INTERACTIVE GRAPHICS SYSTEM FOR TRANSIT ROUTE OPTIMIZATION

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A person-computer interactive graphics system for optimizing the routing structure on an urban transit network is presented. The system allows a user to design bus, streetcar, and subway routes on a display scope and to specify route frequencies and types of vehicles. The computer predicts the effects of the routing structure by assigning potential transit trips to the network, and it displays the route loadings along with statistics on travel times, rolling stock use, and operating costs. After evaluation, the user can partially or totally modify his or her designs and thereby move toward routing schemes that come closest to planning objectives. The system is based on a multipath transit assignment model that is a further development of R. B. Dial's stochastic assignment algorithm. The model is implemented on a CDC 7326 series computer with a display scope, and it has been tested by being applied to the Lausanne, Switzerland, public transit system. A second implementation of the model has been realized on a small computer environment and is being used productively for optimizing the 24-route tramway and bus network of Basel, Switzerland. The methodology and some results of these applications are described.

•THIS PAPER treats a problem related to the optimization of urban public transit operation (1). A public transit operator seeks to offer the service that is most attractive to the traveler while trying to limit operating expenses. Possible actions are limited by many political, economic, and social constraints. To increase transit attractiveness, one can apply 3 social constraints:

1. Increase or improve the elements of supply, that is, provide a denser network, more frequent service, and more comfortable rolling stock;
2. Reduce fares; and
3. Attempt a better matching of demand and supply.

An increase in services or a reduction of fares deteriorates the financial situation because increased operating cost and reduced fare box revenues normally are not offset by increased ridership (because of the feeble elasticity of transit demand). However, a better matching of supply and demand can increase service quality and decrease operating cost. This paper presents the recherche heuristique d'itinéraires de transports urbains collectifs (RHITUC) system, which is a tool for transit operators to improve the matching of traveler demand and supply of transit services through network and route optimization (2). This tool serves not so much to find long-term solutions in which new technologies or important land use changes must be examined as to find short-term adaptations of the transit network and line structure to changing traveler demand. The RHITUC system allows one to answer a number of questions.

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1. Could some radial transit lines be merged to form diametrical lines?
2. Should certain concentric lines be introduced or suppressed?
3. Should the capacity of any of the radial or diametrical lines be staged through implementation of additional turning points?
4. Could certain lines along a heavily served axis be moved to parallel axes in the same corridor?

Each transit network modification can be motivated by various intentions. One may wish to decrease the number of transfers and concentrate transfer movements to a few well-developed transfer points, or one may wish to decrease user trip lengths by eliminating path detours that result from a nonoptimal network structure.

Thus the optimization problem can be formulated according to the data given in Table 1.

Complex network analysis and routing problems do not lend themselves to direct mathematical programming optimization methods, and most heuristic methods require either an enormous computational effort or unrealistic simplifications. However, it has been demonstrated that transport analysts who are familiar with the problem can rapidly find optimal or near-optimal solutions if they are equipped with a tool that allows them to rapidly generate, evaluate, and improve alternative designs. Interactive graphic systems that make use of a computer with an on-line cathode ray tube (CRT) have been shown to offer this possibility (3, 4, 5). A state-of-the-art review of the potentials and problems of interactive graphics in transportation is given elsewhere (6).

RHITUC SYSTEM

System Overview

Figure 1 shows an overview of the RHITUC system. The base network (set of potential transit links) is geocoded and stored on a computer disk from which it can be displayed selectively on the CRT screen (Figure 2). The transit demand [origin-destination (O-D) trip table] is prepared and stored also, and can be displayed in the form of desire lines (Figure 3) and zonal productions and attractions (Figure 4). The user then may specify transit routes by pointing sequentially with the light pen to those nodes of the base network that are to become transit stops. The line attributes, that is, line frequency and types of vehicles, are entered on the CRT keyboard. By using a trip-assignment algorithm, the computer then predicts the trip volumes on the transit lines and network links. These volumes, the number of transfer movements at each transfer point, and such data as mean travel times, vehicle demand, and operating costs that are numerically presented are displayed graphically (Figures 5, 6, and 7). Based on these results, the user can modify the route structure or the line attributes and thus evaluate other alternatives. Alternatives can be stored, recalled, summarized, and compared (Figures 8 and 9). Because the cycle of route definition, computation, and result analysis takes only a few minutes, the search for an optimal design is more efficient with this method than it is with any of the traditional methods.

Data Requirements

All those elements of the transport system that are supposed to be constant during the optimization process form the data base that is prepared and stored beforehand. The choice of the constant versus variable components depends on the nature of the problem. For example, although transit demand must be assumed to vary with changing land use and accessibility in long-range planning, it is assumed to remain constant if only short-term effects of operational measures are to be evaluated. In the RHITUC system, the following data are considered to be constants:

1. Transit demand,
2. The base network, and
3. The transit vehicle characteristics.

If, in a particular case, a part of these data should be variable for the optimization process, the user can prepare and use more than 1 data base. On the other hand, if other data than those previously mentioned should be held constant, the user must keep their values unchanged during the interactive definition of all alternatives.

Because the RHITUC system is mainly a tool for finding short-term improvements, the data base can, in most cases, be limited to a description of the existing situation. Thus, the data base more often will be extracted from inventories than from prediction models.

Trip Table

The transit demand must be introduced in the form of an O-D trip table, and each matrix element must correspond to the number of actual or predicted transit trips between a pair of zones. Network and route optimization requires a fair amount of disaggregation; the most effective solution is one in which each zone corresponds to the passenger shed of only 1 transit station or a cluster of bus stops. This will be the case automatically if the trip table is obtained from transit passenger surveys.

