

Transfer Optimization in an Interactive Graphic System for Transit Planning

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This paper describes a coordinated four-stage interactive graphic process for operational transit planning. Stage 1 deals with route, headway, and vehicle-type optimization; stage 2 attempts to optimize transfer delays; stage 3 designs runs so that the service resulting from the previous stages can be operationalized; and stage 4 provides computer assistance in making manpower assignments. The network optimization procedure of stage 1 has been previously reported on, and the latter two stages are currently under development. This paper deals principally with the transfer optimization tool of stage 2. The operational tool to optimize transfer delays involves the automated-iterative modification of terminal departure times. An interactive graphic computer approach is used to increase the transparency of the tool to the planner. The analysis takes into account the calculation of expected waiting times for transfers between transit lines with different headways and the interdependence of terminal departure times. Within the interactive graphic optimization process, the user can request computer-generated and computer-drawn charts of transfer movements and delays, time-distance diagrams of individual routes, and computer-produced transfer statistics at individual stops as well as the entire system. The process has been applied to the Basel Transit System in Switzerland, which serves a population of 500 000. In comparison with the existing hand-generated timetable, the optimized timetable reduces the total transfer delays by approximately 20 percent with no increase in operating costs.

Operational transit planning has a short time horizon and for our purposes can be described as shown in Figure 1. The input to this planning process is a number of items that must, in the short run, be fixed. These items are the demand for transit service in terms of trip origin and destination (O-D), which are stratified perhaps by time of day; a base network (existing rail right-of-way and arterial streets), terminals, depots, and other infrastructures; and the characteristics of available rolling stock.

The planning process should generally be guided by user objectives (e.g., minimum total travel time); it is constrained both by the financial considerations of the operator (e.g., maximum allowable deficit) and by ex-

isting labor contracts (e.g., required terminal layovers). The desired output from the operational planning process is the transit routes, the vehicle types serving each route and the headway with which they are served, the timetables, the runs used to operationally service the routes, and the vehicle and driver assignments.

INTERACTIVE GRAPHIC APPROACH

Past experience has shown that, given the current state of our analytic tools and of computer hardware, it is impossible to treat the entire operational transit planning process in one step as shown in Figure 1. In the past, the approach has been to treat subareas of the total problem separately, and in most cases disjointedly, and to apply to each subproblem an analytic technique that seemed best suited to it. The methods that have been used in the past include simulation-modeling techniques to design bus routes; mathematical programming techniques (integer programming); and heuristic techniques to construct timetables, define runs, and assign vehicle and driver resources. A useful description of some of these past efforts is given by Wren (1). The following principles were used as guidelines to approach the problem of operational transit planning.

One of the principal desires was to make the entire process as transparent as possible to the transit planner and to adapt as many as possible of the planner's existing methods and tools. This desire was motivated by the fact that highly sophisticated, but nontransparent, computer models that employ drastically different methods are only reluctantly accepted within the existing planning and operations framework of transit properties.

It was also decided to build the entire operational planning tool around an environment of minicomputer hardware by using low-cost storage tubes (cathode ray tubes) as shown in Figure 2. Currently, only this type of environment gives the user the quick response time needed, and at a price that is compatible with small and medium-sized transit operators. In the network optimization stage, a computer with 32-K words memory can analyze a transit network with 250 nodes, 950 links, and 60 lines. (This memory is automatically expanded to account for transfer movements to 700 nodes and 2300 links.)

Publication of this paper sponsored by Task Force on Computer Graphics and Interactive Graphics.

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Third, and most important, all the functions of operational transit planning had to be coordinated into a unified process. The operational planning process that resulted from these considerations is shown in Figure 3. The problem was segmented into four stages so it could be tractable with minicomputers and existing analytic techniques. However, the data flow between stages is explicitly linked to highlight the dependence of one analysis stage on the output of the preceding one and to maintain the desired coordination of the process as a whole. To increase the transparency of the process to the planner and to facilitate the adaption of existing operational planning tools, we adopted the interactive graphic person-computer approach. This technique, as demonstrated in past applications, has the added benefit of allowing the discovery of near-optimal solutions by use of simple analytic techniques and low-cost computer hardware (2, 3, 4).

