Deriving the Traffic Consequences of Airport Location Alternatives

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The primary objectives of the research reported in this paper were to structure the airport location process and to develop a methodology for deriving the traffic consequences of various airport location alternatives. A number of interconnected analyses were identified in the location procedure, including demand forecasting, constraint recognition, cost estimates, and airport location evaluation. A demand model based on systems engineering concepts was presented. Linear graph analysis was used to describe mathematically the travel volumes on each link of the intercity travel network. It was shown that by using the complementary travel pressure variable, the traffic consequences of various airport locations on the short-haul travel market could be derived. Finally, the results of the model were used to determine the user travel benefits associated with each of three Toronto airport location alternatives.

•RECENT STUDIES of airport development (1, 2, 3) have considered variables such as land costs, ground transportation costs, meteorological factors, and aircraft noise contours for optimum airport location. None of these studies, however, has related the demand for air travel to the airport location.

The location of the airport defines the ground transportation portion of the air trip in terms of travel costs and travel times. Considering both ends of a trip, ground travel can be in excess of 60 percent of the total air trip time for lengths of less than 300 miles (4). Furthermore, within the 100- to 400-mile trip lengths, air travel is in direct competition with other intercity modes. Any increase or decrease in the ground portion of the air trip can alter the existing intercity modal distribution as well as the total number of air travelers. In the short-haul distances, it is unrealistic to assume that the location of an airport has no effect on the demand for air travel.

It is the objective of this paper to present a method by which the traffic consequences of airport locations can be derived. The technique is based on systems theory, which requires that each of the individual components of a system be defined mathematically and that these components be interconnected to form a complete interdependent and analytical model of, in this example, an intercity travel network. The technique is applied to several Toronto International Airport locations, and the consequences on Toronto-Montreal and Toronto-Ottawa traffic are derived.

LOCATION ANALYSIS PROCEDURE

The basic objective that must be fulfilled by an airport system may be stated as minimizing the sum of the capital and operating cost of the airport terminal system and the ground transportation costs of passengers, consistent with satisfactory ground access times and the constraints imposed by navigational and safety requirements and those by human habitation (5).

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Figure 1 shows the location process structured into a logical framework of interconnected analyses. The first phase requires a statement of future air travel demands, and this is a statement of need for new or expanded facilities. Methodologies of air traffic forecasting have been presented by a number of authors (6, 7, 8, 9, 10).

The next phase of the framework requires that the various costs be assessed for each location alternative. At this level of comparison, the major objective is to choose between different airport sites. General cost figures are required so that a decision can be made between broad classes of airport location solutions. Costs germane to the framework include

1. Overall construction costs, including support facilities such as new connecting roadways;
2. Operating costs, including salaries, overhead, and maintenance for the planned life of the project; and
3. Operating revenues for the project life.

These costs should be considered using an appropriate interest rate. Wohl (11) has suggested that the interest rate is incorporated easily by calculating the net present value. This reduces all future monies to present-day terms. The net present value is obtained from

$$NPV(C) = \sum_{0}^{t} \frac{C_k}{(1 + i)^k} - \sum_{0}^{t} \frac{R_k}{(1 + i)^k} \quad (1)$$

where

t = number of years of the project;
NPV(C) = net present value of costs;
C = total costs occurring in year k;
i = interest rate; and
R = revenues occurring in year k.

The next phase of the framework (the main area of interest in this paper) requires the evaluation of the total number of air passengers, their origins and destinations, and the level of ground transport service associated with each airport location alternative. The ground travel costs and times can be traded off against the total airport costs.

