City Corridor, including the creation of "VIA RAIL", and the creation of "AMTRAK" in the United States are typical examples.

Benefits to the users are typically limited to savings in travel times and out-of-pocket costs. Apart from the debatable issue of value of travel time savings, some aspects of the transport service which have an impact on the users are difficult to monetize. The distribution of benefits among the system users is another difficulty.

A third optimization criterion, which the methodology also permits testing, is the minimization of the total system cost divided by the number of revenue passengers, or more practically the number of revenue passenger-miles. To further reflect the users' viewpoint in the design optimization, a fourth approach is to augment the total system cost in this minimum-unit-cost criterion by the users' cost. Sensitivity of the optimal system design to application of this combined unit cost criterion is demonstrated in the two example applications presented in Chapters 8 and 9.

The objective function does not include here other system impacts such as the environmental or social effects that the system might have. Although it is desirable to view the evaluation of the system outputs from such wide perspectives, yet these external impacts were not considered for two main reasons. First, changes in the magnitudes of such impacts due to altering the values of the design optimization variables is seen to be minimal. Second, no reliable procedure exists to measure in dollar terms these effects. Similarly, issues of regional equity in terms of distribution of system benefits are not discussed here. However, in choosing among a number of alternative transport systems these impacts should be considered.

6.2 Formulation of The Objective Function

As discussed above, the quantity to be maximized in the economic viability approach is the present worth of the total

revenues the public is willing to contribute to the service provided minus the present worth of the capital and operating expenses of the system. Evaluation of system revenues and costs is carried out here over a selected analysis period. All cash flows (costs and revenues) are inflated to the year in which they occur and then discounted back to a selected base year using assumed inflation and discount rates. This procedure reduces the streams of costs and revenues to equivalent amounts of money at the base year (present worth) and permits proper comparison among candidate optimal values for the system design variables. The objective function can be written as:

$$\text{Maximize } Z = \sum_{i=1}^N (R_i - c_i) \quad \text{..... (6.1)}$$

where

Z = value of objective function (present worth)

R_i = revenues generated in year i from all city-pair services, discounted to a given base year

c_i = operating costs and capital recovery payments incurred in year i , discounted to the same base year

N = length (in years) of the selected analysis period.

Estimation of the various cost components and revenues of the system has been presented in the preceding Chapter.

Optimization Constraints:

Since both the system costs and revenues are related to the system design optimization variables, the objective function

is, in essence, expressed implicitly in terms of these variables. Technological and/or operational constraints which reflect inherent physical or service limitations on the vehicle performance and system operation can be incorporated in the optimization routine to confine the search for the optimum to only the feasible choices of the decision variables (design variables). An example of such constraints is an upper and/or lower bound on the value of any of these variables.

6.3 Discounting Costs and Revenues

All costs and revenues experienced throughout the selected analysis period are discounted to a common base year using a specified discount rate. The present worth of a capital investment made in a given year is calculated by first computing the equal annual recovery payments of that investment (= capital cost x capital recovery factor*). Only the capital recovery payments incurred during the portion of the service life of the facility which lies within the selected study period are accounted for in the analysis. These annualized equal payments are then discounted to the base year. If i is the discount rate, the present worth, PW , of a cash flow (cost or revenue), A , incurred m years beyond the base year is

$$PW = A \cdot \frac{1}{(1+i)^m} \quad \dots (6.2)$$

The system infrastructure must be provided by the time of start of system operation. Sizing of such structures which are not easy to adapt with increases in demand levels (e.g. a terminal) is based on the highest demand level expected during the chosen study period. Other capital investments can, however, be made whenever the need exists such as acquisition of additional vehicles or rolling stock to meet increases in traffic demands.

* Capital recovery factor, $CRF = i(1+i)^n / [(1+i)^n - 1]$, where i is the discount rate and n is the service or economic life span of the facility whose cost is being annualized.

In such a case, capital investments are made at different points in time within the study period. Discounting of the annualized costs in this case takes account of the time in which the investments are made.

Accounting for all the cost and revenue streams throughout a designated analysis period is believed to be more realistic and desirable than consideration of just one single year. A system operating in loss in its initial period may show an overall net profit when its costs and revenues are evaluated over a period of time (e.g. 15 years).

Choice of Discount Rate:

A discount rate is to be specified in order to compute the present worth of the system costs and revenues. To establish a set of criteria for selecting the appropriate rate of discount against which public transportation projects should be evaluated, is difficult and complex⁷⁰. The basis for determining the appropriate discount rate is the opportunity cost of capital which involves the returns lost by diverting funds to the project under consideration⁶⁹. Although this basis is theoretically sound, its implementation is not easy⁶⁹. Determination of what value should the discount rate take is beyond the scope of this investigation. Rather, a rate based on current practice of evaluation of public transport projects will be used. It would then be desirable to see how sensitive the design optimization results are to different discount rates being chosen. This is, in effect, demonstrated in Chapters 8 and 9.

A review of current practice of evaluating public transport projects suggests the use of a rate of 10%. de Neufville and Stafford⁶⁹ point out that discount rates of 10% or more on government projects are commonly used for project evaluations throughout the world.

6.4 Treatment of Uncertainty in Travel Demands

Because the demand for travel by a transport mode depends upon the perception of travelers to its service characteristics, and because this perception cannot be modeled with certainty

especially in situations involving new modes or improvement of existing transport systems, it is desirable to treat the travel demand as uncertain. Uncertainty in demands spreads out to the system supply and hence costs and revenues because their levels are determined on the basis of the travel demand forecasts.

Two approaches are proposed here to incorporate this feature into the model analysis. The first approach requires furnishing probability distributions for the perception coefficients involved in the set of demand functions used. These distributions are randomly sampled whereby a drawn set of values of such coefficients defines a probable demand state and an associated probability of occurrence. In the second approach a probable range of variation of the value of the system travel market share predicted by the demand model is specified based on previous experience or perhaps on the basis of the accuracies (confidence intervals) associated with the demand models employed. Associated with each possible market share value within this range is a probability of occurrence. The distribution of probabilities over this range could be assumed bell-shaped (normally distributed) or, simply, triangular.

The first approach requires defining a rather large number of probability distributions especially if the demand models are of the disaggregate type. Data required to define these distributions are likely to be difficult to obtain, and one might inevitably assume arbitrary distributions. This approach is also time-consuming. The other approach, which is adopted in the design model, is, however, simpler, much less time-consuming, and requires no specific data.

In this investigation a triangular probability distribution was assumed [Figure (6.1)]. The base of the triangle represents the possible range of variation in the estimated system market share, with its two ends representing assumed probable highest and lowest demand levels, and the mid point being the mean or the value estimated by the demand model. Any other probability distribution (e.g. normal) can be used instead, but the triangular distribution is computationally convenient.

FIGURE (6.1) - ASSUMED PROBABILITY DISTRIBUTION OF SYSTEM DEMAND

The assumed triangular probability distribution is divided into a number of slices. The area of each slice is equal to the probability of occurrence of the demand level represented by the centroid of that area (area of triangle = 1.0). At any trial combination of the system design optimization variables, the objective function is evaluated sequentially for each of these selected slices (i.e. probable system demand levels). A value of the function corresponding to a certain slice is credited with a probability value equal to the area of that slice. The "expected" value of the function, for a given combination of values of the optimization variables, is therefore computed by considering all probable demand levels (i.e. all triangle slices) and their associated probabilities. The search for the optimal value of the objective function is carried out by comparing its "expected" values at different combinations of the values of the system design optimization variables. This expected value approach has been outlined mathematically in Chapter 2 [equation (2.1)].

6.5 The Optimization Technique

A search method is suited for finding the optimal value of the objective function formulated above. Two basic search procedures are available: the gradient method (e.g. steepest descent) and the direct search method. The second procedure is best suited for the particular optimization problem explored here for a number of reasons. The problem dealt with is of large size (a macro design model) whereby a large number of different kinds of relationships defining the various elements of the system design are involved. It would be very difficult, if not impossible, to provide in this case analytical functions for the derivatives needed in a gradient or derivative optimization technique. Although numerical evaluation of derivatives by different techniques can be substituted for direct evaluation of the analytical derivatives, Himmelblau⁷¹ points out that the numerical error introduced, particularly in the vicinity of the optimum, can impair the use of such substitutions. He also indicates that optimization algorithms based on evaluation of derivatives require a relatively large amount of problem preparation before the problem is introduced into the algorithm. The direct search method, on the other hand, does not require regularity or continuity of the objective function nor the existence of derivatives⁷¹. It extends naturally to functions that have no analytic form. This is a distinct advantage in handling complicated engineering or economic problems of the type dealt with here. The disadvantage of the direct search method is that it is slower to execute for simple problems⁷¹.

A number of direct search schemes are available. A simple type of direct search strategy is to change one individual variable at a time while keeping all the others unchanged until the best* possible (i.e. optimal) value of the objective function is reached. The same procedure is applied to the remaining variables on a rotational basis, and the process is repeated until the objective function cannot be improved* any further. This

* "Best" or "improvement" refer to reduction in value of objective function if minimizing, or increase in value if maximizing.

[Note: Maximize $Z \equiv$ Minimize $(-Z)$].

strategy, though simple and easy to implement, performs poorly if there are interactions between the independent variables, and its use is limited⁷¹.

More sophisticated direct search techniques have been developed, in which the optimization variables are varied simultaneously. Among these is the technique developed by Hooke and Jeeves⁷² which is called "Pattern Search". This particular method was adopted in the present investigation. It performed well and gave results that are believed to be satisfactory. As Cooper and Steinberg⁷³ put it, "It should be clearly recognized that no one is in a position to state categorically that any one optimization method is clearly superior to all others for all conceivable classes of problems. Which one will be best suited to a particular problem will be determined by experience". It has in fact been indicated in the literature that the Pattern Search method has been used successfully by many investigators^{73,74}.

The Pattern Search Method:

Detailed description of the search algorithm of this method can be found in the optimization literature. The basic scheme of the method is outlined below when no optimization constraints are involved and is illustrated in Figure (6.2). The way in which the constraints can be handled is described at the end of the outline. The operating procedure outlined below is based on References 71 through 75:

- (1) Initial values (guesses) are to be provided for all the independent variables (optimization variables) included in the objective function. These coordinates define the initial "base point". The objective function is evaluated at that point. Initial incremental change (step size) for each of the variables must also be supplied.
- (2) The first "exploratory search" is then initiated by perturbing or varying one of the variables by an amount equal to its specified step size. If this

FIGURE (6.2) - ILLUSTRATION OF A TWO-DIMENSIONAL PATTERN SEARCH

change improves the objective function the new (perturbed) value of the variable replaces its original value. If it does not, the variable is perturbed in the other coordinate direction by reversing the sign of the incremental change applied to its original value, and the objective function is re-evaluated. If the value of the objective function is not improved by either procedure, the original value of that variable is retained. A final value of the variable is, therefore, established depending on which of these three possibilities yields the best value of the function. The remaining variables are similarly perturbed, one at a time. (The final value established for a variable is used in evaluating the objective function each time another variable is perturbed). The first exploratory search is now complete. If this exploratory search is successful (i.e. the resulting (final) value of the objective function has been improved relative to the value at the base point) the best point obtained so far through perturbing all the variables is designated as the "new base point". The successfully perturbed variables (i.e. those variable changes that improved the objective function) establish a "successful search direction". That is the line joining the newly found base point with its predecessor.

- (3) It is then assumed that a promising search direction which may have a high degree of success is to proceed along the successful direction established above. Therefore, instead of now searching around the current base point, the exploratory search is started from a "temporary point" extrapolated along that direction. This is regarded as an accelerating move (called "pattern move") which is attempted under the assumption that the same behavior of the objective function might

prevail along that particular direction. The temporary point is located by first defining the position vector of the latest base point with respect to its predecessor, and then extending it a distance arbitrarily equal to its length.

- (4) Another exploratory search procedure is now carried out from the temporary point. If this search is successful a new (better) base point is, therefore, established, and another pattern move is then made. A monotone sequence of base points is thus generated as the search continues. (The scheme of extending the pattern ahead to new temporary points accelerates the search process). On the other hand, if the exploratory search around the temporary point fails to improve the objective function over its value at the current base point, the pattern move is said to have failed and the jump made in that direction is cancelled. The search algorithm "retreats" in this case to the current base point where it starts the exploration in the usual manner. Should the exploratory search around a base point fail, the step size is gradually reduced until either a new successful search direction is established or each step size is reduced sufficiently (i.e. becomes smaller than a specified tolerance), in which case the optimal value of the objective function is taken as the value at the latest base point.

When the algorithm terminates a check can be made to verify whether the final base point is a local optimum. The whole search procedure can be restarted from that point using a different step size.

In addition to its simple logic and basic advantage of dealing directly with the objective function and avoiding the difficulties of calculating derivatives, this method can readily

cope with optimization constraints. A very large* value can be assigned to the objective function wherever a constraint is violated, thus repelling the search back into the feasible region.

The above search procedure was coded in Fortran IV by the author. The Fortran program is included as a separate subprogram in the overall computer program of the system design optimization model (documented in Appendix F).

* "Large" for minimization and "small" for maximization.

CHAPTER 7

PROJECTED CHARACTERISTICS OF THE TRANSPORT
AND ACTIVITY SYSTEMS IN THE STUDY REGION

A study area was selected for the application of the design optimization methodology. Figure (7.1) shows a schematic representation of the Quebec City-Windsor Corridor. More than half the population of Canada lives along this Corridor⁷⁶. Most of Canada's economic activity is concentrated within that area. The concentration of population in 1971 around four of the Corridor's major cities (Toronto, Ottawa, Montreal, and Quebec City) exceeded one third of Canada's population⁷⁶. The network joining the largest three cities in this area, namely Toronto, Ottawa, and Montreal, is the most heavily traveled within the Corridor, and is shown in thick lines in the Figure. This triangular network is selected here for application of the methodology. Although only this three-city network is considered for the model application, yet trips originated from or destined to other cities within the Corridor are accounted for in the analysis.

In order to estimate future travel demands between these three cities, it is necessary to project the characteristics of the existing (competing) transport systems* as well as the socio-economics (population, employment, income) within each city. These characteristics must be estimated throughout a selected analysis period. Generation of such information is presented in this Chapter. Before presenting this information, two applications of the methodology are identified and selection of their analysis periods is discussed.

Two mutually-exclusive systems are considered (one at a time):

- (1) Short Take Off and Landing (STOL) air system, serving the three links of Toronto-Ottawa, Ottawa-Montreal, and Montreal-Toronto, and
- (2) Improved Passenger Rail system, serving the linear network (Corridor) of Toronto-Ottawa-Montreal. A number of alternative rail improvements are analyzed.

* Those of the designed system have already been defined in terms of the design optimization variables and performance measures.

FIGURE (7.1) - THE QUEBEC CITY-WINDSOR CORRIDOR AND THE SELECTED STUDY NETWORK

A starting date of operation of either system was assumed to be in 1980. This assumption was made in light of current initiatives taken by the Canadian government to upgrade present rail passenger services in the Corridor, and the termination of the Montreal-Ottawa STOL demonstration experiment. The length of the analysis period considered for either system was made, for computational convenience, equal to the average economic life span of the vehicles. An analysis period of 13 and 16 years (i.e. 1980-1992 and 1980-1995) was, therefore, assumed for the STOL and the Improved Rail systems, respectively. Obviously, alternative starting and/or ending dates of the analysis periods could be selected since the objective is to merely demonstrate the workability of the system design optimization methodology.

Details of these two case studies are presented in the next two Chapters. The input information and demand forecasting procedure and assumptions which are common to both applications are discussed in the various sections of this Chapter.

7.1 Level of Service of the Competing Modes

In the first case study, conventional air, bus, and rail modes are assumed to be competing with the proposed STOL system for the common carrier travel market. In the second case study, present rail passenger service is replaced with a higher speed service. The common carrier competing modes are in this case the conventional air and the bus. Current (1976) travel times and frequencies of service of these three competing modes, as described in their service schedules, were assumed to prevail throughout the analysis period. No information was available to assume otherwise. Travel fares by each of these competing modes were escalated to 1980 from their 1976 levels in accordance with an assumed rate of increase in the consumer price index (see Appendix E). Beyond 1980, an annual inflation rate of 6% was assumed based on the information presented in Appendix E.

The procedure followed in evaluating the level of service measures is the same as that adopted in calibrating the demand models. Such procedure has been outlined in Appendix B. Components of total travel times other than the line-haul portions (i.e. access, terminal waiting, terminal exiting, egress, schedule

overrun times) were taken for all the competing modes as equal to those used in calibrating the demand models*.

Future access costs to the various modal terminals were estimated by first escalating to 1980 the 1969 figures that were used in the demand models calibration. An average escalation factor of 2.2 based on past and assumed future inflation rates from 1969 to 1980 (Appendix E) was used for that purpose. Similar to the line-haul fare inflation rates, an annual increase of 6% in access costs was assumed throughout the analysis period (beyond 1980).

Table (7.1) summarizes the projected 1980 level of service characteristics for the three competing modes, and for the three network links. The tabulated information is further disaggregated with respect to trip purpose.

7.2 Population Projections

Population projections for Canada and the provinces were prepared by Statistics Canada for the period 1972-2001. These projections were not disaggregated to the metropolitan area level. To obtain the future populations within each of the cities considered here, a ratio method was employed. Future ratios of the population in a given city to the population in the province to which it belongs were estimated based on past ratio trends. From the available projections of provincial population and the extrapolated ratios, future populations within each metropolitan area were computed.

Statistics Canada produced a number of alternative projections based on different assumptions about migration and fertility rates so as to indicate the "range" of future population of Canada and the provinces. The projection designated by Statistics Canada as "medium" was used here.

The principal computational steps followed in estimating the future populations in Toronto, Ottawa, and Montreal are summarized in Table (7.2).

* Relocation of the bus terminal in Ottawa was assumed not to change the average access times or costs significantly. No data was available to check this assumption.

TABLE (7.1) - PROJECTED 1980 LEVEL OF SERVICE CHARACTERISTICS OF COMPETING MODES

	MODE	BUSINESS TRAVEL			NON-BUSINESS TRAVEL		
		TORONTO- OTTAWA	OTTAWA- MONTREAL	MONTREAL- TORONTO	TORONTO- OTTAWA	OTTAWA- MONTREAL	MONTREAL- TORONTO
AVERAGE LINE-HAUL TRAVEL TIME (HOURS)	CTOL*	.83	.50	1.03	.83	.50	1.03
	BUS	5.08	2.08	6.18	5.08	2.08	6.18
	RAIL	5.58	2.22	4.88	5.60	2.22	5.03
AVERAGE TOTAL TRAVEL TIME (HOURS)	CTOL	2.48	2.07	2.78	2.65	2.21	3.00
	BUS	6.38	3.33	7.47	6.45	3.40	7.70
	RAIL	6.85	3.42	6.23	7.00	3.55	6.60
LINE-HAUL TRAVEL FARE (1980 DOLLARS)	CTOL	53.74	34.45	64.77	53.74	34.45	64.77
	BUS	17.16	8.13	21.70	17.16	8.13	21.70
	RAIL	19.50	9.10	26.33	19.50	9.10	26.33
AVERAGE TOTAL TRAVEL COST (1980 DOLLARS)	CTOL	65.22	45.25	76.94	61.35	42.13	73.86
	BUS	20.75	11.34	25.24	20.13	11.10	24.96
	RAIL	24.58	13.81	30.58	22.87	12.33	29.89
AVERAGE EFFECTIVE FREQUENCY (DEPARTURES/DAY/DIRECTION)	CTOL	17.2	16.7	22.8	19.2	17.8	23.9
	BUS	7.0	14.0	2.3	12.1	18.0	5.3
	RAIL	1.7	6.0	4.7	2.9	6.9	5.7

Sources: 1975 and 1976 service schedules of all common carriers serving the shown three city-pairs.

Note: Based on the information given in Appendix E, the 1980 line-haul fares were obtained by escalating those of 1976 by 30%.

* Conventional Take Off and Landing (Existing Air System).

TABLE (7.2) - POPULATION PROJECTIONS

	1971	1980	1983	1986	1989	1992	1995
POPULATION* (IN THOUSANDS)							
ONTARIO	7703	9015	9540	10074	10593	11089	11566
QUEBEC	6028	6329	6477	6620	6739	6823	6874
POPULATION (TORONTO/ONTARIO)	34.15	35.82	36.45	37.08	37.71	38.34	38.97
(OTTAWA/ONTARIO)	7.83	8.24	8.39	8.54	8.69	8.84	8.99
(MONTREAL/QUEBEC)	45.64	47.18	47.75	48.32	48.89	49.46	50.03
RATIO** (%)							
POPULATION (IN THOUSANDS)							
TORONTO	2628	3229	3478	3735	3995	4251	4507
OTTAWA	603	743	800	860	921	980	1040
MONTREAL	2743	2986	3093	3199	3236	3375	3439

* Source: Statistics Canada, Catalogue No.91-514, "Population Projections for Canada and the Provinces", (June 1974).

** Extrapolated from information given in Statistics Canada Catalogues No.91-201 (August 1974) and No.91-207 (May 1973).

7.3 Employment Projections

To estimate the future number of employed persons in each city, the following steps were followed:

- (1) Population projections for ages over 14 years were extracted from Statistics Canada figures and were computed for each city. The same procedure adopted in the preceding section is used here for that purpose.
- (2) Projected rates of change in the labor force participation rates* from 1971 figures were also estimated for each of the three cities. The 1971 participation rates were furnished by Statistics Canada.
- (3) These two pieces of information were then used to compute future labor force participation rates in the three cities. Future labor force estimates were then obtained by multiplying the future populations over 14 years of age by the projected rates of participation in the labor force.
- (4) Long range average unemployment rates of 5% and 7% were assumed, based on recent Statistics Canada figures, for Ontario and Quebec, respectively. These rates were applied to the labor force estimates obtained in the previous step to produce the future numbers of employed persons in each of the three cities.

Table (7.3) summarizes the basic computational steps involved in the above procedure.

7.4 Projection of Average Income and Income Distribution

Latest Statistics Canada figures on family incomes are available up to year 1973, and on a provincial metropolitan area basis. Projection of average family incomes to year 1980 was made on the basis of past and expected change in the consumer price indices as reported in Appendix E. Beyond 1980, an annual

* Labor force participation rate = (labor force/population over 14 years of age).

TABLE (7.3) - EMPLOYMENT PROJECTIONS

	1980	1983	1986	1989	1992	1995
POPULATION OVER 14 YEARS¹						
(IN THOUSANDS)						
ONTARIO	6842	7227	7582	7931	8304	8729
QUEBEC	4934	5067	5142	5176	5232	5319
% INCREASE IN LABOR FORCE						
TORONTO	3.85	4.88	5.78	6.67	7.70	8.97
OTTAWA	4.35	5.39	6.23	7.07	8.07	9.39
MONTREAL	3.44	4.33	5.10	5.87	6.77	7.94
1971						
LABOR FORCE PARTICIPATION						
TORONTO	68.40	69.07	69.67	70.25	70.93	71.77
OTTAWA	65.01	65.66	66.18	66.70	67.33	68.15
MONTREAL	57.69	58.18	58.61	59.04	59.54	60.20
RATE³						
(%)						
NO. OF EMPLOYED PERSONS⁴						
TORONTO	1593	1728	1861	1996	2145	2319
OTTAWA	348	378	407	437	470	508
MONTREAL	1249	1309	1354	1390	1433	1490

1. Extracted from Statistics Canada projections of provincial populations, Catalogue No. 91-514 (June 1974).

2. Computed from information given in "Urban Canada: Problems and Prospects", Research Monograph 5 -- The Urban Future, Pages 86, 90, 94, 98, Government of Canada, Ottawa, (1971).

3. The 1971 labor force participation rates are computed from Statistics Canada Catalogue No. 94-707, page 21-1, (November 1974), and are as follows: Toronto (65.86%), Ottawa (62.30%), and Montreal (55.77%).

4. Employment rates of 95% in Toronto and Ottawa and 93% in Montreal were assumed based on employment rates reported in Statistics Canada Catalogue No. 71-001, "The Labor Force", (various years).

"net" increase in family income of 1% was assumed in the analysis. That is, the annual rate of income increase from 1980 on was assumed at 7% (the corresponding rate assumed for consumer price index was 6%). The average income levels and the corresponding consumer price indices are shown in Table (7.4) for a selected number of years.

TABLE (7.4) - AVERAGE INCOME AND CONSUMER PRICE INDEX

		TORONTO	OTTAWA	MONTREAL
AVERAGE FAMILY INCOME ¹ (\$)	1969 ¹	10,420	10,050	8,416
	1973 ²	14,234	13,728	11,252
	1980 ³	24,838	23,955	19,634
CONSUMER PRICE INDEX ² (1969 IS BASE YEAR)	1975 ⁴	141.9	144.2	141.8
	1980 ³	200.8	204.1	200.7

1. Source: Statistics Canada Catalogue No.62-537.
2. Computed from average income data reported in Statistics Canada Catalogue No.13-207.
3. Based on assumed increases in Consumer Price Index given in Appendix E.
4. Source: Canadian Statistical Review, Statistics Canada Publication No.11-003E (1975), (1976).

Income Distribution:

Because the demand estimating models operate on user income groups, it is necessary to stratify the projected population and employment figures with respect to income. In other words, a relationship is required to estimate the percentage of population (and employed persons) in each income bracket.

Distribution functions of family incomes in metropolitan areas in Ontario and Quebec in 1965, 1967, 1969, 1971, 1972, and

1973 were obtained from Statistics Canada publications*. The original Statistics Canada data reported on the percentage of "family units" in each income group. Additional Statistics Canada information on distribution of the average size of the income unit and the number of income earners within it were, therefore, used to determine the percentage of "persons" (and income earners) in each income group. Cumulative distribution curves of the percentage of persons and of employed individuals versus income were plotted for the six-year time series. Having the mean income in each income group normalized by the average income in the metropolitan area, the observations for all six years and two provinces were found to define a unique distribution curve. Figure (7.2) shows the plot of the observations of cumulative number of persons versus family income normalized by the average income in the metropolitan area. It is seen from the Figure that although the average income increases over time, yet the distribution of individuals with respect to income remained almost the same during the six-year period. Using non-linear regression analysis, the equations of the curves that best fit the observations were obtained and are given below.

For use with business trips demand model:

$$P_1(I) = 145.232 \exp [-1.187/(I^{1.249})] \quad \dots (7.1)$$

[t=(26.2) (27.2) .. (23.1), n=130 l.o.s.<0.1%]

For use with non-business trips demand model:

$$P_2(I) = 145.572 \exp [-1.071/I^{1.150}] \quad \dots (7.2)$$

[t=(24.3) (22.9) .. (21.0), n=130 l.o.s.<0.1%]

* Catalogues #13-528, 13-534, 13-544, and 13-207.

FIGURE (7.2) - CUMULATIVE INCOME DISTRIBUTION FOR ONTARIO AND QUEBEC METROPOLITAN AREAS

where

$P_1(I)$ = percentage of persons with relative family income $\leq I$,

$P_2(I)$ = percentage of employed persons with relative family income $\leq I$

I = relative family income = (mean family income[†] / average family income in the metropolitan area).

Equations (7.1) and (7.2) are used to produce a set of normalized* weights to determine the relative contribution of each income group to the overall market shares for business and non-business travel, respectively. The weights obtained by equation (7.1) are further weighted, as discussed in Chapter 3, by those computed from equation (3.26). The resulting composite weights* are then applied to apportion the predicted total volume of business trips among the various user (income) groups. This procedure can be seen in detail in the computer program listing included in Appendix F.

7.5 Procedure of Forecasting Future Travel Demand

To properly account for the effect of income on travel demand, annual increases in income are compared to corresponding increases in consumer price index. Specifically, the value of the income variable used in the demand estimating functions (given in Chapter 3) is assumed to be equal to the actual family income in a given year divided by that year's consumer price index (indexed to the base year - 1969). This procedure ensures appropriate reflection of the income variable as a factor in perceiving the generalized cost of travel.

To forecast the system travel demand in a given year, the modal split models presented in Chapter 3 are first applied to all income groups to produce a set of modal weights (modal splits). Such weights are used to combine the levels of service of the available travel modes between each pair of cities. The weighted (or composite) level of service of the modal mix together with the

[†] in a given income group.

* Sum of weights = 1.0.

projected population and employment figures* are inserted in the total demand models to predict the total business and non-business demands between each two cities. The above weights (modal splits) are then used to compute the share of each mode out of each city-pair's total demand.

It was shown in Chapter 3 that the calibrated total demand models [equations (3.24) and (3.25)] possess highly acceptable statistical measures. Those measures apply to the models in their linear transformations (logarithmic form). Discrepancies existed, however, between the actual observed demand volumes (those input to the models' calibration) and the corresponding volumes predicted (reproduced) by the demand models. The statistical significance of the elasticity coefficients (exponents in the demand functions) was rather very high. This high degree of reliability in estimating the demand elasticity coefficients warrants in itself the use of the regression demand functions to predict the growth in total travel demands due to future changes in the characteristics of the transport and activity systems.

To achieve a high predictive accuracy, the total demand models are used in the following manner. Future values of the explanatory variables contained in these models (population, employment, language pairing index, composite level of transport service) relative to their base year (1969) values are computed. The magnitudes of future passenger demand volumes relative to those actually observed in the base year are then determined based on the relative values of the demand explanatory variables and the values of elasticity coefficients. In mathematical terms, this procedure can be described as follows:

$$\frac{T_i}{T_o} = \frac{\prod_r x_{ri}^{\alpha_r}}{\prod_r x_{ro}^{\alpha_r}} \quad \dots (7.1)$$

--- for a given trip purpose and
origin-destination

* Language pairing indices were assumed to remain unchanged from their 1969 values.

or

$$T_i = T_o \cdot \prod_r \left(\frac{x_{ri}}{x_{ro}} \right)^{\alpha_r} \quad \dots (7.2)$$

--- for a given trip purpose and
origin-destination

where

- T_i = number of trips generated in a future year i
- T_o = number of trips "observed" in the base year o
- x_{ri} = value of demand explanatory variable number r in year i
- x_{ro} = value of that variable in the base year o
- α_r = elasticity of total demand with respect to that explanatory variable.

(The general form of the demand function shown in equation (7.1) follows directly from equations (3.24) and (3.25) which were given in Chapter 3).

7.6 Consideration of Trips from Outside the Study Network

The system design is based on the passenger volume on each of its links. The passenger traffic on the links of the selected triangular network is likely to include trips with origins and/or destinations at other cities of the Corridor. The volumes of such external trips which are expected to use those links were expressed as ratios of the trips generated between the three city-pairs themselves. With reference to Figure (7.1) and use of the Canadian Transport Commission travel survey data², these ratios were computed as shown in the Table below.

These trip generation ratios were used in the Improved Rail example to augment the passenger traffic volumes generated from Toronto, Ottawa, and Montreal. In the STOL example application, passengers were assumed, however, to have their origins and destinations within these three cities. This was felt to be an appropriate assumption since the STOL service

TABLE (7.5) - EXTENT OF EXTERNAL TRAFFIC FLOWING ON THE ANALYZED NETWORK

CITY-PAIR (LINK)	OTHER O-D'S CONTRIBUTING TO TRAFFIC ON THE LINK	EXTENT OF CONTRIBUTION* (%)	
TORONTO- OTTAWA	HAMILTON-OTTAWA	8.4**	} 18.0
	LONDON-OTTAWA	6.3	
	WINDSOR-OTTAWA	3.4	
OTTAWA- MONTREAL	OTTAWA-QUEBEC	6.8	6.8
MONTREAL- TORONTO	MONTREAL-HAMILTON	4.9	} 17.0
	MONTREAL-LONDON	3.4	
	MONTREAL-WINDSOR	3.5	
	QUEBEC-TORONTO	4.8	
	QUEBEC-HAMILTON	0.3	

* computed from origin-destination flows given in Reference 2, Page 26.

** i.e. the ratio of the passenger trips generated between Hamilton and Ottawa to those between Toronto and Ottawa is 0.084.

is limited to only the Toronto-Ottawa-Montreal network as contrasted to the rail system which is expected to permit transfer at any of its stations (same existing ones) to other rail routes and modes in the Corridor. Possibility of transfer between STOL and other modes was regarded as remote in this particular example application.

7.7 Two Basic Assumptions Implied in Predicting Future Travel Demand

In terms of application of the calibrated demand models to forecast travel demand for the proposed STOL or Improved Rail system, two basic assumptions are implicitly made.

The first assumption is that the traveler's decision process with respect to selection of travel mode remains unchanged by the introduction of the new service. In other words, the user choice mechanism will still be based on the relative values of the level of service variables of the available travel alternatives. These variables include, as was shown in Chapter 3, the travel time, travel cost, and frequency of service. The relative weights attached by the traveler to these variables are allowed, however, to vary with changes in his attributes (income). This was also indicated in Chapter 3. The validity of this assumption can be demonstrated by the fact that different demand models estimated at different points in time and in different locations* reveal significant dependence of the choice of mode upon the relative values of the level of service variables of the available modes (particularly, travel time, travel cost, and service frequency variables).

The second assumption requires the basic structure of the relationship between trip making and the characteristics of the transport and activity systems to remain unchanged over time. That is, the values of the demand elasticities with respect to the socio-economic and level of transport service are assumed to stay the same throughout the analysis period. The validity of this assumption can only be checked through repeated applications of the forecasting models at different points in time⁷⁷. No time series data are available to check this assumption. If one examines, however, the demand models reported in the literature, he would probably conclude that the elasticities of travel demand with respect to the various socio-economic and transport service variables do not change significantly over a reasonable length of time for the analysis period.

In the following two Chapters the application of the design optimization methodology is demonstrated for the STOL and the Improved Rail systems with reference to the Toronto-Ottawa-Montreal Network. The model is implemented by the author in the form of a FORTRAN IV computer program. The program listing and a description of it are provided in Appendix F.

* see for example References 1, 2, 3 and 4.

CHAPTER 8

EXAMPLE APPLICATION 1: DESIGN OF A STOL SYSTEM

Conventional air transport systems have proven incapable of solving the problem of efficient door-to-door transport for short routes. STOL transportation is being developed for realization of travel time savings through provision of fast downtown-to-downtown service. Also, STOL transport is expected to relieve congestion in present air transportation systems whether in the air, at the airport, or in the airport access system. Major airports in some cities may be functioning at or beyond their capacities, thus giving rise to increasing congestion. The problems of locating and funding additional air terminal facilities are becoming insoluble in the face of financial, environmental and ecological problems. STOL technology may not eliminate completely the need for additional airports but it does significantly change the magnitude of the problem. A high proportion of air traffic is short-haul. A reliable STOL system can, through its swift handling of passengers and provision of shorter door-to-door travel times, take away most of those short-haul travelers from the conventional air system. This would ease the load on existing airports and therefore obviate the need for more airport space. Conventional airline delay costs could also be reduced as a result. STOL ports require much less space than the conventional airports.

In this chapter the system design optimization methodology is applied to a STOL system serving the three links of Toronto-Ottawa, Ottawa-Montreal, and Montreal-Toronto. The STOL service network is shown in Figure (8.1).

FIGURE (8.1) - THE STOL SERVICE NETWORK

8.1 Data and Assumptions

In the particular transport network analyzed here, STOL passengers traveling between any two cities are expected to take the direct link connecting them (i.e. the travel route passing by the third city is not regarded as a feasible alternative). The validity of this assumption was proven in Appendix B from the travel survey results.

The exact locations* of the STOL ports within the three cities are not known at the present time. Average STOL port access time and cost in a city were, therefore, assumed to be equal to those of the existing rail terminal in that city. Such an assumption appears to be compatible with the location criteria for STOL ports. Rail access times and costs are included in Appendix B, while projected 1980 access costs are determinable

* This is an input information to the design optimization model.

from Table (7.1). Only one STOL port in each city was assumed in the analysis. Average terminal waiting time and time spent by the traveler exiting* the STOL port were arbitrarily taken to be 15 and 5 minutes, respectively. This is believed to be consistent with the STOL characteristic of swift handling of passengers and aircraft movement. In terms of service reliability, an average schedule overrun time of 3 minutes was observed in the Montreal-Ottawa STOL demonstration service⁴³. The above pieces of information are tabulated below for the three links and for both trip purposes.

TABLE (8.1). - ASSUMED AVERAGE FIXED TIMES AND COSTS BY STOL

	T-O		O-M		M-T	
	B	NB	B	NB	B	NB
ACCESS + EGRESS TIME ..(MIN.)	38	42	34	39	40	47
TERMINAL WAITING TIME ..(MIN.)	15	15	15	15	15	15
TERMINAL EXITING TIME ..(MIN.)	5	5	5	5	5	5
SCHEDULE OVERRUN TIME ..(MIN.)	3	3	3	3	3	3
TOTAL FIXED TIME(MIN.)	61	65	57	62	63	70
1980 ACCESS + EGRESS COST (\$)	5.08	3.37	4.71	3.23	4.25	3.56

Abbreviations: T = Toronto O = Ottawa M = Montreal
 B = Business travel NB = Non-business travel

The value of the STOL constant term (bias) which appears in the generalized travel cost expression [equation (3.13)] was made equal to that obtained by calibration for the air mode. Departures from this value are implicitly accounted for through treatment of uncertainty in the STOL travel market share.