Some transit companies do not regularly perform O-D studies. They only do surveys of station patronage. It is possible to estimate O-D movements from station trip ends by means of a distribution model (for example, a gravity model) or by updating an old trip table by means of the Fratar method. The trip table should correspond to the peak period, and it is therefore neither symmetrical nor triangular.

Base Network

The base network is the set of all links that potentially can be used by any transit line. It contains, therefore, a part of the street network and, if streetcar or subway links exist, the urban rail network. The stops, junctions, and terminals form the nodes of the base network. For homogeneous areas, a number of stops can be aggregated to a single node. For display purposes, coordinates must be assigned to all nodes.

Each link of the base network belongs to 1 or more of the following 5 transit submodes:

1. Submode 1: bus on mixed traffic street,
2. Submode 2: bus on exclusive lanes,
3. Submode 3: railcar on mixed traffic rights-of-way,
4. Submode 4: railcar on exclusive rights-of-way, and
5. Submode 5: pedestrian connections.

In practice, most links of the base network are dedicated to 1 exclusive submode. The length and the travel speeds of all submodes employing it must be assigned to each link.

Vehicle Characteristics

The different types of vehicles are defined through the submodes (rubber-tired vehicles or railcars), vehicle capacity (seating and standing), and vehicle operating costs [cost per mile (kilometer) and hourly costs].

The Prediction Model

At the heart of the RHITUC system, a prediction model simulates the effects of a design that has been specified interactively. The model yields the following values:

1. Network loads expressed in number of patrons on each link of the base network,
2. Line loads expressed in number of patrons on each route segment of a line,
3. Number of transfers at each stop,
4. Number of vehicles per type of vehicle per line and in total,
5. Number of vehicle miles (kilometers) per line and in total,
6. Operating costs per line and in total, and
7. Quality of service expressed in mean travel time and average number of transfers.

Network and line loads result from the assignment of transit demand onto the most probable paths. The assignment algorithm is an extension of Dial's multipath assignment model (7), which is based on the hypothesis that travelers probably choose the path with the least resistance but that all other nonbacktracking paths have a certain likelihood of being used. Dial's model has been developed for highway trip assignment and therefore requires a homogeneous network. For public transit 2 difficulties arise.

1. Total path resistance is the sum of several components: pedestrian access time to a transit stop, waiting time, travel time, transfer time, and pedestrian time between a transit stop and the final destination of the trip.
2. The principle of optimality, which is the underlying idea of both the Moore algorithm (8) used for finding the shortest paths and Dial's assignment model (7), is not straightforwardly applicable in the case of public transit. According to this principle, if a minimum path from node A to node C passes through node B, it employs the minimum paths from A to B and from B to C. As shown in Figure 10, this principle does not hold for some cases.

These 2 difficulties can be circumvented by transforming the transit network into a homogeneous highway network by adding dummy links according to 3 rules.

1. For each stop n_i along a transit line k, a dummy stop $n_{i'}$ is generated. The length $d_{ii'}$ assigned to the link from n_i to n_i corresponds to the part t_i of the transfer time at n_i that is not a function of the service frequencies but is only a function of station design (time to transfer from one boarding platform to another, or to cross streets, and so forth). That is,

$$d_{ii'} = t_i \tag{1}$$

2. For each line segment between 2 successive stops n_i and n_j, 2 directed links are introduced. One link is $1_{i'j'}$ from $n_{i'}$ to $n_{j'}$. Its length corresponds to the travel time t_{ijm} from n_i to n_j by submode m of the line k. That is

$$d_{i'j'} = t_{ijm} \tag{2}$$

One link is $1_{i'j}$ from $n_{i'}$ to n_j. Its length is computed according to the formula

$$d_{i'j} = t_{ijm} + \alpha(f_k) \tag{3}$$

Table 1. Formulation of optimization problem.

Given	Unknown	Objective Function and Constraints
Intensity and distribution of demand for transit rides Structure of base network of transit[b] Available rolling stock[d]	Route structure[a] Rolling stock allocation[c]	Minimize operating costs, mean user travel times user trip lengths, and number of transfers

[a]Succession of links of base network to be used by each line.
[b]Rail network for subway and streetcar systems, network of roads suited to bus service, and major pedestrian links.
[c]Headways and type of vehicles on each line.
[d]Number and capacity of each type of vehicle.

Figure 1. RHITUC overview.

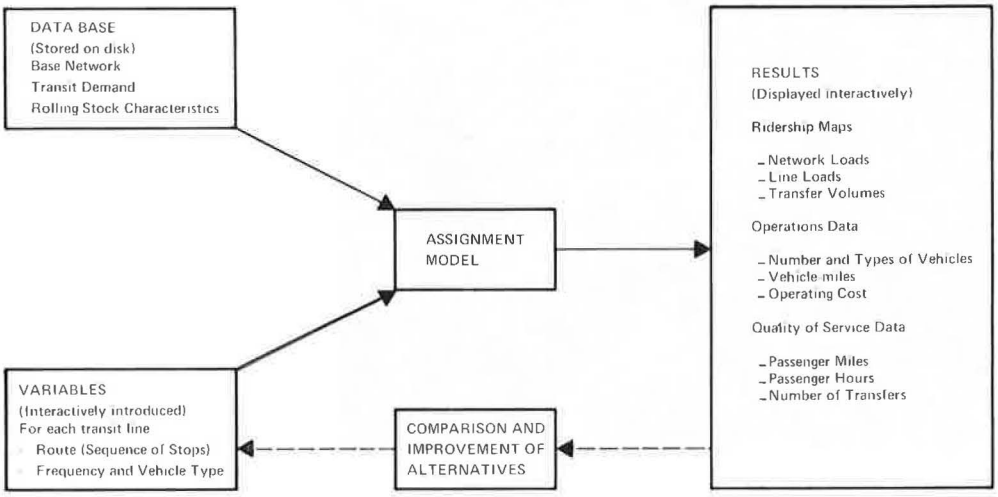


Figure 2. Base network display.