Stage I (network optimization) has been previously reported on (5) and documented (6). This stage was applied to the problem of coordinating the suburban and urban transit routes in the Basel, Switzerland, area. Optimum solutions to this problem, defined by planner objectives and limited by the iterative search process, were efficiently generated (7). This paper describes stage 2 (transfer optimization), which has recently been operationalized. Stages 3 and 4 (run allocation and manpower assignment procedures) are currently under development and will be reported on later.

Figure 1. Operational transit planning defined by input and output.

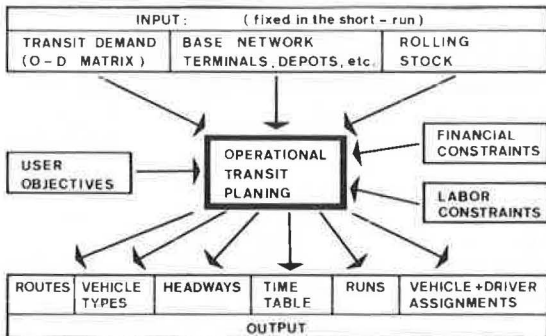


Figure 2. Typical storage terminal for interactive graphic data.



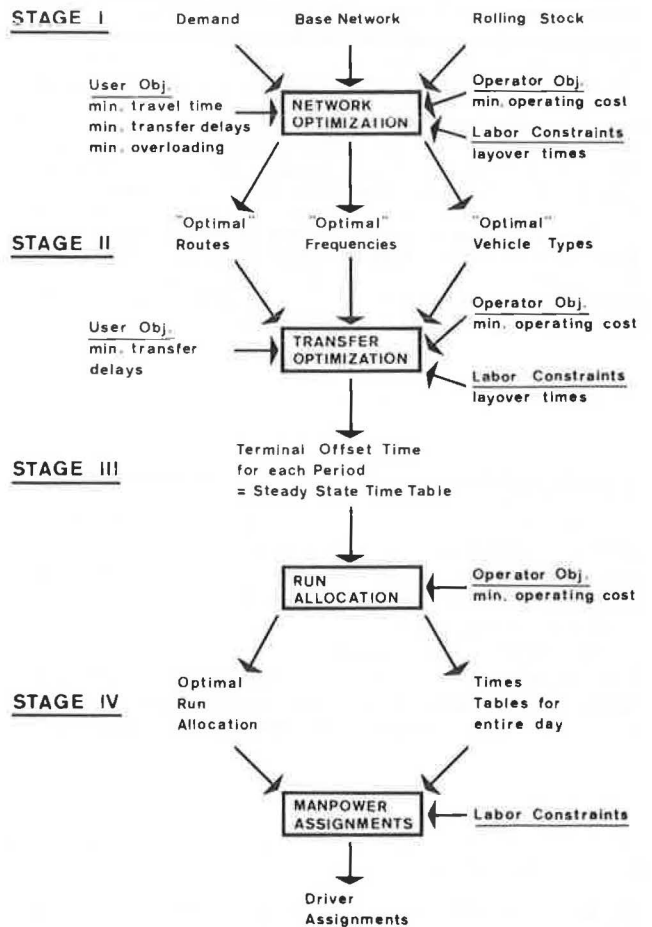
TRANSFER-OPTIMIZATION PROBLEM

Except in the case of a highly sophisticated, fully automated transit technology, e.g., personal rapid transit (PRT), most transit operations will require some transfer movements from one route to another to serve the diverse origin-destination patterns of the current urban agglomerations. To minimize the adverse effects (in terms of the competition between public transit and private automobile), the transit operator must try to (a) reduce the required number of transfers by adjusting the routing to the given O-D pattern of transit trips and (b) minimize the transfer delays (i.e., the waiting time at the transfer point). As shown in Figure 2 and described elsewhere (5, 6), the first part of this problem is solved during stage 1. Thus, transfer optimization can be attained by minimizing transfer delays.

The typical operating day of a transit system can be divided into a number of periods that are characterized by the level of demand and thus the headway that can be justified. Typically, there will be the morning and evening peak periods during which demand is high and consequently the headways rather short (from less than 1 min to about 6 min) and the off-peak periods during which headways can range from 15 to 60 min. The minimization of transfer delays will be treated separately for each of these periods of constant headway. Since, in general, the waiting time is proportional to the headway, it is primarily in the off-peak periods that transfer optimization is important.

The transfer situation at a given stop is shown in Figure 4, and the waiting times between stops on the

Figure 3. Coordinated, four-stage, operational transit planning process.