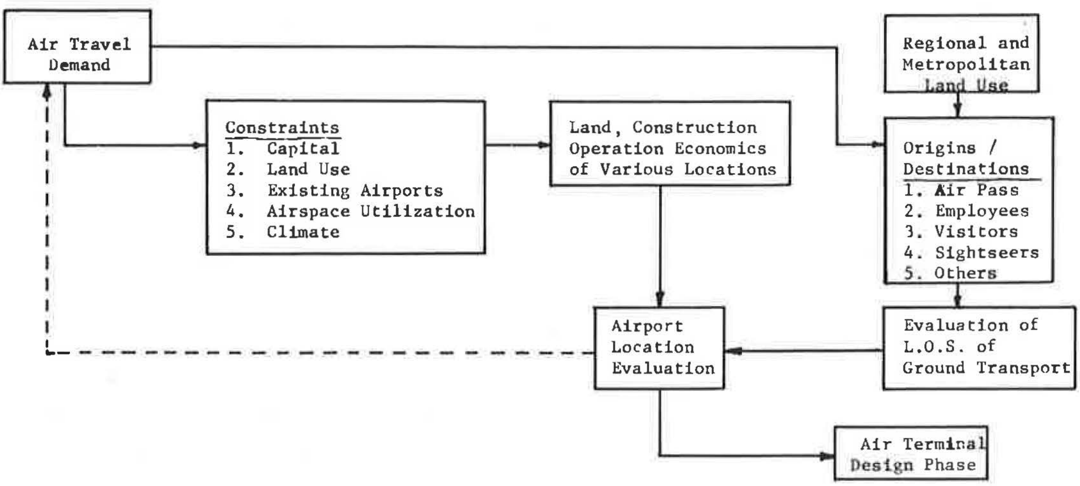


Figure 1. A framework for evaluating airport location alternatives.

In the evaluation phase, the optional project can be defined by

$$NPV(B - C) = NPV(C) - \sum_{0}^{t} \frac{B_k}{(1 + i)^k} \tag{2}$$

where B is the benefits occurring in year k.

AIR TRAVEL DEMAND CONSIDERATIONS

In most airport location studies, the traffic volumes are assumed constant. In other words, only the travel costs and times vary with airport location. In the short-haul distances, however, air travel is in competition with the highway and rail modes. Any variation within the ground portion of the trip can result in an increased or decreased number of air passengers.

Figure 2, for example, shows the traffic volumes for two airport location alternatives. For the existing intercity system, the equilibrium volume is V_{e1}, which is the sum of the air (V_{a1}), rail (V_{r1}), and highway (V_{h1}) volumes. In relation to the system prices P, the total travel benefits from the proposed airport locations are

$$\tfrac{1}{2}(P_{e1} - P_{e2})(V_{e1} + V_{e2}) = \tfrac{1}{2}(P_{a1} - P_{a2})(V_{a1} + V_{a2}) + \tfrac{1}{2}(P_{r1} - P_{r2})(V_{r1} + V_{r2}) + \tfrac{1}{2}(P_{h1} - P_{h2})(V_{h1} - V_{h2}) \tag{3}$$