The diurnal distribution of passenger demand for STOL service along each of the three links was assumed to be identical

* includes deplaning time.

to that observed in the Montreal-Ottawa STOL demonstration service which was sketched in Chapter 4 (page 92). As mentioned in that chapter, the dispatching of flights conforms to the variation in the diurnal distribution of demand. Therefore, an effective frequency of service factor can be approximated from that distribution for each link. This factor is then multiplied by the daily number of flights along the link to obtain the effective frequency of service which is one of the variables in the business travel demand models. Following the same procedure adopted in Appendix B for calculating the effective frequency of service, and using the particular diurnal distribution sketched in Figure (4.3), the effective frequency of service factor along a link of transit time t hours was found to be approximately equal to $(0.94 - 0.06t)$.

With regard to accumulation of passengers in the STOL system terminals, average values of the variables introduced in Section 4.5 were assumed to be:

- QSTART = 25 minutes
- QEND = 5 minutes
- QOUT = 3 minutes

To estimate the terminal space requirement, the following assumptions were made and appear to be consistent with common practice:

- average ratio of well-wishers to STOL passengers* = 37.8%
- space per occupant in the waiting area = 15 ft²
- space per passenger in the ticketing area = 10 ft²
- aircraft wing span = 95 ft.
- minimum aircraft storage clearance = 25 ft.
- aircraft seat pitch = 32 in.
- number of seats abreast = 2 for up to 20 seats
- = 3 for 21 to 30 seats
- = 4 for 31 to 60 seats
- = 5 for 61 to 125 seats
- = 6 for 126 to 240 seats

* This ratio is used to augment the number of passengers occupying the waiting area. The value shown was computed from the results of an airport survey reported in Reference 78. In the absence of well-wisher data specific to travel by STOL, it was necessary to

Since the majority of STOL passengers are expected to be traveling on business, a 5-day servicing week was assumed. That is, the weekly patronage predicted by the demand models was spread equally over the five days during which the proposed STOL service will be provided. In fact, travel surveys carried out in connection with the Montreal-Ottawa STOL demonstration service revealed that only about 3% of the STOL passenger trips were made during the weekends. As a result, the service, which was originally provided throughout the entire week, was later discontinued during the weekends and holidays. A period of 250 servicing days was, therefore, assumed in the analysis.

The following values were also assumed for other system variables introduced in Chapter 4:

- Demand peaking factor = 1.30*
- average aircraft turn-around time
[appears in Equation (4.21)] = 10** min.
- minimum number of flights per day on any
link (per direction) = 8
- maximum number of flights per day on any
link (per direction) = 60

The minimum-daily-flights condition was introduced to ensure a minimum acceptable level of STOL service. The upper limit on the daily number of flights acts as a constraint on the optimized value of the aircraft size (seating capacity). Assuming a daily servicing period of 15 hours, the proposed limit of 60 flights per day corresponds to a minimum average headway of 15 minutes between departures. The assumed diurnal distribution of demand suggests that the headway time during the peak periods is approximately equal to 2/3 the average headway. Accordingly, the 15-minute minimum average headway implies a 10-minute minimum headway during the peak periods, which appears to be practical.

* i.e., peak (design) day volume = 1.30 x average day volume
(Reference 2, p.68).

** A minimum of 7 minutes was suggested by DeHavilland of Canada for the Dash 7. (Source: Dash 7 brochure).

STOL system costs were presented in Chapter 5. The following values were assumed for the cost components and variables that were not explicitly given in that Chapter. All costs are expressed in terms of 1975 dollars, unless otherwise indicated.

- unit construction cost of passenger terminal building, cp = \$61.7/sq.ft.*
- unit construction cost of aircraft storage area, cv = \$30.3/sq.ft.*
- fixed construction cost of the 3 STOL ports, 3 x cf = \$20 Millions**
- cost of terminal land, cl, excluded (data unavailable)
- service life of aircraft (zero salvage value) = 13 years
- service life of STOL ports = 30 years
- aircraft spare parts allowance = 15% of aircraft basic price
- number of spare aircraft = 20% of minimum fleet size

The evaluation of the objective function was carried out under the following assumptions:

- STOL system will start operation in year 1980
- length of analysis period (1980-1992) = 13 years
- evaluation interval*** = 3 years
- rate of increase in family incomes (beyond 1980) = 7%/year
- rate of increase in costs (beyond 1980) = 6%/year
- rate of increase in fare (beyond 1980) = 6%/year
- rate of increase in consumer price index (beyond 1980) = 6%/year
- discount rate, i = 10%
- base year = year 1975

* derived from construction costs of the terminal buildings and hangars in Montreal and Ottawa demonstration STOL ports⁷⁹.

** based on estimated construction cost of a "typical" STOL port (Ref.58, pp.105-106) and actual costs reported in Reference 79.

*** i.e., the system demand, supply, costs, revenues, and, hence, value of objective function were evaluated every 3 years. Intermediate values of system costs and revenues were obtained

Construction of the three STOL ports was assumed to spread over a period of two years prior to the start of the system operation in 1980. This was taken into account in escalating the assumed 1975 STOL port cost estimates. Also, capital recovery payments of the STOL ports cost were assumed to commence in 1980 and extend over the assumed service life of the ports. Only the costs and revenues realized within the analysis period were considered in evaluating the objective function.

Uncertainty in STOL travel market share was treated by assuming a triangular demand probability distribution. The STOL demand share which is predicted by the demand models given in Chapter 3 was assumed to vary within $\pm U\%$ as shown in Figure (8.2). The same distribution was used for both business and non-business trips.

FIGURE (8.2) - PROBABILITY DISTRIBUTION OF THE SYSTEM DEMAND

For computational convenience, the base of the above triangle was divided into four equal ranges as shown above. Accordingly, four probable demand states (d_1 , d_2 , d_3 , d_4) were considered in the analysis. These are related to the estimated system demand, d , (predicted by the demand models) and the range of uncertainty, U ($U = U\%/100$), as follows:

$d_1 = (1 - \frac{2}{3} U)d$ with probability of occurrence = $1/8$

$d_2 = (1 - \frac{2}{9} U)d$ with probability of occurrence = $3/8$

$d_3 = (1 + \frac{2}{9} U)d$ with probability of occurrence = $3/8$

$d_4 = (1 + \frac{2}{3} U)d$ with probability of occurrence = $1/8$

The optimization results to be presented in this and the following Chapters are based on a U-value of 20%.

The input information introduced in this and the preceding Chapters is maintained in a parametric form in the computer program to permit flexibility. Sensitivity of the system design optimization to variation in the assumed values of a set of key input variables as well as to a second optimization criterion will be demonstrated.

8.2 STOL Design Optimization Procedure

The preceding five Chapters described in detail the various parts of the system design optimization methodology which was outlined in Chapter 2. This section outlines the procedure followed in determining the optimal STOL system design.

STOL Design Optimization Variables:

The design optimization variables selected for the STOL system are: aircraft cruise speed, aircraft size (seating capacity) and fare structure. The pricing scheme of existing domestic air travel was assumed applicable to STOL. Analysis of Air Canada fares for a number of short-haul city-pairs suggested the following relationship:

$$\text{FARE} = a + b \cdot \text{DISTANCE} \quad (\$/\text{Passenger}) \quad \dots (8.1)$$

where

a = fixed portion of fare (\$/passenger)

b = variable portion of fare .. (\$/passenger-mile)

DISTANCE = air distance traveled (miles)

This formula was estimated by linear regression analysis using

fares between eight city-pairs within the Quebec City-Windsor corridor. The fare-distance data are given in Table (8.2) and are followed by the regression results.

TABLE (8.2) - AIR CANADA FARES FOR SHORT-HAUL DISTANCES*

CITY-PAIR	AIR DISTANCE	1976 FARE (\$)	1975 FARE (\$)
MONTREAL - TORONTO	316	47	42
- OTTAWA	102	25	23
- QUEBEC	145	30	28
OTTAWA - TORONTO	218	39	36
- QUEBEC	247	39	36
- LONDON	325	46	42
TORONTO - LONDON	107	25	23
- WINDSOR	207	36	33

$$1975 \text{ FARE} = 14.75 + 8.70 \times \left(\frac{\text{Distance}}{100} \right) \dots (\$/\text{passenger}) \dots (8.2)$$

$$\begin{aligned} [t = \dots (17), n=8, \quad \text{l.o.s.} < 0.1\%, \\ s_e = 1.18 \quad c_v = 3.6\% \quad R^2 = 0.98] \end{aligned}$$

$$1976 \text{ FARE} = 15.35 + 9.85 \times \left(\frac{\text{Distance}}{100} \right) \dots (\$/\text{passenger}) \dots (8.3)$$

$$\begin{aligned} [t = \dots (19), n=8, \quad \text{l.o.s.} < 0.1\%, \\ s_e = 1.19 \quad c_v = 3.3\% \quad R^2 = 0.98] \end{aligned}$$

The statistical significance of these two equations is very high. The equations show that for an average short-haul distance of, say, 200 miles, the increase in fare from 1975 to 1976 is about 9%. The increase in the value of a is, however, much less than that in the value of b (about 4% and 13%, respectively).

* The shown fares are quoted in Air Canada Service Tables and do not include airport tax. The air distances are given in Reference 36.

The same form of fare structure given by equation (8.1) was employed in pricing the STOL service. This form implies that the STOL fare be represented by two optimization variables: a and b . As will be shown in the following chapter, similar fare structure analysis conducted for existing short-haul rail passenger services indicated that the " a " term in expression (8.1) does not exist for rail. Hence, only one fare optimization variable is dealt with in the rail case, which is the b -coefficient in that expression. For purposes of computational convenience and consistency in representation of the fare variable in both the air and rail cases, the fare structure is represented in either case by one optimization variable: the b -coefficient. The optimal value of the fixed portion of the STOL fare (the a term) is determined, however, by repeating the optimization process for a range of values of a . (The optimal value of a thus obtained is kept unchanged in the STOL sensitivity analyses).

Initially, the STOL system design is optimized on the basis of employing one common aircraft size for all the three links. This condition is, however, relaxed at a later stage to permit the aircraft to be sized independently for each link. In this case, each of the three links is served by an aircraft of different seating capacity, thus entailing the use of five optimization variables instead of three.

STOL Demand Variables:

The STOL system variables which appear in the demand functions include: travel time, travel cost, and frequency of service. Terminal-to-terminal travel time by STOL is calculated from the STOL block time equation given in Chapter 4 [equation (4.3)]. The "fixed" travel time by STOL is shown in Table (8.1). The second variable, total travel cost, is computed from the values being tried for the two fare variables, " a " and " b ", and from the "fixed" access cost to and from STOL ports, which is also given in Table (8.1). The last variable, frequency of service, is not treated as an optimization variable in this

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application. Its value is, however, determined from the chosen value for the aircraft size(s) and the "as yet undetermined" volume of passengers to be transported. Consequently, an initial value is to be assumed for this variable in order to predict the STOL demand. This value is iteratively modified until the number of departures on each link which is used in predicting the demand matches that actually required to transport the resulting volume of passengers on that link. This iterative procedure was found to converge very rapidly because of the diminishing marginal return property of demand versus frequency of service.

Prediction of STOL Demand:

The procedure of predicting the system travel demand has been described in the preceding chapter (section 7.5). The percentage share of the STOL system as computed by using the modal split model is adjusted by multiplying it by the demand uncertainty factors established in section 8.1. The total common carrier demand and the STOL market share in a given year are then computed for each probable demand state.

STOL System Supply:

For a given demand state, the passenger design volume on each STOL link is computed by multiplying the average volume thus predicted by the daily design factor assumed in the preceding section. The number of flights required to meet the daily demand on each link are computed in terms of the size of aircraft assigned to that link and are spread over the servicing day in accordance with the assumed diurnal distribution of demand. Generation of the aircraft departure times from one end of a link determines the set of arrival times at the other. Cumulative departure and arrival step functions at each of the three ports are then constructed by merging in order of time of day the set of departures to and the set of arrivals from all directions at that port [see Figure (4.6)]. The vehicle fleet size is then computed together with other system operational measures (such as aircraft loading factors and daily number of aircraft flight

hours). For the case of aircraft size being determined independently for each link, these measures and the required aircraft fleet are determined for each type (size) separately. The maximum possible accumulation of passengers is also computed directly from the vehicle departure timetables. The terminal space required to accommodate the passengers and to store the aircraft is determined accordingly.

STOL Design Objective Function:

The optimization objective function demonstrated here is the expected difference between STOL fare revenue and total STOL cost (capital recovery payments plus operating costs). That is, the design objective is the maximization of the net revenue. Both costs and revenues are expressed in present worth (in terms of 1975 dollars). Sensitivity of the optimal STOL design to another optimization criterion including users' cost is also presented in this chapter.

A probable value of the objective function is determined by repeating the above steps throughout the analysis period (every evaluation interval). Its expected value, which corresponds to a given value specification for the optimization variables, is obtained by further repeating the entire procedure to sample all the probable demand states.

Optimal STOL Design:

The direct search method of optimization is used to determine the optimal values of the selected set of design optimization variables together with the corresponding maximum value of the objective function. Upon successful termination of the search procedure, all the above aspects of the STOL system design are determined in terms of the final values of the optimization variables. These design aspects are output every evaluation interval throughout the analysis period and for every probable STOL demand state.

8.3 STOL Design Optimization Results

Table (8.3) gives the optimal values obtained for the STOL design optimization variables and the objective function (net revenue).

TABLE (8.3) - OPTIMAL VALUES OF THE STOL DESIGN VARIABLES AND NET REVENUE

OPTIMAL 1980 FARE STRUCTURE*	= $18 + 17.5 \left(\frac{\text{DISTANCE}}{100} \right) \dots (\$/\text{PASSENGER})$
OPTIMAL AIRCRAFT CRUISE SPEED	= 385 MILES PER HOUR
OPTIMAL AIRCRAFT SIZE	= 96 SEATS
MAXIMUM NET REVENUE (1980-92)	= 176.338 MILLIONS OF 1975 DOLLARS

The optimization procedure was first carried out to determine the optimal value of the fixed component, a, in the fare structure formula. Twenty values ranging between 10 and 32 dollars were tried for that component. The variation in the value of the objective function over that range was rather narrow. The lowest value was \$172.077 millions and the highest was \$176.338 millions which occurred at a fixed fare value of 18 dollars. The optimal maximum cruise speed remained at the same value of 385 mph. The optimal aircraft size came out at the same value too, and was equal to 96 seats. As was expected, the optimal value of the variable portion of fare, b, consistently decreased as the value of the fixed component, a, was increased.

The optimal values of the STOL design variables are plausible and appear to be practically consistent. The optimal value obtained for fare is just about equal to that being charged by present airlines. The optimal cruise speed and size of the

* According to the cost indices given in Appendix E, this corresponds to a 1975 fare structure of about $12.7 + 12.4 \left(\frac{\text{DISTANCE}}{100} \right)$. Also, fare is assumed to increase at a rate of 6% per annum after 1980.

STOL aircraft are higher than those of the DeHavilland's Dash 7*, but are close to those considered by NASA for STOL aircraft serving U.S. markets. In examining new transport technology that could be applicable in the Quebec City-Windsor Corridor, the Dash 7 was seen by the Canadian Transport Commission² as being suited for operation in the Corridor until 1980 at which time it would be replaced by an augmentor-wing aircraft representative of a proposed second-generation STOL technology. The maximum cruise speed of this proposed STOL aircraft is 506 mph and the seating capacity is 100 seats. The optimal values obtained above for these two parameters suggest that for the period 1980-1992, the augmentor-wing aircraft has the right size for the Toronto-Ottawa-Montreal network, but its cruise speed is not optimal. A maximum cruise speed of 385 mph is, according to this analysis, the most economical.

The maximum net revenue obtained above is for thirteen years (1980-1992) and is expressed in terms of 1975 dollars (present worth). It should be noted, however, that there are some cost elements which were not accounted for such as the cost of property (land) and ground-based navigational aids**. Parking facilities were assumed self-supporting, and were not included in the terminal cost. Corporate taxes, which are not a function of costs, but of cost-revenue results, were not included in the analysis. Revenues were assumed to be drawn from fare-paying scheduled passengers. Revenues generated from (and additional costs incurred for) non-passenger services such as mail or parcel services were not accounted for.

Table (8.4) shows the values of the objective function at different combinations of the aircraft cruise speed and the variable portion of the fare (b). Since the function is three-dimensional, several such Tables are produced for different aircraft sizes. The Table shown corresponds to the optimal aircraft size -- 96 seats. It is evident from the Table that

* It cruises at a maximum speed of 281 miles per hour and seats 50 passengers.

** The magnitudes of most of these costs are assumed not affected by the values of the design optimization variables. Their exclusion does not therefore alter the optimal values of the variables, but does increase the net revenue of the system.

TABLE (8.4) - VALUES OF THE OBJECTIVE FUNCTION AT DIFFERENT COMBINATIONS OF SPEED AND FARE

		AIRCRAFT MAXIMUM CRUISE SPEED (MPH)									
		120	160	200	240	280	320	360	400	440	480
10	(c/PASSENGER-MILE)	22.8	21.2	23.4	28.7						
12	OF FARE, "b"	52.8	56.5	64.4	73.5	88.3	108.0				
14	1980 VARIABLE PORTION	64.0	73.2	82.0	97.4	117.1	140.0	151.8	138.8	125.8	94.0
16		63.6	75.4	88.8	104.6	122.9	149.4	166.1	157.2	144.3	122.6
18		53.6	69.2	82.4	101.7	122.2	154.2	169.7	165.7	154.0	132.7
20		38.0	52.1	68.5	86.8	111.0	142.5	159.3	156.2	148.1	130.3
22		18.4	33.2	48.5	65.8	87.0	122.8	138.8	136.4	130.8	121.2
24		-.7 (loss)	11.8	26.2	43.9	63.3	99.7	114.1	112.2	104.0	103.3

- Notes:
1. Aircraft size = 96 seats; fixed portion of 1980 fare = \$18.0
 2. Function values represent expected net revenue in millions of 1975 dollars, for the period 1980-1992.
 3. Function values at some low fare-high speed combinations are not shown, because such combinations resulted in a frequency of service exceeding an assumed practical upper limit.

the objective function has one global maximum within the shown range of variables. The optimal solution can be seen from the Table to be interior to the region of practically feasible speeds and fares.⁴

A profile of the objective function along each of its three directions: fare, speed, and aircraft size, is plotted in Figures (8.3), (8.4), and (8.5), respectively. Shown also in the Figures are the total STOL passenger volume and passenger-miles. Figure (8.3) shows that the net revenue increases with increasing the fare up to a certain level beyond which it decreases steadily with further fare increases due to loss of passengers to other travel modes. It can also be deduced from the Figure that not only does the STOL passenger volume decrease with increasing the fare but so does the average distance traveled. According to the results plotted in the Figure, the average distance traveled at 13¢/passenger-mile is 267 miles while that at 33¢/passenger-mile is 226 miles. This suggests that the impact on STOL ridership of increasing the variable portion of the fare is more noticeable on the long links rather than on the short links; since the fixed portion of the fare remains unchanged.

Similar comments can be made about the results plotted in Figure (8.4) except that increasing the cruise speed in this case have favorable effects on the net revenue and the STOL ridership. The form of variation of the objective function with the aircraft size which is illustrated in Figure (8.5) is similar to that resulting from changing the fare [Figure (8.3)]. It is seen from Figure (8.5) that increasing the vehicle size beyond a certain level has little impact on the STOL market share. The shown slight reduction in the STOL ridership as the aircraft size increases is due to the resulting cut-back on the number of flights (to an assumed minimum of eight departures per day per direction on each link).

It might be interesting to note here that evaluation of the objective function over a relatively long period of time, as is being done here, tends to minimize the effect of possible "jumps"

FIGURE (8.3) - VARIATION OF STOL NET REVENUE AND RIDERSHIP WITH STOL FARE

FIGURE (8.4) - VARIATION OF STOL NET REVENUE AND RIDERSHIP WITH AIRCRAFT CRUISE SPEED

FIGURE (8.5) - VARIATION OF STOL NET REVENUE AND RIDERSHIP WITH AIRCRAFT SIZE

in the objective function on its continuity. Such discontinuities or jumps normally exist because of the "indivisibility" characteristic of some of the transport system components which cannot be varied continuously so as to provide the exact amount of capacity to serve a particular demand volume. An example of this typical transport system characteristic is the acquisition of additional vehicle(s).

The travel demand estimates corresponding to the optimal values of the STOL design variables are summarized in Table (8.5) for a selected year, 1989. For illustration purposes, demand estimates pertaining to only one probable STOL market penetration state are shown. Specifically, the modal splits and STOL volumes shown are for the case of "STOL market shares being 0-10% below predictions made by the demand models". As given earlier, the probability of occurrence of this state = 0.375. For comparison purposes, the split of the travel market among the existing three modes: air, bus, and rail if the STOL system is not at all introduced was also computed, and is included in the Table.

A number of observations can be made from this Table:

1. STOL penetration in the travel market is significant, particularly for business travel.
2. Number of STOL passengers traveling on business is much greater than those traveling for non-business purposes.
3. STOL market share is higher than that of CTOL on all links. The difference in shares is much larger for business trips than for non-business.
4. For business trips, the STOL share is captured mostly from the air mode (CTOL). For non-business trips, the shift of travelers to STOL is rather made from all modes at almost equal proportions.

These observations appear to be plausible and are agreeable with expected market behavior of STOL systems.

In Table (8.6) a summary of expected values of basic STOL demand and economic indicators is presented. These measures are

TABLE (8.5) - STOL TRAVEL DEMAND IN A SELECTED YEAR, 1989*

TRIP PURPOSE	CITY-PAIR	MODAL SPLIT (%)			STOL WEEKLY PASSENGER VOLUME PER DIRECTION	MODAL SPLIT (%) IF STOL IS NOT INTRODUCED		
		CTOL	BUS	RAIL		CTOL	BUS	RAIL
BUSINESS	T-O	32.8	.8	.3	3510	96.6	2.4	1.0
	O-M	28.5	7.7	21.1	995	49.8	13.4	36.8
	M-T	34.5	.2	5.2	6983	86.4	.5	13.1
NON-BUSINESS	T-O	21.2	34.5	17.3	1776	29.1	47.3	23.6
	O-M	7.2	37.9	46.8	701	7.8	41.3	50.9
	M-T	16.3	18.0	46.9	2057	20.1	22.2	57.7
ALL TRIPS	T-O	28.9	12.1	6.0	5286	56.1	29.3	14.5
	O-M	19.7	20.2	31.7	1696	20.7	34.0	45.4
	M-T	30.4	4.2	14.7	9040	51.4	11.9	36.6

Abbreviations: T = Toronto O = Ottawa M = Montreal

CTOL = Conventional Take Off and Landing air mode

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

aggregated over the analysis period (1980-1992) and for all the network links. Costs and revenue shown are expressed in present worth (1975 dollars).

TABLE (8.6) - EXPECTED VALUES OF STOL DEMAND AND ECONOMIC INDICATORS

EXPECTED NUMBER OF PASSENGERS CARRIED BY STOL	=	19.46 MILLIONS
EXPECTED NUMBER OF STOL PASSENGER-MILES	 =	5.08 BILLIONS
EXPECTED SUM OF FARE REVENUES	 =	\$605.00 MILLIONS
EXPECTED SUM OF CAPITAL COST PAYMENTS	 =	\$140.75 MILLIONS
EXPECTED SUM OF SYSTEM OPERATING COST	 =	\$287.91 MILLIONS
EXPECTED SUM OF NET REVENUE	 =	\$176.34 MILLIONS
EXPECTED SYSTEM UNIT COST (PER PASSENGER-MILE)	=	8.46 ¢

A breakdown of the STOL system cost and revenue is shown in Table (8.7). The information presented in the Table is based on the selected demand state of "STOL demand share being 5-10% below what the demand models predict", with a probability of occurrence of 0.375. Subsequent tabulated results are also selected for this particular demand state. The cost and revenue figures shown in the Table for a given year are expressed in that year's dollars. It is seen from the Table that the three biggest components of the STOL system operating cost are the aircraft maintenance, passenger servicing, and aircraft fuel consumption. The system net revenue increases over time because the additional revenue drawn from growth in patronage increasingly exceeds the incremental cost incurred.

For the probable demand state selected above, Table (8.8) presents information about the STOL passenger volumes on the system links and the maximum possible accumulation of passengers in each terminal. Presented also in the Table are the minimum STOL aircraft requirement and the associated operational measures. This demand and supply information is shown for five selected years within the analysis period.

TABLE (8.7) - STOL SYSTEM COST AND REVENUE BREAKDOWN*

(In Millions of the Shown Year's Dollars)

YEAR:	1980	1983	1986	1989	1992
<u>FLIGHT PERSONNEL:</u>					
- FLIGHT CREW	2.22	3.07	4.49	6.34	8.93
- CABIN ATTENDANTS	0.76	1.05	1.54	2.17	3.05
<u>AIRCRAFT MAINTENANCE:</u>					
- MAINTENANCE	4.02	5.47	7.92	11.10	15.51
- MAINTENANCE BURDEN	3.27	4.46	6.46	9.63	12.67
<u>AIRCRAFT SERVICING:</u>					
- INSPECTION, FUELING, ETC.	1.90	2.63	3.77	5.28	7.39
- AIRCRAFT CONTROL	0.71	0.95	1.37	1.91	2.65
<u>PASSENGER SERVICING:</u>					
- SALES AND PROMOTION	4.99	7.46	11.09	15.99	23.01
- IN-FLIGHT FOOD	0.87	1.31	1.94	2.80	4.03
<u>AIRCRAFT FUEL CONSUMED</u>	4.20	5.88	8.59	12.14	17.15
<u>AIRCRAFT INSURANCE</u>	1.92	2.72	4.01	5.40	7.52
<u>GROUND PROPERTY & EQUIPMENT</u>	1.09	1.48	2.14	3.01	4.20
<u>STOL PORTS MAINTENANCE & ADMIN.</u>	2.97	3.54	4.22	5.02	5.98
<u>GENERAL ADMINISTRATIVE</u>	1.30	1.82	2.67	3.76	5.31
<u>INVESTMENT IN AIRCRAFT**</u>	96.11	21.63	38.65	30.69	54.82
<u>INVESTMENT IN STOL PORTS</u>	44.84	-	-	-	-
<u>TOTAL SYSTEM OPERATING COST</u>	30.22	41.86	60.21	83.97	117.39
<u>CAPITAL RECOVERY PAYMENT</u>	20.32	23.82	30.08	35.04	43.92
<u>TOTAL STOL SYSTEM COST</u>	50.54	65.68	90.29	119.01	161.31
<u>STOL FARE REVENUES</u>	56.04	83.92	124.77	179.88	258.84
<u>NET REVENUE</u>	5.50	18.24	34.48	60.87	97.53

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

** includes 20% spare airplanes and 15% spare parts.

TABLE (8.8) - STOL DEMAND AND SUPPLY MEASURES*

	YEAR:	1980	1983	1986	1989	1992
STOL PASSENGER	T-O	637	818	1084	1374	1706
DESIGN VOLUME	O-M	280	331	385	441	511
(PER DAY PER DIRECTION)	M-T	1279	1606	1971	2350	2815
STOL PASSENGER VOLUME ($\times 10^6$)		.882	1.106	1.381	1.672	2.020
STOL PASSENGER-MILES ($\times 10^8$)		2.295	2.889	3.606	4.364	5.273
MAXIMUM ACCUMULATION	T	171	185	184	193	210
OF PASSENGERS	O	115	132	139	147	159
IN TERMINALS	M	126	136	142	150	158
MINIMUM** NO. OF AIRCRAFT ACQUIRED		8	2	2	2	2
MINIMUM** AIRCRAFT FLEET	T	3	4	5	6	7
NEEDED (AND STORED)	O	2	2	3	3	3
AT EACH TERMINAL	M	3	4	4	5	6
DAILY NUMBER	T-O	8	9	12	15	18
OF FLIGHTS	O-M	8	8	8	8	8
PER DIRECTION	M-T	14	17	21	25	30
GATE-TO-GATE	T-O			50		
(BLOCK) TIME	O-M			32		
(IN MINUTES)	M-T			65		
DESIGN DAY	T-O	83.0	94.7	94.2	95.4	98.7
LOADING FACTOR	O-M	36.4	43.0	50.1	57.4	66.5
OF AIRCRAFT (%)	M-T	95.2	98.4	97.7	97.9	97.8

Abbreviations: T = Toronto O = Ottawa M = Montreal

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

** not including spare aircraft.

The Table shows that a large proportion of the aircraft fleet is acquired in the first year of operation and that additional aircraft needed are gradually acquired over the years. As the demand builds up, more STOL carrying capacity is provided in the form of additional flights; since the aircraft size is fixed throughout the analysis period. Accordingly, additional aircraft fleet is acquired to carry out the expanded departure schedules. It is also evident from the Table that the chosen aircraft is "over-sized" for the Ottawa-Montreal link because of the relatively low STOL passenger volume on that link. Although increases with time, the aircraft loading factor on that link is significantly lower than that on any of the other two links. Sizing of the aircraft for each link will be presented in the next section.

Figure (8.6) presents graphically the aircraft departure schedule along each of the network links, and shows how it expands over time. This again pertains to the same probable demand state selected before for illustration. Because the optimal aircraft size is bigger than what is actually needed for the Ottawa-Montreal link, the frequency of service along that link remained unchanged throughout the analysis period.

8.4 The Case of Multi-Size Aircraft

In this section the results obtained for the case of letting the proper aircraft size be determined separately for each link of the network are presented. Three types (sizes) of aircraft are being dealt with for the triangular network analyzed here. Each link of the network is served by a different aircraft size. The only difference between this case and the previous STOL application in terms of problem formulation is that the vehicle size variable in the previous case is replaced here by three optimization variables (vehicle sizes); one for each link.

The computer program developed by the author for the system design optimization methodology (listed in Appendix F) is constructed in such a way that this case can automatically be

FIGURE (8.6) - DEPARTURE PATTERN OF STOL FLIGHTS

investigated without any additional programming. The principal effect on STOL demand of using different aircraft sizes is through the resulting change in the frequency of service. The number of daily aircraft departures along a link depends on the size of aircraft used on that link for a given passenger volume. With regard to the STOL supply, aircraft departure scheduling, fleet size needed, and other operational measures are determined separately for each aircraft size. System costs and revenues are also affected by using multi-size aircraft. Table (8.9) presents the optimal values obtained for the STOL design optimization variables and objective function in this case.

TABLE (8.9) - OPTIMAL VALUES OF THE STOL DESIGN VARIABLES AND
NET REVENUE FOR THE CASE OF MULTI-SIZE AIRCRAFT

OPTIMAL 1980 FARE STRUCTURE* = $18 + 15.5 \left(\frac{\text{DISTANCE}}{100} \right) \dots (\$/\text{PASSENGER})$

OPTIMAL AIRCRAFT CRUISE SPEED = 385 MILES PER HOUR

OPTIMAL AIRCRAFT SIZES:

- FOR THE TORONTO-OTTAWA LINK = 136 SEATS
 - FOR THE OTTAWA-MONTREAL LINK = 56 SEATS
 - FOR THE MONTREAL-TORONTO LINK = 136 SEATS
- MAXIMUM NET REVENUE (1980-1992) = 185.333 MILLIONS OF 1975 DOLLARS

The Table reveals that the optimal fare structure is reduced by 2¢/passenger-mile from the value it took in the previous case. The optimal cruise speed is the same as before. It was in fact shown in Chapter 4 that the marginal reduction in travel time for cruise speeds higher than 385 miles per hour is less than that for speeds below it. As was expected, a smaller size aircraft

* According to the cost indices given in Appendix E, this corresponds to a 1975 fare structure of about $12.7 + 11 \left(\frac{\text{DISTANCE}}{100} \right)$. Also, fare is assumed to increase at a rate of 6% per annum after 1980. (Note: the fixed portion of fare "a" was taken equal to its optimal value established in the previous case).

(56 seats) was found to be best suited for the Ottawa-Montreal link. The other two links were found to be best served by one airplane of a larger size (136 seats); as any of them carries more traffic than does the Ottawa-Montreal link. Although different combinations of aircraft sizes along those two heavier-traffic links were tried by the search algorithm, only one size of aircraft serving both links was found to be most economical. The principal implication of this result to transport networks in general is to diversify the size of the vehicle only when substantial differences in traffic volumes exist.

The maximum net revenue was nearly \$10 millions (or about 5%) higher than that obtained for the one-common-size case. Reduction in the optimal fare charged per passenger-mile contributed to this increase as it increased the STOL demand particularly on the long-distance links (e.g. Toronto-Montreal), and resulted in an overall increase in the gross revenues.

The travel demand estimates corresponding to the optimal values of the STOL design variables in this case are summarized in Table (8.10). To permit comparison with the previous case, the tabulated results are for the same selected year (1989) and same probable STOL demand state (0 - 10% below demand model predictions). The Table shows that the STOL demand is very slightly higher in this case than in the case of using one common aircraft size. The observations and comments made earlier for the latter case about the penetration of the STOL system in the travel market still apply here.

TABLE (8.10) - STOL TRAVEL DEMAND IN A SELECTED YEAR, 1989*,
FOR THE CASE OF MULTI-SIZE AIRCRAFT

TRIP PURPOSE	CITY- PAIR	MODAL SPLIT (%)				STOL WEEKLY PASSENGER VOLUME PER DIRECTION
		CTOL	BUS	RAIL	STOL	
BUSINESS	T-O	31.8	.8	.3	67.1	3626
	O-M	26.9	7.2	19.8	46.1	1127
	M-T	30.9	.2	4.7	64.2	7953
NON- BUSINESS	T-O	20.9	33.9	17.0	28.2	1881
	O-M	7.1	37.4	46.2	9.3	793
	M-T	15.7	17.4	45.2	21.7	2417
ALL TRIPS	T-O	28.1	12.1	6.0	53.8	5507
	O-M	18.7	19.7	30.7	30.9	1920
	M-T	27.4	4.2	14.1	54.3	10370

Abbreviations: T = Toronto O = Ottawa M = Montreal
CTOL = Conventional Take Off and Landing air mode

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

A summary of expected values of basic STOL demand and economic indicators is presented in Table (8.11). These measures are aggregated over the analysis period (1980-1992) with costs and revenues being expressed in present worth (1975 dollars). The values shown are very close to those previously presented for the one-size aircraft case.

TABLE (8.11) - EXPECTED VALUES OF STOL DEMAND AND ECONOMIC INDICATORS FOR THE CASE OF MULTI-SIZE AIRCRAFT

EXPECTED NUMBER OF PASSENGERS CARRIED BY STOL =	21.91 MILLIONS
EXPECTED NUMBER OF STOL PASSENGER-MILES =	5.74 BILLIONS
EXPECTED SUM OF FARE REVENUES =	\$626.91 MILLIONS
EXPECTED SUM OF CAPITAL COST PAYMENTS =	\$149.80 MILLIONS
EXPECTED SUM OF SYSTEM OPERATING COST =	\$291.78 MILLIONS
EXPECTED SUM OF NET REVENUE =	\$185.33 MILLIONS
EXPECTED SYSTEM UNIT COST (PER PASSENGER-MILE)=	7.71 ¢

A breakdown of the STOL system cost and revenue pertaining to this case is presented in Table (8.12) for the same selected probable STOL demand state. While some cost items are lower in this case than before, the use of a relatively larger aircraft size for the two heavier STOL links contributed to increasing the cost of some other components such as cabin attendants, aircraft investment, and aircraft insurance. Passenger servicing costs as well as drawn revenues are also increased due to the higher STOL demand volumes in this case.

Selected measures of STOL demand and supply are presented in Table (8.13) for the same demand state and for five selected years within the analysis period. The same comments made in the previous case with regard to these measures still apply here, except that the aircraft loading factor between Ottawa and Montreal is now much higher than it was in that case.

Finally, Figure (8.7) presents a graphical representation of the aircraft departure schedules along the three links for the above selected STOL demand state.