Basel Transit System are given in Table 1. As given in Table 1, the longest wait (5.5 min) occurs for transfers from line 36 at stop KU to line 15 at stop TE. This waiting time could be reduced to 0 min by moving line 36 ahead by 5.5 min, thus reducing the total waiting time (average waiting time \times number of transfers) by 38 min. However, the 23 passengers wanting to transfer from KU to STB would miss their connection, and their average waiting time would increase by 5.5 min. Added complications arise from the following:

1. Since a given line will intersect more than one other line, then a change in arrival-departure times at one stop will have repercussions at a number of other transfer points;
2. Since the headways on two intersecting lines need not be the same, then the optimization of the transfer at one point in time will not necessarily yield an overall optimum transfer situation, even at one stop; and
3. Since the arrival and departure times are directly linked to terminal layover times, and layover times are constrained by labor regulations, then more vehicles will be needed to serve a given route, if the layover times are longer.

Thus, transfer optimization can be attained by an interactive modification of arrival and departure times at stops. This modification is used to reduce the total waiting times throughout the system by taking into account the added complications of multiple-transfer points on a given line, nonuniform headways between lines, and the interdependence of layover times and vehicle requirements.

INTERACTIVE GRAPHIC TRANSFER OPTIMIZATION

Network Optimization

The interactive graphic computer approach to transfer optimization is part of a coordinated operational transit planning process. As such, the input to the transfer optimization is derived directly from the network optimization (stage 1). Thus, the following is a brief overview of the network-optimization system (NOPTS). Basic input to NOPTS consists of a base network (existing streetcar and subway trackage, subset of the street network suitable for bus transit, and some pedestrian connectors), a transit-trip O-D matrix, and the characteristics of available rolling stock (capacities and operating costs). A transit system is then designed interactively by specifying the routings, vehicle types, and frequencies of individual lines. A multipath stochastic model (8,9) is used to assign the demand to the system of routes. This assignment allows the calculation of some performance parameters of the particular transit system design. By iterating this design-evaluation cycle, the planner can quickly approach an optimum transit network design that is indicated by the choice of design objectives (e.g., minimize operating costs and number of required transfers).

The output from this iterative procedure for network optimization that is important for the subsequent transfer optimization is (a) the selected (optimum) route structure and headways for each line; and (b) at each transfer point, the number of transfer motions between all applicable pairs of transit lines. The fact that the detailed transfer movements can be retrieved from the trip assignment is an important feature that is obtained by using Dial's algorithm (8). As previously mentioned, transfer optimization is conducted separately for each operating period during which headways are constant,

and, thus, the route-headway optimization must also be done for each of these operating periods.

Minimization of Transfer Delays

Since the operating period is a portion of the daily operation during which headways remain constant, then a particular transit line is completely described in time and space, during such an operating period, by the following three parameters:

1. The geographic routing (i.e., sequence of stops),
2. The headway (i.e., the time interval between vehicles passing a given stop), and
3. The terminal offset times (i.e., the time delay, at both terminals of the line, that begins at the start of the operating period and continues until the departure of the first vehicle).

Parameters 1 and 2 result from the network optimization described above, and parameter 3 represents the primary design variables for the transfer-optimization procedure. The iterative design process is aimed at finding a set of terminal offset times that will minimize the aggregate transfer delays systemwide; however, the process is constrained by the operator's desire to keep the operating costs (i.e., the number of vehicles required) at a minimum.

This cost constraint is important because it limits the degree of freedom with which terminal offset times can be varied. This phenomenon is observed in Figure 5, which shows the time-distance diagrams. The terminal offsets (the design variables in the interactive graphic process) shown on the upper diagram have the effect that three vehicles are needed, whereas, in the offsets shown on the lower diagram, one vehicle can be saved without violating the minimum layover time requirements.

In the optimization process, the terminal offsets (departure times at any intermediate stop) are repeatedly varied with the objective of reducing the transfer delays systemwide. The complications of multiple line-crossings, nonuniform headways, and the relation between layover times and vehicle requirements are automatically taken into account. To this effect, the planner can demand the following tasks:

1. Display graphically the internal desire lines of any transfer point;
2. Perform input and interactive editing of terminal phase offsets;
3. Display the current set of terminal offsets, layover times, and the corresponding number of vehicles needed;
4. Display the transfer statistics (arrival time, departure time, number of transferring passengers, wait times) between any pair of lines at any transfer point;
5. Display global statistics (sum of transfer delays, etc.);
6. Display time-distance diagrams of any transit line;
7. Print timetables (departure times at all stops on any line); and
8. Move departure times of lines or groups of lines forward or backward.