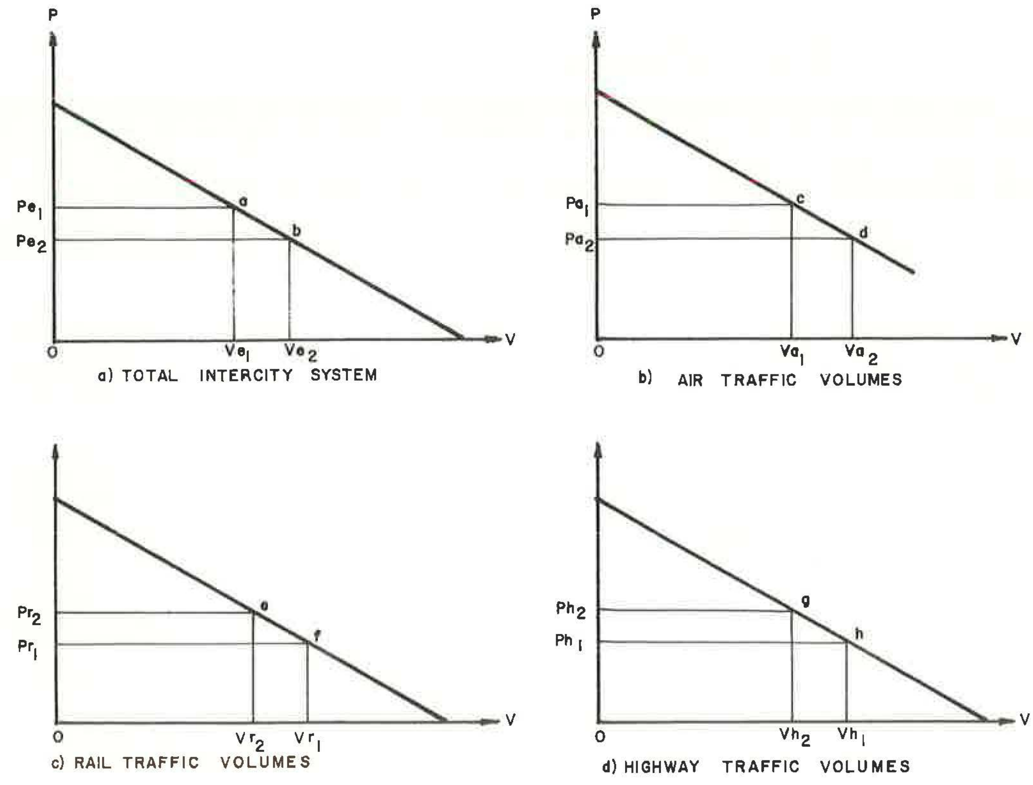


Figure 2. Total system benefits resulting from construction of a new airport.

In terms of the total system travel, the increase in benefits can be derived by determining the system equilibrium prices in terms of the weighted prices of the three modes. The prices weighted by traffic volumes are

$$P_{e1} = \frac{V_{a1}}{V_{e1}} P_{a1} + \frac{V_{r1}}{V_{e1}} P_{r1} + \frac{V_{h1}}{V_{e1}} P_{h1}$$

and

$$P_{e2} = \frac{V_{a2}}{V_{e2}} P_{a2} + \frac{V_{r2}}{V_{e2}} P_{r2} + \frac{V_{h2}}{V_{e2}} \qquad (4)$$

There are diseconomies associated with inaccurate demand estimates. If the demand is overestimated, capital cannot be recovered during the facility's service life or, in the case of staged construction, during a planned development stage. This results in a loss of investment opportunity. If the demand is underestimated, the planned facility will not perform adequately. If an early retirement results, invested capital will not be recovered. If no further investment occurs, and the facility is forced to operate under unsatisfactory conditions, losses to the economy because of delays or lost traffic will be incurred. These diseconomies are shown in Figure 3a.

Figure 3b shows the diseconomies associated with underestimates of demand with project reinvestment. A project phased into the existing system was chosen considering the benefits and costs reduced to time t = 0. The project exhibited the following cost characteristics:

1. An initial investment of C_1 dollars for stage I; and
2. An investment of C_2 dollars at year n for stage II.

The value of this investment was $C_2/(1 + i)^n$ at t = 0. The project's performance, however, became unsatisfactory at time k (k > n). Stage II then was constructed at a cost C_2. Finally, an additional investment of C_3 was required at time r.

A number of costs were not considered by the decision-maker at time t = 0. The reduced value of these costs are as follows:

1. $C_2[1/(1 + i)^k - 1/(1 + i)^n]$, which is the additional cost resulting from the premature construction of stage II.
2. $C_3[1/(1 + i)^r]$, which is the additional cost caused by the investment in year r.

It is recognized that the benefits resulting from the unanticipated traffic volumes also were not considered by the planner. In fact, the actual history of the project may represent the "best" solution. Two distinct diseconomies exist, however, and these are

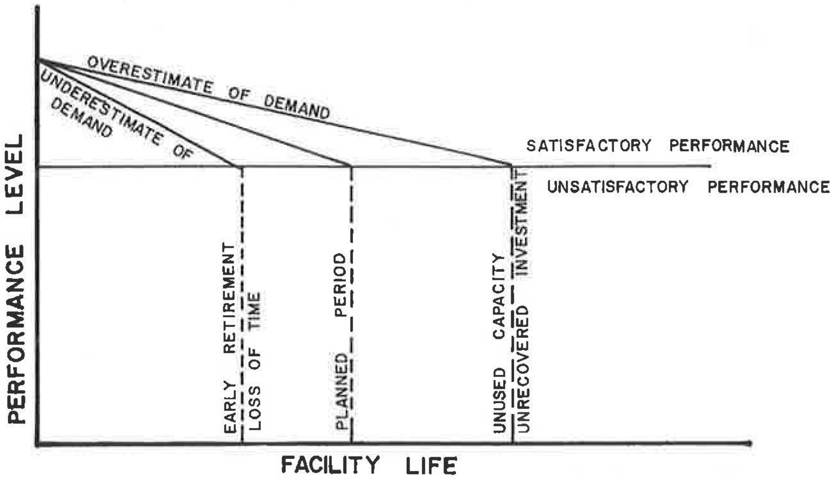
1. The additional capital was not considered in the planning process and, therefore, the project incurred an additional cost; and
2. Had all costs (and benefits) been included, there is a distinct possibility that an alternative project would have been chosen.