8.5 Sensitivity Analyses

Two types of sensitivity analyses are of interest in system design. The first type tests the impact on the optimal system design of changes in some of the principal factors assumed in the analysis. The second type examines the response of the optimal

TABLE (8.12) - STOL SYSTEM COST AND REVENUE BREAKDOWN*
FOR THE CASE OF MULTI-SIZE AIRCRAFT

(In Millions of the Shown Year's Dollars)

YEAR:	1980	1983	1986	1989	1992
<u>FLIGHT PERSONNEL:</u>					
- FLIGHT CREW	2.00	2.75	3.72	5.39	7.92
- CABIN ATTENDANTS	0.94	1.29	1.74	2.52	3.71
<u>AIRCRAFT MAINTENANCE:</u>					
- MAINTENANCE	4.00	5.42	7.25	10.54	15.53
- MAINTENANCE BURDEN	3.15	4.26	5.69	8.26	12.19
<u>AIRCRAFT SERVICING:</u>					
- INSPECTION, FUELING, ETC.	1.87	2.61	3.61	5.25	7.73
- AIRCRAFT CONTROL	0.63	0.84	1.10	1.59	2.37
<u>PASSENGER SERVICING:</u>					
- SALES AND PROMOTION	5.63	8.37	12.09	17.76	26.03
- IN-FLIGHT FOOD	0.99	1.47	2.11	3.11	4.56
<u>AIRCRAFT FUEL CONSUMED</u>	4.13	5.75	7.83	11.38	16.68
<u>AIRCRAFT INSURANCE</u>	2.40	2.86	4.08	5.66	8.17
<u>GROUND PROPERTY & EQUIPMENT</u>	1.04	1.41	1.89	2.74	4.04
<u>STOL PORTS MAINTENANCE & ADMIN.</u>	2.97	3.54	4.22	5.02	5.98
<u>GENERAL ADMINISTRATIVE</u>	1.34	1.85	2.56	3.71	5.45
<u>INVESTMENT IN AIRCRAFT**</u>	120.20	-	33.54	39.94	71.36
<u>INVESTMENT IN STOL PORTS</u>	44.31	-	-	-	-
<u>TOTAL SYSTEM OPERATING COST</u>	31.09	42.43	57.90	82.94	120.34
<u>CAPITAL RECOVERY PAYMENTS</u>	24.16	24.16	29.59	36.06	47.61
<u>TOTAL STOL SYSTEM COST</u>	55.25	66.59	87.49	119.00	167.95
<u>STOL FARE REVENUES</u>	58.16	86.95	125.94	184.19	268.38
<u>NET REVENUE</u>	2.91	20.36	38.45	65.19	100.43

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

** includes 20% spare airplanes and 15% spare parts.

TABLE (8.13) - STOL DEMAND AND SUPPLY MEASURES*
FOR THE CASE OF MULTI-SIZE AIRCRAFT

	YEAR:	1980	1983	1986	1989	1992
STOL PASSENGER	T-O	727	888	1072	1432	1819
DESIGN VOLUME	O-M	303	356	414	499	644
(PER DAY PER DIRECTION)	M-T	1448	1849	2265	2696	3229
STOL PASSENGER VOLUME (X 10 ⁶)		.995	1.242	1.505	1.857	2.285
STOL PASSENGER-MILES (X 10 ⁸)		2.597	3.268	3.980	4.877	5.952
MAXIMUM ACCUMULATION	T	223	243	267	265	265
OF PASSENGERS	O	129	156	186	186	184
IN TERMINALS	M	170	177	185	190	193
MINIMUM** NO. OF AIRCRAFT ACQUIRED (6,2) (0,0) (2,0) (2,0) (2,0)						
(136 SEATS, 56 SEATS)						
AIRCRAFT FLEET* NEEDED (AND	T	(3,0)	(3,0)	(4,0)	(5,0)	(6,0)
STORED) AT EACH TERMINAL	O	(1,1)	(1,1)	(1,1)	(2,1)	(2,1)
(136 SEATS, 56 SEATS)	M	(2,1)	(2,1)	(3,1)	(3,1)	(4,1)
DAILY FLIGHTS	T-O	8	8	8	11	14
PER DIRECTION	O-M	8	8	8	9	12
	M-T	11	14	17	20	24
GATE-TO-GATE	T-O			50		
(BLOCK) TIME	O-M			32		
(IN MINUTES)	M-T			65		
DESIGN DAY	T-O	67.0	81.6	98.5	95.6	95.5
LOADING FACTOR	O-M	67.5	79.5	92.4	99.0	95.8
OF AIRCRAFT (%)	M-T	96.8	97.0	97.9	99.0	98.9

Abbreviations: T = Toronto O = Ottawa M = Montreal

* for a selected demand state of "STOL market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

** not including spare aircraft.

FIGURE (8.7) - DEPARTURE PATTERN OF STOL FLIGHTS FOR THE CASE OF MULTI-SIZE AIRCRAFT

system design to an alternative optimization criterion. For computational reasons, all sensitivity tests were conducted for the case of one common aircraft size. The case of multi-size aircraft is expected to yield similar results.

Sensitivity of the optimal STOL system design to total common carrier demand, rate of discounting costs and revenues, and to capital investment in STOL ports was tested, and the results are shown in Figures (8.8), (8.9) and (8.10), respectively. Variation in the total common carrier demand (which is to be split among the available public modes including STOL) indirectly reflects over- or under-estimation of the cities' socio-economic characteristics, variation in the level of service of the modes competing with STOL, and/or adequacy of the calibrated demand models to predict future travel demands. Varying the total common carrier demand automatically changes the STOL market share by the same extent. In other words, the STOL demand is varied without actually changing the STOL level of service so as to induce such a variation. As a result, the drawn fare revenues vary at a much faster rate than the system cost. Figure (8.8) demonstrates that increased STOL demand calls for a larger aircraft size and tends to slightly reduce the fare charged. The optimal speed remains, however, unchanged from its previous value of 385 mph. It is seen from the Figure that the maximum net revenue of the STOL system is highly sensitive to changes in travel demand.

The most important point to be gained from Figure (8.9), which shows sensitivity of the optimal STOL design to the rate used for discounting the costs and revenues, is that the adopted discount rate significantly influences the economic viability picture of the system. Lower discount rates result in a more economically viable system design. Higher rates do the opposite. The Figure shows that the same optimal values obtained before for the adopted discount rate of 10% still optimize the system design at 6, 8, 12, or 14%.

FIGURE (8.8) - SENSITIVITY OF THE OPTIMAL STOL DESIGN TO TOTAL COMMON CARRIER DEMAND

FIGURE (8.9) - SENSITIVITY OF THE OPTIMAL STOL DESIGN TO DISCOUNT RATE

Sensitivity of the optimal STOL design to variation in the capital cost of the three STOL ports is presented in Figure (8.10). The varied capital cost includes the construction cost of the passenger and vehicle terminal areas as well as the other "fixed" cost components of the STOL terminals [the c_f -term in equation (5.1)]. It is seen from the Figure that variations in the STOL ports investment does not affect the optimal values obtained previously for the system design variables. This is because the major portion of the STOL port cost is fixed (the c_f -term) and as such it does not change the optimal solution. The principal effect of increasing the capital cost of the STOL ports is the reduction of the economic viability (revenues minus costs) of the system. The Figure demonstrates that the rate of change in the maximum economic viability of the STOL system due to variation in the STOL ports investment is fairly low. This result was also expected because the infrastructure cost for a STOL system represents a small proportion of its total cost as contrasted to a ground mode, such as rail, where the infrastructure cost is very substantial.

Model Response to an Alternative Optimization Criterion:

The optimization criterion adopted thus far has been the maximization of the system net revenue. Sensitivity of the system design optimization to another criterion was tested. The criterion applied here is the minimization of the system unit cost, including the cost to the users. The users cost is composed here of travel time cost plus out-of-pocket cost. To avoid double counting of the fare, the system revenues are subtracted from the combined system and users cost. Also, since the users' cost is, in simple terms, equal to the number of passengers carried by the system times the cost per passenger, it was necessary to divide the combined net cost (which is to be minimized) by the number of passengers, or more practically, by the number of passenger-miles to yield a unit cost. This procedure eliminates the possibility of obtaining trivial optimal solutions (e.g. zero or minimal number of passengers).

FIGURE (8.10) - SENSITIVITY OF THE OPTIMAL STOL DESIGN
TO INVESTMENT COST IN STOL PORTS

The objective function tested here is in effect similar to that used before except that the users' cost is added to the negative of the net revenue (which was maximized by the previous criterion) and the resulting net cost is then divided by the total passenger-miles traveled. This particular structure of the objective function implies that the viewpoint of the system carrier (or government) and that of the users are simultaneously considered and are equally weighted in the optimization. Symbolically, this objective function can be written as:

$$\text{Minimize } Z' = \frac{1}{PM} \cdot \sum_i (C_i - R_i + tt_i + tc_i) \dots\dots (3.4)$$

where

Z' = value of the objective function (present worth)
 -- system unit cost (\$/passenger-mile)

C_i = system operating costs and capital recovery payments incurred in year i , discounted to a given base year

R_i = fare revenues earned in year i from all city-pair services, discounted to the same base year

tt_i = users' total travel time cost in year i , aggregated over all user groups (by income), and discounted to the same base year

tc_i = users' total out-of-pocket travel cost in year i , aggregated over all the users, and discounted to the same base year

PM = total passenger-miles traveled during the analysis period. (It is equal to the passenger volume on each link times the length of that link, summed over all the network links and throughout the period of analysis).

Passengers' travel time was valued by using the imputed values of travel time (see Chapter 5, section 5.7). The users' time and money costs which appear in the above objective function are, therefore, determined as follows:

$$tt_i = \sum_l \sum_u [(5.6266 I_{ui} \cdot T \cdot P_{ui}) + (3.2531 I'_{ui} \cdot T' \cdot P'_{ui})] \quad \dots (8.5)$$

$$tc_i = \sum_l (c_i \cdot P_i + c'_i \cdot P'_i) \quad \dots (8.6)$$

where

I_{ui} = mean income in year i of user group u .. (\$10,000's)

T = total (door-to-door) travel time for a business trip along link (origin to destination) l (hours)

P_{ui} = number of passengers belonging to user group u who are traveling in year i on business (passengers/year)

c_i = total (door-to-door) cost of traveling on business in year i along link l (\$/passenger)

P_i = total number of business passengers in year i on link l ($= \sum_u P_{ui}$) (passengers/year)

T', P'_{ui}, c'_i, P'_i are similar to T, P_{ui}, c_i, P_i but pertain to non-business travel.

In expression (8.5) the quantities $(5.6266 I_{ui})$ and $(3.2531 I'_{ui})$ represent the imputed values of travel time for business and non-business travel, respectively.

Apart from the particular structure of the objective function, the optimization procedure is exactly the same as before. (It can be seen from the computer program which is listed in Appendix F that the system design optimization can be carried out

based on either criterion without any additional programming at all. Other criteria could easily be incorporated). The optimization results based on the criterion of minimum unit cost (including users' cost) are graphically illustrated in Figure (8.11) for different values of the variable portion of the fare "b". [The same previous value of the fixed fare portion "a" was applied here (i.e. \$18.00 in 1980)].

A number of observations can be made from Figure (8.11). Increasing the variable portion of the fare (b) results in higher users' out-of-pocket cost and reduces the STOL demand at a relatively slower rate. As a result of decreasing the STOL demand, the earned revenues are reduced. These factors together conspire to increase the minimum value of the objective function (unit cost) as the fare is increased. The Figure shows that the rate of increase in the minimum unit cost is faster at high fare values than at low fare levels. Although lower b-values are favored in terms of reducing the users' cost (and hence unit cost), the optimal STOL design may be determined based on this optimization criterion for only a specified fare value (for a and b).

As was shown in the previous sensitivity analyses, the objective function is minimized here by the same aircraft cruise speed of 385 mph. Figure (8.11) demonstrates that as the STOL demand is reduced (because of increasing the fare) the optimal aircraft size gets smaller, which is an expected result. It is interesting to note that at a fare level equal to the optimal fare obtained by using the previous optimization criterion, the optimal aircraft speed and size obtained here are identical to those that maximized the STOL net revenue.

FIGURE (8.11) - THE OPTIMAL STOL SYSTEM DESIGN BASED ON MINIMIZATION OF UNIT COST

CHAPTER 9

EXAMPLE APPLICATION 2: DESIGN OF AN IMPROVED PASSENGER RAILWAY SYSTEM

This chapter reports on a second example application of the design optimization methodology developed here. The methodology is re-applied to the optimization of the design of a number of passenger rail improvements between the same three cities of Toronto, Ottawa, and Montreal. In other words, the STOL system analyzed in the preceding chapter is replaced here by an improved rail passenger service along the same network. Because a number of mutually-exclusive rail improvements are analyzed in this application, this example represents also a typical situation in which the methodology is used to optimize and help choose among a number of transport alternatives.

Increasing attention is being focused at the present time on upgrading passenger rail services in North America as well as in other parts of the world. As was pointed out in Chapter 7, more than half of Canada's population lives within the Windsor-Quebec City Corridor. The main railway lines are concentrated in that area. At present, the Canadian government is giving serious consideration to upgrading the rail passenger services in the corridor⁸⁰. The objective is to develop a better rail system thereby avoiding some demands for highways and airports, and the use of transportation systems that are less efficient in their use of energy and land. Coupled with this objective is the aim of providing a financially self-supporting rail service because the revenues drawn from present Corridor services cover only about one-half of the total costs of providing the services⁸⁰. (The government pays 80% of the losses in the form of subsidies to the railway carriers⁸⁰).

9.1 Existing Passenger Rail Service and Proposed Improvements

Present passenger rail service between the three cities has been described in terms of travel time, travel cost, and departure frequency in Chapter 7 [Table (7.1)]. Approximate

average travel times and daily frequencies of service are re-tabulated below for the present service. It is seen from the Table that, in terms of the speed alone, the level of service is quite low, and that the Toronto-Ottawa link is poorly served by rail. A layout of the existing railway lines between Toronto, Ottawa, and Montreal is sketched in Figure (9.1).

TABLE (9.1) - AVERAGE TRAVEL TIMES AND FREQUENCIES
OF PRESENT RAIL SERVICE

CITY-PAIR	RAIL DISTANCE (MILES)	AVERAGE TRAVEL TIME (HOURS)	AVERAGE SPEED (MPH)	AVERAGE FREQUENCY OF SERVICE
T-O	277*	5.60	49	3/DAY/DIRN.
O-M	116**	2.22	52	7/DAY/DIRN.
M-T	335	4.95***	68	6/DAY/DIRN.

Abbreviations: T = Toronto O = Ottawa M = Montreal

Note: Shown travel times are based on those given in the system time-tables. Actual travel times may differ from those shown.

* Canadian National line via Brockville. It is equal to 248 miles via Napanee.

** Canadian National line. It is equal to 109 miles along the south-shore Canadian Pacific line.

*** The Turbo train takes 4.25 hours, but only 2 trains are dispatched daily in each direction.

A new generation of high-speed light-weight diesel-electric trains known as the LRC (for Light Rapid and Comfortable) trains are being manufactured in Canada. A prototype LRC train has been built and tested. The train cruises at or beyond 120 miles per hour and is provided with a sophisticated suspension system that permits train banking while negotiating curves at a speed much

FIGURE (9.1) - EXISTING RAIL LINES IN THE STUDY AREA

higher than that of conventional trains. Detailed characteristics of this train can be found elsewhere⁴¹. The optimization results presented here are based on using the LRC train for the new (improved) service between the three cities,

To fully utilize the higher performance capabilities of new generation of passenger trains (e.g. LRC trains, Turbotrains) the railway tracks (including signaling system) must be upgraded. Protection of all crossings along the rail lines is also necessary to permit higher speed operation. For that purpose, a number of alternative track improvements between the three cities were studied and approximately costed, as part of an overall passenger services project carried out recently by the Canadian Government⁴⁵. From the track upgrading cost information reported⁴⁵, it was possible to synthesize four mutually-exclusive alternatives for track improvement. These are illustrated in Figure (9.2). The following assumptions were made in the analysis:

MONTREAL

OTTAWA

TORONTO

CP 107 MILES
95 MPH

NAPANEE CN 110 MILES
95 MPH

CN 135 MILES

DO-NOTHING (AS IS)

TRACK INVESTMENT
= \$103 MILLIONS
(IN 1975 DOLLARS)

120 MPH

120 MPH

TRACK INVESTMENT
= \$157 MILLIONS

DO-NOTHING (AS IS)

120 MPH

120 MPH

TRACK INVESTMENT
= \$256 MILLIONS

ADDITIONAL
TRACK

120 MPH

120 MPH

120 MPH

TRACK INVESTMENT
= \$393 MILLIONS

120 MPH

FIGURE (9.2) - TRACK IMPROVEMENT ALTERNATIVES

- The existing passenger service is replaced in 1980 by LRC service between Toronto, Ottawa, and Montreal.
- No direct Toronto-Montreal service. That is, Toronto-Montreal trains stop at Ottawa. As the Figure shows, by doing so the travel distance between Toronto and Montreal is increased by only 17 miles.
- The proposition of amalgamation of rail services offered by Canadian National (CN) and Canadian Pacific (CP) companies is assumed.
- Because parallel rail lines exist between these three cities, interference with freight trains was excluded from the analysis. This relates primarily to the Montreal-Ottawa-Napanee portion of the route where freight traffic is low relative to the Napanee-Toronto segment.

In Figure (9.2) four alternative track improvement schemes (in terms of maximum track speed) are shown. Because upgrading of the tracks involves re-alignment of some segments of the route (e.g. flattening out the horizontal curves), the total length of the line is slightly reduced from 357 miles to 352 miles⁴⁵. The capital investment shown beside each alternative is for upgrading the tracks, signaling system and right-of-way protection (level crossings and fencing) and are expressed in terms of 1975 dollars*. In the first two alternatives the line between Toronto and Napanee (135 miles) is double-tracked and presently permits a maximum speed of 95 mph on some sections of it. No track improvement is considered for this portion of the line in either of these two alternatives. The passenger trains are assumed to be run on that segment in exactly the same manner as they are being handled at the present time. In alternative C the maximum speed on this portion of the line is raised to 120 mph. As a result, an additional track is proposed because such a high speed would leave little track capacity to run freight trains on the same track.

* These costs were obtained by assembling the reported costs of improving various parts of the line as estimated by the Canadian Ministry of Transport⁴⁵. (A cost escalation rate of 10% was applied to the reported costs to express them in terms of 1975 dollars). The investment required for alternative D and that for the Toronto-Napanee portion of alternative C were based on FENCO estimates of one million dollars per mile (1974 dollars) to upgrade and double track existing single lines in the Corridor area (to 120 mph).

In the first three alternatives, most of the rail line is single-tracked (from Napanee to Montreal via Ottawa). Opposing fast passenger trains could therefore meet each other on the sections between stations. Should this happen, the high speed advantage of the trains would be wasted as the travel time will substantially increase in such case due to meet delays. To avoid en-route meets, the timetable of the trains was constructed for each alternative in such a way that opposing trains could only meet in Ottawa station or on the double-tracked portion of the line (between Napanee and Toronto). Such a scheme imposed a constraint on the daily number of trains that could be dispatched in either direction without inflicting meet delays on opposing trains. The maximum number of departures per direction per day were computed from the en-route travel times shown in Figure (9.3) and were found to be equal to 7 for alternative A, and 8 for alternatives B or C.

The last alternative is double-tracked thereby providing a much greater track capacity. Train meets are eliminated altogether and the maximum number of trains that could be dispatched is increased. The maximum number of departures is constrained here by only the operating headway time between successive trains. That is, if a minimum headway time of 10 minutes is assumed, this alternative would then permit dispatching 91 equally-spaced departures per direction over a daily servicing period of 15 hours.

Station-to-station travel times were approximately computed for each alternative from the maximum speeds indicated in Figure (9.2), assumed station stopping times, and LRC acceleration characteristics⁴¹. These times are shown in Figure (9.3). It was not possible to take into account the effect of grades in computing travel times because the specific alignment of the route is not known at the present time. However, this was felt to be an uncritical factor because trains are assumed to be provided with front and rear locomotives and that excess power is likely to be available most of the time to overcome grade resistance.

FIGURE (9.3) - IMPROVED TRAVEL TIMES AND AVERAGE SPEEDS

Apart from the capability of increasing the frequency of train service along the Toronto-Ottawa-Montreal route, comparison of the information presented in Figure (9.3) with those shown previously in Table (9.1) indicates that the average line-haul speed has been substantially increased. The Toronto-Ottawa link, which is presently the poorest served, benefited the most from the proposed improvement schemes, followed by the Ottawa-Montreal link, and finally by the Montreal-Toronto city-pair.

The Optimization Problem:

Having described the existing rail service and outlined possible improvement alternatives, the principal questions to be answered by the design optimization methodology are:

(A) For each proposed improvement scheme:

(1) What is the optimal frequency of service?

(2) What is the optimal fare to be charged?

Such that the rail economic viability is maximized.

(3) How far could the improved rail service penetrate in the travel market?

(4) What level of rail supply should be provided in each year of operation [e.g. train consist (number of locomotives and number of cars in the train), and resulting loading factors]?

(5) What magnitudes of costs (broken down by components) and revenues are involved in each year throughout the analysis period?

(B) Which of the proposed alternative improvement schemes is more economically viable?

(C) How would the optimal rail design determined above shift if input conditions or assumptions change (e.g. change in future populations of the cities, change in total common carrier travel demand, over- or under-estimation of track improvement investment, use of a different discount rate, and finally application of another optimization criterion)?

9.2 Data, Assumptions and Optimization Procedure

In this particular case study, the discrete level of track improvement (alternatives A, B, C and D) replaces the vehicle speed as an optimization variable. Also, because the seating capacity of a passenger rail car is fairly standard, the number of cars per train replaces the vehicle size variable. However, the frequency of service along the Toronto-Ottawa-Montreal route was rather treated as an optimization variable and the train consist was determined accordingly. The fare structure was treated as a design optimization variable. The objective function is the same as that applied in the STOL example application (i.e. maximization of net revenue).

Data and assumptions common to both STOL and rail applications in the study area have already been recorded in the previous two chapters. Specific data and assumptions which pertain exclusively to the rail system application are described in the following paragraphs.

Existing rail stations were utilized. No investment was assumed for expanding or renovating existing terminal facilities.

Average access times and costs to the rail stations as well as average terminal waiting times, terminal exiting time, and schedule overrun time were taken equal to those used in calibrating the demand models (Appendix B). Projected 1980 rail access costs have already been given in the preceding chapter [Table (8.1)].

The value of the rail constant term (modal bias) which appears in the generalized travel cost expression [equation (3.13)] was made equal to that designated in Chapter 3 for the rail mode. Departures from this value are implicitly accounted for through treatment of uncertainty in the rail market share.

Due to lack of data on the diurnal distribution of rail passenger demand on one hand, and the constraint of maximum number of daily departures for the first three alternatives on the other, train departures were assumed to be regularly spaced in time of day. A daily servicing period of 15 hours was also assumed in the analysis. Following the same procedure adopted in Appendix B.

for calculating the effective frequency of service, average effective frequency of service factors were computed for a wide range of service frequencies and were found to be approximately equal to 0.75, 0.82, 0.70 for the Toronto-Ottawa, Ottawa-Montreal, and Montreal-Toronto city-pairs.

The demand peaking factor was assumed to be the same as that used in the STOL application (i.e. 1.30). A 7-day week and 365 servicing days per year were, however, assumed for rail. As was described in Chapter 7, passengers with origins and/or destinations at major corridor cities other than Toronto, Ottawa, or Montreal were accounted for in the analysis.

The number of locomotives and cars per train and the required number of such train sets were determined based on the highest passenger demand rate along the route and the value of frequency of service. The acquisition cost of rolling stock was then evaluated using unit prices quoted for the LRC locomotives and cars⁴⁵. The following LRC data⁴¹ were used:

- seating capacity per car = 76 seats
- maximum number of cars per train = 20 cars
- empty weight of car = 45 tons
- dry weight of locomotive = 97.75 tons
- gross horsepower output per locomotive = 2900 HP
- net horsepower for traction (at the rail)
per locomotive = 2000 HP
- auxiliary (service) power requirement = 80 KW/car
- each train is provided with a front and a
rear locomotive. Additional locomotives
are determined based on the train resistance
(given in Chapter 4).
- train turn-around time (in Toronto and
Montreal) = 15 minutes
- price of locomotive (1975 dollars) = \$900,000
- price of car (1975 dollars) = \$500,000
- rolling stock spare parts cost = 15% of basic price
- number of spare train sets .. = 20% of minimum fleet size.

Evaluation of the objective function for rail is similar to that described previously for the STOL system application. Uncertainty in improved rail market shares was handled in exactly the same way as was done for STOL. The following specific data and assumptions were also used in evaluating rail costs and revenues:

- improved rail system will start operation in year 1980
- track upgrading is spread over 2 years prior to 1980
- length of analysis period (1980-1995) = 16 years
- evaluation interval = 3 years
- service life of rolling stock (zero salvage value) = 16 years
- service life of tracks (zero salvage value) = 30 years
- discount rate, i = 10%
- rate of increase in income, consumer price index, costs, and fares = same as used in the STOL application
- base year = year 1975

The same design optimization procedure outlined in the preceding chapter (section 8.2) for the STOL system was applied here. Note that because the frequency of service is treated here as an optimization variable, the rail supply and demand are automatically in-equilibrium, and no iterations are therefore required to ensure that the same value of frequency of service is used in both the supply and demand functions. The fare structure, which is treated here as an optimization variable, was found by linear regression analysis to be directly proportional to the rail distance. Canadian National fare-distance data are given in Table (9.2) and are followed by the regression results.

TABLE (9.2) - CANADIAN NATIONAL "WHITE" FARES IN 1975

CITY-PAIR	DISTANCE (MILES)	FARE (\$)	CITY-PAIR	DISTANCE (MILES)	FARE (\$)
MONTREAL-QUEBEC	167	10.25	TORONTO-LONDON	115	7.00
-OTTAWA	116	7.00	-WINDSOR	223	13.00
-TORONTO	335	19.25	-KINGSTON	161	9.75
OTTAWA-TORONTO	248	14.50	-NORTH BAY	228	13.00
-HAMILTON	287	17.00	LONDON-WINDSOR	108	6.50
HAMILTON-WINDSOR	184	11.50	SASKATOON- EDMONTON	323	19.25

Source: Canadian National System Timetable and Tariffs Table, 1975.

$$*1975 \text{ RAIL FARE} = 6x\left(\frac{\text{DISTANCE}}{100}\right) \dots\dots\dots (\$/\text{passenger}) \dots\dots(9.1)$$

$$[t=(133), n=12 \quad \text{l.o.s.} < 0.1\%$$

$$s_e = .34 \quad c_v = 2.76\% \quad R^2 = .999]$$

9.3 Rail Design Optimization Results

Table (9.3) gives the optimal values obtained for the rail optimization variables and the objective function, for the four track improvements tested.

TABLE (9.3) - OPTIMAL VALUES OF THE RAIL DESIGN VARIABLES AND MAXIMUM NET REVENUE

ALTERNATIVE	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
OPTIMAL FREQUENCY OF SERVICE (TRAIN DEPARTURES/DAY/DIRECTION)	7	8	8	12
OPTIMAL 1980 FARE* (¢/PASSENGER-MILE)	15.5	16.0	16.0	16.0
MAXIMUM NET REVENUE (MILLIONS OF 1975 DOLLARS)	146.73	136.58	94.27	-36.17

* According to the cost indices given in Appendix E, the shown values correspond to 1975 fares of about 11.0, 11.3, 11.3 and 11.3 ¢/passenger-mile, for the four alternatives, respectively. Fare is assumed to increase at a rate of 6% per annum after 1980.

The optimal frequency of service obtained for any of the first three alternatives is equal to the maximum achievable frequency without inflicting meet delays on opposing trains. Alternative D, which provides substantially high track capacity, demonstrates that most of that capacity is not necessary; as a frequency of only 12 departures per day per direction is optimal. This result is attributed to the diminishing marginal return property of the passenger demand-frequency relationship. That is, beyond a certain level of departure frequency, an increased number of vehicle departures cannot attract passenger volumes to fill them, and the net revenue starts decreasing progressively as a result.

The optimal rail fare, which is almost the same for the four alternatives, is higher than the fare charged by present rail service. Such a result was, however, expected because the new rail service represents a substantial improvement over existing service. It should also be noted that the optimal rail fare is significantly lower than corresponding air fares.

The maximum net revenue obtained above does not necessarily mean that any of the first three alternatives is profitable, because a number of cost components were left out of account mainly due to lack of data*. Examples of such costs include property (land) costs, construction and maintenance of structures (e.g. bridges) along the rail right-of-way, basic maintenance of the track signaling system**, additional fuel consumption on non-main line tracks (e.g. yards), investment in stations, operation and maintenance of stations other than ticketing personnel, reservation system, yard expenses, on-board services, and corporate taxes which are not a function of costs, but of cost-revenue results.

As Table (9.3) shows, alternative A offers the highest maximum net revenue, followed by alternative B, then by alternative C, and finally by alternative D which shows a loss. This relative economic viability picture is illustrated in Figure (9.4). The reason why the first alternative produced the highest net return is because it offers a substantial improvement in the rail level of service over existing conditions, and that additional revenues drawn from improving the service further to level B, C, or D were not sufficient enough to offset the incremental costs involved. However, as will be demonstrated in the sensitivity analyses, this result is only valid for the particular traffic densities involved within the study area. If the study area is more heavily-populated (hence higher traffic volumes) the above ranking of the alternatives in terms of their economic viabilities could change.

* The magnitudes of most of these costs are assumed not affected by the values of the design optimization variables. Their exclusion does not therefore alter the optimal values of the variables, but does increase the net revenue of the system.

** Only the incremental signal maintenance cost was accounted for in the analysis.

FIGURE (9.4) - MAXIMUM ECONOMIC VIABILITY OF RAIL IMPROVEMENTS

The economic viability of existing rail passenger service between the three city-pairs in question is also shown in Figure (9.4) for comparison purposes. The magnitude of operating deficit shown for the existing rail is based on the assumption that current unprofitability level will prevail throughout the analysis period if service is not upgraded*.

The four track upgrading alternatives were also ranked on the basis of the incremental net present worth of operating revenues and capital investment in track upgrading. The existing rail service was considered as the basic or "do-nothing" alternative for this incremental analysis. The results of the analysis are presented in Table (9.4) which again confirm that alternative A is highly desirable relative to the other three.

TABLE (9.4) - RANKING OF ALTERNATIVES BY INCREMENTAL ANALYSIS

ALTERNATIVE	TRACK INVESTMENT C	NET REVENUE [†] NR	$\frac{\Delta NR}{\Delta NC}$
DO-NOTHING	0	-166	-
A	103	281	4.3 ^{††}
B	157	316	3.1
C	256	360	2.1
D	393	360	1.3

Shown costs and revenues are in millions of 1975 dollars (present worth).

† Net of rolling stock capital recovery payments and operating costs.

†† $[281 - (-166)] / [103 - 0]$.

* A 1974 total loss of \$16 millions is reported for the rail passenger services between Toronto, Ottawa, and Montreal⁸⁰. Assuming that costs and revenues of present rail service are escalated beyond 1974 at the same rates considered in the present analysis, and also upon deflating the resulting net losses throughout the analysis period at the same discount rate (10%), an expected present worth of such losses was found to be about 166 millions of 1975 dollars. These computational assumptions are rather conservative in comparison with reported and anticipated rates of increase in these losses⁸⁰.

Tables (9.5) and (9.6) show the values of the optimized objective function at different combinations of fare and frequency of service. To avoid unnecessary repetition, these results are presented for only alternative A, as being the optimal upgrading scheme, and for alternative D, as it does not impose a constraint on the frequency of service. The behavior of the function shown in Table (9.5) is, however, typical of that associated with alternative B or C. In Table (9.5) the net revenue of alternative A increases as the frequency of service is increased to its upper limit of 7 daily train departures in each direction. Had more track capacity been available, the net revenue could have kept on increasing up to a certain frequency level then started to decrease steadily. Such behavior is apparent in Table (9.6). In both Tables, the net revenue function exhibits a hill-shaped surface with respect to rail fare. It can also be seen from the two Tables that the optimal solution is unique and is interior to the region of practically feasible frequencies and fares. The information displayed in Table (9.6) is graphically illustrated in Figure (9.5).

The behavior of the function is also demonstrated in Figures (9.6) and (9.7) with respect to each optimization variable alone when the value of the other is held constant at its optimal level. The variations of the rail passenger volume and passenger-miles with respect to each of the two variables are also shown in these two Figures. The information presented in the two Figures is typical of those pertaining to other alternatives.

Figure (9.6) re-affirms the observation made earlier that beyond a certain fare level, increasing the fare will no longer increase the carrier's revenues, but will rather do the opposite. As the fare is increased less passengers use the system. Since the system supply is matched to its demand, the cost of providing the service is accordingly reduced. The point at which the maximum difference between revenue and cost occurs represents the optimal fare level (which may or may not correspond to the point of maximum revenue).

TABLE (9.5) - VALUES OF THE OBJECTIVE FUNCTION AT DIFFERENT
COMBINATIONS OF FREQUENCY AND FARE,
FOR IMPROVEMENT ALTERNATIVE A

		FREQUENCY OF SERVICE (DEPARTURES/DAY/DIRECTION)			
		2	4	6	7
1980 FARE (¢/PASSENGER-MILE)	6	-134.2	- 66.7	- 46.2	- 33.0
	8	-100.5	- 7.9	24.7	42.1
	10	- 76.6	34.0	75.7	91.9
	12	- 61.8	59.3	107.4	124.4
	14	- 54.5	71.6	123.4	141.7
	16	- 52.2	76.4	127.4	146.6
	18	- 53.0	73.3	124.7	142.8
	20	- 56.0	65.1	115.7	132.8
	22	- 60.0	53.8	101.7	117.1
	24	- 66.3	40.8	84.1	99.0
	26	- 72.1	26.9	66.7	80.1
	28	- 77.5	12.6	48.4	60.6
	30	- 82.6	- 1.3	29.3	39.6
	32	- 88.0	- 14.1	11.7	20.1
	34	- 92.9	- 26.7	- 5.3	0.9
	36	- 97.2	- 38.6	- 21.5	- 16.0

Note: Function values represent expected net revenue in millions of 1975 dollars. (Negative values indicate loss).

TABLE (9.6) - VALUES OF THE OBJECTIVE FUNCTION AT DIFFERENT COMBINATIONS OF FREQUENCY AND FARE, FOR IMPROVEMENT ALTERNATIVE D

		FREQUENCY OF SERVICE (DEPARTURES/DAY/DIRECTION)															
		2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32
1980 FARE 0 PASSENGER-MILE	6	424	355	334	316	317	317	333	342	367	379	404	431	448	480	492	525
	8	378	279	239	204	207	200	217	224	244	256	283	315	326	351	378	399
	10	345	221	172	135	129	126	143	150	170	179	200	223	247	272	281	318
	12	324	185	125	87	83	76	89	90	116	129	154	175	184	218	229	258
	14	311	163	100	61	57	49	57	64	83	93	121	146	156	182	203	225
	16	305	154	90	52	45	36	49	56	74	83	102	132	147	169	193	219
	18	305	155	90	54	46	40	54	58	76	86	107	132	151	177	197	225
	20	308	162	100	62	56	53	65	69	88	100	123	147	168	194	216	238
	22	313	174	115	80	75	71	80	87	108	123	147	171	192	214	235	253
	24	320	189	134	108	98	93	106	115	136	152	176	202	217	238	258	278
	26	327	205	156	127	125	122	136	146	166	182	204	229	244	265	285	304
	28	334	223	178	152	150	152	168	180	201	211	233	257	273	294	314	336
	30	341	240	200	178	181	183	201	210	230	244	265	287	303	326	347	373
	32	347	257	221	204	209	214	229	242	258	273	294	317	336	361	383	413
	34	353	273	243	230	236	240	259	269	289	301	326	350	370	398	422	451
	36	359	287	264	253	261	267	283	294	314	330	355	382	404	434	457	487

Note: Function values represent expected net loss in millions of 1975 dollars.

FIGURE (9.5) -- CONTOURS OF ALTERNATIVE D EXPECTED LOSSES

FIGURE (9.6) - VARIATION OF IMPROVED RAIL REVENUE, COST, AND RIDERSHIP WITH RAIL FARE

FIGURE (9.7) - VARIATION OF IMPROVED RAIL REVENUE, COST, AND RIDERSHIP WITH FREQUENCY OF SERVICE

The same observation made in discussing a similar STOL Figure regarding the impact of increasing the fare on the average distance traveled is also evident from Figure (9.6). As the rail fare is increased not only does the rail demand decrease but so also does the average distance traveled. This can be observed from the Figure by comparing the magnitudes of passenger volume and passenger-miles at different fare levels.

In Figure (9.7) alternative D does not produce a net profit no matter how frequent the service is. The revenue curve is always underneath the cost curve thereby showing a loss (deficit). The "diminishing marginal return property" of the system demand-frequency curve can be seen clearly in this Figure. Beyond a certain point, increased frequency of service does not generate a proportional increase in traffic; causing the net revenue to fall (or deficit to increase, for alternative D). This point is located where the cost and revenue curves of alternative D are closest to each other, and is seen in the Figure to be at 12 departures/day/direction.

Again, as was previously noted for the STOL system, the curves shown in the Figures are fairly smooth. The lack of jumps in the objective function is attributed to its particular structure in that the system costs and revenues are evaluated over a time horizon, and that the timing at which capital investments* are made is considered in computing the applicable capital recovery payments.

The travel demand estimates corresponding to the optimal values of the improved rail design variables (frequency of service and fare) are summarized in Table (9.7) for the same selected year (1989) and probable rail demand state. [Note that the split of the travel market in that year among the existing three modes: air, bus, and "existing" rail was shown previously in Table (8.5)].

* particularly for acquisition of rolling stock [see Tables (9.9) and (9.10)].

TABLE (9.7) - IMPROVED RAIL SYSTEM TRAVEL DEMAND*
IN A TYPICAL YEAR, 1989

CITY-PAIR:		TORONTO- OTTAWA	OTTAWA- MONTREAL	MONTREAL- TORONTO
A	AIR	30.0	13.8	38.7
	MODAL SPLIT (%) BUS	24.5	34.0	25.9
	RAIL	45.5	52.2	35.3
	AV.WEEKLY RAIL PASSENGER VOLUME/DIRECTION	5022	6310	5777
B	AIR	29.4	12.8	38.6
	MODAL SPLIT (%) BUS	22.7	31.2	23.4
	RAIL	47.9	56.0	38.0
	AV.WEEKLY RAIL PASSENGER VOLUME/DIRECTION	5496	7101	6586
C	AIR	28.0	12.8	38.2
	MODAL SPLIT (%) BUS	19.9	31.2	21.0
	RAIL	52.1	56.0	40.8
	AV.WEEKLY RAIL PASSENGER VOLUME/DIRECTION	6347	7101	7490
D	AIR	26.3	11.7	37.1
	MODAL SPLIT (%) BUS	18.0	28.4	19.0
	RAIL	55.7	59.9	43.9
	AV.WEEKLY RAIL PASSENGER VOLUME/DIRECTION	7123	8143	8454

* For a selected demand state of "improved rail market shares being 0-10% below values predicted by the demand models".
Probability of occurrence of this state = 0.375.