The number of possible transfer movements (i.e., direction-specific pairs of lines at each transfer point) is very high, even in a medium-sized city (1200 to 4000). Therefore, it would be impossible to find optimal solutions without some degree of automation. A heuristic technique was developed that searches all the possible terminal point phase offsets of one line (directional) and selects the one offset that produces, with all crossing or parallel lines, the shortest total of transfer delays. The

search process is repeated until the total systemwide delays can no longer be reduced. Of course, the heuristic technique is only able to locate local minima, and it is dependent on the starting point (in terms of the set of initial phase offsets) and on the order in which the transit lines are treated in the iterative process.

SYSTEM APPLICATION

To demonstrate the potential reduction in transfer delays that can be achieved, we applied this system to the existing Basel Transit System shown in Figure 6, which had been coded for another project (6). The public time schedules were used to obtain the phase offsets at the evening off-peak period from 8:00 p.m. to 12:00 m.n.

During this period, most lines have a headway of 12 min, and some lines operate every 15, 24, 30 or 36 min. A total of 82 vehicles were used. NOPTS was used to assign the evening off-peak transit demand to the network, and the number of transfers, the transfer point desire lines, transfer wait, and the total transfer delay (passenger-minutes per hour) were calculated for each stop. The total systemwide transfer delay for 82 vehicles operating on this existing service schedule was 20 544 passenger-min/h. This transfer delay represented the state in which an application of the transfer optimization can be used for improvement.

The heuristic technique was applied, and a minimum in the total transfer delay was achieved. This minimum was 15 600 passenger-min/h or a reduction of about 25

Figure 4. Transfer movements at a typical transfer point.

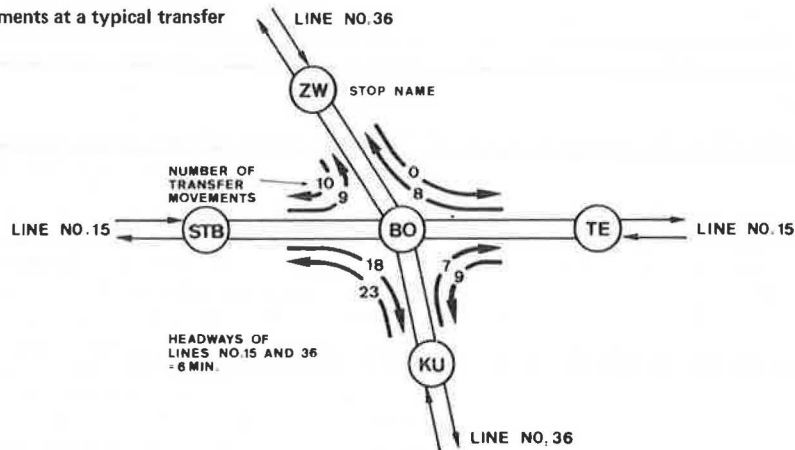


Table 1. Waiting times between example stops.

From Stop	Line	Arrival at BO (min)	To Stop	Line	Departure From BO (min)	Avg Wait at BO (min)	No. of Transfers	Total Wait (min)
STB	15	5.5	ZW	36	6.0	0.5	9	4.5
STB	15	5.5	KU	36	7.5	2.0	18	36.0
TE	15	5.0	ZW	36	6.0	1.0	8	8.0
TE	15	5.0	KU	36	7.5	2.5	9	22.5
KU	36	0.0	TE	15	5.5	5.5	7	38.5
KU	36	0.0	STB	15	5.0	5.0	23	115.0
ZW	36	1.5	STB	15	5.0	3.5	10	35.0
Total								259.5

Figure 5. Relation between terminal offsets and vehicle requirements.