A MODEL OF INTERCITY TRAVEL DEMAND

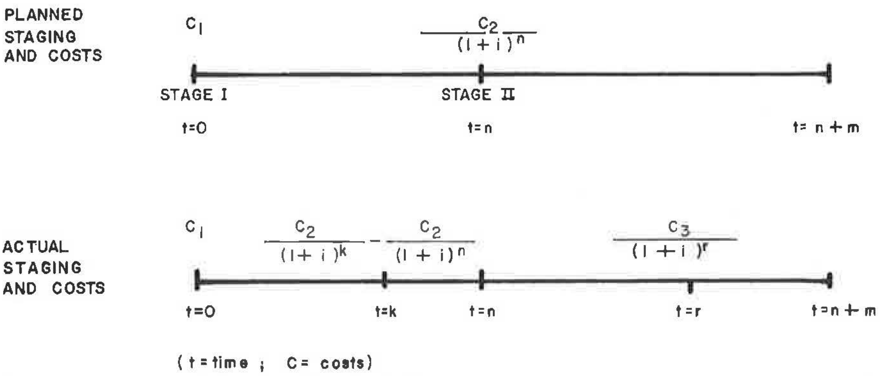
Systems engineering techniques were applied to the Toronto-Ottawa and Toronto-Montreal intercity travel system. With the application of linear graph analysis, it was possible to derive the traffic consequences of several Toronto airport locations.

Linear graph analysis requires individual components to be modeled separately in terms of complementary pressure and flow variables. The imposition of their interconnection pattern then yields a model for the entire system. The procedure is analytic in form and theory and provides a consistent and rigorous approach for modeling systems. Furthermore, these techniques have been applied to socioeconomic systems, including traffic networks (12, 13, 14).

Linear graph analysis, as presented in this paper, was used to develop a set of linear equations that characterize the flow on all links of the intercity travel network (including the airport access). Because every link on the system is described math-



a) A CONCEPTUALIZATION OF FACILITY LIFE DISECONOMICS



b) A CONCEPTUALIZATION OF INVESTMENT DISECONOMICS

Figure 3. Diseconomies resulting from inaccurate estimates of travel demand.

ematically, the equilibrium demand components of generation, distribution, model distribution, and assignment are completed simultaneously.

The model development is presented under the following subheadings:

1. System identification by purpose and function and component choice;
2. Component measurement;
3. Components' terminal equations;
4. System graph;
5. System equations; and
6. Model results.

System Identification and Component Choice

The primary purpose of the model was to simulate the demand for intercity travel by mode associated with several Toronto airport locations. Because of data limitations, the study was restricted to annual business travel. The components included the Toronto airport region generators; access links to the airport, rail, and highway terminals; the intercity routes to Montreal and Ottawa; and measures of the Montreal and Ottawa destination attractions.

Measurement on Components

Linear graph analysis requires that the following requirements be met:

1. The individual system components must be quantitatively describable by two fundamental variables. These variables are a y or flow variable and a complementary x or pressure variable that causes flow.
2. The components are connected at their ends (vertices) to yield a model for the entire system. The interconnected model must satisfy the two generalized Kirchoff laws. The first law states that the algebraic sum of all flows (y) at a vertex is zero. The second law states that the algebraic sum of all pressures around any closed loop of the system must be zero.
3. The flow and pressure variables must be related by a linear or nonlinear function.

The y variable for the intercity travel network is person-trips per year. This satisfies the first Kirchoff law and eliminates the necessity of modeling for storage within the system. That is, all business travelers are assumed to return to their origin over the yearly period.

The x variable is postulated to be a value measure used by the travelers in making a trip and a choice of mode. It is analogous to the portion of the travel potential of an origin that is used as a trip is made and thus is the pressure that caused flow. The x variable is not a measure of the total perceived value of making trips but rather the measurable perceived total cost of making the trip.