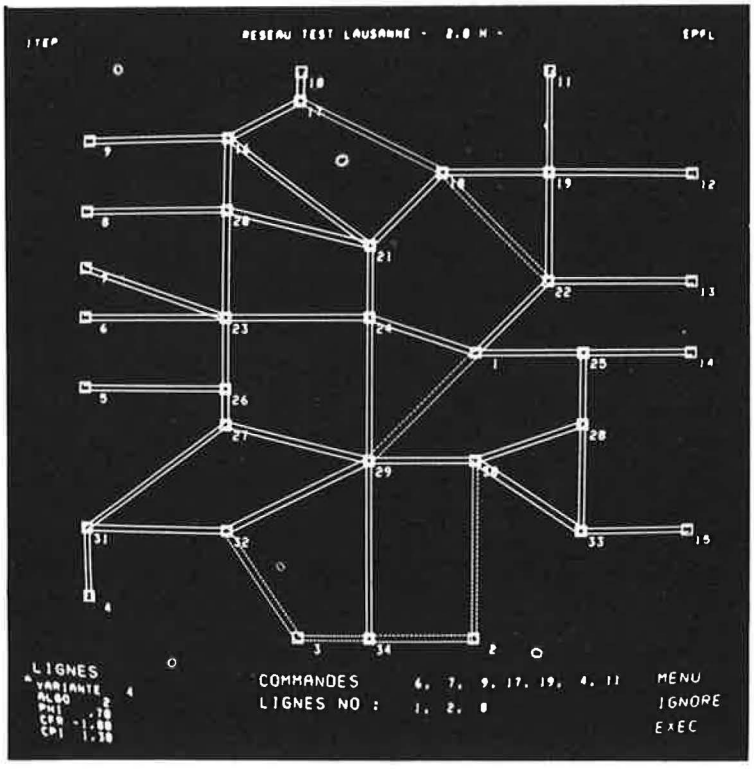


Figure 3. Transit desire line display.

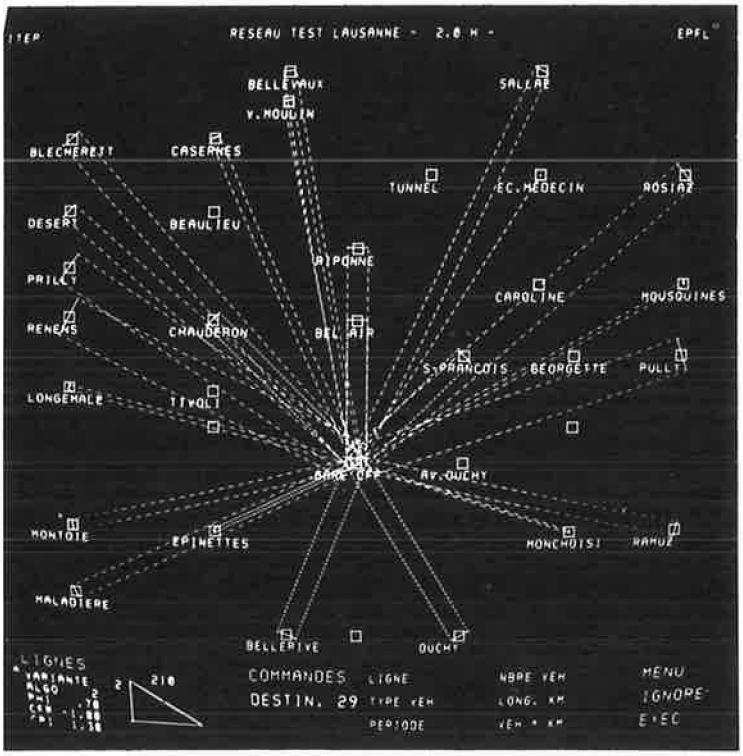


Figure 4. Transit productions and attractions display.

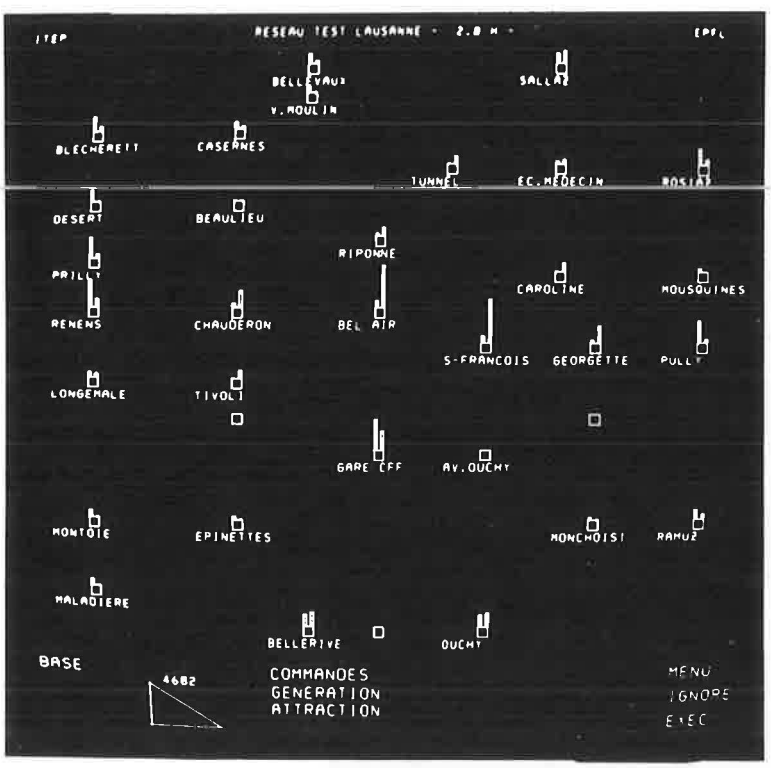


Figure 5. Transit network loads.