Table (9.7) demonstrates that upgrading the present rail service, as being proposed here, results in significant increase in its patronage. Decreasing the travel time, making the service more frequent and charging the appropriate fare, in addition to

the inherent comfort characteristic of the train relative to other public modes*, together increase the rail market share substantially. The Table also shows that as the service is further improved (i.e. going from improvement A to B, to C, and to D), the rail passenger volume increases significantly. However, the resulting marginal revenue was not high enough for any of the last three alternatives to offset the substantial incremental investment in track upgrading and other system costs. As shown earlier, the economic viability (net revenue) of the rail system decreased as the system was further improved. This result is, however, governed by the conditions in the particular study area considered here, and will be tested later under different assumptions about future population estimates in the area.

Another sample of the type of results that can be obtained from application of the design optimization model is shown in Table (9.8). A summary of expected values of rail demand and economic indicators is presented in the Table for the four track upgrading alternatives. These measures are aggregated over the analysis period (1980-1995) and for all the network links. The shown costs and revenues are expressed in present worth (1975 dollars).

* as reflected by the values obtained by calibration for the bias terms of the air and bus modes relative to rail [see Table (3.3)].

TABLE (9.8) - EXPECTED VALUES OF IMPROVED RAIL DEMAND
AND ECONOMIC INDICATORS

	TRACK UPGRADING ALTERNATIVE			
	A	B	C	D
EXPECTED NUMBER OF PASSENGERS CARRIED BY RAIL(MILLIONS)	28.59	32.07	35.00	39.74
EXPECTED NUMBER OF RAIL PASSENGER-MILES(BILLIONS)	6.58	7.39	8.27	9.35
EXPECTED SUM OF FARE REVENUES(\$ MILLIONS)	474.65	550.19	615.30	696.21
EXPECTED SUM OF CAPITAL COST PAYMENTS(\$ MILLIONS)	110.72	156.49	241.45	364.73
EXPECTED SUM OF SYSTEM OPERATING COST(\$ MILLIONS)	217.20	257.12	279.57	367.65
EXPECTED SUM OF NET REVENUE(\$ MILLIONS)	146.73	136.58	94.27	-36.17
EXPECTED SYSTEM UNIT COST (¢/PASSENGER-MILE)	5.00	5.62	6.33	7.86

An illustration of the breakdown of the cost and revenue associated with the optimal alternative A is presented in Table (9.9) for the selected probable rail demand state of 0-10% below demand models prediction. Aside from the track upgrading investment, the revenue and cost components of the other alternatives are higher in magnitude than those shown in the Table, but are similar in their relative contributions to the overall system operating cost.

The Table shows that the largest four components of the rail operating cost are: passenger servicing (ticket sales and service promotion), maintenance of rolling stock, maintenance of tracks and signals, and train crew expenses. It is interesting to note that the Table confirms the fact that trains are more efficient than STOL aircraft in terms of fuel consumption. Comparison of the information given in the Table with corresponding results presented

TABLE (9.9) - COST AND REVENUE BREAKDOWN FOR THE OPTIMAL
ALTERNATIVE A*

(In Millions of the Shown Year's Dollars)

YEAR:	1980	1983	1986	1989	1992	1995
TRAIN CREW EXPENSES	5.09	6.06	7.22	8.60	10.25	12.20
TRAIN FUEL CONSUMED	1.61	1.91	2.54	3.02	3.60	4.73
ROLLING STOCK MAINTENANCE	4.29	5.11	7.27	8.66	10.31	14.28
TRAIN DISPATCHING EXPENSES	.41	.49	.58	.69	.82	.98
TRACK & SIGNAL MAINTENANCE	3.66	4.36	5.39	6.43	7.68	9.46
TICKET SALES IN TERMINALS	2.67	3.40	4.57	5.87	7.61	9.95
SERVICE PROMOTION (MARKETING)	2.24	3.04	4.08	5.38	7.18	9.45
LIABILITY	.80	.97	1.27	1.55	1.90	2.44
OVERHEAD COSTS	2.89	3.46	4.47	5.35	6.42	8.22
GENERAL AND ADMINISTRATIVE	1.66	2.02	2.62	3.19	3.90	5.02
ROLLING STOCK INVESTMENT [†]	26.89	-	3.79	-	-	8.01
TRACK UPGRADING INVESTMENT	154.18	-	-	-	-	-
TOTAL SYSTEM OPERATING COST	25.31	30.82	40.00	48.74	59.66	76.73
CAPITAL RECOVERY PAYMENT	20.31	20.31	20.87	20.87	20.87	22.04
TOTAL RAIL SYSTEM COST	45.62	51.13	60.87	69.61	80.53	98.77
RAIL FARE REVENUE	44.88	60.72	81.55	107.65	143.56	188.92
NET REVENUE	-.74	9.59	20.68	38.04	63.03	90.15

* for a selected demand state of "improved rail market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

† includes 20% spare rolling stock and 15% spare parts.

in the previous Chapter for the STOL system indicates that the fuel cost component is much lower for rail than for STOL in terms of both its magnitude and contribution to system operating cost.

Table (9.10) shows the rail passenger design volume, train consist and corresponding train loading factor, and the rolling stock

needed in five selected years within the analysis period. Although the information presented in the Table is shown for only alternative A, yet they are typical of those obtained for the other alternatives.

TABLE (9.10) - RAIL DEMAND AND SUPPLY MEASURES FOR THE OPTIMAL ALTERNATIVE A*

YEAR	RAIL PASSENGER DESIGN VOLUME/DAY/DIRECTION		TRAIN CONSIST	TRAIN LOADING FACTOR (%)		MINIMUM ROLLING STOCK ACQUIRED**	
	(T-O) LINK	(O-M) LINK		(T-O)	(O-M)	LOCOS.	CARS
1980	1454	1728	1-4-1 [†]	68.3	81.2	8	16
1983	1662	1940	1-4-1	78.1	91.1	-	-
1986	1885	2161	1-5-1	70.9	81.3	-	4
1989	2106	2357	1-5-1	79.2	88.6	-	-
1992	2367	2617	1-5-1	89.0	98.4	-	-
1995	2631	2857	1-6-1	82.4	89.5	-	4

Abbreviations: T = Toronto O = Ottawa M = Montreal

* for a selected demand state of "improved rail market shares being 0-10% below predictions made by the demand models". Probability of occurrence of this state = 0.375.

** not including spare rolling stock.

† i.e. four cars sandwiched between two locomotives (a pull-push configuration).

In the STOL system application, the growth in passenger volume over the years was shown to be met by increasing the number of aircraft flights, since the chosen aircraft size cannot be altered. As Table (9.10) shows, the opposite approach is taken for a rail system. That is, as the rail demand grows, the train consist is modified (more cars are added to the train) without changing the optimal frequency of train departure.

9.4 Sensitivity Analyses

Sensitivity tests similar to those performed for the STOL system are carried out here. Specifically, the optimal design of the Toronto-Ottawa-Montreal rail system is tested here for:

- 1) variation in total common carrier travel demand,
- 2) different forecasts of future populations in the study area,
- 3) over- or under-estimation of track upgrading investment,
- 4) use of a discount rate other than 10%, and
- 5) application of a different optimization criterion -- minimization of system unit cost, including users' cost.

Sensitivity of the optimal rail design to changes in the total common carrier travel demand (which is to be split among the available public modes including the improved rail) is demonstrated in Figure (9.8) for the four track upgrading alternatives. The maximum net revenue (or minimum loss) and the optimal frequency of service and fare were obtained for each alternative for four levels of total demand: 50 and 25% below and above those predicted by the demand models. The optimal values of the objective function and frequency of service are plotted in the Figure. The fare is not shown because its optimal value at the four demand levels tested was more or less equal to its null optimal value (i.e. at zero % change in total demand) for all the alternatives.

As was pointed out while discussing the sensitivity of the optimal STOL design to total common carrier demand, varying the total demand changes the rail market share without actually altering the rail level of service so as to induce such a variation. That is, the variation in total common carrier demand is regarded as attributable to the demographic characteristics in the study area and/or the accuracy of the demand models used. As a result of increasing the travel demand, the drawn rail revenues, for a given track upgrading alternative, are increased at a much faster rate than the incremental costs involved to meet the demand. The Figure demonstrates that the economic viability of the improved rail system increases almost linearly as the total demand increases and vice versa. As the rail system is further improved (i.e. going

FIGURE (9.8) - SENSITIVITY OF THE OPTIMAL RAIL DESIGN TO TOTAL COMMON CARRIER DEMAND

from alternative A to B, to C, or to D) the rate of increase in the economic viability is accelerated due to the inherent higher market shares associated with the highly improved alternatives. Another implication of the Figure is that alternative A does not remain the optimal upgrading scheme as the total demand increases. Rather, as the Figure implies, it is replaced by alternative B, C, or possibly D depending on the degree of increase in total demand. The Figure also shows that the optimal frequency of service increases incrementally for alternative D as the demand increases, but remains unchanged from the maximum achievable for the other three alternatives.

The above sensitivity test was extended further by assuming that the above percentage changes apply solely to projections of future populations (and hence employments) within the study area. That is, assuming the adequacy of the calibrated demand models for predicting future travel demands, the object of this test is to see whether improving the rail passenger system becomes more economically viable in heavily populated regions. The results of this test, which are shown in Figure (9.9), indicate that this is so. The Figure shows that improvement of the present rail passenger system becomes more economically viable as the population of the cities it serves (and hence rail traffic) increases*. The Figure indicates also that as the rail route becomes more heavily populated, the optimal level of track upgrading shifts towards the alternative offering the highest level of service (which normally involves higher capital investment). The reasons behind this result have already been given in the previous sensitivity test. Note here that varying the cities' populations applies to both the origin and destination cities of each city-pair; thus resulting in a compounded effect on travel demand.

It was pointed out in Chapter 7 that the STOL and rail design optimization results are based on use of the "medium" population projections prepared by Statistics Canada. The relative

* Optimal values of frequency of service and fare were typical of those obtained in the previous sensitivity test.

FIGURE (9.9) - SENSITIVITY OF MAXIMUM ECONOMIC VIABILITY OF RAIL IMPROVEMENTS TO FUTURE POPULATIONS IN THE STUDY AREA

economic viabilities of the four alternatives are also illustrated in Figure (9.9) for the "low" and "high" population estimates of Statistics Canada.

Sensitivity of the optimal rail system design to over- or under-estimation of the track upgrading investment was carried out for the four alternatives. The optimal values of the rail design variables (frequency and fare) were not different from those obtained before (for the zero % change case). The maximum net revenues (or minimum deficits) are shown in Figure (9.10) for different estimates of track upgrading investment. Unlike the STOL ports investment which was shown previously to have a small effect on the STOL economic viability, Figure (9.10) demonstrates the significant impact of track upgrading investment on rail profitability. It can also be seen from the Figure that if track upgrading to the specified service standards involves less capital investment than the estimates used in the analysis, the optimal upgrading scheme will shift in such case towards the alternative that offers the highest level of service.

As outlined earlier, both the system costs and revenues are deflated (discounted) from the year in which they occur to a selected base year (1975) using the same rate of discount. The implications of using a discount rate different from the one adopted in the analysis (10%) can be seen from Figure (9.11). The optimal values obtained previously for the rail design variables did not change here as a result of using different discount rates. Rather, it is the rail economic viability which changed significantly. High discount rates are shown in the Figure to have worsened the system economic viability, whereas low rates showed the opposite. This is mostly because high rates of discount tend to magnify the cost impact of capital investment in rail infrastructure. Low rates lessen this effect; thereby showing a more economically viable rail design.

The Figure shows that track upgrading alternative B is as equally profitable as the optimal alternative A at a discount rate

FIGURE (9.10) - SENSITIVITY OF MAXIMUM ECONOMIC VIABILITY OF RAIL IMPROVEMENTS TO TRACK INVESTMENT COST

FIGURE (9.11) - SENSITIVITY OF MAXIMUM ECONOMIC VIABILITY OF RAIL IMPROVEMENTS TO DISCOUNT RATE

of 8%, and is more economically viable than A at rates below that. At further lower discount rates, alternative C, which offers a level of service better than that offered by either alternatives, tends to take over as the optimal upgrading scheme. Thus the question of which rail improvement alternative is the most economically viable depends on the chosen rate of discount. The gap between the economic viabilities of the alternatives (particularly A, B, and C) tends, however, to get narrower at low rates of discount. Alternative D, which involves a substantially high capital investment, consistently shows a significantly lower economic viability relative to the other three alternatives.

Finally, the response of the optimization model to using an alternative optimization criterion for designing the rail system was also tested. Specifically, the criterion of minimization of system unit cost (including users' cost) was substituted for the objective of maximizing the system economic viability. The implications of this criterion and the formulation of the objective function has already been described in the previous chapter. The results are shown here in Figure (9.12).

The same comments made on the results obtained by using this criterion for optimizing the STOL system design apply here as well. That is, increasing the rail fare results in higher system unit cost due to the associated increase in users' cost and reduction in rail ridership. The Figure shows that the rate of increase in the minimum unit cost is faster at high fare levels than at low fare values. It is also interesting to note that the optimal frequency of service obtained previously for each of the alternatives by using the criterion of maximum net revenue was found by the present criterion to be still optimal over the range of fares explored.

The Figure indicates that alternative D is the least desirable on the basis of the minimum unit cost. At 1980 fare levels of about 12¢/passenger-mile or less the other three alternatives appear to offer almost equivalent minimum unit costs. But alternative A consistently shows the absolute lowest value at all fare levels.

FIGURE (9.12) - THE OPTIMAL IMPROVED RAIL SYSTEM DESIGN
BASED ON MINIMIZATION OF UNIT COST

CHAPTER 10

SUMMARY, CONCLUSIONS, AND EXTENSIONS

10.1 Summary

The work presented in this thesis is aimed at developing a rational methodology for optimizing the design of common carrier passenger transport systems. A comprehensive procedure has been structured and tested for determining the optimal level of service of a public transport system serving a network of cities with the objective of maximizing its economic viability. Such an objective can mostly be achieved through the system design by determining the optimal specifications of a set of design variables which have a major impact on the system demand, supply, and economic consequences. The optimization variables that have been dealt with in the analysis include the vehicle speed, the vehicle seating capacity, the frequency of service, and the fare structure.

The reported methodology for system design optimization can be viewed as consisting of four major sequential, but simultaneously interacting, components. The first component involves estimation of the travel demands for the system. A disaggregated behavioral demand model has been developed and calibrated for that purpose. The second component deals with analyzing and modeling the system supply and performance measures. The methodology brings together, in the network context, both the demand and supply sides of the transport system and permits their interaction explicitly. Uncertainty in future travel market shares is also treated in designing the system. The third component involves modeling the various system cost elements with emphasis on short-haul air (STOL) and passenger rail systems. All of the system demand, supply and performance, and economic consequences are modeled in terms of the selected set of design optimization variables. The optimal values of such variables are searched for through

maximization of the present worth of an objective function which reflects the economic viability of the system over a specified analysis period. Specifically, the optimization criterion emphasized in the analysis is the maximization of the system net revenue. Determination of the optimal specifications of the design variables in turn determines the corresponding levels of system demand, supply, and economic measures.

In addition to being useful in analyzing the problem of introducing new travel modes or improving the level of service of an existing transport system, the reported optimization methodology can also be applied to identify the optimal implementation strategy of system introduction (or improvement) along the various links of a given network. A meaningful process of selecting among a number of transport system alternatives can only be made through determining the optimal level of service that each alternative can deliver. The optimization methodology can effectively be used in this regard as well.

The workability and usefulness of the methodology have been demonstrated in the thesis by means of applying it to two case studies involving STOL and Improved Passenger Rail systems, with reference to the Toronto-Ottawa-Montreal network.

10.2 Conclusions

A review of the existing approaches to system design appeared to indicate that there is no satisfactory rational method available to design public transport systems in the context described in this research. Neither does there appear to be a method for determining the "optimal" system design based on realistic consideration of the system environment.

The research described here is an original attempt to analyze rationally the design of public transport networks with explicit consideration of the system supply-demand interaction, treatment of uncertainty in travel demand forecasts, and realistic assessment of the system costs and revenues. The problem dealt

with is large and complex and the methodology possesses the capability of being quite flexible with respect to the situations it can analyze.

This research is believed to be of immediate practical application to analysis and improvement of intercity passenger transport systems. Its primary practical contribution is the development of a rational methodology, based on the concepts of systems analysis, which can be used effectively to provide answers to important practical questions such as:

1. how far can the system penetrate in the travel market?
2. what level of system supply (which includes vehicular and fixed facilities requirements) should be provided?
3. what level of performance will the system have?
4. will the system be economically viable? and what magnitudes of costs and revenues are involved? and
5. given a set of alternative systems or system improvement schemes, which alternative is the most economically viable?.

For example, there are those who tend to believe that improving existing passenger railways can never bail the rail service out of its financial losses. There are also others who expect that improving certain existing rail passenger services will improve the rail financial viability to the extent of being self-supporting. There is, however, no method available to check either argument or to analyze rationally a range of design and policy options. Inefficient decisions could, as a result, be made by decision makers. The methodology developed here provides a quantitative means of analyzing such situations and identifying the most economically viable system design or improvement scheme. The method can also be used as a tool for conducting objective evaluation of mutually-exclusive transport system alternatives. In such a case, the methodology is applied to maximize the economic viability of each alternative prior to

the process of comparing them. Not only is this research expected to be a useful tool to government agencies in charge of intercity transportation, but the common carrier operators could also use it effectively to explore the implications of a broad range of level of service provision and operating policy options.

Examination of the results obtained in the two applications of the methodology seems to confirm the validity of the methodology. Both case studies, although not necessarily perfect real-life situations, are of major current concern to transport authorities. Given the conditions described in these two applications, the methodology appears to work well. This is suggested by the reasonableness and consistency of the results obtained as well as by the logical response of the method when tested under a variety of conditions.

On the basis of the results of the two example applications, the conclusions listed below can be made. It is noted that although the data information used in these applications were accurate and realistic to the extent possible, yet the conclusions drawn below are still governed by the particular assumptions and input data information utilized. Also, the conclusions relate, of course, to the specific study area considered in the analysis. Application of the methodology to other locations is not likely, however, to alter the major findings of the two applications.

1. The optimal cruise speed of a STOL aircraft for a 1980-1992 operation between Toronto, Ottawa and Montreal should be higher than that of the DeHavilland's Dash 7, but lower than the speed of a proposed second generation STOL aircraft. A seating capacity of about twice the size of the Dash 7 appears to be the most economical common aircraft size for this particular application.
2. Diversification of the airplane size over the STOL network shows significant payoffs only when the network links carry substantially different volumes of traffic.
3. Fare structure of present airlines appears to be optimal for STOL operation. The optimal STOL fare was found to be very close to that charged by conventional airlines.

4. The STOL system is expected to penetrate significantly in the travel market particularly for business travel. Its market share is captured mostly from conventional air for business trips, and from all the common carrier modes for non-business travel.
5. The level of investment required for STOL ports is relatively small, and the service, when optimized, is expected to be highly profitable for the particular network analyzed.
6. On the other hand, improving the present rail passenger services involves substantial capital investments to upgrade the tracks (including the signaling system and crossing protection). This high capital cost lowers the level of rail profitability relative to STOL.
7. The frequency of train departure which is optimal for this particular study area during the period 1980-1995 is roughly every 1½ to 2½ hours, depending on the available track capacity.
8. To permit the improved rail service to be financially self-supporting, the optimal fare should be higher than that charged for present service (approximately twice as much), but significantly below that charged by the airlines. Such a fare structure was found to maximize the economic viability (net revenue) of the rail system.
9. Rail transportation is more efficient in terms of fuel consumption relative to transport by STOL.
10. Although the STOL system provided an overall higher net revenue than rail, yet the rail mode carried more passengers and had more passenger-miles than did the STOL system. It was also shown that the total system cost (irrespective of users' cost) per revenue passenger-mile was lower for rail than for STOL.
11. Capital investment in upgrading existing railway tracks to permit higher speeds appears to be economically justified along the proposed Toronto-Ottawa-Montreal route. However, massive investment in upgrading and double tracking the existing lines seems to be less desirable. The track improvement scheme

which produced the highest economic viability involved modest improvements to the existing rail system with more emphasis being placed on upgrading the poorer services. However, it was demonstrated in this application that, as the cities' populations (and hence rail traffic volumes) increase, the incremental cost of further improving the service becomes a more attractive investment proposition because of the corresponding increase in rail ridership.

12. It is interesting to point out that for a given fare level, the optimal designs of the STOL and the improved rail systems did not change when the criterion of maximum net revenue was replaced by that of minimum system unit cost. It should be noted, however, that the former criterion is the most stringent and has been applied in almost every passenger transportation study².
13. The rate used for discounting the system costs and revenues significantly influences the economic viability of the designed system. Low rates were shown to result in a highly economically viable design; while high rates did the opposite.
14. The effect of over- or under-estimation of the investment in STOL infrastructure does not significantly influence the system economic viability. By contrast, this cost component is substantially higher for a rail system and has, therefore, a much greater impact on its net return.
15. Sensitivity of the STOL and Improved Rail optimal designs to variation in the total demand generated within the study area as well as to different sizes of the cities' populations indicates that the "high density" travel markets are essential for new or improved travel modes to be financially self-supporting.

10.3 Extensions

A number of extensions to this work could be proposed. One desirable extension is that of accounting for possible transfer of travel from highways (car travel) to common carrier. Exclusion of this effect was one of the simplifying assumptions

that had to be made in the analysis. As was argued in the text, there were two basic reasons for making that assumption. First, there is a significant lack of data on automobile travel between cities. Second, the car mode is viewed as being in a class by itself in terms of its unique level of service as compared to the common carrier modes (air, rail or bus). As an extension, it is desirable, however, to bring in the car in estimating the demand for the designed system. A separate common carrier-automobile demand model could be structured, calibrated, and incorporated in the analysis. Such a modification can be easily accommodated within the method. In fact, the methodology is structured in such a way that it permits modification of any of its components, say demand estimation, without perturbing the rest of its structure. In its present form, the methodology permits, however, its user to impose assumptions about marginal gains or losses of automobile trips to the common carrier, the assumptions being in some way related to the optimization variables of the designed system.

Another possible, and related, extension of this investigation is to explore the implications of future prices and availability of fuel on the shift of passengers to certain travel modes. This again affects the travel demand for the designed system and is likely to alter the "optimal" system design. Another implication of this aspect in relation to choosing among a number of alternative systems, is that the alternative which is the most efficient in energy use is expected to be favored. An optimization criterion could in such a case be based on the "efficiency in energy use".

The development and application of the methodology focused on intercity networks. As an extension, or rather a different version of the method, urban or suburban networks could be analyzed. This is likely to entail modification of the demand and supply components of the methodology.

A fourth extension, which may be rather viewed as a different application of the methodology, is the consideration of "staged" implementation of system introduction or improvement

along the links of a network. In such a case, different parts of the network are implemented at different points in time and investments are therefore made at different dates. The methodology could be easily adapted to handle such a situation. It can also be used to identify the optimal implementation strategy among a proposed number of staging schemes.

The method is developed for analyzing networks of any size (number of links). However, the size of computer memory allocated in the computer program relates to a triangular network. This allocation can be easily modified to accommodate larger networks. As a possible refinement of the operation of the model, optimization of the computer memory requirement and execution time is highly desirable in order to increase the efficiency of the method; particularly for large-scale networks.

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APPENDIX A

DERIVATION OF THE EQUATION OF THE MULTINOMIAL LOGIT MODEL OF
MODE CHOICE

The generalized cost (or disutility) associated with a travel alternative has been expressed by equation (3.7) in the text. It appears reasonable to assume that the choice behavior cannot, however, be determined completely on the basis of this cost and that a more desirable generalized cost measure could be regarded as being composed of a measurable deterministic component, G , which is given by equation (3.7), and a stochastic term, w , which reflects the random influence on the behavior of travelers of choice factors not accounted for in the measurable component*. That is, the generalized cost, G'_i , of traveling by alternative i as perceived by a given individual (or a homogeneous group of individuals) for a given trip purpose, can be written in the following stochastic form:

$$G'_i = G_i + w_i \quad \dots \quad (A.1)$$

Two assumptions are made here in order to model the mode choice behavior. First, each traveler is aware of the alternatives available to him and of their characteristics and can compare them. Second, the traveler is "rational" in his choice behavior in that he will choose the alternative which offers him the least generalized cost. In other words, the choice decision is based on individual utility maximization. From these two assumptions, it follows that an individual (or a homogeneous group of individuals) will choose an alternative ~~out~~ of M alternatives available to him, for a given trip purpose, if

$$G'_i < G'_k \quad (k = 1, 2, \dots, M \quad k \neq i) \quad \dots \quad (A.2)$$

* In that sense, the logit model reflects the uncertainty in choice of mode as modeled in terms of the generalized cost of travel.

The probability p_i of choosing alternative i is therefore:

$$p_i = \text{prob}\{G_i' \leq G_k'\} \quad (k=1,2,\dots,M \quad k \neq i) \quad \dots\dots (A.3)$$

Using equation (A.1) the above probability expression can be written as:

$$p_i = \text{prob}\{(w_i - w_k) \leq (G_k - G_i)\} \quad (k=1,2,\dots,M \quad k \neq i) \quad \dots\dots (A.4)$$

or

$$p_i = \text{prob}\{(w_i - w_k) \leq g_{ki}\} \quad (k=1,2,\dots,M \quad k \neq i) \quad \dots\dots (A.5)$$

where

$$g_{ki} = (G_k - G_i)$$

In order to obtain an analytical expression for the mode choice probability, a distribution function must be assumed for the stochastic component of the generalized cost, w . Obviously, a number of probability functions (e.g. normal distribution) may be assumed. However, it appears that for the ogive-shaped choice curve, a probability distribution other than the double-exponential distribution given below by equation (A.6) imposes greater difficulty in deriving analytically the equation of the choice curve²¹. This particular probability function leads, however, according to Kendall and Stuart³¹, to the well-known "logistic curve", and has been used in a similar derivation made by Charles River Associates²¹. It has also been shown in Chapter 3 that the logistic curve has appealing behavioral properties in terms of explaining travel mode choice.

The assumption to be made about the probability distribution of the stochastic cost elements (w 's) is that they are independently and identically distributed according to the following distribution function³¹:

$$F_w(x) = \text{prob}(w \leq x) = \exp(-e^{-x}) \quad \dots\dots (A.6)$$

where x is any value that w can take.

The probability density function of w is then

$$f_w(x) = \frac{d F_w(x)}{dx} = e^{-x} \cdot \exp(-e^{-x}) \quad \dots\dots (A.7)$$

Assume, initially, that the choice domain consists of only two alternatives: i and k (i.e. $M = 2$). The probability p_i of choosing alternative i can be obtained in this case by using equations (A.5) and (A.7) as follows:

$$p_i = \int_{x_k=-\infty}^{\infty} \int_{x_i=-\infty}^{x_k + g_{ki}} e^{-x_i} \cdot \exp(-e^{-x_i}) \cdot e^{-x_k} \cdot \exp(-e^{-x_k}) \cdot dx_i \cdot dx_k$$

$$p_i = \int_{x_k=-\infty}^{\infty} e^{-x_k} \cdot \exp(-e^{-x_k}) \cdot \exp(-e^{-x_k - g_{ki}}) \cdot dx_k$$

$$p_i = \int_{x_k=-\infty}^{\infty} e^{-x_k} \cdot \exp[-(1 + e^{-g_{ki}}) \cdot e^{-x_k}] \cdot dx_k$$

$$p_i = \frac{1}{1 + e^{-g_{ki}}} \int_{x_k=-\infty}^{\infty} (1 + e^{-g_{ki}}) \cdot e^{-x_k} \cdot \exp[-(1 + e^{-g_{ki}}) \cdot e^{-x_k}] \cdot dx_k$$

$$p_i = \frac{1}{1 + e^{-g_{ki}}} \left| \exp[-(1 + e^{-g_{ki}}) \cdot e^{-x_k}] \right|^{x_k} \quad \dots\dots (A.8)$$

Since $p_i + p_k = 1.0$ in this particular case, it follows that

$$p_k = \frac{e^{-g_{ki}}}{1 + e^{-g_{ki}}} \quad \dots\dots (A.8)'$$

Equations (A.8) and (A.8)' represent the "binary" choice logistic curve which has been illustrated in the text in Figure (3.1).

Dividing equation (A.8) by equation (A.8)' yields:

$$(p_i/p_k) = e^{g_{ki}} = e^{G_k - G_i} \quad \dots\dots (A.9)$$

This result is in fact true whether the choice domain consists of two alternatives i and k or more than two. This conforms to Luce's axiom of "independence of irrelevant alternatives"³² which requires that the relative odds of two options being chosen be independent of the presence or absence of alternatives other than these two. Expression (A.9) can thus be rewritten as:

$$p_i - p_k \cdot e^{G_k - G_i} = 0 \quad (k=1, 2, \dots, M \quad k \neq i) \quad \dots\dots (A.10)$$

with the following condition being satisfied:

$$\sum_{i=1}^M p_i = 1.0 \quad \dots\dots (A.11)$$

Equations (A.10) and (A.11) represent a set of M linear equations in M unknowns: $P_1, P_2, \dots, P_M$. Solving this set of equations simultaneously yields the values of these M choice probabilities. To derive a closed-form expression for the probability of choosing any of the M alternatives, consider, for instance, the case of 3-alternatives. Equations (A.10) and (A.11) can be written in this case as follows:

$$P_1 - P_2 e^{G_2 - G_1} = 0$$

$$P_1 - P_3 e^{G_3 - G_1} = 0$$

$$P_1 + P_2 + P_3 = 1$$

Solving these three linear equations simultaneously yields:

$$P_1 = \frac{1}{1 + e^{G_1 - G_2} + e^{G_1 - G_3}}$$

$$P_2 = \frac{1}{1 + e^{G_2 - G_1} + e^{G_2 - G_3}} \quad \text{and}$$

$$P_3 = \frac{1}{1 + e^{G_3 - G_1} + e^{G_3 - G_2}}$$

Thus, in general, the probability of choosing alternative i out of M available alternatives can be written as:

$$P_i = \frac{1}{1 + \sum_{\substack{r=1 \\ r \neq i}}^M e^{G_i - G_r}} \quad \dots (A.12)$$

or

$$P_i = \frac{e^{-G_i}}{\sum_{r=1}^M e^{-G_r}} \quad i \in r \quad \dots (A.12)'$$

Elasticity of the Multinomial Choice Probability:

Elasticity with respect to a particular independent variable is defined as the percentage change in the dependent variable caused by 1% change in the independent variable. The generalized cost G_i of traveling by alternative i is given by equation (3.7) and is reproduced here for convenience.

$$G_i = \sum_j (a_j L_{ji}) + b_i \quad \dots\dots (A.13)$$

where

L_{ji} = j^{th} level of service variable of alternative i

a_j & b_i = constants to be statistically estimated.

Thus, the elasticity η_{ki} of the probability of choosing alternative i with respect to any of its level of service variables, say L_{ki} , (direct elasticity) can be written as:

$$\eta_{ki} = \frac{\partial p_i}{p_i} / \frac{\partial L_{ki}}{L_{ki}} = \frac{\partial p_i}{\partial L_{ki}} \cdot \frac{L_{ki}}{p_i} \quad \dots\dots (A.14)$$

From equation (A.12), it follows that

$$\eta_{ki} = \frac{-Y \cdot a_k}{(1+Y)^2} \cdot \frac{L_{ki} \cdot (1+Y)}{1}, \quad \text{where } Y = \sum_{\substack{r=1 \\ r \neq i}}^M e^{G_i - G_r}$$

$$\eta_{ki} = a_k (-L_{ki}) \left(\frac{Y}{1+Y} \right)$$

or

$$\eta_{ki} = a_k (-L_{ki}) (1 - p_i) \quad \dots\dots (A.15)$$

APPENDIX B

DATA USED IN CALIBRATING THE DEMAND MODELS

B.1. The Canadian Transport Commission Travel Survey

The Canadian Transport Commission (CTC) travel survey² was carried out over nine inclusive weeks in summer of 1969 and covered five city-pair links in the Windsor-Quebec City Corridor as shown in Figure (B.1). Each link was sampled in both directions for the three common carrier modes: air, rail, and bus. Each sampled traveler reported information related to origin and destination of his trip, city of residence, access time and cost to the intercity terminal, terminal waiting times, trip purpose, family income, age, sex, and other personal information. Reference 2 contains a full description of this survey.

FIGURE (B.1) - COVERAGE OF THE CANADIAN TRANSPORT COMMISSION TRAVEL SURVEY

Copies of the magnetic tapes containing the compiled survey data were made available by the Commission, and were analyzed here in order to extract the particular type of information required to calibrate the structured demand models. Data analysis results pertaining to modal split are summarized in Table (B.1) while those relating to total (by all common carrier modes) passenger flows between cities are presented in Table (B.2). Total passenger volumes shown in Table (B.3) are computed from the information given in Table (B.2). Table (B.4) presents disaggregated information regarding access times and costs to and waiting times in the sampled intercity terminals.

The analysis of CTC data indicated also that the majority of passengers preferred to travel via a direct link between a given city-pair rather than stopping at intermediate cities. For example, the ratio of Montreal-Toronto passengers traveling via Ottawa to those choosing the direct Montreal-Toronto link was about 2%.

B.2 Service Characteristics of the Transport Modes

Information regarding the characteristics of the transport system were obtained from the 1969 common carrier service schedules and from the CTC², and are summarized in Tables (B.5) and (B.6) for business and non-business trip purposes, respectively.

The travel fares reported in these two Tables were given in the 1969 airline schedules for the air mode, and were reported by the CTC² for rail and bus. With regard to the terminal-to-terminal travel time and the effective service frequency, these were obtained by analyzing the common carrier schedules for each city-pair. For non-business trips, the average one-way vehicle departures per day along a given link was obtained by weighting each vehicle departure along that link by its weekly frequency (7 days per week). This quantity was taken as the effective service frequency for non-business travel along the link. Average terminal-to-terminal travel times were computed similarly and included, wherever applicable, time spent in intermediate terminals waiting for connections.

TABLE (B.1) - 1969 OBSERVED MODAL SPLITS (%) FOR DIFFERENT LINKS AND INCOME GROUPS

BUSINESS TRAVEL	TRAVEL LINK: MONTREAL-TORONTO						MONTREAL-OTTAWA						TORONTO-OTTAWA						MONTREAL-QUEBEC					
	TRAVEL MODE:		AIR		RAIL		BUS		AIR		RAIL		BUS		AIR		RAIL		BUS		AIR		RAIL	
NON-BUSINESS TRAVEL	Income Group (\$)		5001- 7000		7001- 9000		9001-11000		11001-13000		13001-20000		>20000		<5000		5001- 9000		9001-13000		13001-15000		15001-20000	
			64.1		33.8		2.2		10.2		57.3		32.5		9.4		28.8		61.8		1.8		45.0	
			74.1		24.1		1.9		24.0		55.1		21.0		91.2		8.0		0.7		28.9		46.6	
			83.1		18.9		0.1		23.3		56.6		20.0		94.4		3.1		2.5		45.6		39.6	
			88.1		11.7		0.3		24.9		56.1		19.0		97.4		2.6		0.0		65.4		25.8	
			89.0		11.0		0.0		31.9		50.5		17.6		96.5		2.5		1.0		70.8		22.7	
BUSINESS TRAVEL			94.1		5.6		0.3		56.0		37.4		6.6		98.5		1.5		0.0		80.0		16.0	
			10.2		60.2		29.6		0.6		34.3		65.2		21.3		33.5		45.2		3.5		49.7	
			20.3		63.7		16.0		1.7		39.4		58.9		33.7		23.8		42.5		5.2		47.5	
			30.4		58.8		10.8		3.9		42.7		53.4		48.0		22.0		30.1		4.7		48.6	
			35.6		53.4		11.0		5.9		49.2		44.9		50.5		19.6		29.9		12.4		44.3	
			44.0		49.1		6.9		7.0		53.1		39.9		59.3		18.6		22.0		14.5		45.9	
			56.1		40.3		3.7		12.7		52.6		34.7											

* 1968 incomes

TABLE (B.2) - 1969 INTERCITY COMMON CARRIER PASSENGER FLOW INFORMATION

CITY-PAIR	TOTAL TRIP VOLUME ²	BUSINESS TRIP RATIO ³	BUSINESS TRIP VOLUME ⁴	NON-BUSINESS TRIP VOLUME ⁴	TRIP GENERATION RATIO ⁵	
					BUSINESS	NON-BUSINESS
M-T ¹	582.0	.477	277.6	304.4	.868	.842
M-O	352.5	.204	71.9	280.6	.860	.579
O-T	208.0	.408	84.9	123.1	.592	.655
M-Q	310.0	.167	51.8	258.2	1.100	1.097
M-L	20.0	.320	6.4	13.6	1.015	.755
M-W	20.5	.212	4.3	16.2	.933	.498
Q-T	28.0	.342	9.6	18.4	.512	.752
Q-O	24.0	.306	7.3	16.7	.909	.690
Q-L	13.0	.234	3.0	10.0	.488	.777
O-W	7.0	.216	1.5	5.5	.364	.279

1: City name abbreviations: L = London M = Montreal O = Ottawa
Q = Quebec City T = Toronto W = Windsor

2: Annual one-way person trips (in thousands), Source: Reference 2, page 26.