The reasoning for the above postulates is as follows:

1. If it is believed that the making of a trip and the choice of mode can be simulated with a reasonable degree of accuracy, then it follows that there is some underlying process made by the traveler in making such a choice.
2. The traveler will act as a free agent and attempt to optimize his degree of satisfaction.
3. Relating points 1 and 2 to a value measurement used in travel allows the origin pressure to dissipate as the trip is made, thus satisfying the second Kirchoff law.

The application of the second Kirchoff postulate to traffic networks as described in this paper requires an assumption, which is: The perceived cost (pressure) of a trip from any particular origin to all destinations is a constant. The reasons for this assumption are as follows:

1. Each origin is modeled with its own unique travel pressure.
2. The origin and travel links form a closed loop with each destination.

Terminal Equations

The origin areas can be characterized as a known flow driver of the form

$$Yi = y \tag{5}$$

where

Yi = the flow from origin i in annual business trips; and
y = a specified value taken from actual data.

The model is built from the existing system data. It then is solved for the complementary pressure variable, and the complementary model is constructed. Then changes can be made in the system to determine the changes in traffic volumes resulting from the implementation of a new airport facility.

The pressure variable was postulated to be of the form

$$X = A(I.P.) + B \tag{6}$$

where

X = the travel potential in cost per year;
A, B = regression constants; and
I.P. = origin area income, population cross product.

This relationship has been verified for the Canadian domestic airway system (14).

The route components have terminal equations of the form

$$X_{ij} = R(y) \times Y_{ij} \tag{7}$$

where

X_{ij} = the perceived value or cost used by the business traveler in crossing the link;
Y_{ij} = the flow in persons per year on link ij; and
$R(y)$ = the resistance function.

The resistance function is of the form

$$R(y) = C(y) + T(y) \tag{8}$$

where

$C(y)$ = the cost in cents to cross a link; and
$T(y)$ = the time, including delay, to cross a link translated to cents per person.

Calibration of the model (14) showed that the time translation constant was 10 cents per minute for air travelers, 6.5 cents per minute for auto travelers, and 15.0 cents per minute for rail travelers. The high value for rail reflects the high rail time and inconvenience perceived by the aggregate of travelers.

The access links included measures of terminal processing times. The egress links included the costs and times associated with overnight stops required for the various modes. Furthermore, the egress links included measures of modal competition (13).

The terminal equations of the destination cities were expressed as

$$Y_k = A_k X_k \tag{9}$$

where

Y_k = the number of business trips per year arriving at destination k;
A_k = the attraction of city k; and
X_k = the cost used across city k.

The attraction measures were based on a study by Air Canada (15). The function was of the form

$$A_k = \varphi\left[\beta_S\left(e_{sk}/e_{s,avg}\right) + \beta_H\left(e_{Hk}/e_{H,avg}\right) + \beta_L\left(e_{Lk}/e_{L,avg}\right)\right] \tag{10}$$

where

A_k = the relative attraction of a destination;
φ = a calibration constant;
e_{sk}, e_{Hk}, e_{Lk} = the employees of a destination city in the service, heavy, and light industries respectively;
$e_{s,avg}, e_{H,avg}, e_{L,avg}$ = the number of employees in the service, heavy, and light industries respectively in the average city of the network; and
$\beta_s, \beta_H, \beta_L$ = the trip attraction characteristics of each employment type (these were found to be 0.452, 0.363, and 0.185 respectively from Air Canada data).

Systems Graph

The systems graph is a set of terminal graphs connected at the vertices to form a one-to-one correspondence with the components of a physical system. Figure 4 shows three alternate Toronto airport locations. Figure 5 shows the systems graph for the expansion of the existing terminal. The elemental numbers are given in Table 1.

Systems Equations

To construct the travel demand model, it is necessary to derive both the chord and branch formulation equations of the system. For purposes of the study, it was assumed that trips outside the Toronto-Montreal-Ottawa triangle would remain unaffected by the airport location. The three origins used in the example were the area northwest of Toronto, the Hamilton-Niagara Peninsula, and Metropolitan Toronto (Fig. 4).