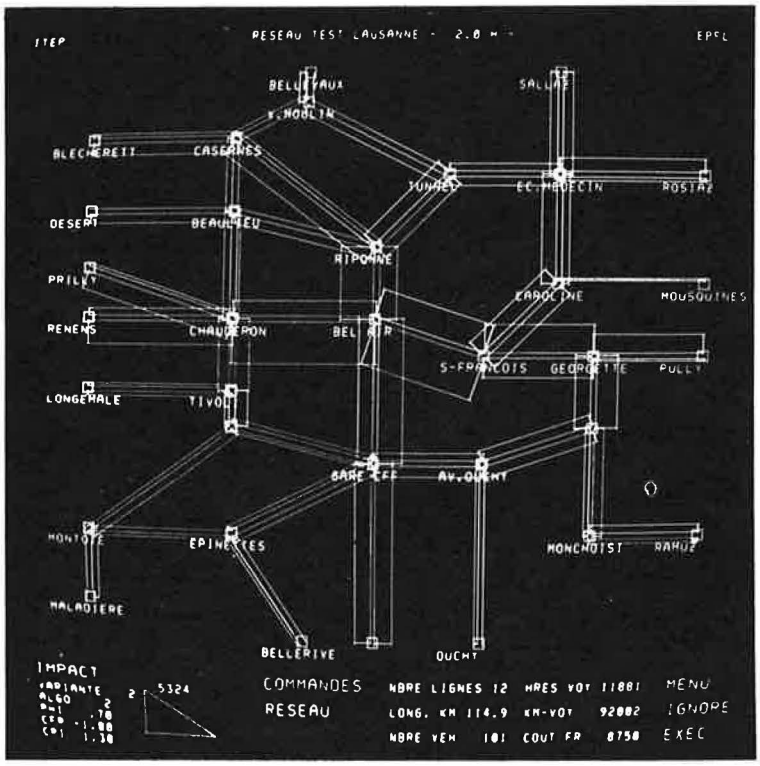


Figure 6. Transit line loads.

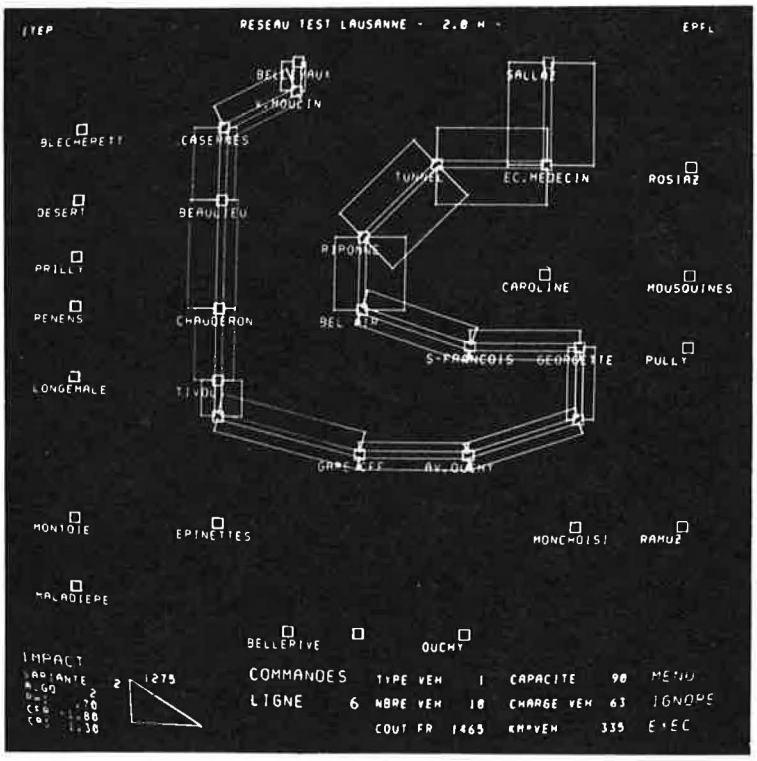


Figure 7. Transfer volumes at transfer points.