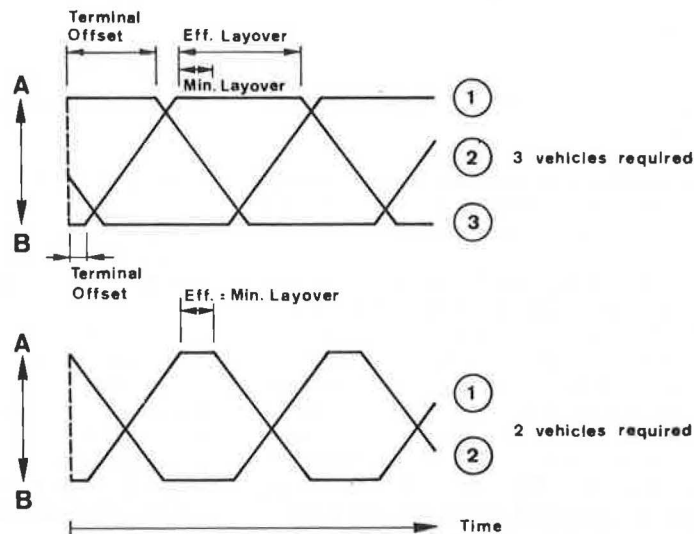


Figure 6. Line map of Basel Transit System.

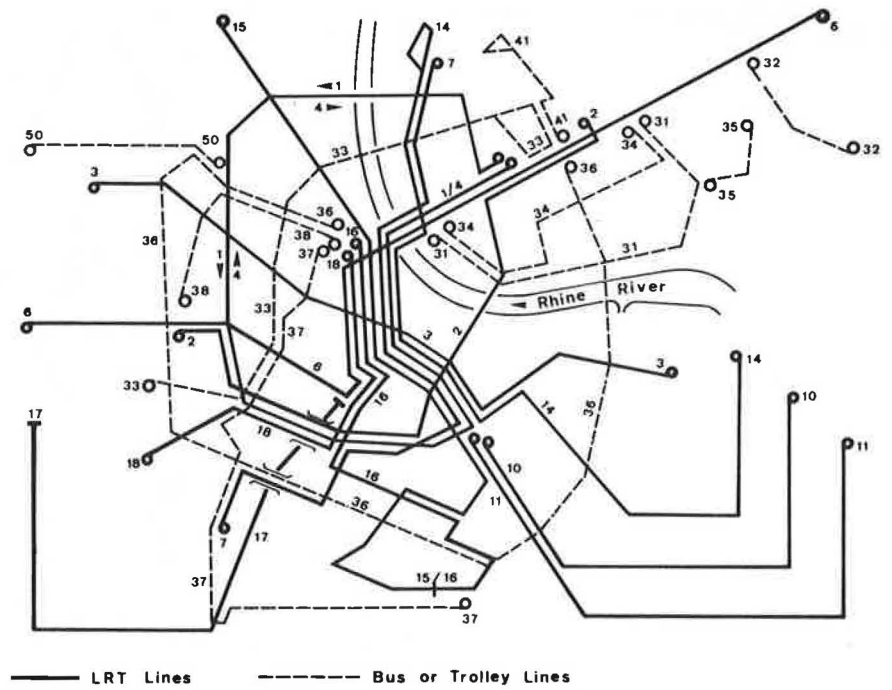


Figure 7. Transfer delay times before and after optimization.