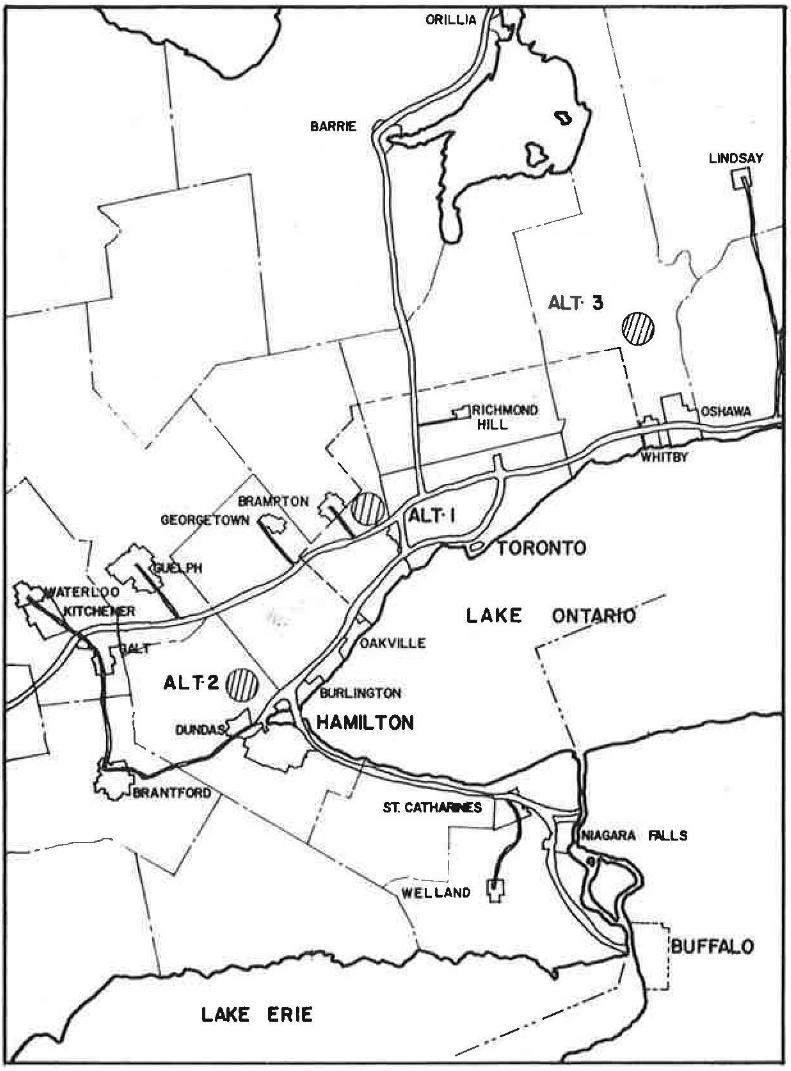


Figure 4. Alternatives for the Toronto International Airport system.

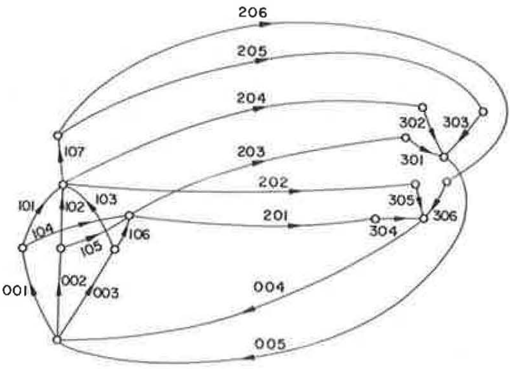


Figure 5. System graph for airport location alternative.

The resistance and attraction values are listed in Table 1. The airport access costs and times were as stated previously. The chord formulation model is of the form

$$[A]\,[R]\,[A^T]\begin{bmatrix}Y_c\\Y_{c1}\end{bmatrix} + \begin{bmatrix}O\\U\end{bmatrix}X_{c1} = 0 \quad (11)$$

These reduce to

$$[Z]\begin{bmatrix}Y_c\\Y_{c1}\end{bmatrix} = 0$$

where

Z = the coefficients of the matrix triple product;
Y_c = the unknown flow values;
Y_{c1} = the known flow values for the three origin areas; and
X_{c1} = the pressure or travel potential for the three origins.