3: Volume of business trips/total volume (business + non-business).

4: Calculated from information presented in second and third columns.

5: Example: Trip generation ratio for city-pair i-j =
(Trips generated in i and destined to j)/trips
generated in j and destined to i).

TABLE (B.3) - 1969 INTERCITY COMMON CARRIER PASSENGER TRIP GENERATION*
(AVERAGE WEEKLY VOLUMES)

	TO FROM	MONTREAL	TORONTO	OTTAWA	QUEBEC	LONDON	WINDSOR
BUSINESS	MONTREAL		2473.2	637.22	518.40	62.28	40.25
	TORONTO	2847.80		1020.50	121.69		
	OTTAWA	740.71	604.64		73.78	19.16	7.67
	QUEBEC	471.44	62.28	67.08			
	LONDON	61.33		39.29			
	WINDSOR	43.12		21.08			
NON-BUSINESS	MONTREAL		2746.30	1972.00	2590.10	112.11	102.53
	TORONTO	3259.90		1425.80	201.23		
	OTTAWA	3406.50	934.27		188.77	83.37	23.00
	QUEBEC	2360.10	151.40	130.32			
	LONDON	148.52		107.32			
	WINDSOR	206.02		82.41			

* Passengers originated in one city and destined to another.

TABLE (B.4) - 1969 AVERAGE VALUES OF REPORTED TERMINAL ACCESS
TIME AND COST AND WAITING TIME

CITY	MODE	TERMINAL ACCESS TIME (MIN.)		TERMINAL ACCESS COST (\$)		TERMINAL WAITING TIME (MIN.)	
		BUSINESS	NON- BUSINESS	BUSINESS	NON- BUSINESS	BUSINESS	NON- BUSINESS
MONTREAL	AIR	24	25	2.61	2.08	38	47
	RAIL	18	22	.88	.78	28	33
	BUS	19	25	.72	.74	22	24
TORONTO	AIR	28	32	2.92	2.05	38	45
	RAIL	22	25	1.05	.84	28	35
	BUS	22	26	.89	.74	24	30
OTTAWA	AIR	24	24	2.30	1.41	31	35
	RAIL	16	17	1.26	.69	21	24
	BUS	21	18	.74	.61	21	21
QUEBEC	AIR	24	31	2.51	2.03	33	39
	RAIL	14	18	1.24	.94	20	24
	BUS	19	21	1.47	.75	26	25

Terminal-to-terminal travel times and effective service frequencies for business trips were obtained in the same manner, except that the business week was considered to be five days only, and that departures made during times of the day that are considered desirable for business trip making (peak periods) were assigned a weight higher than that assigned to departures made during other times (off-peak periods). The desirable morning travel times were considered as extending over a period from approximately 7 a.m. to the time which results in being delivered at the destination terminal by approximately 1 p.m. The evening period was considered to start at around 3 p.m. and ends at such a time that results in arrival at the destination terminal by about 10 p.m.

These time boundaries were arbitrarily chosen based on empirical knowledge of business demand profiles, and were allowed to shift flexibly enough (say $\pm 1/2$ hr) to conform to the "natural boundaries" in the carriers' time-tables. This procedure is believed to lead to a more realistic measurement of users' perception of the transport service. The weights attached to the peak and off-peak periods were obtained from examination of demand profiles for air travel (mostly business). Analysis of the demand profiles reported in the studies made for the Canadian Transportation Development Agency³⁶ and for STOL Planning³⁷ indicated that such weights are approximately 1 for peak periods and $1/3$ for off-peak periods. In other words, the effective departure frequency for business travel can be computed as the number of departures made during the two peak periods plus one-third of those made during other times of the day. Weights reflecting weekly frequency of departures were also further applied. Terminal-to-terminal travel times were determined and weighted in the same manner.

Total travel times shown in Tables (B.5) and (B.6) are composed of the following components:

- 1) terminal-to-terminal travel time, as determined above,
 - 2) access and egress times, as given in Table (B.4),
 - 3) waiting time at the terminal, as given in Table (B.4),
 - 4) schedule overrun time (delay), as reported by the CTC².
- 5, 8, and 8 minutes, for air, rail, and bus modes, respectively, and

TABLE (B.5) - 1969 COMMON CARRIER SERVICE CHARACTERISTICS - (BUSINESS TRAVEL)

CITY-PAIR:	M-T*	M-O	M-Q	M-L	M-W	T-O	T-Q	O-Q	O-L	O-W	Q-L	Q-W
TRAVEL FARE (\$)	AIR	25.00	15.00	15.00	35.00	44.00	21.00	40.00	25.50	31.00	34.00	55.00
	RAIL	11.90	4.10	6.20	16.10	15.90	8.90	15.00	10.10	12.90	14.80	19.50
	BUS	12.15	4.50	5.80	16.10	19.80	9.60	17.95	10.30	13.55	17.25	25.60
TERMINAL-TO-TERMINAL TRAVEL TIME (HR.)	AIR	1.09	0.55	0.75	2.56	2.89	0.94	2.44	1.87	2.70	2.58	4.34
	RAIL	5.27	2.19	3.25	9.53	12.17	5.17	10.07	6.14	8.21	11.92	16.77
	BUS	6.17	2.31	2.83	9.64	12.57	5.19	9.57	5.56	8.92	11.08	15.45
TOTAL TRAVEL TIME (HR.)	AIR	2.83	2.12	2.33	4.05	4.45	2.57	4.08	3.37	4.12	3.98	5.82
	RAIL	6.61	3.38	4.40	10.78	13.42	6.45	11.32	7.20	3.37	13.08	17.87
	BUS	7.45	3.50	4.08	10.85	13.77	6.47	10.87	6.82	4.13	12.33	14.12
TOTAL TRAVEL COST (\$)	AIR	30.53	19.91	20.12	39.62	48.61	26.22	45.43	30.31	35.31	43.30	62.51
	RAIL	13.83	6.24	8.32	17.78	17.38	11.21	17.29	12.60	14.96	16.86	21.54
	BUS	13.76	5.96	7.99	17.42	21.12	11.23	20.31	12.51	14.89	18.59	27.17
EFFECTIVE DAILY FREQUENCY	AIR	21.6	10.8	10.6	4.8	3.3	11.8	7.3	6.3	3.5	2.83	2.5
	RAIL	3.3	6.3	4.7	1.3	1.0	1.3	1.0	1.6	1.0	1.0	1.0
	BUS	2.3	13.7	10.7	2.2	1.8	5.1	2.8	6.7	2.7	2.0	1.0

* City name abbreviations:

L = London M = Montreal O = Ottawa Q = Quebec City T = Toronto W = Windsor

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TABLE (B.6) - 1969 COMMON CARRIER SERVICE CHARACTERISTICS - (NON-BUSINESS TRAVEL)

CITY-PAIR:	M-T*	M-O	M-Q	M-L	M-W	T-O	T-Q	Q-Q	O-L	O-W	Q-L	Q-W
TRAVEL FARE (\$)												
AIR	25.00	15.00	15.00	35.00	44.00	21.00	40.00	25.50	31.00	34.00	50.00	58.00
RAIL	11.90	4.10	6.20	16.10	15.90	8.90	15.00	10.10	12.90	14.80	17.00	19.50
BUS	12.15	4.50	5.80	16.10	19.80	9.60	17.95	10.30	13.55	17.25	21.90	25.60
TERMINAL-TO-TERMINAL TRAVEL TIME (HR.)												
AIR	1.09	0.55	.77	2.56	2.94	0.95	2.44	1.87	2.90	2.70	4.07	4.31
RAIL	5.42	2.19	3.30	9.54	12.18	5.29	10.07	6.49	8.21	11.92	12.87	16.75
BUS	6.22	2.31	2.83	9.64	12.69	5.14	9.57	5.56	8.80	11.04	12.87	15.45
TOTAL TRAVEL TIME (HR.)												
AIR	3.05	2.25	2.62	4.27	4.60	2.75	4.38	3.57	4.37	4.27	5.78	6.02
RAIL	6.98	3.52	4.65	10.93	13.58	6.73	11.52	7.68	9.43	13.17	14.12	18.02
BUS	7.72	3.57	4.22	10.17	14.02	6.50	11.00	6.80	9.97	12.28	14.12	16.68
TOTAL TRAVEL COST (\$)												
AIR	29.13	18.49	19.11	38.17	47.49	24.46	44.08	28.94	33.50	41.82	53.12	61.44
RAIL	13.52	5.57	7.92	17.48	17.28	10.43	16.78	11.73	14.19	16.09	18.54	21.04
BUS	13.63	5.85	7.29	17.27	21.08	10.95	19.44	11.66	14.59	18.40	23.08	26.89
EFFECTIVE DAILY FREQUENCY												
AIR	24.2	11.5	11.0	5.5	4.0	12.8	9.2	6.9	4.5	3.5	4.3	3.3
RAIL	4.0	7.1	6.0	2.0	1.0	2.0	1.0	2.7	1.0	1.0	1.0	1.0
BUS	5.0	17.0	13.8	2.5	2.5	6.8	3.5	13.0	3.0	2.0	1.5	1.0

* City name abbreviations:

L = London M = Montreal O = Ottawa Q = Quebec City T = Toronto W = Windsor

- 5). time spent negotiating the destination terminal:
 assumed to be 5 minutes in rail or bus terminals,
 10 minutes in Montreal and Toronto airports, and
 5 minutes in other airports.

Total travel costs shown in Tables (B.5) and (B.6) were also obtained as sums of all out-of-pocket costs of the trip; i.e., fares plus access and egress costs.

B.3 Socio-Economic Characteristics of the Cities' Population

Information regarding the socio-economic characteristics of the resident population of each city were obtained mainly from Statistics Canada and are presented here in Tables (B.7) and (B.8). In the Tables, the "family unit" is defined by Statistics Canada as a group of persons living in the same dwelling and dependent on a common or pooled income, or one financially independent individual living alone. Also, the shown employment figures represent the total employed (with jobs) labor force. Any information reported for Ottawa is meant to be for Ottawa and Hull together (the whole metropolitan area).

The information given in Table (B.8) was used to disaggregate the total travel demand (by all modes) by income group. For example, from the shown % distribution of family units by income group and the corresponding average number of income earners, the ratio between the number of employed persons in a given income group to the total labor force can be determined. Similarly, the ratio between the number of trips made by individuals of that group to the total number of trips made can be obtained from the travel data sample. The ratio between those two quantities yields an observation for the dependent variable in equation (3.26), RT . The corresponding independent variable in that equation, RI , can also be evaluated directly from Table (B.8). (The type of information presented in that Table was not available on a city-level basis).

The family income figures obtained by the CTC travel survey were for 1968. These were escalated here to 1969 using a rate of income increase of 9%, which was reported by Statistics Canada (Catalogue #13.544, page 12) for that period.

TABLE (B.7). - CITIES' SOCIO-ECONOMIC CHARACTERISTICS

MONTREAL TORONTO OTTAWA QUEBEC HAMILTON LONDON WINDSOR							
P O P U L A T I O N							
(1966) ¹	2436817	2158496	494535	413397	449116	207396	211697
(1971) ²	2743210	2628040	602510	480505	498525	286010	258645
(1969)*	2620653	2440222	558735	453659	478761	254564	239866
E M P L O Y M E N T							
(1961) ³	783067	767764	164164	123189	146292	72117	65060
1969 Index ⁴	1.227	1.343	1.377	1.181	1.212	1.252	1.527
(1969)	960823	1031107	226054	145486	177306	90290	99347
A V. F A M I L Y I N C O M E (\$)							
(1969) ⁵	8,416	10,420	10,050	7,803	9,071	9,031	9,139
L A N G U A G E P A I R I N G I N D E X ⁶							
MONTREAL	.60	.75	.85	.60	.60	.65	
TORONTO		.85	.30	1.0	1.0	1.0	
OTTAWA			.60	.85	.85	.90	
QUEBEC				.30	.30	.35	
HAMILTON					1.0	1.0	
LONDON						1.0	

Sources:

1. Statistics Canada, Catalogue #92.610
 2. Statistics Canada, Catalogue #92.715
 3. Statistics Canada, Catalogue #94.533
 4. Statistics Canada, Catalogue #72.201, (1961 is the base year)
 5. Statistics Canada, Catalogue #62.537
 6. Provided by the CTC
- * Obtained by interpolation between 1966 and 1971 figures

TABLE (B.8) - FAMILY UNIT CHARACTERISTICS

INCOME GROUP	% DISTRIBUTION OF FAMILY UNITS IN METROPOLITAN AREAS		FAMILY UNIT CHARACTERISTICS	
	ONTARIO	QUEBEC	AV. SIZE OF FAMILY UNIT	AV. NUMBER OF INCOME EARNERS*
< \$1000	2.1	4.1	1.51	.54
1000 - 1999	6.3	6.8	1.44	.38
2000 - 2999	5.4	6.3	2.28	.67
3000 - 3999	5.1	8.5	2.57	.94
4000 - 4999	6.6	7.1	2.89	1.14
5000 - 5999	7.1	8.3	3.03	1.29
6000 - 6999	6.8	8.9	3.29	1.36
7000 - 7999	7.5	10.1	3.50	1.47
8000 - 8999	8.8	7.5	3.69	1.60
9000 - 9999	6.8	5.3	3.94	1.71
10000 - 11999	12.7	9.3	3.82	1.84
12000 - 14999	12.8	8.0	3.87	2.07
15000 - 24999	10.3	7.8	4.15	2.30
25000 +	1.6	2.1	4.04	1.86
<u>Average Income</u>	\$9004.	\$8026		

* Average number of persons with wages and salaries or net income from self-employment.

Source: Statistics Canada, Catalogue #13.544.

APPENDIX C

THE LIKELIHOOD FUNCTION OF THE MULTINOMIAL LOGIT MODEL
AND ITS ASSOCIATED STATISTICAL MEASURESC.1 The Likelihood Function

The logarithm of the likelihood function $\text{Log } L$ given by equation (3.16) can be written as:

$$\text{Log } L = \sum_i P x_i \cdot \log p_i \quad \dots\dots (C.1)$$

where

$P x_i$ = number of passengers observed in a choice case i described by a given link, a given mode, and a given income group. Since there are 4 links, 3 modes, and 6 income groups, i runs from 1 to 72.

p_i = choice probability of the mode in case i , which can be written according to equation (3.10) as:

$$p_i = \frac{e^{-G_i}}{e^{-G_m} + e^{-G_{m+1}} + e^{-G_{m+2}}} \quad \dots\dots (C.2)$$

where $m = 1 + (3 \cdot \langle (i-1)/3 \rangle)$

(the brackets $\langle \rangle$ indicate "smallest integer").

In fact, the calibration data are arranged in such a way that air observations are followed by rail observations which are in turn followed by bus observations; for the same link and income group.

Equation (C.1) can thus be written as:

$$\text{Log } L = \sum_i -[P x_i \cdot G_i] - \sum_i [P x_i \cdot \log (E_m + E_{m+1} + E_{m+2})] \quad \dots\dots (C.3)$$

where

$E_r = e^{-G_r}$ for any choice case r ($i = 1, 2, \dots, r, \dots, 72$)

G_r = can be written, as given by equation (3.13), as:

$$G_r = \begin{cases} c_r + a_1 I_r \cdot t_r + a_2 / F_r + b_{air} & \text{for air} \\ c_r + a_1 I_r \cdot t_r + a_2 / F_r + b_{rail} & \text{for rail} \\ c_r + a_1 I_r \cdot t_r + a_2 / F_r + b_{bus} & \text{for bus} \end{cases} \dots (C.4)$$

Maximization of the Log L function means minimization of the quantity $(-\text{Log } L)$ with respect to the four coefficients involved: a_1 , a_2 , b_{air} , and b_{bus} .

C.2 Partial Derivatives of the Log L Function

From equations (C.3) and (C.4) the first partial derivatives of Log L with respect to a_1 is:

$$\frac{\partial \text{Log } L}{\partial a_1} = \sum_i -P x_i (I_i t_i + \sum_i P x_i (E_m \cdot I_i t_m + E_{m+1} \cdot I_i t_{m+1} + E_{m+2} \cdot I_i t_{m+2}) / EE_i) \dots (C.5)$$

where

$$EE_i = E_m + E_{m+1} + E_{m+2}$$

Differentiation of equation (C.5) with respect to a_1 yields, after arrangement of terms, the following expression:

$$\frac{\partial^2 \text{Log } L}{\partial a_1^2} = \sum_i I_i^2 \cdot P x_i \{ [(E_m \cdot t_m + E_{m+1} \cdot t_{m+1} + E_{m+2} \cdot t_{m+2}) / EE_i]^2 - [(E_m \cdot t_m^2 + E_{m+1} \cdot t_{m+1}^2 + E_{m+2} \cdot t_{m+2}^2) / EE_i] \} \dots (C.6)$$

[†] As discussed in Chapter 3, the rail mode was arbitrarily regarded as a "reference" mode with respect to the modal bias in choice of mode. The term b_{rail} was therefore assigned a zero value.

The expected value of the quantity given by equation (C.6) is obtained by multiplying the probability of choosing the mode in each case i by 100* and substituting it for Px_i . That is

$$E[Px_i] = 100 p_i \quad \text{.....(C.7)}$$

i.e.

$$E[Px_i] = f(a_1, a_2, b_{air}, b_{bus}) = f(\theta)$$

The negative of this expected value is the element r_{11} in the second-derivative matrix $R(\theta)$ [see Chapter 3, equation (3.17)]. Derivation of the expression for the other elements is similar to that shown above for a_1 . The final equations are given below.

$$-r_{12} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_1 \partial a_2}\right] = \sum_i \frac{100 p_i \cdot I_i}{EE_i^2} [Y \cdot Z - EE \cdot (E_m \cdot t_m / F_m + E_{m+1} \cdot t_{m+1} / F_{m+1} + E_{m+2} \cdot t_{m+2} / F_{m+2})]$$

$$-r_{13} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_1 \partial b_{air}}\right] = \sum_i \frac{100 p_i \cdot I_i}{EE_i^2} (E_m \cdot Y - EE \cdot E_m \cdot t_m)$$

$$-r_{14} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_1 \partial b_{bus}}\right] = \sum_i \frac{100 p_i \cdot I_i}{EE_i^2} (E_{m+2} \cdot Y - EE \cdot E_{m+2} \cdot t_{m+2})$$

$$-r_{22} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_2^2}\right] = \sum_i \frac{100 p_i}{EE_i^2} [Z^2 - EE \cdot (E_m / F_m^2 + E_{m+1} / F_{m+1}^2 + E_{m+2} / F_{m+2}^2)]$$

$$-r_{23} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_2 \partial b_{air}}\right] = \sum_i \frac{100 p_i}{EE_i^2} (E_m \cdot Z - EE \cdot E_m / F_m)$$

$$-r_{24} = E\left[\frac{\partial^2 \text{Log } L}{\partial a_2 \partial b_{bus}}\right] = \sum_i \frac{100 p_i}{EE_i^2} (E_{m+2} \cdot Z - EE \cdot E_{m+2} / F_{m+2})$$

* The number of passengers choosing among the three travel modes: air, rail and bus was normalized to 100 for each link and income group.

$$-r_{33} = E\left[\frac{\partial^2 \text{Log } L}{\partial b_{\text{air}}^2}\right] = \sum_i \frac{100 P_i}{EE_i^2} (E_m^2 - EE \cdot E_m)$$

$$-r_{34} = E\left[\frac{\partial^2 \text{Log } L}{\partial b_{\text{air}} \partial b_{\text{bus}}}\right] = \sum_i \frac{100 P_i}{EE_i^2} (E_m \cdot E_{m+2})$$

$$-r_{44} = E\left[\frac{\partial^2 \text{Log } L}{\partial b_{\text{bus}}^2}\right] = \sum_i \frac{100 P_i}{EE_i^2} (E_{m+2}^2 - EE \cdot E_{m+2})$$

where

$$Y = E_m \cdot t_m + E_{m+1} \cdot t_{m+1} + E_{m+2} \cdot t_{m+2}$$

$$Z = E_m / F_m + E_{m+1} / F_{m+1} + E_{m+2} / F_{m+2}$$

[Note: the $R(\theta)$ matrix is 4×4 and is symmetrical (e.g. $r_{12} = r_{21}$)]

C.3 Variances and t-Statistics of the Estimates of the Coefficients

The standard errors of estimate of the values obtained by calibration for the coefficients a_1 , a_2 , b_{air} , and b_{bus} can be found by inverting the $R(\theta)$ matrix whose elements are defined above. These elements are first evaluated at the maximum likelihood estimates $\{\hat{a}_1, \hat{a}_2, \hat{b}_{\text{air}}, \hat{b}_{\text{bus}}\}$. The four elements of the main diagonal of the inverted matrix (covariance matrix) represent the variances (squares of the standard error of estimate) of these four estimators. Given this information, the statistical significance of the estimators can be tested by calculating their t-statistics.

APPENDIX D

COMPILED AIRCRAFT DATA TABLES

TABLE (D.1) -- SHORT-HAUL BLOCK TIME DATA

A I R C R A F T	CRUISE SPEED V (MPH)	FIXED GROUND TIME, t _g (MINS.) ^g	FIXED AIR TIME, t _a (MINS.) ^a	AVERAGE TIME PER MILE, f(V) (MINS./MILE)
DHC-6 "TWIN OTTER"	208	4	10	.2855
SHORT SD3-30	228	5	10	.2700
DHC-7 "DASH 7"	281	4	8	.2246
HS 748	283	6	11	.2296
F-27 MK 500	298	6	14	.2215
VFW 614	457	6	14	.1400
HS 146	490	6	13	.1300
F-28 MK 1000	528	7	15	.1190
GAC-100	337	5	11	.1899
MD-188	305	5	11	.2152
MD-210E	400	5	11	.1519
MD-210G	372	5	11	.1677
MD-210M	425	5	11	.1456

Note: Data shown for the first eight aircraft are given in Ref.39, page 8.

Cruise speeds of the last five aircraft and their block times for the Montreal-Toronto link (316 miles) were reported in data source No.1*. Average fixed ground and air times based on the first seven aircraft shown in the table were applied to the last five to determine the distance-dependent portion of their block times (i.e.f(V) values).

* Data sources are listed at the end of this Appendix.

TABLE (D.2) - AIRCRAFT LENGTH-SEATING CAPACITY DATA

A I R C R A F T	NO.OF SEATS	SEAT PITCH (INCHES)	NO. ABREAST	LENGTH (FEET)	DATA SOURCE NO.
BOEING 747	500	32	10	231.33	2
MD DC-10	380	32	10	181.58	2
BOEING 707	219	29	6	152.75	2
MD DC-8-62	189	34	6	157.50	2
L1011 - TRISTAR	400	30	10	178.58	2
BOEING 727-200	189	30	6	153.17	2
BAC 111-475	89	29	5	93.50	2
BAC 111-500	119	29	5	107.00	2
BOEING 737-200	130	30	6	100.00	2
DASSAULT MERCURE	162	30	6	120.42	2
MD DC-9-20	90	32	5	104.42	2
MD DC-9-30	115	32	5	119.33	2
MD DC-9-40	125	32	5	125.58	2
MD DC-9-50	139	31	5	132.00	2
MYSTERE 40	40	31	4	64.83	2
F-28 MK 2000	79	31	5	97.17	2
HS 146-100	88	31	6	85.83	2
HS 146-200	102	31	6	93.12	2
VFW 614	44	32	4	67.50	2
YAK 40	33	29	3	66.75	2
NORD 262 c FREGATE	29	28	3	63.25	2
ANTONOV AN 24V-II	50	30	4	77.25	2
F-27 MK 500	56	29	4	82.25	2
SHORT SD3-30	30	30	3	58.04	2
BREGUET 941C	57	29	4	79.92	3
NAMC YS 11A-200	60	34	4	86.33	3
GAC-100	36	33	4	67.00	3
BERIEV Be-30	14	29	2	49.25	3
CASA C212 AVIOCAR	18	31	3	49.75	3
JETSTREAM I	18	30	3	47.17	3
ARAVA	20	30	4	42.58	3
OMNIPOL L-410	19	30	3	44.58	3
SWEARINGER METRO	20	30	2	59.33	3
DHC-7 "DASH 7"	50	32	4	80.67	4
DHC-6 "TWIN OTTER"	20	30	3	51.75	5

TABLE (D.3) - AIRCRAFT PRICE DATA

A I R C R A F T	CRUISE SPEED (MPH)	NO. OF SEATS	SEAT PITCH (INCHES)	PRICE* (\$ MILLIONS)	DATA SOURCES NO.
DHC-6 "TWIN OTTER"	210	20	30	.800	6,7,8,9,10
JETSTREAM 200	285	18	29	1.100	7,8,11
SHORT SD3-30	227	30	30	1.350	2,12
F-27 MK 500	292	56	29	1.650	2,12
HS 748-2A	283	60	28	1.800	2,12
NAMCO YS-11A-200	293	60	34	2.200	13,14
YAK-40	342	33	29	1.600	2,7,15
VFW 614	457	44	32	3.500	2,15,16
F-28 MK 1000	527	65	31	4.000	2
HS 146-100	491	88	31	4.400	2,13
BAC 111-500	526	119	29	5.200	2
BOEING 737-200	564	130	30	6.000	2
DC-9-40	562	125	32	6.100	2,12

* Equipped 1974 prices. Spare parts cost not included.

TABLE (D.4) - AIRCRAFT EMPTY WEIGHT - SEATING CAPACITY DATA

A I R C R A F T	NO. OF SEATS	PITCH (INCHES)	EMPTY WEIGHT* (POUNDS)	DATA SOURCE NO.
BAC 111-500	119	29	54470	2
BOEING 737-200	130	30	59660	2
DASSAULT MERCURE	162	30	69330	2
DC-9-30	115	32	55660	2
DC-9-40	125	32	58660	2
DC-9-50	139	31	64660	2
MYSTERE 40	40	31	21400	2
F-28 MK 1000	65	31	35180	2
F-28 MK 2000	79	31	36610	2
HS 146-100	88	31	42640	2
HS 146-200	102	31	45160	2
VFW 614	44	32	27220	2
YAKOVLEV YAK-40	33	29	20260	2
NORD 262 c FREGATE	29	28	15590	2
ANTONOV AN 24V-II	50	30	28980	2
F-27 MK 200/400/600	48	29	24960	2
F-27 MK 500	56	29	26000	2
HS 748-2A	60	28	25660	2
SHORT SD3-30	30	30	13860	2
NAMC YS-11A-200	60	34	33610	3
GAC-100	36	33	17300	3
BERIEV Be-30	14	29	9350	3
JETSTREAM I	18	30	8020	3
DHC-7 "DASH 7"	50	32	25520	4

* Empty weight = the operational weight empty reported in the shown data source less the weight of the flight crew (2 @ 170 lbs each).

TABLE (D.5) - AIRCRAFT FUEL CONSUMPTION DATA

A I R C R A F T	CRUISE SPEED (KNOTS)*	TAKE-OFF GROSS WT. (1000's LB)	FUEL CONSUMPTION (LBS/HR.)	DATA SOURCE NO.
DHC-6 "TWIN OTTER"	175	12.50	583	3
BEECH B99A	221	12.40	600	3
JETSTREAM I	244	12.50	599	3
SHORT SD3-30	197	22.00	920	17
NORD 262 c FREGATE	211	23.81	770	17
DHC-7 "DASH 7"	244	43.00	1730	17
F.27 MK 200/400/500/600	256	45.00	1510	17
HS 748-2A	242	46.50	1650	17
NAMC YS-11A	254	52.91	2310	3
YAK-40	281	35.28	2180	17
MYSTERE 30 & 40	450	35.28	2950	2
VFW 614	390	44.00	3290	17
F.28 MK 1000/2000	451	65.00	5470	17
HS 146-200	411	87.50	5750	17
BAC 111-475	459	81.50	6059	17
BAC 111-500	457	89.00	6111	17
DASSAULT MERCURE	471	124.56	6930	17
BOEING 727-100	495	169.50	9130	2
BOEING 727-200	495	209.00	10720	17

Note: The above data are for direct operating cost economical cruise. Whenever this information was not reported, the maximum cruise speed data were used instead.

* 1 knot = 1.15092 miles per hour.

TABLE (D.6) **COMPARISON OF RATE OF FUEL CONSUMPTION
AS COMPUTED BY EQUATION (5.19) AND
AVERAGE RATE OF BLOCK FUEL CONSUMPTION**

A I R C R A F T	BLOCK FUEL RATE* (LBS/HR.)	FUEL RATE FROM THE EQUATION (LBS/HR.)
HS 748-2A	1885	1751
DHC-7 "DASH 7"	1840	1684
F.27 MK 500	1820	1843
DHC-6 "TWIN OTTER"	615	501
BEECH B99A	587	602

* Source of data: Reference No.61.

LIST OF DATA SOURCES USED IN THIS APPENDIX

1. CANADIAN TRANSPORT COMMISSION, "A Parametric Study of First Generation Turboprop STOL Aircraft", Report No.14, Research Branch, pages 5 & 14, (April 1971)
2. FLIGHT INTERNATIONAL, (24 October 1974)
3. FLIGHT INTERNATIONAL, (20 November 1969)
4. DeHAVILLAND AIRCRAFT OF CANADA, "Dash 7 Quiet STOL Airliner"; (January 1975)
5. DeHAVILLAND AIRCRAFT OF CANADA, "The Twin Otter -- From a Proven Background", Technical Data Summary, (Sept. 1972)
6. FLIGHT INTERNATIONAL, (27 July 1972)
7. FLIGHT INTERNATIONAL, (28 June 1973)
8. FLIGHT INTERNATIONAL, (19 September 1974)
9. AVIATION WEEK AND SPACE TECHNOLOGY, (13 March 1972)
10. FLIGHT INTERNATIONAL, (21 August, 1975)
11. JANES' - "ALL THE WORLD AIRCRAFT", (1973-74)
12. FLIGHT INTERNATIONAL, (31 October 1974)
13. FLIGHT INTERNATIONAL, (30 May 1974)
14. FLIGHT INTERNATIONAL, (18 November 1971)
15. FLIGHT INTERNATIONAL, (27 March 1975)
16. FLIGHT INTERNATIONAL, (18 April 1974)
17. FLIGHT INTERNATIONAL, (23 October 1975)

APPENDIX E
PRICE INDICES

TABLE (E.1) - CONSUMER PRICE INDEX

(BASE YEAR: 1971)	TORONTO	OTTAWA	MONTREAL
1969	95.9	94.2	96.2
1973	111.3	111.9	110.7
1974	123.0	123.9	123.0
1975	136.1	135.8	136.4

Source: Statistics Canada Catalogues: No.62-009 (May 1976), No.11-003E (Dec.1975), No.62-002 (Oct.1975).

Beyond 1975, the following rates of increase in Consumer Price Index were assumed for the three cities. The trend shown is believed to be consistent with the Canadian government efforts and policies to curb inflation.

<u>1976</u>	<u>1977</u>	<u>1978</u>	<u>1979 and on</u>
9%	8%	7%	6%

All system cost components are assumed to increase beyond their 1975 values according to these rates. For example, a cost of \$A in 1975 would, according to the above assumed rates, be equal to \$(A X 1.4153) in year 1980.

TABLE (E.2) - INDEX OF WAGE RATE AND MATERIALS PRICE
FOR U.S. RAILWAY OPERATION

<u>YEAR</u>	<u>WAGE*</u> <u>INDEX</u>	<u>MATERIALS[†]</u> <u>PRICE</u> <u>INDEX</u>	<u>YEAR</u>	<u>WAGE*</u> <u>INDEX</u>	<u>MATERIALS[†]</u> <u>PRICE</u> <u>INDEX</u>
1965	88.9	94.9	1970	125.6	109.4
1966	92.9	96.5	1971	139.4	113.5
1967	100.0	100.0	1972	153.4	118.7
1968	106.3	102.6	1973	173.9	122.9
1969	113.6	105.5	1974	187.5	142.1

Source: Railway Age, page 73, (27 Jan., 1975)..

* Including supplements.

† Other than fuel.

Corresponding 1975 indices were assumed 10% higher than those in 1974.

Latest statistics on family incomes in metropolitan areas are reported by Statistics Canada for 1973. Beyond 1973, the following trend in family income growth rate is assumed.

<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>	<u>1978 and on</u>
10%	10%	9%	8%	7%

APPENDIX F

THE COMPUTER PROGRAM

The system design optimization model presented in this thesis is implemented in the form of a FORTRAN IV computer program which was also developed by the author. The computerized package consists of a main program and six subprograms. In the main program the input data are read in and printed out. Calculation of the demand, supply, and economic factors which do not change while carrying out the optimization is also done in the main program. Such factors are passed to the various subprograms through COMMON statements. A call to the direct search algorithm which is made from the main program evokes the optimization process. Upon termination of the search for the optimal values of the design variables, the details of the optimal system design (demand, supply and performance, and revenues) are generated.

The search algorithm (Pattern Search method) is coded in Subroutine "SEARCH". The function minimized by the search algorithm is calculated in Subroutine "FUN", which in turn calls Subroutines "UPDATE", "DEMAND", and "SUPPLY" in order to evaluate the value of the objective function. For a given value combination of the design optimization variables, Subroutine "UPDATE" computes the resulting changes in the system level of service. The updated service variables are then fed into Subroutine "DEMAND", where the total demand, market shares, and users' cost are calculated. The corresponding system supply and performance measures are computed in Subroutine "SUPPLY" which contains a supply model for STOL and another for Rail. In order to evaluate the rail horsepower requirement, the LRC train resistance is computed in a separate Subroutine called "RESIST".

Having evaluated the system demands and supply measures, its economic consequences are estimated and the value of the

objective function is accordingly determined for the trial value combination of the design variables. This is carried out in the Function "FUN". The whole procedure is then repeated according to the selected number of probable system demand states.

The sequence of the computational activities involved in the computer program follows closely the flow chart of the methodology framework which was presented in Figure (2.1). Below is a glossary of the computer program terms relating to the input and output information, and is followed by the listing of the program.

The entire program was compiled on the Xerox computer "Sigma 9" in about 10 seconds using the "FLAG" compiler. The actual size (core requirement) of the program depends on the size and specifics of the transport network analyzed. For the 3-node network and other related conditions which were considered in the two case studies, the actual size of the program was about 13500 words (or 13K). The storage allocated in the program for this particular network can be easily changed when dealing with different network configurations. Among the main factors affecting the optimization execution time are the size and specifics of the transport network, number of optimization variables, number of evaluation intervals, number of probable demand states, and the starting point for carrying out the optimization. For the particular 3-variable STOL and 2-variable 4-alternative Rail case studies presented here, the optimization execution times (using FLAG) were about 3 and 2 minutes, respectively. These times are based on four probable system demand states, and four 3-year time intervals for STOL (five, for Rail). The execution time is almost directly proportional to any of these two factors.