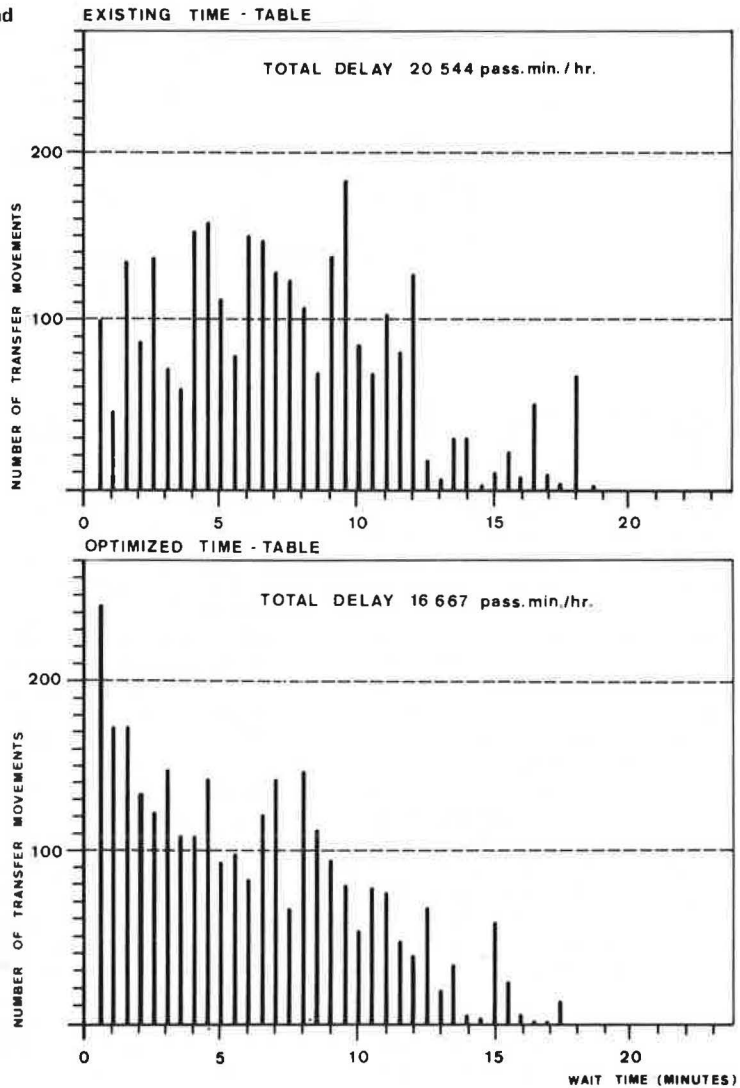
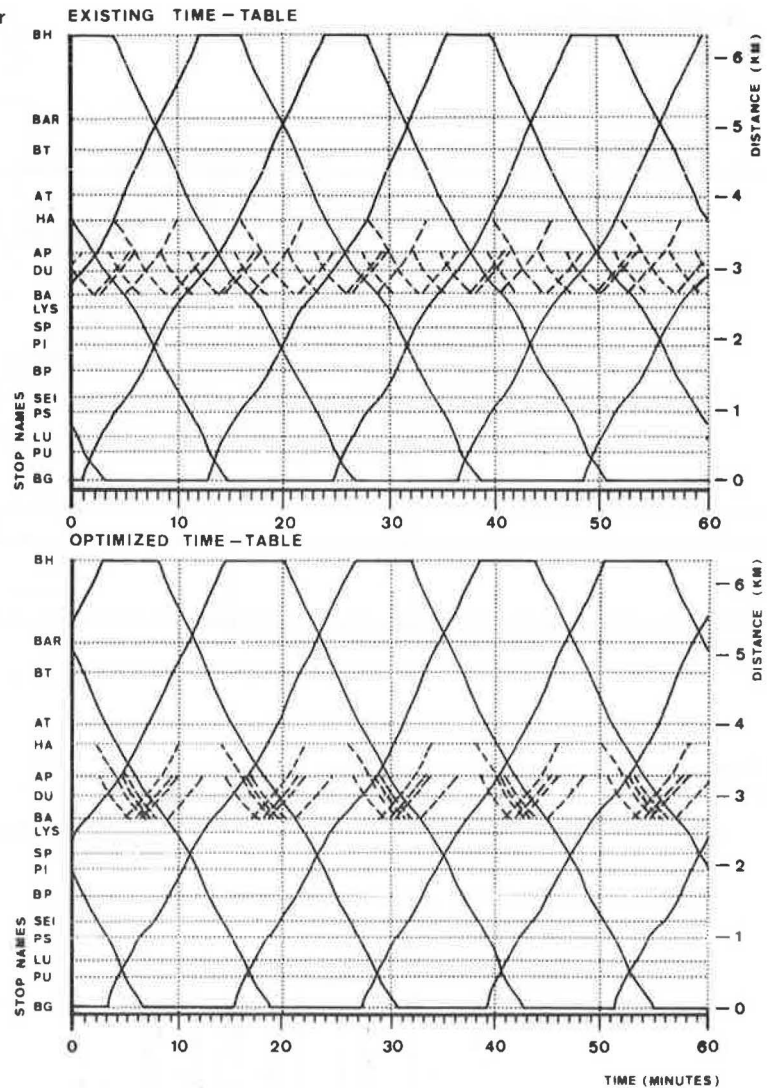


Figure 8. Sample time-distance diagram before and after optimization for line 3.



percent. The optimized set of terminal phase offsets proved to require 86 vehicles. Thus, a 25 percent reduction in total transfer delay was bought by an addition of 4 vehicles during this period.

With the aid of the time-distance diagrams shown in Figure 5, these extra vehicles can be eliminated; however, they can generally be eliminated only at the expense of increased transfer delays. After eliminating all extra vehicles by judiciously shifting the phase offsets at one terminal point of the affected lines, the total transfer delay increased to 16 667 passenger-min/h. This increase still represents a 19 percent improvement over the original state, and there is no increase in the number of vehicles (and drivers) or vehicle-kilometers.