The unknown flow values are calculated. These values are substituted in the last three equations of the set (18), and the travel potentials of the origin area are derived. The flow values for alternative 1 were verified with actual data. These are given in Table 2.

New resistance values for alternatives 2 and 3 then are employed. With these new resistance values and the derived travel potentials, the branch formulation models are solved to determine the traffic consequences associated with each airport location. The branch formulation equations are of the form

$$\begin{bmatrix}U\\O\end{bmatrix}Y_{c1} + [B]\,[R]\,[B^T]\begin{bmatrix}X_{B1}\\X_B\end{bmatrix} = 0 \quad (12)$$

TABLE 1

VALUES FOR LINK RESISTANCES, ALTERNATIVE 1

Link No.	Type	Resistance	Attraction	Flow
001	Toronto North-West			50,000
002	Hamilton-Niagara			61,400
003	Toronto (Metro)			223,000
004	Ottawa		1.253	
005	Montreal		4.038	
101	Air-highway access	2,540		
102	Air-highway access	2,730		
103	Air-highway access	1,540		
104	Rail access	4,565		
105	Rail access	4,940		
106	Rail access	1,310		
107	Airport process	760		
201	Rail link	10,715		
202	Highway link	4,565		
203	Rail link	19,450		
204	Highway link	3,460		
205	Air link	3,680		
206	Air link	3,340		
301q	Rail egress	5,850		
302	Highway egress	5,900		
303	Air egress	1,160		
304	Rail egress	5,850		
305	Highway egress	5,850		
306	Air egress	1,100		

Sources: 1. Regional Studies, Department of Highways of Ontario.
2. Airline Statistics 1964, Air Transport Board.
3. Point-to-Point Passenger Volumes, Canadian National Railways.

TABLE 2
DERIVED TRAFFIC VOLUMES FOR ALTERNATE AIRPORT SITES

Origin Toronto	One-Way Business Trips (persons/yr)					
	Montreal			Ottawa		
	Air	Rail	Road	Air	Rail	Road
Alternate 1	97,900	70,439	62,602	52,310	18,042	40,427
Alternate 2	103,300	69,094	60,064	59,500	16,100	38,872
Alternate 3	89,300	72,094	64,064	43,500	20,082	42,383

Note: Base year 1964.

where X_B is the known travel potentials for the three origins.

Having solved for X_{B1} (the unknown pressures), the link volumes are derived from the terminal equations. The results, in terms of 1964 business trips, are given in Table 2.

Model Results

The results of the branch model are as would be anticipated. The lower access associated with alternative 2 (Toronto Airport plus Hamilton Airport) resulted in a generated air traffic volume of about 1,500 yearly business passengers on the Toronto-to-Montreal air link as compared to alternative 1. [Generated traffic equals new air volume minus old air volume minus diverted traffic; i.e., 103,300 - 97,900 - (70,439 - 69,094) + (62,602 - 60,064) = 1,497.] Furthermore, 1,345 annual trips were diverted from rail and 2,558 from automobile. For the Toronto-Ottawa city pair, 3,693 new trips were generated on the air mode, whereas 1,942 were diverted from rail and 1,555 were diverted from automobile.

Under alternative 3 (new regional airport east of Toronto), it is anticipated that about 5,500 business trips per year would not be made from Toronto to Montreal as compared to alternative 1 [total air traffic lost minus traffic diverted to auto and rail; i.e., (97,900 - 89,300) - (72,094 - 70,439) - (64,064 - 62,602) = 5,483]. On the Toronto-Ottawa route, about 4,800 annual business trips would not be made, whereas 2,040 trips would be lost to rail and 1,956 trips would be lost to automobile.

The accuracy of these results, of course, cannot be verified. The travel elasticities, however, appear reasonable.

APPLICATION TO AIRPORT LOCATION PROCESS

The user travel benefits for the airport location example were calculated. The calculation was based on the assumption that the travel link resistance measures represent the perceived cost of travel for the aggregate of travelers. The measurement of benefits was for the Toronto-to-Montreal route only.