GLOSSARY OF COMPUTER PROGRAM TERMS

ACC(I)	Required accuracy in the final value of optimization variable i
ACCONT	Total aircraft control expenses in a given year
ACSERV	Total aircraft servicing cost in a given year
ADDA(I)	Additional aircraft of type (size) i acquired in a given year
ADDCAR	Additional train cars acquired in a given year
ADDLOC	Additional locomotives acquired in a given year
AINS	Total aircraft insurance payment in a given year
ALIAB	Total liability expenses in a given year
AMAIN	Total aircraft maintenance cost (materials + labor) in a given year
AMAINB	Total aircraft maintenance burden cost in a given year
AMAINL	Total aircraft maintenance labor cost in a given year
AMAINM	Total aircraft maintenance material cost in a given year
APRICE(I)	Price of a STOL airplane of type i
AVUTIL(I)	Average utilization of vehicles type i (hours/day)
B(I)	Optimal value obtained for design variable i
BIAS(I,J)	Modal choice bias term for mode i (j=1: business, j=2: non-business)
CAB	Total cabin attendants expenses in a given year
CABIN(I)	Cabin attendants expenses for a vehicle of type i -- (\$/hr)
CAPCAR	Seating capacity of a train car
CCONST(I,J)	Access and egress travel cost between city-pair i (j=1: business, j=2: non-business) -- (\$10's)
CALINC(I,J)	Family income used in calibrating the demand models for city-pair j (i=1: origin city, i=2: destination city) -- (\$10,000's)
CFARE	Fixed portion of system fare (b-value)
COEFF(I,J)	Time and cost coefficients in the generalized travel cost expression for mode i (j=1: business, j=2: non-business)
CP	Construction cost (1975 dollars) per unit floor space in the passenger accommodation area of the terminal -- (\$/sq.ft.)
CPI(I,J)	Consumer price index in the starting year of operation for city-pair j (i=1: origin city, i=2: destination city)

CPLINK(I,J)	Jth city-pair served by link i
CPROUT(I,J)	Jth city-pair served by route i
CREW	Total vehicle crew expenses in a given year
CRFT	Capital recovery factor for infrastructure investment
CRFV	Capital recovery factor for vehicles investment
CRT	Annual capital recovery payment for infrastructure
CRTS	Annual capital recovery payment for passenger and vehicle terminal space investment
CV	Construction cost (1975 dollars) per unit floor space in the vehicle storage area of the terminal -- (\$/sq.ft.)
DAYS	System annual utilization -- (servicing days/year)
DDF	Design demand factor (>1.0)
DEPL(I,J)	Time of the ith departure along route j
DISCNT	Rate of discount -- (decimal, e.g. 0.10)
DISTCP(I)	Travel distance between city-pair i
DIST(I)	Travel distance along link i -- (miles)
DOC	Total direct operating cost in a given year
DPX(J)	Maximum instantaneous number of departing passengers at terminal j
DV	Track design speed -- (mph)
DWTLOC	Dry weight of locomotive -- (tons)
ECFLOW(1)	Present worth of expected total capital recovery payments.
ECFLOW(2)	Present worth of expected total operating costs
ECFLOW(3)	Present worth of expected total fare revenues
ECFLOW(4)	Present worth of expected total users cost
EP	Expected total passengers carried by the system
EPM	Expected total passenger-miles via the system
ETAB(I,J)	Expected values of the cash flows given in array PWTAB(K)
ETC	Present worth of expected total system cost
EWTCAR	Empty weight of train car -- (tons)
EXPECT	Logical variable, to be assigned a ".TRUE." value if the expected values of the system economic and demand measures are to be printed for each search iteration
FAC(I)	Fraction of daily demand which occurs in time slice i
FACB(I)	Factor multiplied by predicted business trips to match observed volumes, for city-pair i
FACNB(I)	Factor multiplied by predicted non-business trips to match observed volumes, for city-pair i

FACTOR	Factor to be multiplied by the demand models predictions to yield a probable system demand level
FINC(I,J)	Family income in the starting year of system operation for city-pair j (i=1: origin city, i=2: destination city)
FLEET(I)	Minimum required fleet size of vehicles type i in a given year
FMIN	Optimal value of the objective function
FOOD	Total passenger food expenses in a given year
FQF(J)	Effective frequency of service factor for city-pair j (<1.0)
FUEL	Total fuel cost in a given year
FUN	Expected value of the objective function
FUN1	Present worth of expected net revenue
FUN2	Present worth of expected system unit cost including users cost (\$/pass.-mile)
FUN3	Present worth of expected system unit cost without users cost (\$/pass.-mile)
GA	Total General and Administrative expenses in a given year
GINC	Annual growth factor for family income -- (>1.0)
GINF	Annual growth factor for cost inflation -- (>1.0)
GPE	Total STOL system ground property and equipment expenses in a given year
ICRIT	Index=1 for maximization of system net revenue, =2 for minimization of system unit cost (including users cost)
IEXIST	Index=1 if the system already exists =0 otherwise
IFIX(I)	Index=1 if the initial value of optimization variable i is to remain unchanged, =0 otherwise
IMPROV	Counter for the number of rail alternatives designed
INT(I)	Index=1 if optimization variable i takes on integer values, =0 otherwise
INTVL	Evaluation interval -- (years)
IRFRQ(J)	Frequency of service along route j
IROUTF(I,J)	Jth route serviced by frequency variable i
ITR	Maximum number of search iterations required
IYR	Year boundaries of evaluation intervals (=1+NYR)

LFRQ(J)	Frequency of service along link j
LINKQ(I,J)	Jth link served by vehicles type i
LKNOD(I,J)	Jth link connected to node i
LSP	Length of the study period -- (years)
MARKET	Total marketing expenses in a given year
MAXCAR	Maximum number of cars per train
MAXFRQ	Maximum frequency of service
MINFRQ	Minimum frequency of service
MODE	Index=3 for designing a rail mode, =4 for designing a STOL mode
N	Number of design optimization variables
NALT(I)	Number of travel alternatives between city-pair i
NCABIN	Number of cabin attendants in the vehicle
NCPAIR	Number of city-pairs
NCPLK(I)	Number of city-pairs served by link i
NCPRT(I)	Number of city-pairs served by route i
NEVAL	Number of objective function evaluations (calls)
NLINK	Number of links in the network
NLKNOD(I)	Number of links connected to node i
NLKQ(I)	Number of links served by vehicle of type (size) i
NLKRT(I)	Number of links contained in route i
NNODE	Number of nodes in the network
NODV(I,J)	Number of vehicles type j needed at terminal i
NRTFRQ(I)	Number of routes serviced by each frequency variable
NROUTE	Number of service routes in the network
NTIME	Number of time slices in the diurnal distribution of passenger demand
NTLIFE	Service life of infrastructure facilities -- (years)
NU	Chosen number of probable demand states
NVLIFE	Service life of vehicles -- (years)
NYR	Number of intervals +1
OPCOST	Total operating cost in a given year
OPT	Logical variable, to be assigned a ".TRUE." value if the details of the system design are to be output for given values of the system design optimization variables
OVHEAD	Total overhead expenses in a given year

PAX	System total passenger volume in a given year
PERIOD(I)	Duration of time slice i in the diurnal distribution of demand -- (minutes)
PFUEL	Price of fuel -- (\$/imperial gallon)
PITCH	Aircraft seat pitch (inches)
PLANG(I)	Language-pairing index for city-pair i -- (<1.0)
PLOADF(J)	Design loading factor of vehicle along link j
PML	Total passenger-miles in a given year
PMAX(I)	Maximum accumulation of passengers in terminal i
PRICEC	Price of a train car (1975 dollars)
PRICEL	Price of a train locomotive (1975 dollars)
PRINT	Logical variable, to be assigned a ".TRUE." value if the values of the objective function and the optimization variables are to be printed after each search iteration
PROB	Probability of occurrence of a particular demand state
PWTAB(K)	Present worth (discounted) of the cash flows given in array TAB(I,K)
PXSERV	Total passenger servicing expenses in a given year
QEND	See text, pp.98-100
QOUT	See text, pp.98-100
QSTART	See text, pp.98-100
REQCAR	Minimum fleet of train cars needed in a given year
REQLOC	Minimum fleet of locomotives needed in a given year
REVENU	Total fare revenue in a given year
RL	Labor rate for aircraft maintenance (1975 dollars/man-hour)
ROUTE(I,J)	Jth descriptor of rail route i (j=1-6: total mileage, mileage at 95 mph, mileage at 120 mph, total running time (hours), running time at 95 mphr, running time at 120 mph)
RTLINK(I,J)	Jth link contained in route i
SHARE(M,I,J)	Demand share (fraction <1.0) for mode m between city-pair i (j=1: business, j=2: non-business) -- (expressed as trip volume for the designed system)
SOCIO(I,J,K)	Socio-economic characteristics for city-pair i, j=1: for population of origin city j=2: for employment of origin city j=3&4: similar to 1 & 2 but for destination city

SPAREA(I)	Spare vehicles of type i acquired in a given year
SPAREC	Spare train cars acquired in a given year
SPAREL	Spare locomotives acquired in a given year
SPT	Space required in the ticketing area per passenger -- (sq.ft.)
SPW	Space required in the waiting area per occupant -- (sq.ft.)
STEP(I)	Search step size for optimization variable i
STSTOP(I)	Total station stopping time along route i per train trip (hours)
TAB(I,K)	Cash flows in a given year i (i=1→LSP) and for a particular demand state, k=1: for total capital recovery payments. k=2: for total operating cost k=3: for total fare revenues k=4: for total users cost (All expressed in year i dollars)
TCNST(I,J)	Fixed portion of total travel time between city-pair i (j=1: for business, j=2: for non-business) -- (10's hours)
TERML	Total terminal expenses for a STOL system in a given year
THRUTF(I)	Through traffic factor for city-pair i (>1.0)
TINV	Infrastructure investment cost (1975 dollars) (=fixed portion of STOL ports investment cost)
TKLINK(I,J)	Trackage of link i (j=1: 95 mph, j=2: 120 mph) -- (miles)
TKMAIN	Total track maintenance expenses in a given year
TOTVOL(I,J)	Total demand volume between city-pair i (j=1: business, j=2: non-business) -- (trips/week/direction)
TRA(I,J,K)	Projected transport system characteristics: i: for city-pairs j: for time, cost, and frequency by each mode, k: for trip purpose (k=1: business, k=2: non-business)
TRAIN(I,J)	Train consist along route i (j=1: no. of locomotives, j=2: no. of cars)
TRDISP	Total train dispatching expenses in a given year
TRMAIN	Total train maintenance expenses in a given year
TSMAX	Maximum total cost of terminals space over the study period

TSPACE	Total cost of passenger and vehicle terminal space in all terminals and in a given year
TTIME(I,J)	Total rail travel time between city-pair i (j=1: business, j=2: non-business) -- (10's hours)
TTL(I)	Travel time along link i -- (hours)
TTT(I)	Terminal-to-terminal travel time between city-pair i -- (hours)
TURN	Vehicle turn-around time -- (minutes)
TZERO(I)	Starting time of the system servicing day along link i -- (minutes)
UCOST	Total users cost in a given year
UNCERT	Range of uncertainty in system market share -- ($\pm$ UNCERT %)
VCOST	Total investment in vehicle acquisition in a given year
VHOURS(I)	Total daily vehicle-hours for vehicles type i
VLOAD(I)	Design day passenger load for vehicles type i
VOL(I,J)	Design day passenger flow per direction for link i (j=1: business, j=2: non-business, j=3: total)
VSPACE(I)	Space required for storing vehicles in terminal i
VTRIPS(I)	Total daily trips made by vehicles type i
WE(I)	Empty weight of a STOL aircraft of type (size) i -- (1000's lbs.)
WWISH	Well-wisher factor (>1.0)
X(I)	Value of optimization variable i

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1.000 C*****
2.000 C
3.000 C      AN OPTIMIZATION MODEL FOR DESIGN AND EVALUATION
4.000 C      OF INTERCITY PASSENGER TRANSPORT SYSTEMS
5.000 C
6.000 C      BY
7.000 C      SALAH G. HAMZAWI
8.000 C
9.000 C      CARLETON UNIVERSITY
10.000 C      (AUGUST 1976)
11.000 C
12.000 C*****
13.000
14.000
15.000
16.000 C      *****  M A I N  P R O G R A M  *****
17.000
18.000      EXTERNAL FUN
19.000      LOGICAL PRINT,OPT,EXPECT
20.000      COMMON /M2/ NPOINT,FINI,FIN2,EXPECT,PRICEL,PRICEC,PFUEL,CRFV,CRFI
21.000      ,DISCNT,UNCERT,STSTOP(3),IKLINK(3,2),PWF(16),CRT,HL,CP,CV,IMPROV
22.000      COMMON /M3/ NCPRF(3),CPRFUT(3,3),TCONST(3,2),CFARE=
23.000      COMMON /M4/ NCPLK(3),CPLINK(3,2),COEFF(2,2),BIAS(4,2),PROP(1,2)
24.000      ,AVR(7),SOCIO(3,4,6),SUMA1(6,3,2),SUMA2(6,3,2),TRA(3,2,2),FINF(6)
25.000      ,EOINC(6,3,2),G1(6,3,2),G2(6,3,2),SUM1(6,3,7,2),SUM2(6,3,7,2)
26.000      ,SPLIT(3,3,2,6),UCFT(3,2,2),FINC(3,2)
27.000      COMMON /M5/ CAPCAR,DWLOC,EWTCAR,MAXCAR,JV,NLKNOD(3),LKNOD(3,2)
28.000      ,NLKRT(3),HTLINK(3,2),ROUTE(3,6),TTT(3),NTIME,NSEA1(5,2),FAC(4)
29.000      ,PERIOD(4),TZERO(3),SPT,SPW,NWISH,OSTART,OEEND,ODUT,OTIME
30.000      COMMON /ALL/ N,NODE,NLINK,NROUTE,NCPAIR,LSP,INTVL,NYR,OPT,DAYS,PF
31.000      ,IEVAL,NEVAL,EOFARE(6,3,2),CCONST(3,2),NRTFRO(3),CINF(6),VCINF(6)
32.000      ,NALT(3),IROUTF(3,2),MAXFRO,ICRIT,DISTCP(3),RVFAC(6),TURNT,PITCH
33.000      ,TTIME(3,2),MINFRO,NLKO(3),LINK(3,3),U(3),DIST(3),MODE,DDF,FQF(3)
34.000      DIMENSION TMR(7),SAVE1(3),SAVE2(3),CALINC(3,2),CPI(3,2),PLANG(3)
35.000      ,R1(3),R2(3),THRUTF(3),FACB(3,2),FACNB(3,2)
36.000      ,X(5),IFIX(5),STEP(5),ACC(5),INT(5),B(5),XI(5)
37.000
38.000 C      =====
39.000 C      FIRST, READ INPUT DATA :
40.000 C      =====
41.000
42.000 C      "LSP" IS NOT TO EXCEED "NVLIFE" OR "NTLIFE" WHICHEVER IS SHORTER
43.000 C      ICRIT=1: MAXIMIZE NET REVENUES (=FARE REVENUES - TOTAL SYSTEM COST)
44.000 C      ICRIT=2: MINIMIZE UNIT SYSTEM COST (TOT.SYSTEM COST- REVENUES+ USERS COST)/PM
45.000 C      IEXIST=0: SYSTEM TO BE DESIGNED IS YET TO BE INTRODUCED INTO SERVICE (NEW)
46.000 C      IEXIST=1: SYSTEM TO BE DESIGNED IS ALREADY IN SERVICE (CASE OF IMPROVEMENT)
47.000 C      MODE = 3 MEANS IMPROVED RAIL SYSTEM;  MODE = 4 MEANS STOL SYSTEM
48.000      READ 500,N,(X(I),I=1,N),(IFIX(I),I=1,N),(STEP(I),I=1,N),
49.000      ,(ACC(I),I=1,N),(INT(I),I=1,N),IFR
50.000      READ 500,MODE,IEXIST,MNODE,NLINK,NCPAIR,TURNT,LSP,INTVL,NYR,DAYS,
51.000      ,GINC,GINF,DISCNT,PFUEL,NVLIFE,NTLIFE,DDF,UNCERT,ICRIT,CFARE
52.000      READ 500,(NALT(I),I=1,NCPAIR)
53.000      READ 500,(DISTCP(I),I=1,NCPAIR)
54.000      READ 500,(THRUTF(I),I=1,NCPAIR)
55.000      READ 500,((FACB(I,J),J=1,2),I=1,NCPAIR),((FACNB(I,J),J=1,2),I=1,
56.000      ,NCPAIR)
57.000      READ 500,(NCPLK(I),I=1,NLINK)
58.000      DO 1 I=1,NLINK
59.000      NJ=NCPLK(I)
60.000      1 READ 500,(CPLINK(I,J),J=1,NJ)
61.000      DO 4 IPURP=1,2
62.000      DO 4 I=1,NCPAIR
63.000      J2=NALT(I)
64.000      IF(IEXIST.EQ.1) J2=J2+1
65.000      NJ=J2*3
66.000      4 READ 500,(TRA(I,J,IPURP),J=1,NJ)
67.000      READ 500,((CCONST(I,IPURP),IPURP=1,2),I=1,NCPAIR)
68.000      READ 500,((BIAS(I,IPURP),I=1,MODE),IPURP=1,2)
69.000      READ 500,((COEFF(I,IPURP),I=1,2),IPURP=1,2)
70.000      READ 500,((SOCIO(I,J,IYR),J=1,4),I=1,NCPAIR),IYR=1,NYR)
71.000      READ 500,((FINC(I,J),J=1,2),I=1,NCPAIR)
72.000      READ 500,((CALINC(I,J),J=1,2),I=1,NCPAIR)
73.000      READ 500,((CPI(I,J),J=1,2),I=1,NCPAIR)
74.000      READ 500,(PLANG(I),I=1,NCPAIR)
75.000
76.000      IF(MODE.EQ.3) GOTO 604

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77.000 C  ADDITIONAL INPUT DATA FOR STOL SYSTEM :
78.000     READ 500,RL,CP,CV,WWISH,SPT,SPW,NTIME,QSTART,QEND,QOUT,MINFRQ
79.000     ,MAXFRQ,TINV,PITCH
80.000     READ 500,((NSEAT(I,J),J=1,2),I=1,5)
81.000     READ 500,(DIST(I),I=1,NLINK)
82.000     READ 500,(TZERO(I),I=1,NLINK)
83.000     READ 500,(PERIOD(I),I=1,NTIME)
84.000     READ 500,(FAC(I),I=1,NTIME)
85.000     READ 500,((TCONST(I,J),J=1,2),I=1,NCPAIR)
86.000     READ 500,(NLKNOD(I),I=1,NNODE)
87.000     DO 602 I=1,NNODE
88.000     NJ=NLKNOD(I)
89.000 602 READ 500,(LKNO(I,J),J=1,NJ)
90.000     JI=N-2
91.000     READ 500,(NLKQ(I),I=1,JI)
92.000     DO 601 I=1,JI
93.000     NJ=NLKQ(I)
94.000 601 READ 500,(LINKQ(I,J),J=1,NJ)
95.000     GOTO 609
96.000 C
97.000 C  ADDITIONAL INPUT DATA FOR RAIL SYSTEM :
98.000 604 READ 500,NROUTE,DWLOC,EWICAR,MAXCAR,PRICEL,PRICEC,CAPCAR,DV
99.000     READ 500,(STSTOP(I),I=1,NROUTE)
100.000    READ 500,(NCPRT(I),I=1,NROUTE)
101.000    READ 500,(NLKRT(I),I=1,NROUTE)
102.000    JI=N-1
103.000    READ 500,(NRTFRQ(I),I=1,JI)
104.000    DO 2 I=1,NROUTE
105.000    NJ=NCPRT(I)
106.000    2 READ 500,(CPRUT(I,J),J=1,NJ)
107.000    DO 3 I=1,NROUTE
108.000    NJ=NLKRT(I)
109.000    3 READ 500,(RTLINK(I,J),J=1,NJ)
110.000    JI=N-1
111.000    DO 33 I=1,JI
112.000    NJ=NRTFRQ(I)
113.000    33 READ 500,(ROUTF(I,J),J=1,NJ)
114.000
115.000 C  =====
116.000 C  SECOND, PRINT INPUT DATA :
117.000 C  =====
118.000
119.000 609 PRINT 501
120.000     PRINT 533
121.000     PRINT 49,MODE,IEXIST,NNODE,NLINK,NCPAIR,TURNT,LSP,INTVL,NYR,DAYS,
122.000     ,GINC,GINF,DISCNT,PFUEL,NVLIFE,NLIFE,DDF,UNCERT,ICRT,CFARE
123.000     PRINT 502,(NALT(I),I=1,NCPAIR)
124.000     PRINT 503,(DISTCP(I),I=1,NCPAIR)
125.000     PRINT 506,(THRUT(I),I=1,NCPAIR)
126.000     PRINT 536,((FACB(I,J),J=1,2),I=1,NCPAIR),((FACNB(I,J),J=1,2),I=1,
127.000     ,NCPAIR)
128.000     PRINT 507,(NCPLK(I),I=1,NLINK)
129.000     PRINT 512,((BIAS(I,J),I=1,MODE),J=1,2)
130.000     PRINT 513,((COEFF(I,J),I=1,2),J=1,2)
131.000     PRINT 511,((CCONST(I,J),J=1,2),I=1,NCPAIR)
132.000     PRINT 533
133.000     IF(MODE.EQ.3) GOTO 611
134.000
135.000 C  PRINT ADDITIONAL INPUT DATA FOR STOL SYSTEM :
136.000     OUTPUT ADDITIONAL INPUT DATA FOR STOL SYSTEM
137.000     PRINT 49,RL,CP,CV,WWISH,SPT,SPW,NTIME,QSTART,QEND,QOUT,MINFRQ
138.000     ,MAXFRQ,PITCH
139.000     PRINT 405,(DIST(I),I=1,NLINK)
140.000     PRINT 406,(TZERO(I),I=1,NLINK)
141.000     PRINT 407,(PERIOD(I),I=1,NTIME)
142.000     PRINT 408,(FAC(I),I=1,NTIME)
143.000     PRINT 410,(NLKNOD(I),I=1,NNODE)
144.000     PRINT 411,((TCONST(I,J),J=1,2),I=1,NCPAIR)
145.000     JI=N-2
146.000     PRINT 415,(NLKQ(I),I=1,JI)
147.000     PRINT 540,(NSEAT(I,1),I=1,5),(NSEAT(I,2),I=1,5)
148.000     PRINT 416
149.000     DO 905 I=1,JI
150.000     NJ=NLKQ(I)
151.000 905 PRINT 417,I,(LINKQ(I,J),J=1,NJ)
152.000     PRINT 419

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153.000      DO 907 I=1,NNODE
154.000      NJ=NLKNOD(I)
155.000 907 PRINT 417,I,(LKNOD(I,J),J=1,NJ)
156.000      GOTO 612
157.000 C
158.000 C PRINT ADDITIONAL INPUT DATA FOR RAIL SYSTEM :
159.000 611 OUTPUT ADDITIONAL INPUT DATA FOR RAIL SYSTEM
160.000      PRINT 49,NROUTE,DWTCAR,ENTCAR,MAXCAR,CAPCAR,JV
161.000      OUTPUT PRICEC,PRICEC
162.000      PRINT 505,(STS(I),I=1,NROUTE)
163.000      PRINT 508,(NCPRT(I),I=1,NROUTE)
164.000      PRINT 509,(NLKRT(I),I=1,NROUTE)
165.000      J1=N-1
166.000      PRINT 504,(NRTFRQ(I),I=1,J1)
167.000      PRINT 516
168.000      DO 6 I=1,NROUTE
169.000      NJ=NCPRT(I)
170.000 6 PRINT 515,I,(CPROUT(I,J),J=1,NJ)
171.000      PRINT 517
172.000      DO 7 I=1,NROUTE
173.000      NJ=NLKRT(I)
174.000 7 PRINT 515,I,(RFLINK(I,J),J=1,NJ)
175.000      PRINT 532
176.000      J1=N-1
177.000      DO 908 I=1,J1
178.000      NJ=NRTFRQ(I)
179.000 908 PRINT 515,I,(IROUTE(I,J),J=1,NJ)
180.000
181.000 612 PRINT 514
182.000      DO 5 I=1,NLINK
183.000      NJ=NCPLK(I)
184.000 5 PRINT 515,I,(CPLINK(I,J),J=1,NJ)
185.000      PRINT 520
186.000      PRINT 521
187.000      DO 8 IPURP=1,2
188.000      IF(IPURP.EQ.1) PRINT 525
189.000      IF(IPURP.EQ.2) PRINT 526
190.000      DO 8 I=1,NCPAIR
191.000      J1=NALT(I)*3
192.000      IF(IEXIST.EQ.1) J1=J1+3
193.000 8 PRINT 522,I,(TRA(I,J,IPURP),J=1,J1)
194.000      PRINT 523
195.000      DO 9 IYR=1,NYR
196.000      J1=1980+(IYR-1)*INTVL
197.000      DO 9 I=1,NCPAIR
198.000      IF(IYR.EQ.1) PRINT 524,J1,I,(SOCIO(I,J,IYR),J=1,4),
199.000      (FINC(I,J),J=1,2),(CALINC(I,J),J=1,2),(CPI(I,J),J=1,2)
200.000      IF(IYR.NE.1) PRINT 524,J1,I,(SOCIO(I,J,IYR),J=1,4)
201.000 9 CONTINUE
202.000      PRINT 539,(PLANG(I),I=1,NCPAIR)
203.000      PRINT 520
204.000      PRINT 527,(X(I),I=1,N)
205.000      PRINT 528,(STEP(I),I=1,N)
206.000      PRINT 529,(ACC(I),I=1,N)
207.000      PRINT 538,(INT(I),I=1,N)
208.000      PRINT 537,(IFIX(I),I=1,N)
209.000
210.000 C FUEL PRICE PER 1000 LBS :
211.000 C ASSUME 1 IMP. GAL = 7.7 LB FOR JP-4 (AIRCRAFT) AND =8.54 LB FOR DIESEL (RAIL)
212.000 707 VAL1=7.7
213.000      IF(MODE.EQ.3) VAL1=8.54
214.000      PFUEL=PFUEL*1000./VAL1
215.000
216.000 C =====
217.000 C THIRD, COMPUTE DATA WHICH WILL REMAIN UNCHANGED WHILE OPTIMIZING :
218.000 C =====
219.000
220.000 C -----
221.000 C FACTORS FOR INFLATING AND DISCOUNTING COSTS & REVENUES
222.000 C AND FOR RELATING FARES TO 1969 FARES :
223.000 C -----
224.000      DO 10 NC=1,NCPAIR
225.000      DO 10 J=1,2
226.000      UCFT(NC,J,1)=52.18*10.*FINC(NC,J)*COEFF(1,1)*2.
227.000 10 UCFT(NC,J,2)=UCFT(NC,J,1)*COEFF(1,2)/COEFF(1,1)
228.000      DO 13 I=1,LSP

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BUSINESS
NON-BUSI

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229.000 J1=I-1
230.000 J2=J1/INTVL
231.000 IF(J2*INTVL.NE.J1) GOTO 13
232.000 J2=J2+1
233.000 CINF(J2)=GINF**(I-1.)
234.000 J=I-INTVL+1
235.000 IF(I.EQ.1) J=1
236.000 VAL1=GINF**(J-1.)
237.000 C AVERAGE INFLATION FACTOR FOR VEHICLE PRICE TO ACCOUNT FOR THE "INTVL" LENGTH
238.000 VCINF(J2)=(CINF(J2)+VAL1)/2.
239.000 FIINF(J2)=GINC**(I-1.)
240.000 RVFAC(J2)=52.18*10.**2.*CINF(J2)
241.000 DO 11 NC=1,NCPAIR
242.000 DO 11 J=1,2
243.000 11. EQFARE(J2,NC,J)=CINF(J2)/(FINC(NC,J)*FIINF(J2)/CALINC(NC,J))
244.000 CINF(J2)=CINF(J2)*1.4153
245.000 VCINF(J2)=VCINF(J2)*1.4153
246.000 13 PWF(I)=1./((1.+DISCNT)**(I-1.+5.))
247.000 FIN1=GINF**INTVL
248.000 FIN2=.63*(1.+DISCNT)*(2.06+DISCNT)
249.000
250.000 PF=52.18/(DDF*DAYS)
251.000 QTIME=QSTART-QEND+QOUT
252.000
253.000 C COMPUTE CAPITAL RECOVERY FACTORS FOR AMORIZING FIXED FACILITIES AND VEHICLES
254.000 C ASSUMING EQUAL ANNUAL PAYMENTS (CRF'S) :
255.000 VAL1=(1.+DISCNT)**NVLIFE
256.000 CRFT=DISCNT*VAL1/(VAL1-1.)
257.000 VAL1=(1.+DISCNT)**NVLIFE
258.000 CRFV=DISCNT*VAL1/(VAL1-1.)
259.000 PRINT 533
260.000 OUTPUT PF,FIN1,FIN2,CRFT,CRFV
261.000 IF(MODE.EQ.4) OUTPUT TINV
262.000 PRINT 520
263.000
264.000 C -----
265.000 C INCOME DISTRIBUTION DATA :
266.000 C -----
267.000
268.000 C PURPOSE:
269.000 C =====
270.000 C A. TO ESTIMATE THE PROPORTION OF INDIVIDUALS WITH A GIVEN INCOME RATIO
271.000 C (I/IAV.) FOR USE IN BUSINESS AND NON-BUSINESS DEMAND MODELS
272.000 C B. TO ESTIMATE THE BUSINESS TRIP-MAKING RATE FACTORS OF THE VARIOUS INCOME
273.000 C GROUPS.
274.000 C NOTES:
275.000 C (1) INCOME RATIOS OF .4 .8 1.2 1.6 2.0 2.4 2.8 ARE USED HERE.
276.000 C FOR OTHER DIFFERENT RATIOS JUST CHANGE DELR & DO-LOOP INDICES BELOW
277.000 C (2) CONCERNING A. ABOVE, SINCE THE CALIBRATED INCOME DISTRIBUTION
278.000 C CURVES ARE VERY ACCURATE UP TO AN R-VALUE OF 2.5 (BEYOND WHICH A
279.000 C PROPORTION > 1.0 RESULTS), AND SINCE THESE CURVES GIVE A PROPORTION
280.000 C OF .0243, .0156 FOR BUSINESS AND NON-BUSINESS, RESPECTIVELY, FOR
281.000 C ALL R>2.4, THEREFORE AN AVERAGE VALUE OF R (FOR R= 2.4 --> 2.0 AND
282.000 C ASSUMING A PARABOLIC CURVE TAIL; C.G. AT 1/4) IS TAKEN =2.8.
283.000 C THE CURVES ARE THEREFORE EMPLOYED UP TO R= 2.4 ONLY.
284.000 C (3) CONCERNING B. ABOVE, THE TMR'S ARE CALCULATED FROM THE CURVE OF
285.000 C TMR VS. R AND ARE THEN NORMALIZED SO THAT THEY COULD BE APPLIED
286.000 C AS WEIGHTS TO THE ABOVE PROPORTIONS (FOR BUSINESS TRIPS).
287.000 C THE RESULTING WEIGHTED PROPORTIONS ARE THEN NORMALIZED (SIGMA=1.0)
288.000
289.000 DELR=.4
290.000 R=0.
291.000 VAL1=0.
292.000 DO 15 INCOME=1,7
293.000 R=R+DEL R
294.000 TMR(INCOME)=14.2541*EXP(-3.4899/(R**.9234))
295.000 15 VAL1=VAL1+TMR(INCOME)
296.000 VAL2=0.
297.000 DO 30 IPURP=1,2
298.000 R=0.
299.000 PREV=0.
300.000 DO 30 INCOME=1,6
301.000 R=R+DEL R
302.000 CG=.5
303.000 IF(R.LT.0.5) CG=.33
304.000 IF (R.GT.2.0) CG=.67

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OVER 80

2-DAY/YR

OVER 15

OVER 15

IN 1975

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305.000     AVR(INCOME)=R-DELR*CG
306.000     IF(IPURP.EQ.2) GOTO 20
307.000     CUM=1.452324*EXP(-1.1870/(R**1.2489))
308.000     PROP(INCOME,1)=(CUM-PREV)*IMR(INCOME)/VAL1
309.000     VAL2=VAL2+PROP(INCOME,1)
310.000     GOTO 30
311.000 20 CUM=1.455720*EXP(-1.0709/(R**1.1501))
312.000     PROP(INCOME,2)=CUM-PREV
313.000 30 PREV=CUM
314.000     AVR(7)=2.8
315.000     PROP(7,1)=.0243*IMR(7)/VAL1
316.000     VAL2=VAL2+PROP(7,1)
317.000     PROP(7,2)=.0156
318.000 C NORMALIZE PROP(INCOME,1)
319.000     DO 40 I=1,7
320.000 40 PROP(I,1)=PROP(I,1)/VAL2
321.000
322.000 C -----
323.000 C DATA FOR TOTAL TRAVEL DEMAND (ON A WEEKLY BASIS) :
324.000 C -----
325.000 C STORE IN "SOCIO" TOTAL DEMAND PORTIONS WHICH DEPEND ON SOCIO-ECONOMICS, ONLY :
326.000     DO 70 I=1,NYR
327.000     DO 70 NC=1,NCPAIR
328.000     VAL1=SOCIO(NC,2,1)
329.000     SOCIO(NC,2,1)=.000567*(VAL1**.9570)*(SOCIO(NC,4,1)**.9468)
330.000     *THRUTF(NC)*FACB(NC,1)
331.000     SOCIO(NC,4,1)=.000567*(SOCIO(NC,4,1)**.9570)*(VAL1**.9468)
332.000     *THRUTF(NC)*FACB(NC,2)
333.000     VAL1=SOCIO(NC,1,1)
334.000     VAL2=PLANG(NC)**.7966
335.000     SOCIO(NC,1,1)=.001926*(VAL1**.8066)*(SOCIO(NC,3,1)**.9452)
336.000     *THRUTF(NC)*FACNB(NC,1)*PLANG(NC)
337.000 70 SOCIO(NC,3,1)=.001926*(SOCIO(NC,3,1)**.8066)*(VAL1**.9452)
338.000     *THRUTF(NC)*FACNB(NC,2)*PLANG(NC)
339.000
340.000 C -----
341.000 C CALCULATE COMPETING MODES DATA FOR USE IN DEMAND FUNCTIONS :
342.000 C -----
343.000     DO 65 I=1,NYR
344.000     R=(GINC/GINF)**((I-1)*INTVL)
345.000     DO 65 NC=1,NCPAIR
346.000     EQINC(I,NC,1)=FINC(NC,1)*R/CPI(NC,1)
347.000     EQINC(I,NC,2)=FINC(NC,2)*R/CPI(NC,2)
348.000     NJ=NALT(NC)
349.000     IF(IEEXIST.EQ.1) NJ=NJ+1
350.000     DO 65 IPURP=1,2
351.000     G1(I,NC,IPURP)=0.
352.000     G2(I,NC,IPURP)=0.
353.000     SUMA1(I,NC,IPURP)=COEFF(1,IPURP)*EQINC(I,NC,1)+1.*COEFF(2,IPURP)
354.000     SUMA2(I,NC,IPURP)=COEFF(1,IPURP)*EQINC(I,NC,2)+1.*COEFF(2,IPURP)
355.000     DO 50 J=1,NJ
356.000     J1=1+(J-1)*3
357.000     J2=J1+1
358.000     J3=J1+2
359.000     SAVE1(J)=TRA(NC,J2,IPURP)*EQFARE(I,NC,1)+
360.000     *COEFF(2,IPURP)/TRA(NC,J3,IPURP)
361.000     SAVE2(J)=TRA(NC,J2,IPURP)*EQFARE(I,NC,2)+
362.000     *COEFF(2,IPURP)/TRA(NC,J3,IPURP)
363.000 50 SPLIT(NC,J,IPURP,1)=0.
364.000
365.000 C-- ESTIMATE EXISTING TRAVEL MARKET SHARES (%) AND
366.000 C COMPUTE WEIGHTED (ACCORDING TO MARKET SHARES) GENERALIZED COST OF TRAVEL :
367.000     GC1=0.
368.000     GC2=0.
369.000     DO 60 INCOME=1,7
370.000     TCOEF1=AVR(INCOME)*EQINC(I,NC,1)*COEFF(1,IPURP)
371.000     TCOEF2=AVR(INCOME)*EQINC(I,NC,2)*COEFF(1,IPURP)
372.000     SUM1(I,NC,INCOME,IPURP)=0.
373.000     SUM2(I,NC,INCOME,IPURP)=0.
374.000     TR1=0.
375.000     TR2=0.
376.000     DO 55 J=1,NJ
377.000     J1=1+(J-1)*3
378.000     R1(J)=EXP(-TCOEF1*TRA(NC,J1,IPURP)-SAVE1(J)-BIAS(J,IPURP))
379.000     R2(J)=EXP(-TCOEF2*TRA(NC,J1,IPURP)-SAVE2(J)-BIAS(J,IPURP))
380.000     TRI=TRI+R1(J)