Figure 7 shows the waiting time distribution. This distribution shows that the transferring passengers can obtain improved conditions with the optimized timetable. Whereas the existing handmade timetable shows an almost random distribution of waiting times in the interval between 0 and 12 min, there is a clear skew to shorter delays in the latter. This tendency could be accentuated if, in the optimization heuristic technique, longer waiting times were weighted more heavily than shorter waiting times.

Figure 8 shows the time-distance diagrams of one transit line. The horizontal axis represents time from the start of the operating period, and the vertical axis

represents distance along the route. Each line corresponds to the time-distance description of one vehicle. The connections of lines at terminal points incorporate the minimum layover times required by labor constraints. The dotted lines in the diagram represent the runs of other transit lines along common links. It can be seen that the runs on the common links through the city center are evenly spaced in the case of the existing timetable, whereas the transfer optimization produces batches of runs. Clearly, the more evenly spaced intervals in the first case have the advantage of lower access waiting times for trips that begin and end in the city center, but the number of these trips is relatively small as compared to the number of transferring through trips. These time-distance diagrams are important tools for operational transit planners, and this is one of the reasons why they were included in the display options of the interactive graphic, transfer-optimization system.

Although much work remains in the development of a heuristic technique to assist in this transfer-optimization process, this application example has shown that there is a potential for improvement over the current operating conditions. The example was for evening-period operations only, but it can be safely projected that application of this method to all off-peak operating periods would reduce the transfer waiting times of the Basel passengers by 500 000 h/year. During peak periods, the payoffs are

smaller because of reduced headways (6 min on most lines), and it is difficult to maintain the timetables in mixed traffic conditions.

The example also highlighted the trade-offs that must be made between improving the level of service by reducing transfer delays and economic considerations, in terms of the number of vehicles needed to mount the service. It is in evaluating these kinds of trade-off possibilities that the interactive graphic implementation of the transfer-optimization system demonstrates its greatest use.

LIMITATIONS OF APPROACH

Implicit in the way the problem of operational transit planning has been approached, there are a number of simplifying assumptions. The most important of these assumptions is that both transit travel demand and number of transfers are fixed. One basic input to this operational transit planning process in general, and the network-optimization stage in particular, is the demand for transit trips. It is thus assumed that changes in transit routing and level of service will not affect the demand for the short planning horizon of interest. The primary reason for making this assumption is that data on transit trips are generally more available than those for travel demand in general. It also avoids the necessity of modal-split modeling, which includes additional data requirements and uncertainty.

Each alternative design during the network-optimization stage will, in general, result in a different network loading (as predicted by the multipath assignment algorithm). These loadings are based on expected transfer waiting times. The transfer optimization, as a separable problem, assumes that transfer time optimization will not significantly affect loading patterns. This decision of problem separation was made primarily on the basis of computational efficiency: Re-computing assignments after every transfer time alteration would increase the computing time to the point of making the interactive approach of questionable use.

CONCLUSIONS

In the past, planners have frequently criticized transit operators for a lack of flexibility in adjusting the transit service to the changing demand patterns. Even within transit companies, route and service planners have often found opposition from the operations departments to adjusting the routings and levels of service to the user's observed patterns of change. On the other hand, the operations departments have criticized planners for a lack of understanding of the complexities of frequent route and service changes in terms of the requirements for schedule coordination, run design, and manpower allocation. Thus, a formalized coordinated procedure is needed that will account for both the planners' objectives and the constraints of operations. It is felt that the coordinated, four-stage, operational planning tool discussed in this paper is a first step in this direction.

The transfer-optimization procedure, as stage 2 in this operational planning tool, considers in detail the line-to-line transfer movements, the complexities of nonuniform headways among transit lines, and the constraints imposed by the linkage of labor requirements, which relate to minimal layover times and the numbers of vehicles needed and thus the operating cost. If this search technique is applied to this complex problem, then the special skills of schedulers and operations experts can be combined with the data-handling powers of the computer. Its application should help transit companies to serve their customers better without increasing their deficits.

ACKNOWLEDGMENTS

The computer models described in this paper have been jointly developed by the Transportation Institute of the Federal Institute of Technology, Lausanne, Switzerland, and by the W. and J. Rapp Company, Basel, Switzerland.

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