TABLE 3
PERCEIVED COSTS AND TOTAL CORRIDOR TRIPS FOR AIRPORT ALTERNATIVES
(Toronto to Montreal only)

Alternative	Total Perceived Costs Per Trip[a] (dollars)				Total Annual Business Trips[b] (000's of person trips)			
	Air[c]	Rail[c]	Road[c]	Total[c]	Air	Rail	Road	Total
1	27.60	51.80	29.40	108.80	97.9	70.4	62.6	230.9
2	27.00	50.70	28.10	105.80	103.3	69.1	60.1	232.5
3	28.10	54.60	30.90	113.60	89.3	72.1	64.1	225.5

[a]Perceived costs are total of access, link, and egress resistance values. Perceived costs by aggregate of travelers.
[b]Business trips are originating in Toronto area for Montreal only.
[c]Total perceived costs are weighted by number of normalized trips originating in Toronto for Montreal. The procedure is outlined in Equation 4.

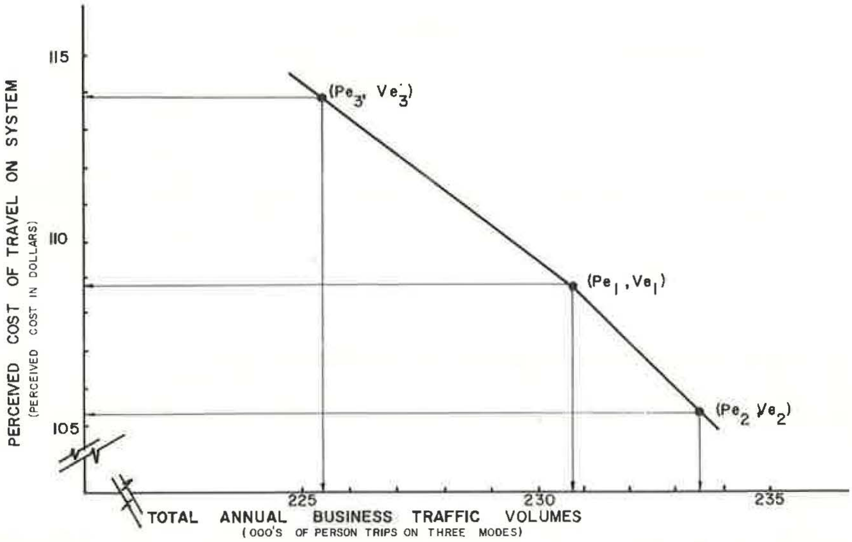


Figure 6. Equilibrium demand points for alternative Toronto airport locations.

The perceived costs and total corridor business trips are given in Table 3. The entries of perceived costs are the weighted resistances of the access, travel route, and egress links. The weighting was achieved by normalizing the total trips on each mode. The total perceived costs and the total business trips associated with each alternative are the derived equilibrium demand points for that alternative.

Figure 6 shows the equilibrium demand points for each alternative. If alternative 1 (Toronto International Airport as proposed) is taken as the do-nothing alternative, then the net user benefits of alternative 2 (Toronto plus Hamilton) and alternative 3 (regional airport east of Toronto) can be determined.

The method of benefit calculation is the Hewes-Oglesby method (19). Comparing alternative 3 with alternative 1, a net disbenefit would result. It would be equal to

$$\tfrac{1}{2}\left(P_{e1} - P_{e3}\right)\left(V_{e3} + V_{e1}\right) = -1{,}095{,}360.00$$

The value is a perceived dollar value for the year 1964. Undoubtedly, all other things being equal, this proposal should be discarded.

The comparison of alternative 2 with alternative 1 produces a net benefit equal to

$$\tfrac{1}{2}\left(P_{e1} - P_{e2}\right)\left(V_{e2} + V_{e1}\right) = 694{,}500$$

The positive perceived value is for the one year. To determine the total user benefits that accrue over the study period, yearly passenger forecasts for pleasure as well as business travel must be made, and the associated benefits calculated. These values must be reduced to present-day terms. The planner then must decide if the additional investment for a Hamilton airport is justified in light of the user benefits (assuming all other things are equal).

SUMMARY

A systems model to forecast air traffic demands was described. One of its uses, within the total airport location study framework, is to assess the impact of airport location on the total traffic potential for short-haul air trips. An example of the method applied in the Toronto region indicates that the procedure can be used effectively.

ACKNOWLEDGMENTS

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