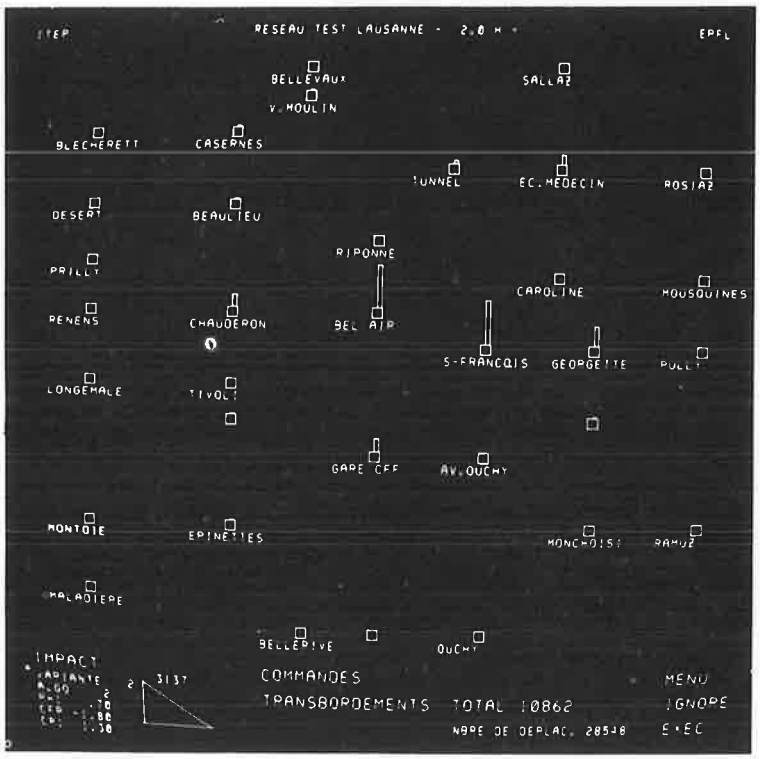
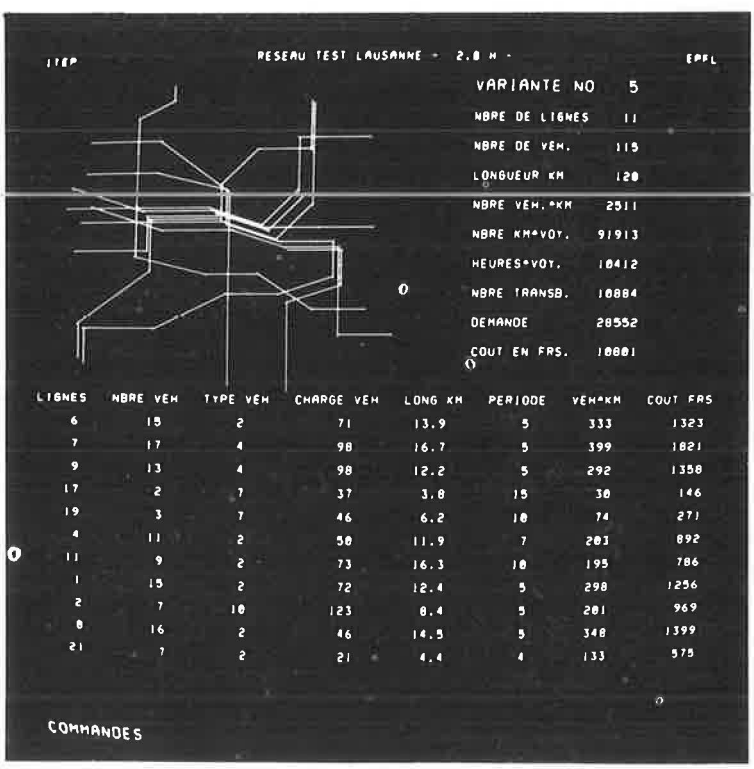


Figure 8. Summarized display of 1 alternative.



LIGNES	NBRE VEH	TYPE VEH	CHARGE VEH	LONG KM	PERIODE	VEH*KM	COUT FRS
6	15	2	71	13.9	5	333	1323
7	17	4	98	16.7	5	399	1821
9	13	4	98	12.2	5	292	1358
17	2	7	37	3.8	15	30	146
19	3	7	46	6.2	10	74	271
4	11	2	50	11.9	7	203	892
11	9	2	73	16.3	10	195	786
1	15	2	72	12.4	5	298	1256
2	7	10	123	8.4	5	201	969
8	16	2	46	14.5	5	348	1399
21	7	2	21	4.4	4	133	575

Figure 9. Comparison display.

ITEP RESEAU TEST LAUSANNE - 2.0 H - EPFL

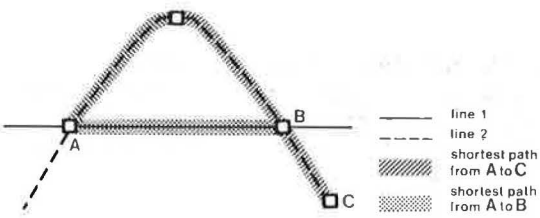
DEMANDE : 28553 DEPL.

TABLEAU COMPARATIF GENERAL

VAR.	RESEAU				VOYAGEURS			
NO	LONGUEUR KM.	VEHICULES TOTAL	VEH*KM.	COUT D' EXPL. FRS	NBRE DE DEPLAC.	KM*VOY	HEURE*VOY	TRANSB.
1	120	115	2511	10881	28552	91913	10412	10884
3	108	98	2164	9360	28553	91990	10439	11713
4	116	108	2377	10226	28551	91438	10455	11270
5	120	115	2511	10881	28552	91913	10412	10884

COMMANDES

Figure 10. Example of a shortest path using a path segment that is not the shortest connection between its end points.



where

t_{ijm} = travel time from n_i to n_j via submode m,
f_k = frequency of line k, and
$\alpha(f_k)$ = a weighting function that relates passenger waiting time to line frequency (according to traveler behavior).

3. If a pedestrian connection exists between n_i and n_j, an additional link l_{ij} is generated with the length

$$d_{ij} = \beta(t_{ijp}) \tag{4}$$

where

t_{ijp} = pedestrian walk time from n_i to n_j, and
$\beta(t)$ = a weighting function for pedestrian walking time.

Figure 11a shows a base of network and lines. Figure 11b shows the transformed network. After transformation, the network is no longer different from a highway network. Each link has an associated real or virtual time, and the sum of the times of all links along a path is equal to total trip time. It is therefore appropriate to apply Dial's multipath assignment algorithm without any restrictions. [In computer implementations of the algorithm, adding the dummy links may be memory consuming. For example, the 150-node, 520-link base network for the Basel, Switzerland, transit system with 29 transit lines results after transformation in a 500-node, 1,500-link network. However, computation time for trip assignment has been found to be 10 times shorter than in the traditional all-or-nothing transit network assignment method based on Dial's transit pathfinder algorithm (9).]

MODEL APPLICATIONS

Application in Lausanne, Switzerland

The first application of the RHITUC system has been realized for the Lausanne, Switzerland, region with the double objective to illustrate the model with some qualitative results and to develop and test a preliminary usage methodology.

Figure 12 shows the 3 principal stages of the application process, which are data preparation, model calibration, and model operation.