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381.000      TR2=TR2+R2(J)
382.000      IF(J.GT.NALT(NC)) GOTO 55
383.000      SUM1(I,NC,INCOME,IPURP)=SUM1(I,NC,INCOME,IPURP)+R1(J)
384.000      SUM2(I,NC,INCOME,IPURP)=SUM2(I,NC,INCOME,IPURP)+R2(J)
385.000      TR11=IR1
386.000      TR22=TR2
387.000  55 CONTINUE
388.000      DO 56 J=1,NJ
389.000      J1=1+(J-1)*3
390.000      WT1=R1(J)*PROP(INCOME,IPURP)/TR1
391.000      WT2=R2(J)*PROP(INCOME,IPURP)/TR2
392.000      SPLIT(NC,J,IPURP,I)=SPLIT(NC,J,IPURP,I)*(WT1+WT2)/2.
393.000      VAL1=(SAVE1(J)+TCDEF1*TRA(NC,J1,IPURP))*WT1
394.000      VAL2=(SAVE2(J)+TCDEF2*TRA(NC,J1,IPURP))*WT2
395.000      GC1=GC1+VAL1
396.000      GC2=GC2+VAL2
397.000      IF(J.GT.NALT(NC)) GOTO 56
398.000      G1(I,NC,IPURP)=G1(I,NC,IPURP)+VAL1*TR1/TR11
399.000      G2(I,NC,IPURP)=G2(I,NC,IPURP)+VAL2*TR2/TR22
400.000  56 CONTINUE
401.000  60 CONTINUE
402.000      GC1=GC1/SUM1(I,NC,IPURP)
403.000      GC2=GC2/SUM2(I,NC,IPURP)
404.000
405.000 C-- ESTIMATE TOTAL (BY ALL EXISTING MODES) WEEKLY TRAVEL DEMAND :
406.000      IF(IPURP.EQ.2) GOTO 51
407.000      VOL1=SOCIO(NC,2,I)/(GC1**2.3302)
408.000      VOL2=SOCIO(NC,4,I)/(GC2**2.3302)
409.000      GOTO 53
410.000  51 VOL1=SOCIO(NC,1,I)/(GC1**1.5254)
411.000      VOL2=SOCIO(NC,3,I)/(GC2**1.5254)
412.000  53 TOTVOL=VOL1+VOL2
413.000      J=1977+I*INTVL
414.000      PRINT 535, J,NC,IPURP,TOTVOL,(SPLIT(NC,J,IPURP,I),J=1,NJ)
415.000
416.000 C-- COMPUTE AND SAVE MODAL SPLIT (%) FOR ONLY THE MODES COMPETING WITH SYSTEM :
417.000      IF(NJ.EQ.NALT(NC)) GOTO 65
418.000      NJ1=NALT(NC)
419.000      VAL1=0.
420.000      DO 61 J=1,NJ1
421.000  61 VAL1=VAL1+SPLIT(NC,J,IPURP,I)
422.000      DO 62 J=1,NJ
423.000  62 SPLIT(NC,J,IPURP,I)=SPLIT(NC,J,IPURP,I)/VAL1
424.000  65 CONTINUE
425.000
426.000 C =====
427.000 C FOURTH, CARRY OUT THE OPTIMIZATION PROCEDURE :
428.000 C =====
429.000
430.000 C TO MINIMIZE THE NO. OF FUN. EVALUATIONS, CHECK BACK OVER A NUMBER OF POINTS
431.000 C "NPOINT" TO SEE IF FUN HAS ALREADY BEEN EVALUATED AT ANY OF SUCH POINTS :
432.000      NPOINT=4
433.000      DO 74 I=1,N
434.000      XI(I)=X(I)
435.000  74 IF(IFIX(I).EQ.0) NPOINT=NPOINT+8
436.000      IF(MODE.EQ.4) GOTO 77
437.000 C R A I L S Y S T E M :
438.000      IMPROV=1
439.000  73 READ 500,TINV,MAXFRO
440.000      READ 500,((ROUTE(I,J),J=1,6),I=1,NROUTE)
441.000      READ 500,((TKLINK(I,J),J=1,2),I=1,NLINK)
442.000      READ 500,((TIME(I,IPURP),IPURP=1,2),I=1,NCPAIR)
443.000      READ 500,(TTT(I),I=1,NCPAIR)
444.000 C RAIL FREQUENCY OF SERVICE FACTORS FOR BUSINESS TRIPS :
445.000      FOF(1)=.75
446.000      FOF(2)=.82
447.000      FOF(3)=.70
448.000      PRINT 520
449.000      OUTPUT IMPROV,TINV,MAXFRO
450.000      PRINT 518
451.000      DO 75 I=1,NROUTE
452.000  75 PRINT 519,I,(ROUTE(I,J),J=1,6)
453.000      PRINT 530
454.000      DO 76 I=1,NLINK
455.000  76 PRINT 531,I,(TKLINK(I,J),J=1,2)
456.000      PRINT 510,((TIME(I,J),J=1,2),I=1,NCPAIR)

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AV 2-WAY

NR1 NJ-1
MODESI-O
O-M
M-I

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457.000      PRINT 534,(TTT(I),I=1,NCPAIR)
458.000 C      EQUIVALENT 1980 INVESTMENT IN FIXED FACILITIES
459.000      77 TINV=TINV+FIN2
460.000 C      COMPUTE ANNUAL CAPITAL RECOVERY FOR FIXED FACILITIES
461.000      CRT=TINV+CRFT
462.000      PRINT 533
463.000      OUTPUT TINV,CR1
464.000      79 DO 110 I=1,N
465.000      110 X(I)=X1(I)
466.000      PRINT=.TRUE.
467.000      EXPECT=.FALSE.
468.000      OPT=.FALSE.
469.000      NEVAL=0
470.000      IEVAL=0
471.000      736 CALL SEARCH(FUN,N,X,IFIX,STEP,ACC,INT,IFR,PRINT,FMIN,B,NEVAL)
472.000
473.000 C      =====
474.000 C      FIFTH, GENERATE AND OUTPUT DETAILS OF THE OPTIMAL SYSTEM DESIGN
475.000 C      =====
476.000
477.000      739 OPT=.TRUE.
478.000      EXPECT=.TRUE.
479.000      IEVAL=0
480.000      VALI=FUN(B)
481.000      IF(MODE.EQ.4) GOTO 100
482.000      OPT=.FALSE.
483.000      EXPECT=.FALSE.
484.000      120 IMPROV=IMPROV+1
485.000      IF(IMPROV.LT.5) GOTO 73
486.000 C
487.000 C      =====
488.000 C      PRINT FORMATS
489.000 C      =====
490.000      49 FORMAT(15F8.2)
491.000      500 FORMAT(12G.0)
492.000      501 FORMAT(1H1,30X,'LIST OF INPUT DATA')
493.000      502 FORMAT('NUMBER OF OTHER TRAVEL ALTERNATIVES PER CITY-PAIR',6I4)
494.000      503 FORMAT('DISTANCE (MILES) BETWEEN EACH PAIR OF CITIES',6F7.1)
495.000      504 FORMAT('NO. OF ROUTES SERVED BY EACH FREQUENCY VARIABLE',6I3)
496.000      505 FORMAT('TOTAL TIME (HR) SPENT IDLING AT STATIONS ALONG EACH ROUTE',
497.000      'F6.3)
498.000      506 FORMAT('EXTERNAL TRAFFIC FACTORS FOR EACH CITY-PAIR',6F8.5)
499.000      507 FORMAT('NUMBER OF CITY-PAIRS SERVED BY EACH LINK',6I4)
500.000      508 FORMAT('NUMBER OF CITY-PAIRS SERVED BY EACH ROUTE',6I4)
501.000      509 FORMAT('NUMBER OF LINKS CONTAINED IN EACH SERVICE ROUTE',6I4)
502.000      510 FORMAT('/','TOT. TRAVEL TIME (10 HRS) BETWEEN EACH CITY-PAIR',6F6.3)
503.000      511 FORMAT('NON SYSTEM DEPENDANT PORTION OF TOTAL TRAVEL COST BETWEEN
504.000      'CITY-PAIRS ($10) ',6F5.3)
505.000      512 FORMAT('RELATIVE MODAL BIASES FOR BOTH TRIP PURPOSES',6F7.3)
506.000      513 FORMAT('TIME AND FREQUENCY COEFFICIENTS FOR BOTH TRIP PURPOSES',
507.000      '2F7.4,3X,2F7.4)
508.000      514 FORMAT('/','LINK I ( CITY-PAIRS SERVED BY LINK I',/,39('---'))
509.000      515 FORMAT(4X,13,' (',3X,6I3)
510.000      516 FORMAT('/','ROUTE I ( CITY-PAIRS SERVED BY ROUTE I',/,39('---'))
511.000      517 FORMAT('/','ROUTE I ( LINKS CONTAINED IN ROUTE I',/,3('---'))
512.000      518 FORMAT('/','ROUTE I ( LENGTH LENGTH 95 LENGTH 120 101 T1. T1
513.000      '.. 95 120',/,70('---'))
514.000      519 FORMAT(14,5X,'(',9F10.3)
515.000      520 FORMAT(1H1)
516.000      521 FORMAT(10X,'PROJECTED 1980 TRANSPORT SYSTEM CHARACTERISTICS',/,
517.000      'CITY',8X,'CTOL',20X,'BUS',20X,'RAIL',/,
518.000      'PAIR',3(3X,4T',6X,'C',6X,'F',5X))
519.000      522 FORMAT(1X,12,3(2F7.3,F6.1,3X))
520.000      523 FORMAT('/',30X,'SOCIO-ECONOMIC CHARACTERISTICS OF THE CITY-PAIRS',/
521.000      '.,. YEAR',1X,'PAIR',2X,'POP. I',2X,'EMP. I',5X,'POP. J',2X,'EMP. J
522.000      '.,. 5X,'INC. I',2X,'INC. J',5X,'69 INC. I',2X,'69 INC. J',5X,
523.000      'CPI I',2X,'CPI J',/)
524.000      524 FORMAT(1X,14,2X,12,1X,2F8.1,3X,2F8.1,3X,2F8.4,2X,2F11.4,4X,2F7.3)
525.000      525 FORMAT(20X,'BUSINESS TRAVEL')
526.000      526 FORMAT(20X,'NON-BUSINESS TRAVEL')
527.000      527 FORMAT('/','INITIAL VALUES OF DESIGN OPTIMIZATION VARIABLES',6F10.2)
528.000      528 FORMAT('INITIAL STEP SIZE VECTOR .....',6F10.2)
529.000      529 FORMAT('REQUIRED ACCURACY IN FINAL VARIABLE VALUES .....',6F10.2)
530.000      530 FORMAT('/','LINK I ( TRACKAGE 95 MPH TRACKAGE 120 MPH',/,42('---'))
531.000      531 FORMAT(14,3X,'(',2F12.1)
532.000      532 FORMAT('/','FREQ. I ( ROUTES SERVED BY FREQUENCY I',/,42('---'))

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IN 1980S

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533.000 533 FORMAT( )
534.000 534 FORMAT(/, 'WITH TERMINAL-TO-TERMINAL TRANSIT TIMES (HRS) OF', 6F6.3)
535.000 535 FORMAT('YEAR', 15, 3X, 'CITY-PAIR', 12, 3X, 'PURPOSE', 12, 6X, 'ONE-WAY TOI
536.000 .AL DEMAND / WEEK =', 18, 3X, 'CTOL. BUS AND RAIL SHARES ARE', 1, 3F5.3)
537.000 536 FORMAT('DEMAND PREDICTION ADJUSTMENT FACTORS ARE', 12F6.3)
538.000 537 FORMAT('INITIAL VARIABLE VALUES TO BE FIXED ? .....', 6I10)
539.000 538 FORMAT('VARIABLE VALUE IS TO BE INTEGER ? .....', 6I10)
540.000 539 FORMAT(/, 'LANGUAGE PAIRING INDICES ARE', 6F7.3)
541.000 540 FORMAT(/, 'NO OF SEATS UP TO', 5I6, /, 'NO OF SEATS AHEAD', 5I6)
542.000 405 FORMAT('LENGTH IN MILES OF EACH OF THE SYSTEM LINKS', 5F5.1)
543.000 406 FORMAT('RELATIVE TIME (MIN) OF SERVICE START FOR CITY-PAIRS', 6I4)
544.000 407 FORMAT('DURATION OF DEMAND PROFILE TIME PERIODS (MIN.)', 6I5)
545.000 408 FORMAT('FRACTION OF DAILY DEMAND WITHIN PROFILE PERIODS', 6F5.2)
546.000 410 FORMAT('NUMBER OF SYSTEM LINKS CONNECTED TO EACH NODE (CITY)', 6I4)
547.000 411 FORMAT('NON SYSTEM DEPENDANT PORTION OF TOTAL TRAVEL TIME BETWEEN
548.000 .CITY-PAIRS (10 HRS)', 6F5.3)
549.000 415 FORMAT('NO. LINKS ASSIGNED TO EACH OF THE VEHICLE SIZES', 3I3)
550.000 416 FORMAT(/, 'SIZE # ( LINKS ASSIGNED THIS VEHICLE SIZE', 7, 42(' ')
551.000 417 FORMAT(4X, 12, ' [', 2X, 6I3)
552.000 419 FORMAT(/, 'NODE I ( SYSTEM LINKS CONNECTED TO NODE I', 7, 42(' ')
553.000 100 STOP
554.000 END

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555.000 SUBROUTINE SEARCH(F,N,X,IFIX,STEP,ACC,INT,ITR,PRINT,FMIN,B,NEVAL) (1)
556.000 DIMENSION X(6),IFIX(6),STEP(6),ACC(6),INT(6),B(6),BNEW(6),SO(6)
557.000 C====> IF N > 6 MODIFY ABOVE DIMENSION STATEMENT AND PRINTOUT FORMATS
558.000 LOGICAL PRINT
559.000 IF(PRINT) PRINT 990
560.000 ZTEMP=F(X)
561.000 FMIN=ZTEMP
562.000 IF(PRINT) PRINT 992,NEVAL,ZTEMP,(X(I),I=1,N)
563.000 DO 1 I=1,N
564.000 SO(I)=STEP(I)
565.000 1 B(I)=X(I)
566.000 IFLAG=0
567.000 IFLAG=1
568.000
569.000 C*** MAKE EXPLORATORY SEARCH (IFLAG=0 AROUND BASE; IFLAG=1 AROUND TEMP. POINT)
570.000
571.000 10 ZNEW=FMIN
572.000 11 IF(NEVAL.GT.ITR) GOTO 995
573.000 IF(PRINT) PRINT 991
574.000 DO 40 I=1,N
575.000 IF(IFIX(I).EQ.1) GOTO 40
576.000 TEMP=X(I)
577.000 X(I)=X(I)+STEP(I)
578.000 Z=F(X)
579.000 IF(PRINT) PRINT 992,NEVAL,Z,(X(J),J=1,N)
580.000 IF(Z.LT.ZTEMP) GOTO 20
581.000 X(I)=TEMP-STEP(I)
582.000 Z=F(X)
583.000 IF(PRINT) PRINT 992,NEVAL,Z,(X(J),J=1,N)
584.000 IF(Z.LT.ZTEMP) GOTO 20
585.000 X(I)=TEMP
586.000 GOTO 40
587.000 20 IF(Z.GE.ZNEW) GOTO 40
588.000 ZNEW=Z
589.000 DO 30 J=1,N
590.000 30 BNEW(J)=X(J)
591.000 40 CONTINUE
592.000 IF(PRINT) PRINT 991
593.000 C*** CHECK IF EXPLORATORY SEARCH WAS SUCCESSFUL
594.000 IF(ZNEW.GE.FMIN) GOTO 60
595.000
596.000 C*** SUCCESSFUL SEARCH. UPDATE BASE AND TEMPORARY POSITIONS
597.000
598.000 DO 50 I=1,N
599.000 X(I)=2.*BNEW(I)-B(I)
600.000 50 B(I)=BNEW(I)
601.000 FMIN=ZNEW
602.000 IF(PRINT) PRINT 993,FMIN,(B(I),I=1,N)
603.000 ZTEMP=F(X)
604.000 IF(PRINT) PRINT 992,NEVAL,ZTEMP,(X(I),I=1,N)

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605.000      IFLAG=1
606.000      IGL0B=1
607.000      IF(ZTEMP.GE.FMIN) GOTO 10
608.000      ZNEW=ZTEMP
609.000      DO 55 I=1,N
610.000 55    BNEW(I)=X(I)
611.000      GOTO 11
612.000 C
613.000 C*** UNSUCCESSFUL SEARCH :
614.000 C
615.000      60 IF(IGLOB.G1.1) GOTO 95
616.000      IF(IFLAG.EQ.0) GOTO 80
617.000 C
618.000 C*** R E T R E A T: EXPLORE AROUND BASE POINT :
619.000      DO 70 I=1,N
620.000 70    X(I)=B(I)
621.000      ZTEMP=FMIN
622.000      IFLAG=0
623.000      IGL0B=1
624.000      IF(PRINT) PRINT 999
625.000      GOTO 10
626.000 C
627.000 C*** CHECK IF STEP SIZE IS NOT SMALL ENOUGH :
628.000      80 DO 90 I=1,N
629.000      90 IF(STEP(I).GT.ACC(I)) GOTO 150
630.000 C
631.000 C*** CHECK IF THIS MINIMUM IS GLOBAL :
632.000      95 GOTO (100,130,997),IGLOB
633.000      100 DO 110 I=1,N
634.000      110 STEP(I)=S0(I)
635.000      IGL0B=2
636.000      120 IF(PRINT) PRINT 994,(STEP(I),I=1,N)
637.000      GOTO 10
638.000      130 DO 140 I=1,N
639.000      STEP(I)=.5*STEP(I)
640.000      140 IF(INT(I).EQ.1) STEP(I)=AINT(STEP(I)+.5)
641.000      IGL0B=3
642.000      GOTO 120
643.000 C
644.000 C*** DECREASE STEP SIZE IF IT IS NOT SMALL ENOUGH :
645.000      150 DO 160 I=1,N
646.000      STEP(I)=.5*STEP(I)
647.000      IF(INT(I).EQ.1) STEP(I)=AINT(STEP(I)+.5)
648.000      160 IF(STEP(I).LT.ACC(I)) STEP(I)=ACC(I)
649.000      IF(PRINT) PRINT 994,(STEP(I),I=1,N)
650.000      GOTO 10
651.000 C
652.000 C*** PRINTOUTS :
653.000 C
654.000      990 FORMAT(1H,'***** RECORD OF MINIMIZATION STEPS *****',///,
655.000      . 'EVALS',2X,'FUN VALUE', 9X,'EXPLORED POINT',
656.000      .,/, '====',2X,'====', 9X,'=====',/)
657.000      991 FORMAT( )
658.000      992 FORMAT(14,E13.6,2X,6F15.6,/,19X,6F15.6)
659.000      993 FORMAT('==> NEW MINIMUM:',E14.6, ' AT POINT',6F13.6,/,41X,6F13.6)
660.000      994 FORMAT('-----> NEW STEP SIZE:',6F13.6,/,23X,6F13.6)
661.000      995 PRINT 996
662.000      996 FORMAT(//,'MAX # FUNCTION EVALS IS EXCEEDED. SEARCH TERMINATED')
663.000      GOTO 1000
664.000      997 IF(PRINT) PRINT 998,NEVAL,FMIN,(B(I),I=1,N)
665.000      998 FORMAT(//,'NORMAL TERMINATION AFTER',16,' FUNCTION EVALUATIONS,
666.000      . MINIMUM FUNCTION VALUE IS',E17.8,/,
667.000      . 'OPTIMAL PARAMETER VALUES ARE',6F15.8,/,30X,6F15.8)
668.000      999 FORMAT('R E T R E A T: EXPLORE AROUND CURRENT MINIMUM POINT')
669.000 C
670.000 C RESTORE BACK ORIGINAL STEP SIZE :
671.000      1000 DO 1001 I=1,N
672.000      1001 STEP(I)=S0(I)
673.000      RETURN
674.000      END

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675.000 FUNCTION FUN(X)
676.000 LOGICAL OPT, EXPECT, MAXF
677.000 COMMON /M2/ NPOINT, FIN1, FIN2, EXPECT, PRICE1, PRICEC, PFUEL, CRFV, CRFI
678.000 ., DISCNT, UNCERT, STSTOP(3), TKLINK(3,2), PWF(16), CR1, RL, CP, CV, IMPROV
679.000 COMMON /ALL/ N, NNODE, NLINK, NROUTE, NCPAIR, LSP, INIVL, NYR, OPT, DAYS, PF
680.000 ., IEVAL, NEVAL, EOFFARE(6,3,2), CCONST(3,2), NRTFRO(3), CINF(6), VCLIN(6)
681.000 ., NALT(3), IROUT(3,2), MAXFRO, ICR11, DISTOP(3), RVFAC(6), JCR1, PITCH
682.000 ., ITIME(3,2), MINFRO, NLKO(3), LINKO(3,3), O(3), DIST(3), WODE, DCF, FCF(3)
683.000 COMMON /S25/ REQLOC, REOCAR, TRMILE, CMILE1, CMILE2, RPHOUR, RPMILE, MAXF
684.000 ., PLOAD(3), AGI(3), DPX(3), ITRAI(3,2), RDEV(3,3), DEPL(6,3), FSPACE(3)
685.000 ., FLEET(3), VSPACE(3), PMAX(3), VIRIPS(3), VMOURS(3), AVJILL(3), VLOAD(3)
686.000 COMMON /S2345/ IYR, TCOST(3,2,2), IRFRO(3), LFRQ(3), TTL(3)
687.000 ., FARE(3), TOTVOL(3,2), SHARE(4,3,2), VOL(3,3), UCOST, BREAK(3), FACTOR
688.000 DIMENSION X(5), PFUN(44), PPOINT(44,5), ETAB(4,4), ETAB(16,4), ECPLOM(4)
689.000 ., TAB(16,4), APRICE(3), CABIN(3), WE(3), CONST(3), IFRU(3,9)
690.000 ., ADDA(3), AVLA(3), SPAREA(3), WEI(3)
691.000
692.000 C =====
693.000 C CHECK FOR VIOLATION OF BOUND CONSTRAINTS :
694.000 C =====
695.000 DO 5 I=1,N
696.000 5 IF(X(I).LE.0.) GOTO 6
697.000 IF(MODE.EQ.4) GOTO 7
698.000 IF(X(2).GT.MAXFRO.OR.X(2).LT.2) GOTO 6
699.000 GOTO 7
700.000 6 FUN=1.E38
701.000 GOTO 99
702.000 C
703.000 C NO NEED TO EVALUATE FUN IF IT HAS ALREADY BEEN EVALUATED PREVIOUSLY :
704.000 7 IF(IEVAL.EQ.0.OR.NEVAL.LT.N+2) GOTO 30
705.000 IEND=MINO(NPOINT,NEVAL)
706.000 DO 20 I=1,IEND
707.000 DO 10 J=1,N
708.000 10 IF(ABS(X(J)-PPOINT(I,J)).GT..001) GOTO 20
709.000 FUN=PFUN(I)
710.000 RETURN
711.000 20 CONTINUE
712.000
713.000 30 NEVAL=NEVAL+1
714.000 EP=0.
715.000 EPM=0.
716.000 FUN1=0.
717.000 FUN2=0.
718.000 FUN3=0.
719.000 DO 301 I=1,LSP
720.000 DO 301 J=1,4
721.000 301 ETAB(I,J)=0.
722.000
723.000 IF(OPT) PRINT 112, (FQF(J), J=1, NCPAIR)
724.000 IF(MODE.EQ.3) GOTO 302
725.000 ADD1=444400.+0.02024*X(2)**3.
726.000 IEND=N-2
727.000 DO 230 I=1,IEND
728.000 J=I+2
729.000 WE(I)=4.113+.4451*X(J)
730.000 APRICE(I)=ADD1+609.6*PITCH*X(J)+16.06*(X(2)**1.4)*WE(I)
731.000 NCABIN=X(J)/50.+1
732.000 CABIN(I)=20.6*NCABIN
733.000 WEI(I)=WE(I)+.500*NCABIN*.130
734.000 FUELV=.1118411*X(2)**1.28223
735.000 230 CONST(I)=.041*WE(I)-775./(WE(I)+148.)
736.000 IF(OPT) PRINT 112, (APRICE(I), WE(I), I=1, IEND), (TTL(I), I=1, NLINK)
737.000
738.000 C LOOP FOR UNCERTAINTY ANALYSIS (4 PROBABLE DEMAND STATES (NU=4) ARE ASSUMED)
739.000 C (IF NU .NE. 4 RECOMPUTE THE UNCERTAINTY FACTORS AND PROBABILITIES BELOW) :
740.000 302 NU=4
741.000 DO 1000 IU=1,NU
742.000 DO 303 I=1,LSP
743.000 303 TAB(I,1)=CRT
744.000 IF(NU.GT.1) GOTO 727
745.000 PROB=1.0
746.000 FACTOR=1.0
747.000 GOTO 737
748.000 727 GOTO(1,2,1,2),IU
749.000 1 FACTOR=1.-.0022222*UNCERT
750.000 PROB=.375

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751.000      GOTO 4
752.000      2 FACTOR=1.-.0066667*UNCERT
753.000      PROB=.125
754.000      4 IF(IU.GT.2) FACTOR=2.-FACTOR
755.000 737 IF(OPT) OUTPUT FACTOR,PROB
756.000
757.000      AVLLOC=0.
758.000      AVLCAR=0.
759.000      SPAREL=0.
760.000      SPAREC=0.
761.000      TPX=0.
762.000      PXMILE=0.
763.000      PINS=0.
764.000      IEND=N-2
765.000      DO 31 I=1,IEND
766.000      AVLA(I)=0.
767.000 31 SPAREA(I)=0.
768.000      TSMAX=0.
769.000
770.000      IYR=1.
771.000      DO 35 I=1,N
772.000      IF(IEVAL.EQ.0.OR.MODE.EQ.4) GOTO 34
773.000      IF(ABS(X(I)-PPOINT(LAST,I)).LT..001) GOTO 35
774.000 34 CALL UPDATE(I,X)
775.000 35 CONTINUE
776.000
777.000 40 CALL DEMAND
778.000      CALL SUPPLY(X)
779.000      IF(MAXF) GOTO 6
780.000 C SAVE FREQUENCIES OF SERVICE :
781.000      IF(MODE.EQ.3) GOTO 12
782.000      DO 11 I=1,NLINK
783.000 11 IFREQ(I,IYR)=LFRQ(I)
784.000
785.000 C ANNUAL PASSENGER VOLUME, PASSENGER-MILES, AND FARE REVENUE :
786.000 12 PAX=0.
787.000      PML=0.
788.000      REVENU=0.
789.000      DO 43 I=1, NCPAIR
790.000      ADD1=SHARE(MODE,I,1)+SHARE(MODE,I,2)
791.000      PAX=PAX+ADD1
792.000      PML=PML+ADD1*DISTCP(I)
793.000 43 REVENU=REVENU+ADD1*FARE(I)
794.000      PAX=PAX*104.36
795.000      PML=PML*104.36
796.000      REVENU=REVENU*RVFAC(IYR)
797.000      IF(IYR.EQ.1) GOTO 44
798.000      TPX=TPX+PX*INTVL+(PAX-PX)*(INTVL+1.)/2.
799.000      PXMILE=PxMILE+PM*INTVL+(PML-PM)*(INTVL+1.)/2.
800.000      GOTO 45
801.000 44 TPX=PAX
802.000      PXMILE=PML
803.000 45 PX=PAX
804.000      PM=PML
805.000      IF(OPT) OUTPUT IYR,PRINT 112,((TOTVOL(I,J),(SHARE(M,I,J),M=1,MODE)
806.000      ,J=1,2),I=1,NCPAIR),((VOL(I,J),J=1,3),I=1,NLINK),(LFRQ(J),J=1,
807.000      ,NCPAIR),PAX,PML
808.000
809.000      IF(MODE.EQ.4) GOTO 50
810.000 C INCREMENTAL RAIL ROLLING STOCK REQUIREMENT & INVESTMENT :
811.000
812.000      ADDLOC=REQLOC-AVLLOC
813.000      ADDCAR=REOCAR-AVLCAR
814.000      IF(ADDLOC.LT.0.) ADDLOC=0.
815.000      IF(ADDCAR.LT.0.) ADDCAR=0.
816.000      AVLCAR=AVLCAR+ADDCAR
817.000      AVLLOC=AVLLOC+ADDLOC
818.000 C SPARE ROLLING STOCK - ASSUME 20 % SPARE VEHICLES :
819.000      ADD1=AIN(.20*AVLLOC+.999)-SPAREL
820.000      ADD2=AIN(.20*AVLCAR+.999)-SPAREC
821.000      IF(ADD1.LT.0.) ADD1=0.
822.000      IF(ADD2.LT.0.) ADD2=0.
823.000      SPAREL=SPAREL+ADD1
824.000      SPAREC=SPAREC+ADD2
825.000 C CAPITAL INVESTMENT IN VEHICLES :
826.000      VCOST=((ADDLOC+ADD1)*PRICEL+(ADDCAR+ADD2)*PRICEC)*VCINF(IYR)

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IN-EASIS

2-WAY/YR

2-WAY/YR

2-WAY/YR

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827.000 IF(OPT) PRINT 112,REQLOC,ADDLOC,SPAREL,REOCAR,ADOCAR,SPAREC,
828.000 ,((TRAIN(I,J),J=1,2),I=1,NROUTE),(PLOADF(J),J=1,NLINK),(IRFRQ(J),J=
829.000 1,NROUTE),(DPX(J),J=1,NNODE)
830.000
831.000 C RAIL SYSTEM OPERATION AND MAINTENANCE EXPENSES :
832.000 CREW=2.00*TRMILE*DAYSCINF(IYR) 2.00$/M
833.000 FUELID=0.
834.000 DO 314 I=1,NROUTE
835.000 314 FUELID=FUELID+.140*STOP(I)*IRFRQ(I)*2. 1.00$/LB
836.000 FUEL=(.003907*HPPHOUR+FUELID)*PFUEL*DAYSCINF(IYR)
837.000 TKMAIN=(.000165*HPPHOUR*210*TRMILE+.28*CMILE1+.36*CMILE2)*DAYSC
838.000 INF(IYR)
839.000 TRDISP=.16*TRMILE*DAYSCINF(IYR)
840.000 TKMAIN=0.
841.000 DO 315 I=1,NLINK
842.000 IF(IMPROV.LI.4) AGT(I)=AGT(I)*2.
843.000 315 TKMAIN=TKMAIN+2642.*AGT(I)**.585*TKLINK(I,1)+3070.*AGT(I)
844.000 **.585*TKLINK(I,2)+3350.*(TKLINK(I,1)+TKLINK(I,2))
845.000 TKMAIN=TKMAIN*CINF(IYR)
846.000 PXSERV=.640.
847.000 DO 344 I=1,NNODE
848.000 NMEN=.05*DPX(I)+.99
849.000 IF(NMEN.LT.2) NMEN=2
850.000 344 PXSERV=PXSERV+120.*NMEN
851.000 PXSERV=PXSERV*DAYSCINF(IYR)
852.000 MARKET=.05*REVENU
853.000 DOC=CREW+FUEL+TRDISP+TKMAIN+PXSERV+MARKET
854.000 ALIAB=.04*DOC
855.000 OVHEAD=.062*(CREW+FUEL+TRDISP+PXSERV)+.186*TKMAIN+.400*TKMAIN
856.000 SUMC=DOC+ALIAB+OVHEAD
857.000 GA=.07*SUMC
858.000 OPCOST=SUMC+GA
859.000 IF(OPT) PRINT 112,VCOST,CREW,FUEL,TRMAIN,TRDISP,TKMAIN,
860.000 ,PXSERV,MARKET,DOC,ALIAB,OVHEAD,GA,OPCOST,REVENU,UCOST
861.000 GOTO 54
862.000 C
863.000 C INCREMENTAL STOL PLANES REQUIREMENT & INVESTMENT :
864.000 50 VCONST=0.
865.000 IEND=N-2
866.000 DO 828 I=1,IEND
867.000 ADDA(I)=FLEET(I)-AVLA(I)
868.000 IF(ADDA(I).LT.0.) ADDA(I)=0.
869.000 AVLA(I)=AVLA(I)+ADDA(I)
870.000 C SPARE STOL PLANES - ASSUME 20 % SPARE AIRCRAFT :
871.000 ADD1=AINT(.20*AVLA(I)+.999)-SPAREA(I)
872.000 IF(ADD1.LT.0.) ADD1=0.
873.000 SPAREA(I)=SPAREA(I)+ADD1
874.000 C CAPITAL INVESTMENT IN STOL PLANES :
875.000 828 VCONST=VCONST+(ADDA(I)+ADD1)*APRICE(I)*VCINF(IYR)
876.000
877.000 C DETERMINE MAX.(OVER THE STUDY PERIOD) TERMINAL SPACE REQUIREMENT: HENCE COST:
878.000 TSPACE=0.
879.000 DO 92 I=1,NNODE
880.000 92 TSPACE=TSPACE+VSPACE(I)*CV+PSPACE(I)*CP
881.000 IF(TSPACE.GT.TSMAX) TSMAX=TSPACE
882.000 IF(.NOT.OPT) GOTO 251
883.000 PRINT 112,(FLEET(I),ADDA(I),SPAREA(I),AVUTIL(I),VTRIPS(I),VHOURS(I)
884.000 ,I=1,IEND),(VLOAD(I),I=1,NLINK),(VSPACE(I),PMAX(I),(NOJV(I,J),J=1
885.000 ,IEND),I=1,NNODE),TSPACE
886.000 DO 250 J=1,NLINK
887.000 K=LFRQ(J)
888.000 250 PRINT 116,(DEPL(I,J),I=1,K)
889.000
890.000 C STOL SYSTEM OPERATION AND MAINTENANCE EXPENSES :
891.000 251 FUEL=0.
892.000 CREW=0.
893.000 CAB=0.
894.000 AMAINM=0.
895.000 AMAINL=0.
896.000 ACSERV=0.
897.000 K=0
898.000 DO 320 I=1,IEND
899.000 ADD3=0.
900.000 J=I+2
901.000 BFO=1.200
902.000 NL=NLKQ(I)

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903.000      DO 305 L=1,NL
904.000      LINK=LINK0(I,L)
905.000      K=K+LFRQ(LINK)
906.000      IF(L.GT.1) BFO=BFUEL*DIST(LINK)/ADD2
907.000      61 TOGW=WEI(I)+VLOAD(I)*.19*PF+BFO*(1.+200./DIST(LINK)+1./TIL(LINK)) 190L3/PX
908.000      BFUEL=(TOGW**+.636*EUELV*TIL(LINK))/1000. 1000'SLB
909.000      IF(ABS(BFO-BFUEL)/BFUEL.LI..10) GOTO 62
910.000      BFO=BFUEL
911.000      GOTO 61
912.000      62 FUEL=FUEL+BFUEL*LFRQ(LINK) /DAY/ JIR
913.000      ADD2=DIST(LINK)
914.000      ADD3=ADD3+LOGW 1000'SLB
915.000      305 CONTINUE
916.000      IF(FLEET(I).LI.0.999) GOTO 320
917.000      ADD3=ADD3/NL AV. 1000
918.000      CREW=CREW+(3.945*(X(2)*ADD3)**.3+35.93)*VHOURS(I)
919.000      CAB=CAB+CABIN(I)*VHOURS(I)
920.000      AMAINM=AMAINM+APRICE(I)*1.E-6*(8.88*VTRIPS(I)+7.29*VHOURS(I))
921.000      ADD1=.0031*ADD3
922.000      AMAINL=AMAINL+RL*(VTRIPS(I)*(7.2+CONST(I)+ADD1)+VHOURS(I)*(6.14+
923.000      .0.59*CONST(I)+ADD1))
924.000      ACSERV=ACSERV+1.30*ADD3*VTRIPS(I)
925.000      320 CONTINUE
926.000      ADD1=DAYS*CINF(IYR)
927.000      CREW=CREW*ADD1
928.000      FUEL=FUEL*2.*PFUEL*1.02*ADD1 AIA 1, J2
929.000      AMAINM=AMAINM*ADD1
930.000      AMAINL=AMAINL*ADD1
931.000      AMAIN=AMAINM+AMAINL
932.000      AMAINB=1.80*AMAINL AIA
933.000      AINS=.02*VCOST+PINS*FINI INS. =2x
934.000      PINS=AINS
935.000      DOC=CREW+FUEL+AMAIN+AMAINB+AINS
936.000      CAB=CAB*ADD1
937.000      ACSERV=ACSERV*ADD1
938.000      ACCONT=33.23*K*2.*ADD1
939.000      PXSERV=4.0*PAX*CINF(IYR)
940.000      FOOD=.70*PAX*CINF(IYR)
941.000      GPE=.597*AMAINL
942.000      SUMC=DOC+CAB+ACSERV+ACCONT+PXSERV+FOOD+GPE
943.000      GA=.05*SUMC
944.000      TERML=2100000.*CINF(IYR)
945.000      OPCOST=SUMC+GA+TERML
946.000      IF(OPT) PRINT 112,VCOST,CREW,FUEL,AMAINM,AMAINL,AMAIN,AMAINB,AINS,
947.000      .DOC,CAB,ACSERV,ACCONT,PXSERV,FOOD,GPE,GA,TERML,OPCOST,REVENU,JCOSI
948.000
949.000 C COMPUTE ANNUAL CAPITAL RECOVERY OF VEHICLES COST (ASSUME 15% FOR SPARE PARTS)
950.000 54 ANNUAL=VCOST*1.15*CRFV
951.000      IY=(IYR-1)*INTVL+1
952.000      JY=IY-INTVL+1
953.000      DO 46 I=IY,LSP
954.000      46 TAB(I,1)=TAB(I,1)+ANNUAL
955.000      IF(IYR.EQ.1) GOTO 52
956.000      IF(INTVL.EQ.1) GOTO 48
957.000 C CONSIDER ACQUISITION OF THE ADDITIONAL VEHICLES AS BEING SPREAD OVER "INTVL"
958.000      ADD3=ANNUAL/INTVL
959.000      IEND=IY-1
960.000      K=0
961.000      DO 47 I=JY,IEND
962.000      K=K+1
963.000      47 TAB(I,1)=TAB(I,1)+K*ADD3
964.000
965.000 C OPERATING COST, FARE REVENUE AND USERS COST IN EACH YEAR OF THE STUDY PERIOD:
966.000
967.000      48 ADD1=(OPCOST-OPC)/INTVL
968.000      ADD2=(REVENU-REV)/INTVL
969.000      ADD3=(UCOST-UC)/INTVL
970.000      K=0
971.000      DO 51 I=JY,IY
972.000      K=K+1
973.000      TAB(I,2)=OPC+K*ADD1
974.000      TAB(I,3)=REV+K*ADD2
975.000      51 TAB(I,4)=UC+K*ADD3
976.000      GOTO 53
977.000      52 TAB(I,2)=OPCOST
978.000      TAB(I,3)=REVENU