Data Preparation

A valuable part of the data base for the Lausanne, Switzerland, application could be drawn from the Lausanne transportation study that had been undertaken recently by the Transportation Institute. The transit trip table for the 2-h morning peak period was retrieved from 1970 Swiss census data. [The 1970 Swiss census questionnaire contained questions on the origin, destination, and mode of travel for the daily work trip of each household member (100 percent sample).] The supply data, such as the base network and the rolling stock characteristics, were collected from the transit companies of the Lausanne, Switzerland, region (one company operates 20 bus lines, and the other provides service on 2 parallel "metro" lines). The base network was aggregated to 35 nodes and 90 links.

To check the proper coding of the network data, the possible paths between pairs of

Figure 11. (a) Base of network and lines and (b) transformed network.

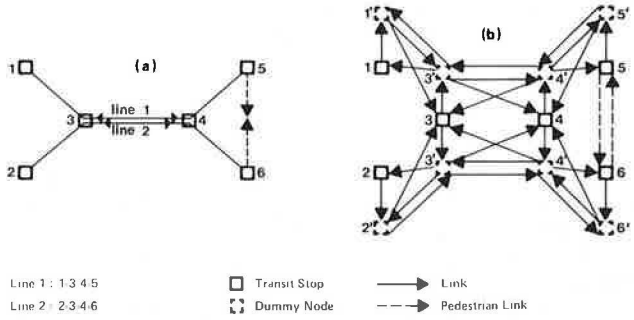
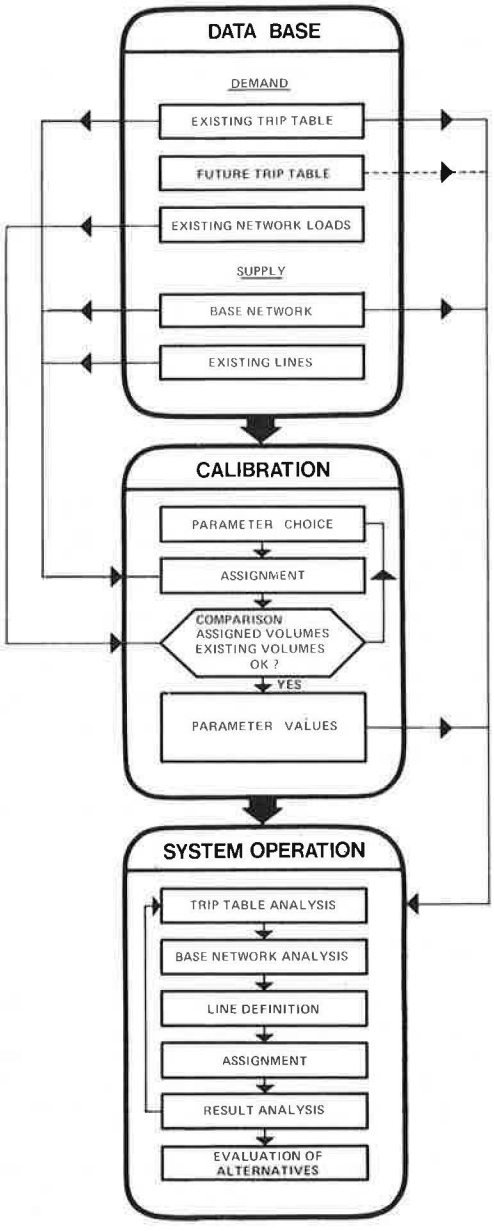


Figure 12. Stages of application of RHITUC system.



major stations were examined. The interactive graphics method has allowed rapid location and correction of network coding errors.

Parameter Calibration

The global parameter Φ of the multipath assignment model and the 2 weighting functions $\alpha(f)$ and $\beta(t)$ must be estimated. In the Lausanne, Switzerland, application, the weighting functions were assumed to be linear; that is, waiting time was assumed to be proportional to headway, and walking time was assumed to be proportional to the length of pedestrian links.

The 3 parameters were determined in a trial-and-error procedure that consisted of selecting parameter values, performing a trip assignment on the existing transit routes, and comparing the predicted link and line volumes with the observed loads from 8 screen-line and 2 cordon surveys. The interactive mode offered significant advantages. In a short time, 3 series of 10 combinations of parameter values were evaluated. The parameter set with the least difference (maximum of 15 percent) between computed and observed volumes is as follows:

		Value	
Parameter	Meaning	Lausanne	Basel
Φ	Global multipath assignment (7)	0.7	0.7
α	Weight of waiting time	1.3	2.0
β	Weight of walking time	1.8	2.0

System Operation

In the Lausanne, Switzerland, application, RHITUC was used directly by its developers. During the interactive graphic design process the users established 10 alternatives, all based on existing route structure. Various modifications, some of which had already been proposed in the Lausanne, Switzerland, transportation study, were tried. The alternatives were evaluated in 2 stages.

1. A feasibility check allowed elimination of alternatives that violated certain constraints imposed by the transit operators (personnel needs, vehicles, operating cost, transfer volumes at certain stations, and line capacities).
2. A dominance analysis eliminated alternatives that were dominated by others.

An alternative was said to be dominated if another alternative had better results with respect to all of the following objectives:

1. Transfer movements,
2. Mean travel time, and
3. Operating costs.

Figure 13 shows the dominance analysis of 2 alternatives that are shown in the comparison display of Figure 9.

This evaluation has allowed the introduction of new modifications that lead to solutions that cannot be dominated. The iterative process to find the entire envelope of "best" solutions and to scan the solution space more thoroughly was completed during 1975.

Because, in the Lausanne, Switzerland, case, the RHITUC users are not identical to the decision makers, the result is a set of alternatives rather than a single plan.

Figure 13. Dominance analysis in which alternative 3 is "dominated" by alternative 1.

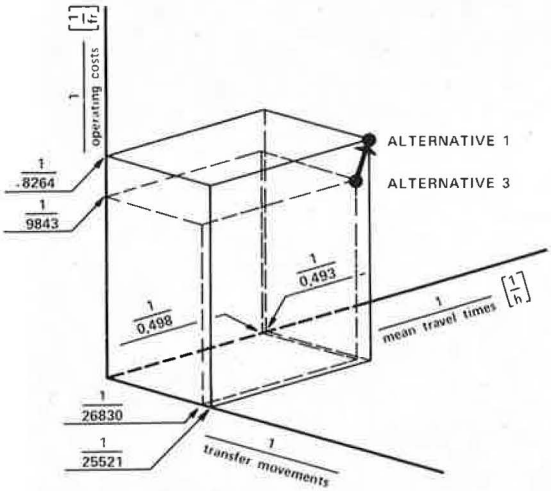


Figure 14. Sample display of line structure for Basel, Switzerland, application.

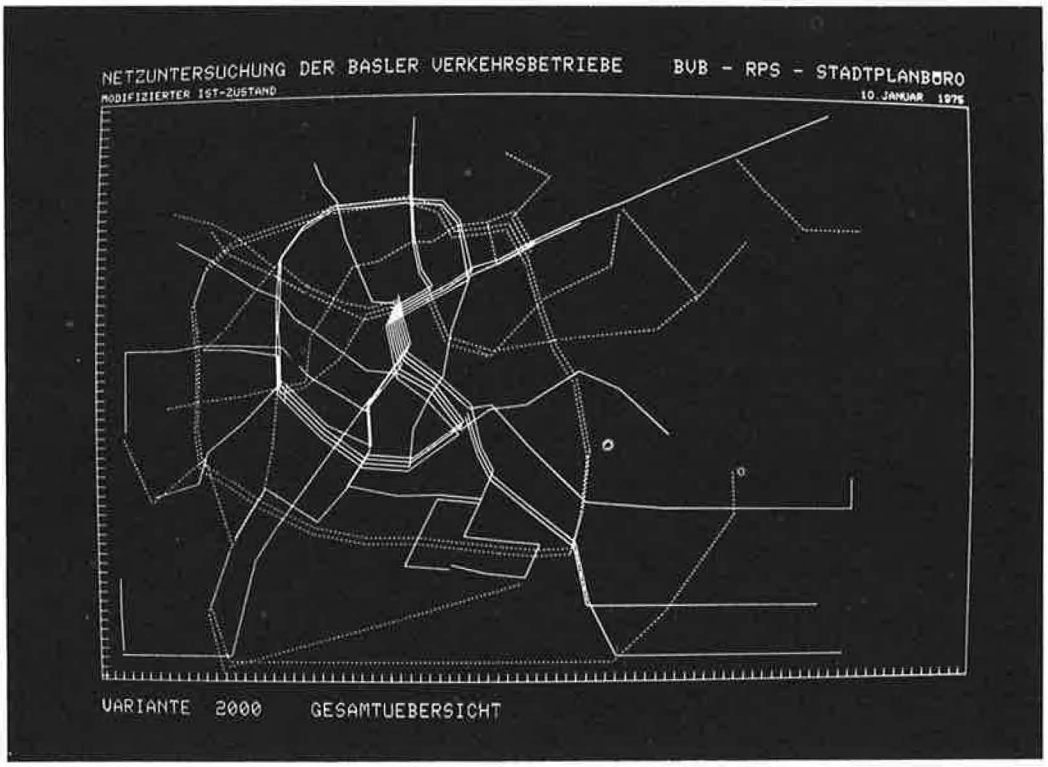


Figure 15. Sample display of network loads for Basel, Switzerland, application.