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979.000      TAB(1,4)=UCOST
980.000      53 OPC=OPCOST
981.000      REV=REVENU
982.000      UC=UCOST
983.000
984.000      IF(IYR.EQ.NYR) GOTO 80
985.000      IYR=IYR+1
986.000      C INFLATE TRAVEL COSTS FOR NEXT TIME PERIOD (IYR) :
987.000      DO 70 I=1,NCPAIR
988.000      DO 70 J=1,2
989.000      ICOST(I,J,1)=(FARE(I)+CCONST(1,1))*EQFARE(IYR,I,J)
990.000      70 ICOST(I,J,2)=(FARE(I)+CCONST(1,2))*EQFARE(IYR,I,J)
991.000      GOTO 40
992.000      C
993.000      C RESET INFLATED VARIABLES BACK TO THEIR FIRST YEAR'S VALUES:
994.000      80 DO 90 I=1,NCPAIR
995.000      IF(MODE.EQ.4) LFRQ(I)=IFRQ(I,1)
996.000      DO 90 J=1,2
997.000      ICOST(I,J,1)=(FARE(I)+CCONST(1,1))*EQFARE(I ,I,J)
998.000      90 ICOST(I,J,2)=(FARE(I)+CCONST(1,2))*EQFARE(I ,I,J)
999.000
1000.000      91 IF(MODE.EQ.3) GOTO 94
1001.000      TSMAX=TSMAX*FIN2
1002.000      CRTS=TSMAX*CRFT
1003.000      IF(OPT) OUTPUT TSMAX,CRTS
1004.000      94 ADD1=J.
1005.000      ADD2=0.
1006.000      ADD3=0.
1007.000      DO 97 I=1,LSP
1008.000      IF(MODE.EQ.4) TAB(I,1)=TAB(I,1)*CRTS
1009.000      DO 96 J=1,4
1010.000      PWTAB(J)=TAB(I,J)*PWF(I)
1011.000      96 ETAB(I,J)=ETAB(I,J)+PWTAB(J)*PROB
1012.000      SUMC=PWTAB(1)+PWTAB(2)+PWTAB(3)
1013.000      ADD1=ADD1+SUMC*PROB
1014.000      ADD2=ADD2+(SUMC+PWTAB(4))*PROB
1015.000      ADD3=ADD3+(PWTAB(1)+PWTAB(2))*PROB
1016.000      97 IF(OPT) PRINT 113,I,(TAB(I,K),K=1,4),(PWTAB(K),K=1,4)
1017.000      FUN1=FUN1+ADD1
1018.000      FUN2=FUN2+ADD2/PXMILE
1019.000      FUN3=FUN3+ADD3/PXMILE
1020.000      EP=EP+IPX*PROB
1021.000      EPM=EPM+PXMILE*PROB
1022.000      1000 CONTINUE
1023.000      IF(ICRIT.EQ.1) FUN=FUN1
1024.000      IF(ICRIT.EQ.2) FUN=FUN2
1025.000      IF(ICRIT.EQ.3) FUN=FUN3
1026.000      IF(.NOT.OPT) GOTO 102
1027.000      PRINT 115
1028.000      K=1979
1029.000      DO 101 I=1,LSP
1030.000      K=K+1
1031.000      101 PRINT 113,K,(ETAB(I,J),J=1,4)
1032.000      102 IF(.NOT.EXPECT) GOTO 99
1033.000      DO 98 J=1,4
1034.000      ECFLOW(J)=0.
1035.000      DO 98 I=1,LSP
1036.000      98 ECFLOW(J)=ECFLOW(J)+ETAB(I,J)
1037.000      ETC=ECFLOW(1)+ECFLOW(2)
1038.000      PRINT 114,ETC,(ECFLOW(J),J=1,4),EP,EPM,FUN3,FUN,(X(I),I=1,N)
1039.000
1040.000      C SAVE FOR SUBSEQUENT OPT'N ITERATIONS VALUES OF DESIGN VARIABLES AND OBJ. FUN.:
1041.000      99 LAST=NEVAL-((NEVAL-1)/NPOINT)*NPOINT
1042.000      IF(LAST.LT.1) LAST=1
1043.000      DO 100 J=1,N
1044.000      100 PPOINT(LAST,J)=X(J)
1045.000      PFUN(LAST)=FUN
1046.000      IEVAL=I
1047.000
1048.000      112 FORMAT(12E10.4)
1049.000      113 FORMAT(1X,14,4E13.6,6X,4E13.6)
1050.000      114 FORMAT(8E11.5,E12.5,F5.1,4F5.0)
1051.000      115 FORMAT(/,' PRESENT WORTH OF EXPECTED CASH FLOWS, 1975 DOLLARS',/)
1052.000      116 FORMAT(20F6.1)
1053.000      RETURN
1054.000      END

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IN 1980S

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1055.000 SUBROUTINE UPDATE(NX,X)
1056.000 LOGICAL OPT
1057.000 COMMON /M3/ NCPRT(3),CPROUT(3,3),TCONST(3,2),CFARE
1058.000 COMMON /ALL/ N,NODE,NLINK,NROUTE,NCPAIR,LSP,INIVL,NYR,OPT,DAYS,PF
1059.000 ,IEVAL,NEVAL,EQFARE(6,3,2),CCONST(3,2),NRIFRQ(3),CINF(6),VCINF(6)
1060.000 ,NALT(3),IROUTF(3,2),MAXFRQ,ICR11,DISTCP(3),RVFAC(6),TURN1,P1CH
1061.000 ,TTIME(3,2),MINFRQ,NLKQ(3),LINK(3,3),Q(3),DIST(3),MODE,EQF,FOF(3)
1062.000 COMMON /S2345/ IYR,TCOST(3,2,2),ISFRQ(3),LFRQ(3),ITL(3)
1063.000 ,FARE(3),TOTVOL(3,2),SHARE(4,3,2),VOL(3,3),BCOST,HPEAK(3),FACTOR
1064.000 DIMENSION X(5)
1065.000
1066.000 IF(MODE.EQ.4) GOTO 49
1067.000 GOTO (10,30,30,30),NX
1068.000 C =====
1069.000 C UPDATION DUE TO ALTERING FARE STRUCTURE X(1) :
1070.000 C =====
1071.000 10 DO 20 I=1,NCPAIR
1072.000 FARE(I)=X(1)*DISTCP(I)/1000.+CFARE
1073.000 DO 20 J=1,2
1074.000 TCOST(I,J,1)=(FARE(I)+CCONST(I,1))*EQFARE(1,I,J)
1075.000 20 TCOST(I,J,2)=(FARE(I)+CCONST(I,2))*EQFARE(1,I,J)
1076.000 RETURN
1077.000 C =====
1078.000 C UPDATION DUE TO ALTERING FREQUENCY OF SERVICE X(2)--> X(N) :
1079.000 C =====
1080.000 30 DO 40 I=1,NCPAIR
1081.000 40 LFRQ(I)=0.
1082.000 DO 70 I=2,N
1083.000 C *SERVICE FREQUENCY ALONG EACH ROUTE :
1084.000 II=I-1
1085.000 NR=NRIFRQ(II)
1086.000 DO 70 J=1,NR
1087.000 IR=IROUTF(II,J)
1088.000 IRFRQ(IR)=X(1)+.001
1089.000 C ASSUME 15-HOURS SERVICING DAY AND REGULARLY SPACED TRAIN DEPARTURES :
1090.000 HPEAK(IR)=15./(IRFRQ(IR)-1.)
1091.000 NCP=NCPRT(IR)
1092.000 DO 70 K=1,NCP
1093.000 NC=CPROUT(IR,K)
1094.000 LFRQ(NC)=LFRQ(NC)+IRFRQ(IR)
1095.000 70 CONTINUE
1096.000 RETURN
1097.000 49 GOTO (10,50,52,52,52),NX
1098.000 C =====
1099.000 C UPDATION DUE TO ALTERING VEHICLE SPEED X(2) :
1100.000 C =====
1101.000 50 IF(X(2).LT.385.) SAVE=.4330-.0007181*X(2)
1102.000 IF(X(2).GE.385.) SAVE=.2545-.0002547*X(2)
1103.000 DO 21 I=1,NLINK
1104.000 ITL(I)=DIST(I)*SAVE/60.+2.667
1105.000 FOF(I)=.94-.06*ITL(I)
1106.000 TTIME(I,1)=TCONST(I,1)+ITL(I)/10.
1107.000 21 TTIME(I,2)=TCONST(I,2)+ITL(I)/10.
1108.000 C (ASSUMING STOL LINK= ROUTE = CITY-PAIR)
1109.000 RETURN
1110.000 C =====
1111.000 C UPDATION DUE TO ALTERING VEHICLE SIZE(S) X(3)--> X(N) :
1112.000 C =====
1113.000 52 DO 53 I=3,N
1114.000 IQ=I-2
1115.000 NJ=NLKQ(IQ)
1116.000 DO 53 J=1,NJ
1117.000 LINK=LINKQ(IQ,J)
1118.000 LFRQ(LINK)=MINFRQ
1119.000 53 Q(LINK)=X(1)
1120.000 C (ASSUMING THAT FOR STOL, LINK I=CITY-PAIR I, AND ONLY ONE VEH. SIZE PER LINK)
1121.000 RETURN
1122.000 END

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S 10'S

BUSINESS
NON-BUSIMIN/MILE
MIN/MILE

HOURS

10'S HRS
10'S HRS

INITIAL

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1123.000 SUBROUTINE DEMAND
1124.000 LOGICAL OPT
1125.000 COMMON /M4/ NCPLK(3),CPLINK(3,2),COEFF(2,2),BIAS(4,2),PROP(1,2)
1126.000 ..AVR(7),SOCIO(3,4,6),SUMA1(6,3,2),SUMA2(6,3,2),IRA(3,9,2),FINF(6)
1127.000 ..EQINC(6,3,2),G1(6,3,2),G2(6,3,2),SUM1(6,3,1,2),SUM2(6,3,1,2)
1128.000 ..SPLIT(3,3,2,6),UCFT(3,2,2),FINC(3,2)
1129.000 COMMON /ALL/ N,NNODE,NLINK,NROUTE,NCPAIR,LSP,INTVL,NYR,OPT,DAYS,PF
1130.000 ..IEVAL,NEVAL,EQFARE(6,3,2),CONST(3,2),NRTHRO(3),CINF(6),VCINF(6)
1131.000 ..NALT(3),IRADUIF(3,2),MAXFRQ,ICRIT,DISICP(3),RVFAC(6),TURN1,PICR
1132.000 ..TTIME(3,2),MINFRQ,NLKO(3),LINKO(3,3),Q(3),DISI(3),MODE,DOF,FOF(3)
1133.000 COMMON /S2345/ IYR,TCOST(3,2,2),IRFRO(3),LFRQ(3),ITL(3)
1134.000 ..FARE(3),TOTVOL(3,2),SHARE(4,3,2),VOL(3,3),UCOS1,RIPEAK(3),FACTOR
1135.000 DIMENSION NOTYET(3),UC(3)
1136.000
1137.000 DO 1 NC=1,NCPAIR
1138.000 1 NOTYET(NC)=1
1139.000 C (I.E. ON ENTRY TO THIS SUBROUTINE CONSIDER "ALL" CITY-PAIRS)
1140.000 5 DO 25 NC=1,NCPAIR
1141.000 IF(NOTYET(NC).EQ.0) GOTO 25
1142.000 UC(NC)=0.
1143.000 NJ=NALT(NC)
1144.000 DO 20 IPURP=1,2
1145.000 E2=1.0
1146.000 IF(IPURP.EQ.1) E2=FOF(NC)
1147.000 E1=COEFF(2,IPURP)/(LFRQ(NC)*E2)
1148.000 RR1=TCOST(NC,1,IPURP)+E1
1149.000 RR2=TCOST(NC,2,IPURP)+E1
1150.000 C ESTIMATE SYSTEM'S TRAVEL MARKET SHARE (%) AND
1151.000 C COMPUTE WEIGHTED (ACCORDING TO MARKET SHARES) GENERALIZED COST OF TRAVEL :
1152.000 PENET1=0.
1153.000 PENET2=0.
1154.000 GC1=0.
1155.000 GC2=0.
1156.000 DO 9 I=1,7
1157.000 E1=AVR(I)*EQINC(IYR,NC,1)
1158.000 E2=AVR(I)*EQINC(IYR,NC,2)
1159.000 R1=RR1+COEFF(1,IPURP)*E1*TTIME(NC,IPURP)+BIAS(MODE,IPURP)
1160.000 R2=RR2+COEFF(1,IPURP)*E2*TTIME(NC,IPURP)+BIAS(MODE,IPURP)
1161.000 E1=EXP(-R1)
1162.000 E2=EXP(-R2)
1163.000 TOTET1=SUM1(IYR,NC,1,IPURP)+E1
1164.000 TOTET2=SUM2(IYR,NC,1,IPURP)+E2
1165.000 WT1=E1*PROP(1,IPURP)/TOTET1
1166.000 WT2=E2*PROP(1,IPURP)/TOTET2
1167.000 PENET1=PENET1+WT1
1168.000 PENET2=PENET2+WT2
1169.000 GC1=GC1+(R1-BIAS(MODE,IPURP))*WT1
1170.000 GC2=GC2+(R2-BIAS(MODE,IPURP))*WT2
1171.000 9 CONTINUE
1172.000 PENET1=PENET1*FACTOR
1173.000 PENET2=PENET2*FACTOR
1174.000 GC1=GC1*FACTOR
1175.000 GC2=GC2*FACTOR
1176.000 GC1=(GC1+G1(IYR,NC,IPURP)*(1.-PENET1))/SUMA1(IYR,NC,IPURP)
1177.000 GC2=(GC2+G2(IYR,NC,IPURP)*(1.-PENET2))/SUMA2(IYR,NC,IPURP)
1178.000
1179.000 C =====
1180.000 C FIRST, ESTIMATE TOTAL (BY ALL MODES) WEEKLY TRAVEL DEMAND :
1181.000 C =====
1182.000 IF(IPURP.EQ.2) GOTO 10
1183.000 VOL1=SOCIO(NC,2,IYR)/(GC1**2.3302)
1184.000 VOL2=SOCIO(NC,4,IYR)/(GC2**2.3302)
1185.000 GOTO 15
1186.000 10 VOL1=SOCIO(NC,1,IYR)/(GC1**1.5254)
1187.000 VOL2=SOCIO(NC,3,IYR)/(GC2**1.5254)
1188.000 15 TOTVOL(NC,IPURP)=VOL1+VOL2
1189.000
1190.000 C =====
1191.000 C SECOND, ESTIMATE MARKET SHARES OF THE MODAL MIX, AND COMPUTE USERS COST :
1192.000 C =====
1193.000 SAVE1=VOL1*PENET1
1194.000 SAVE2=VOL2*PENET2
1195.000 SHARE(MODE,NC,IPURP)=SAVE1+SAVE2
1196.000 IF(.NOT.OPT) GOTO 13
1197.000 REST=VOL1+VOL2-SHARE(MODE,NC,IPURP)
1198.000 REST=REST/(VOL1+VOL2)

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UNCERT.)
IN)
DEMAND)

*RETURN
VOLUME
(%)

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1199.000      DO 12 J=1,NJ
1200.000      12 SHARE(J,NC,IPURP)=REST*SPLIT(NC,J,IPURP,IYR)
1201.000
1202.000 C    COMPUTE THIS CITY-PAIR'S SYSTEM USERS* COST :
1203.000      13 DO 14 I=1,7
1204.000      14 UC(NC)=UC(NC)+(SAVE1*((CONST(NC,IPURP)+FARE(NC))*RVFAC(IYR)+
1205.000          .TIME(NC,IPURP)*JCFT(NC,1,IPURP)*FINT(IYR)*AVR(1))+
1206.000          SAVE2*((CONST(NC,IPURP)+FARE(NC))*RVFAC(IYR)+
1207.000          .TIME(NC,IPURP)*JCFT(NC,2,IPURP)*FINT(IYR)*AVR(1))*PROP(1,IPURP)
1208.000      20 CONTINUE
1209.000      25 CONTINUE
1210.000
1211.000 C    =====
1212.000 C    THIRD, COMPUTE DAILY TRAFFIC VOLUMES ON THE DESIGNED SYSTEM LINKS :
1213.000 C    =====
1214.000      DO 40 I=1,NLINK
1215.000      VOL(I,1)=0.
1216.000      VOL(I,2)=0.
1217.000      NCP=NCPLK(I)
1218.000      DO 30 J=1,NCP
1219.000      NC=CPLINK(I,J)
1220.000      VOL(I,1)=VOL(I,1)+SHARE(MODE,NC,1)*DDF
1221.000      30 VOL(I,2)=VOL(I,2)+SHARE(MODE,NC,2)*DDF
1222.000      40 VOL(I,3)=VOL(I,1)+VOL(I,2)
1223.000
1224.000      IF(MODE.EQ.3) GOTO 70
1225.000
1226.000 C    =====
1227.000 C    FOURTH, ENSURE EQUILIBRIUM BETWEEN DEMAND AND SUPPLY (CARRYING CAPACITY) :
1228.000 C    =====
1229.000      DO 50 I=1,NLINK
1230.000      NOTYET(I)=0
1231.000      J=VOL(I,3)/O(I)+.999
1232.000      IF(J.GT.LFRQ(I)) GOTO 45
1233.000      IF(LFRQ(I)-J.LE.1.OR.LFRQ(I).EQ.MINFRQ) GOTO 50
1234.000 C    (I.E. FREQUENCY IS WITHIN 1 DEPARTURE FROM THAT REQUIRED AT 100% L.F.)
1235.000      45 NOTYET(I)=1
1236.000      LFRQ(I)=MAXO(J,MINFRQ)
1237.000      50 CONTINUE
1238.000 C    (ASSUMING THAT STOL LINK #I = CITY-PAIR #I)
1239.000      DO 60 I=1,NCPAIR
1240.000      60 IF(NOTYET(I).EQ.1) GOTO 5
1241.000
1242.000 C    =====
1243.000 C    FIFTH, COMPUTE THE OVERALL NETWORK USERS COST :
1244.000 C    =====
1245.000      70 UCOST=0.
1246.000      DO 80 NC=1,NCPAIR
1247.000      80 UCOST=UCOST+UC(NC)
1248.000      RETURN
1249.000      END

1250.000      SUBROUTINE SUPPLY(X)
1251.000      LOGICAL MAXF,OPT
1252.000      COMMON /MS/ CAPCAR,DATLOC,ENTCAR,MAXCAR,DV,NLNOD(3),LANOD(3,2)
1253.000      ,NLKRT(3),RTLINK(3,2),ROUTE(3,6),ITT(3),TIME,NSEAT(5,2),FAC(4)
1254.000      ,PERIOD(4),TZERO(3),SPT,SPW,WHISH,QSTART,QEND,QOUT,QTIME
1255.000      COMMON /ALL/ N,NNODE,NLINK,NROUTE,NCPAIR,LSP,INTVL,NYR,OPT,DAYS,PF
1256.000      ,IEVAL,NEVAL,EQFARE(6,3,2),CONST(3,2),NRTHRO(3),CINF(6),VCINF(6)
1257.000      ,NALT(3),IROUTF(3,2),MAXFRQ,ICRIT,DISTCP(3),RVFAC(6),TURN,PITCH
1258.000      ,TIME(3,2),MINFRQ,NLKO(3),LINKO(3,3),O(3),DIST(3),MODE,DDF,POF(3)
1259.000      COMMON /S25/ RELOC,REOCAR,TRMILE,CMILE1,CMILE2,HPHOUR,HPMILE,MAXF
1260.000      ,PLOADF(3),AGT(3),DPX(3),TRAFF(3,2),NGDV(3,3),DEPL(60,3),PSPACE(3)
1261.000      ,FLEET(3),VSPACE(3),PMAK(3),VTRIPS(3),VHOURS(3),AVUTIL(3),VLOAD(3)
1262.000      COMMON /S2345/ IYR,ICOST(3,2,2),IRFRQ(3),LFRQ(3),FTL(3)
1263.000      ,FARE(3),TOTVOL(3,2),SHARE(4,3,2),VOL(3,3),UCOST,HPEAK(3),FACTOR
1264.000      ,DIMENSION SCAN(3),K1(3),K2(3),LKSET(2),DEP(120),ARR(120),X(5)
1265.000      ,SPACE(3)
1266.000
1267.000      MAXF=.FALSE.
1268.000      IF(MODE.EQ.4) GOTO 1000
1269.000
1270.000

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1271.000 C RAIL SYSTEM SUPPLY MODEL :
1272.000 REOCAR=0.
1273.000 REQLOC=0.
1274.000 TRMILE=0.
1275.000 CMILE1=0.
1276.000 CMILE2=0.
1277.000 HPHOUR=0.
1278.000 HPMILE=0.
1279.000 DO 1 J=1,NLINK
1280.000 1 AGT(J)=0.
1281.000
1282.000 C =====
1283.000 C (1) NUMBER OF TRAIN SETS REQUIRED :
1284.000 C =====
1285.000 DO 36 IR=1,NROUTE
1286.000 NTRAIN=(TT1(3)+TURN1)/HPEAK(IR)+.999
1287.000 NTRAIN=NTRAIN*2.
1288.000
1289.000 C =====
1290.000 C (2) MINIMUM NUMBER OF CARS PER TRAIN :
1291.000 C =====
1292.000 NLK=NLKRT(IR)
1293.000 C FOR THAT PURPOSE FIND THE HEAVIEST LINK LOAD ALONG THIS ROUTE :
1294.000 HIVOL=0.
1295.000 DO 10 J=1,NLK
1296.000 LK=RTLINK(IR,J)
1297.000 10 IF(VOL(LK,3).GT.HIVOL) HIVOL=VOL(LK,3)
1298.000 NCAR=HIVOL/(IRFREQ(IR)*CAPCAR)+.999
1299.000 IF(NCAR.GT.MAXCAR) MAX=.FALSE.: RETURN
1300.000 IF(NCAR.LT.1) NCAR=1
1301.000 CAP=NCAR*CAPCAR
1302.000 TRAIN(IR,2)=NCAR
1303.000 REOCAR=REOCAR+NCAR*NTRAIN.
1304.000
1305.000 C =====
1306.000 C (3) TRAIN LOADING FACTORS OVER EACH LINK :
1307.000 C =====
1308.000 HILF=0.
1309.000 TEST=CAP*IRFREQ(IR)
1310.000 DO 26 J=1,NLK
1311.000 LK=RTLINK(IR,J)
1312.000 PLOADF(LK)=VOL(LK,3)/TEST
1313.000 IF(PLOADF(LK).GT.HILF) HILF=PLOADF(LK)
1314.000 26 CONTINUE
1315.000
1316.000 C =====
1317.000 C (4) MINIMUM NUMBER OF LOCOMOTIVES REQUIRED :
1318.000 C =====
1319.000 C ASSUME TWO LOCOMOTIVES (TO ELIMINATE SWITCHING TOO), CHECK IF MORE ARE NEEDED
1320.000 NL=2
1321.000 C CALCULATE HP REQUIREMENT (ASSUME HIGHEST LOADING OF LOCOMOTIVES AND CARS) :
1322.000 WC=EWTCAR+HILF*CAPCAR*.095+.16/NCAR
1323.000 27 NL=DWTLLOC+(.9*NCAR+.24)/NL+1.24
1324.000 CALL RESIST(NL,NCAR,NL,WC,DV,HP)
1325.000 NL1=HP/2000.+.999
1326.000 IF(NL1.LE.NL) GO TO 28
1327.000 NL=NL1
1328.000 GO TO 27
1329.000 28 TRAIN(IR,1)=NL
1330.000 REQLOC=REQLOC+NL*NTRAIN
1331.000
1332.000 C =====
1333.000 C (5) DAILY TRAIN-MILES AND CAR-MILES :
1334.000 C =====
1335.000 TRMILE=TRMILE+ROUTE(IR,1)*IRFREQ(IR)
1336.000 CMILE1=CMILE1+NCAR*ROUTE(IR,2)*IRFREQ(IR)
1337.000 CMILE2=CMILE2+NCAR*ROUTE(IR,3)*IRFREQ(IR)
1338.000
1339.000 C =====
1340.000 C (6) AVERAGE DAILY HP-HOURS AND HP-MILES :
1341.000 C =====
1342.000 NL=DWTLLOC+(.675*NCAR+.24)/NL+1.24
1343.000 C ASSUME HERE AN AVERAGE CAR LOADING FACTOR OF ABOUT 65 % (OVER THE YEAR)
1344.000 WC=EWTCAR+.65*CAPCAR*.095+.16/NCAR
1345.000 V=95.
1346.000 CALL RESIST(NL,NCAR,NL,WC,V,HP)

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2 DIRECT

.0951/2

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2 ATTEM


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1347.000   ETA=.87
1348.000   AUXHP=100.*NL+107.2*NCAR
1349.000   HP95=HP/ETA+AUXHP
1350.000   V=120.
1351.000   CALL RESIST(NL,NCAR,NL,WC,V,HP)
1352.000   HPI20=HP/ETA+AUXHP
1353.000   HPHOUR=HPHOUR+((HP95/NL)**.886*ROUTE(IR,5)+
1354.000   .(HPI20/NL)**.886*ROUTE(IR,6))*NL*IRFRO(IR)
1355.000 C   FRONT AND REAR LOCOMOTIVES ARE ASSUMED TO SHARE EQUALLY THE HP REQUIRED
1356.000   HPMILE=HPMILE+(HP95*ROUTE(IR,2)+HPI20*ROUTE(IR,3))*IRFRO(IR)
1357.000
1358.000 C   =====
1359.000 C   (7) AVERAGE ONE-WAY ANNUAL GROSS TONS CARRIED OVER EACH LINK :
1360.000 C   =====
1361.000   WT=NL*NL+NCAR*ENICAR+.10
1362.000   DO 29 J=1,NLK
1363.000   LK=RTLINK(IR,J)
1364.000   29 AGT(LK)=AGT(LK)+(WT+PLOADF(LK)*CAP*PF*.095)*IRFRO(IR)*DAYS*1.E-6
1365.000   36 CONTINUE
1366.000
1367.000 C   =====
1368.000 C   (8) MAXIMUM NUMBER OF PASSENGERS DEPARTING AT EACH TERMINAL :
1369.000 C   =====
1370.000   DPX(1)=PLOADF(1)*CAP
1371.000   DRX(3)=PLOADF(2)*CAP
1372.000   DPX(2)=DPX(1)*(SHARE(MODE,1,1)+SHARE(MODE,1,2))*DDF/VOL(1,3)+
1373.000   . DPX(3)*(SHARE(MODE,2,1)+SHARE(MODE,2,2))*DDF/VOL(2,3)
1374.000
1375.000   TRMILE=TRMILE*2.
1376.000   CMILE1=CMILE1*2.
1377.000   CMILE2=CMILE2*2.
1378.000   HPHOUR=HPHOUR*2.
1379.000   HPMILE=HPMILE*2.
1380.000   RETURN
1381.000 C
1382.000 C
1383.000 C   S T O L   S Y S T E M   S U P P L Y   M O D E L :
1384.000 C
1385.000 C   =====
1386.000 C   (1) GENERATE DEPARTURE TIMES FOR EACH LINK :
1387.000 C   =====
1388.000   1000 DO 3100 LINK=1,NLINK
1389.000   VLOAD(LINK)=VOL(LINK,3)/LFRQ(LINK)
1390.000   EXPAX=0.
1391.000   EXTIME=0.
1392.000   I=0
1393.000   TLAST=TZERO(LINK)
1394.000   DO 3000 IT=1,NTIME
1395.000   PAX=FAC(IT)*VOL(LINK,3)
1396.000   IF(EXPAX+PAX.GE.VLOAD(LINK)) GOTO 20
1397.000   EXPAX=EXPAX+PAX
1398.000   EXTIME=EXTIME+PERIOD(IT)
1399.000   IF(IT.LT.NTIME) GOTO 3000
1400.000   I=I+1
1401.000   IF(I.GT.MAXFRQ) MAXF=.TRUE.; RETURN
1402.000   DEPL(I,LINK)=TLAST+EXTIME
1403.000   GOTO 3100
1404.000   20 RATE=PAX/PERIOD(IT)
1405.000   REST=VLOAD(LINK)-EXPAX
1406.000   DELT=REST/RATE
1407.000   I=I+1
1408.000   IF(I.GT.MAXFRQ) MAXF=.TRUE.; RETURN
1409.000   DEPL(I,LINK)=TLAST+EXTIME+DELT
1410.000   TLAST=DEPL(I,LINK)
1411.000   NVLOAD=RATE*(PERIOD(IT)-DELT)/VLOAD(LINK)+.001
1412.000   HDNY=VLOAD(LINK)/RATE
1413.000   IF(NVLOAD.EQ.0) GOTO 30
1414.000   DO 2000 J=1,NVLOAD
1415.000   I=I+1
1416.000   IF(I.GT.MAXFRQ) MAXF=.TRUE.; RETURN
1417.000   2000 DEPL(I,LINK)=TLAST+J*HDNY
1418.000   TLAST=DEPL(I,LINK)
1419.000   30 EXPAX=PAX-NVLOAD*VLOAD(LINK)-REST
1420.000   EXTIME=PERIOD(IT)-NVLOAD*HDNY-DELT
1421.000   3000 CONTINUE
1422.000   3100 CONTINUE
1423.000

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LRCFOR FUEL
CONSUMP.2 A. LND
USE
ACTUAL
L.F. AND
190L3/PXTORONTO
MONTREAL
ATLANTA
FRA. "E" 12 DIRECT
2 DIRECT
2 DIRECT
2 DIRECT
2 DIRECT

MAX FRQ.

MAX FRQ.

MAX FRQ.

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1424.000 C -----
1425.000 C (2) CALCULATE I. MINIMUM FLEET SIZE NEEDED (FOR EACH VEHICLE SIZE)
1426.000 C II. MAXIMUM PASSENGER ACCUMULATION IN EACH TERMINAL
1427.000 C III. TERMINAL SPACE REQUIREMENTS FOR VEHICLES AND PASSENGERS
1428.000 C -----
1429.000 L=N-2
1430.000 DO 3500 I=1,L
1431.000 FLEET(I)=0.
1432.000 VIRIPS(I)=0.
1433.000 VHOURL(I)=0.
1434.000 AVAIL(I)=0.
1435.000 DO 3200 NODE=1,NNODE
1436.000 3200 NODV(NODE,4)=0
1437.000 AK2=I+2
1438.000 DO 3300 J=1,5
1439.000 KK1=NSEAT(J,2)
1440.000 3300 IF(X(KK2).LT.NSEAT(J,1)) GOTO 3500
1441.000 3500 SPACE(I)=120.*(50.6+.1265*X(KK2)*PITCH/KK1)
1442.000 DO 15000 NODE=1,NNODE
1443.000 VSPACE(NODE)=0.
1444.000 C -- FOR EACH NODE, SORT OUT ITS LINKS ACCORDING TO VEH. SIZE ASSIGNED TO EACH
1445.000 NL=LNKNO(NODE)
1446.000 DO 4000 J=1,NL
1447.000 LINK=LKNOD(NODE,J)
1448.000 4000 SCAN(LINK)=0.
1449.000 DO 11000 JL=1,NL
1450.000 LINK=LKNOD(NODE,JL)
1451.000 IF(SCAN(LINK).EQ.1.) GOTO 11000
1452.000 L=1
1453.000 LKSET(L)=LINK
1454.000 IF(JL.EQ.NL) GOTO 40
1455.000 NJ=JL+1
1456.000 DO 5000 J=NJ,NL
1457.000 LK=LKNOD(NODE,J)
1458.000 IF(ABS(Q(LK)-Q(LINK)).GT.1.) GOTO 5000
1459.000 L=L+1
1460.000 LKSET(L)=LK
1461.000 SCAN(LK)=1.
1462.000 5000 CONTINUE
1463.000 C -- MERGE, IN ORDER OF TIME OF DAY, DEP.& ARR. TIMES OF THESE SAME-VLH.-LINKS
1464.000 40 IF(L.EQ.1) GOTO 60
1465.000 NND=0
1466.000 DO 6000 J=1,L
1467.000 LK=LKSET(J)
1468.000 NND=NND+LFRQ(LK)
1469.000 K1(LK)=1
1470.000 6000 K2(LK)=1
1471.000 DO 8000 I=1,NND
1472.000 BIG1=9999999.
1473.000 BIG2=9999999.
1474.000 DO 7000 J=1,L
1475.000 LK=LKSET(J)
1476.000 C D E P A R T U R E S :
1477.000 KK1=K1(LK)
1478.000 IF(KK1.GT.LFRQ(LK).OR.DEPL(KK1,LK).GT.BIG1) GOTO 50
1479.000 BIG1=DEPL(KK1,LK)
1480.000 LSAVE1=LK
1481.000 C A R R I V A L S :
1482.000 50 KK2=K2(LK)
1483.000 IF(KK2.GT.LFRQ(LK)) GOTO 7000
1484.000 TEST=DEPL(KK2,LK)+60.*ITL(LK)+TURN
1485.000 IF(TEST.GT.BIG2) GOTO 7000
1486.000 BIG2=TEST
1487.000 LSAVE2=LK
1488.000 7000 CONTINUE
1489.000 DEP(I)=BIG1
1490.000 ARR(I)=BIG2
1491.000 K1(LSAVE1)=K1(LSAVE1)+1
1492.000 K2(LSAVE2)=K2(LSAVE2)+1
1493.000 8000 CONTINUE
1494.000 GOTO 70
1495.000 C -- CASE OF EACH LINK BEING ASSIGNED A DIFFERENT SIZE OF VEHICLE
1496.000 60 NND=LFRQ(LINK)
1497.000 DO 9000 I=1,NND
1498.000 DEP(I)=DEPL(I,LINK)
1499.000 9000 ARR(I)=DEP(I)+60.*ITL(LINK)+TURN
1500.000

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1501.000 C DETERMINE MINIMUM FLEET SIZE(S) NEEDED :
1502.000 70 FLEETI=0.
1503.000 J=1
1504.000 DO 10000 I=1,NND
1505.000 80 IF(ARR(J).GT.DEP(I)) GOTO 90
1506.000 IF(J.EQ.NND) GOTO 100
1507.000 J=J+1
1508.000 IF(J.LE.1) GOTO 80
1509.000 GOTO 10000
1510.000 90 DIFF=I-(J-1.)
1511.000 IF(DIFF.GT.FLEETI) FLEETI=DIFF
1512.000 10000 CONTINUE
1513.000
1514.000 C -- VEHICLE FLEET REQUIREMENT & UTILIZATION :
1515.000 100 I=2
1516.000 101 I=I+1
1517.000 IF(I.GT.N) OUTPUT '---> E R R O R : LINE 273 IN SUPPLY: I>N'>REID
1518.000 IF(ABS(Q(LINK)-X(I)).GT.1) GOTO 101
1519.000 NJ=I-2
1520.000 NODV(NODE,NJ)=FLEETI
1521.000 FLEET(NJ)=FLEET(NJ)+FLEETI
1522.000 DO 1050 J=1,L
1523.000 LK=LKSET(J)
1524.000 VTRIPS(NJ)=VTRIPS(NJ)+LFRQ(LK)
1525.000 1050 VHOURLS(NJ)=VHOURLS(NJ)+LFRQ(LK)*TIL(LK)
1526.000 AVUTIL(NJ)=VHOURLS(NJ)/FLEET(NJ)
1527.000
1528.000 C -- TERMINAL SPACE REQUIREMENT FOR VEHICLE STORAGE (ASSUME 20% SPARE VEHICLES):
1529.000 VSPACE(NODE)=VSPACE(NODE)+FLEETI*SPACE(NJ)*1.20
1530.000 11000 CONTINUE
1531.000
1532.000 C FOR THIS NODE, CALCULATE THE MAX. POSSIBLE PAX. ACCUMULATION IN ITS TERMINAL
1533.000 C AND HENCE, REQUIRED TERMINAL SPACE:
1534.000 PMAX(NODE)=0.
1535.000 DO 14000 JL=1,NL
1536.000 DO 12000 I=1,NL
1537.000 LK=LKNOD(NODE,I)
1538.000 12000 KI(LK)=1
1539.000 LINK=LKNOD(NODE,JL)
1540.000 NND=LFRQ(LINK)
1541.000 DO 14000 I=1,NND
1542.000 TEST=VLOAD(LINK)
1543.000 DO 13000 J=1,NL
1544.000 LK=LKNOD(NODE,J)
1545.000 IF(LK.EQ.LINK) KI(LK)=I+1
1546.000 110 IF(KI(LK).GT.LFRQ(LK)) GOTO 13000
1547.000 KKI=KI(LK)
1548.000 DIFF=DEPL(KKI,LK)+QOUT-DEPL(I,LINK)
1549.000 IF(DIFF.LT.0.) GOTO 120
1550.000 IF(DIFF.GE.QTIME) GOTO 13000
1551.000 IF(DIFF.LE.QOUT) TEST=TEST+VLOAD(LK)*DIFF/QOUT
1552.000 IF(DIFF.GT.QOUT) TEST=TEST+VLOAD(LK)*(QTIME-DIFF)/(QSIARI-QEND)
1553.000 120 KI(LK)=KI(LK)+1
1554.000 GOTO 110
1555.000 13000 CONTINUE
1556.000 IF(PMAX(NODE).LT.TEST) PMAX(NODE)=TEST
1557.000 14000 CONTINUE
1558.000 PSPACE(NODE)=PMAX(NODE)*(SPT+SPW*NNISH)
1559.000 15000 CONTINUE
1560.000 RETURN
1561.000 END

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1562.000 SUBROUTINE RESIST(NL,NCAR,WL,WC,V,HP)
1563.000 NV=NL+NCAR
1564.000 DA=.283*(.63+.13*(NV-2))*V*V
1565.000 DRL=70.+WL*(.8+.0450*V)
1566.000 DRC=70.+WC*(.8+.0375*V)
1567.000 D=DA+DRL*NL+DRC*NCAR
1568.000 HP=D*V/375.
1569.000 RETURN
1570.000 END
1571.000

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1572.000 ***** PROGRAM LISTING COMPLETE *****

(6)

LRC

END

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FIN