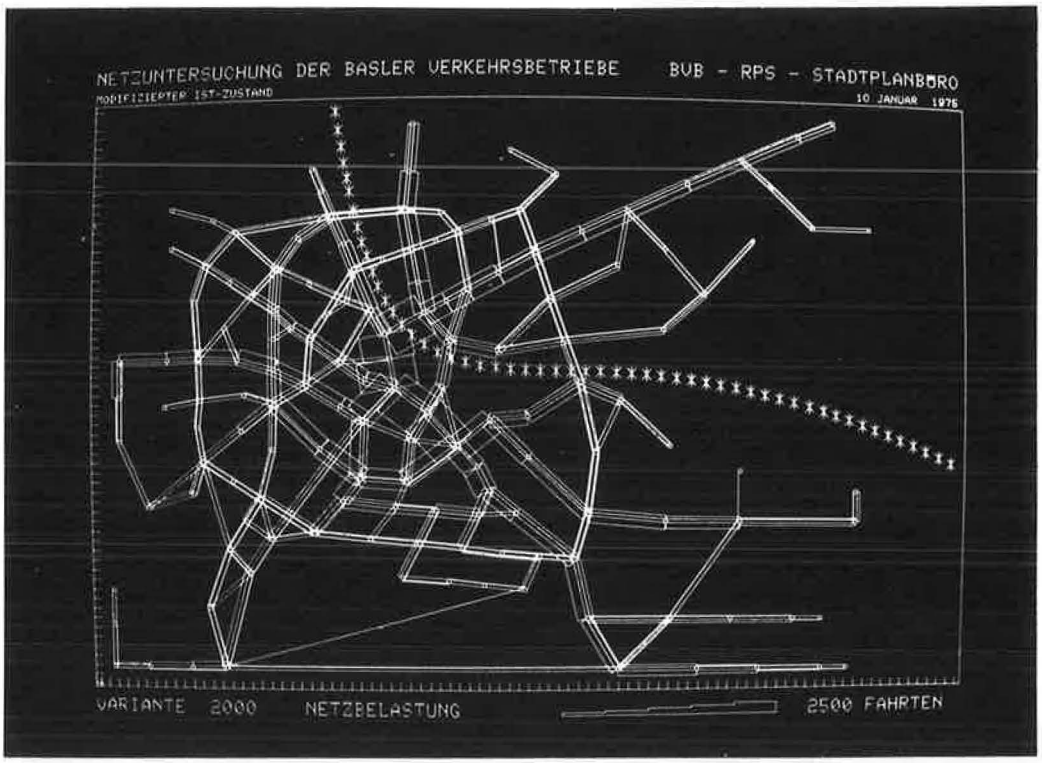
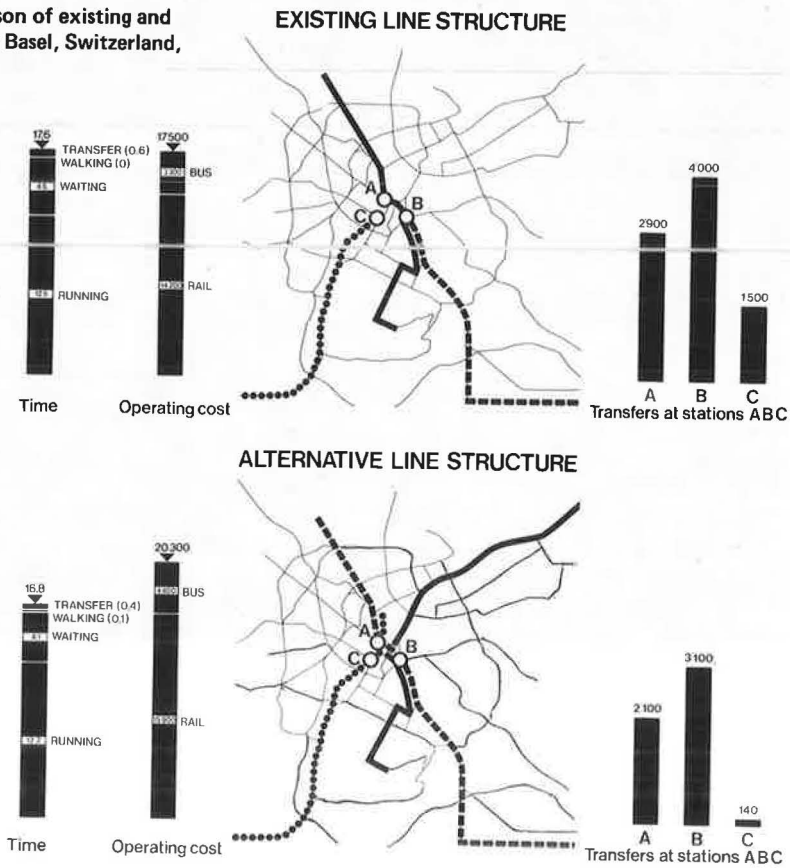


Figure 16. Sample comparison of existing and alternative line structure for Basel, Switzerland, application.



The final choice of the actions to be undertaken will result from a further multicriteria evaluation based on the elements prepared by the RHITUC application.

Application in Basel, Switzerland

A second application of the RHITUC system is being undertaken by 2 engineering firms for the public transport system of the region of Basel, Switzerland. The Basel transit company operates 12 rail lines (streetcar lines in the downtown and fringe areas and separate rights-of-way in the suburban areas) and an equal number of bus routes. In addition, another public operator offers service on 2 suburban rail lines. These latter lines end at the fringe of the central business district, thus forcing most passengers to transfer to 1 of the urban lines. The purpose of the RHITUC application is to examine the possibilities of introducing all suburban lines into the central business district on the urban rail network and to combine suburban lines to form through routes. The objective for the optimization is to reduce transfer movements without simultaneously increasing rolling stock and personnel needs.

Demand data were retrieved from an extensive 1962 passenger O-D survey in which transit trips counted between any pair of the 229 transit stops. For RHITUC, the 229 × 229 trip table was aggregated to a 150 × 150 matrix and updated to the 1974 level by means of recent screen-line counts. In the Basel, Switzerland, case, the base network has 150 nodes and 520 links.

The Basel, Switzerland, application takes place on a small Hewlett Packard 2100 computer system (32,000 word memory) with an on-line storage CRT. The institutional framework is such that the consultant prepares the data and the RHITUC programs and offers the computer time, but the transit company representatives and city planning officer use the system interactively to search for and choose the best transit network design.

CRT displays from the Basel, Switzerland, case are shown in Figures 14 and 15. Figure 14 shows the line structure of an alternative with 15 streetcar routes and 14 bus routes, and Figure 15 shows the corresponding network loadings.

A comparison of the existing operation and a typical, interactively generated alternative is shown in Figure 16.

CONCLUSIONS

The 2 important features of the RHITUC system are the interactive graphics aspects and the multipath assignment technique for transit networks.

The assignment algorithm is based on Dial's probabilistic highway trip assignment model and is adapted for networks that are composed of lines. We have found that the multipath model is easier to calibrate and requires less computation time than the traditional all-or-nothing transit-trip-assignment technique. However, great care must be exercised in computer implementations to allocate storage space most economically for the addition of the great number of dummy links.

At the current stage, RHITUC has 2 limitations.

1. The O-D trip table remains constant during the optimization process, and in reality modal split and transit demand are influenced by the quality of service offered. This, in turn, depends on the result of the network optimization process.
2. The transit trip assignment ignores any effects of limited capacity on passenger path selection.

By corroborating former experiences with interactive graphic applications in transport planning, the RHITUC studies suggest that the method of person-computer synergism opens great possibilities for solving network optimization problems where planners are faced with a large number of variables and constraints that are not easily brought into an analytical form. The graphic representation of all phenomena allows

the planner to always have an overview and easy control over the operation while the machine performs all cumbersome analytical tasks.

ACKNOWLEDGMENTS

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