




4-1973

# Skip-Stop Operation as a Method for Transit Speed Increase

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## Recommended Citation

Vukan R. Vuchic, "Skip-Stop Operation as a Method for Transit Speed Increase", *Traffic Quarterly*, 307-327. April 1973.

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# Skip-Stop Operation as a Method for Transit Speed Increase

## **Abstract**

Increase of transit speeds is one of the most effective ways of increasing the attractiveness of transit for urban travel. While surface transit in particular suffers from low speed, the desirability of higher speeds is not limited to it. Rapid transit has adequate speed for short to medium-distance trips in urban areas. However, for longer trips, particularly when there is a competing freeway facility, the requirement for speed is rather high. Since many station spacings are adopted on the basis of area coverage, high operating speed of the trains often cannot be achieved. Thus, typical lines of urban rapid transit with average interstation spacings of approximately one-half mile have only limited length on which their speeds are satisfactory; for distances longer than, typically, 5-7 miles, they often become too slow. This is becoming an increasing problem with the spatial spread of cities.

This article describes the main alternative solutions to this problem and then focuses on the skip-stop operation, presenting a methodology for its analysis and evaluation of its applicability. Although the article discusses rail services, the basic aspects of the problem are common for any technology. For example, there are a number of bus services for which skip-stop service could be considered utilizing the methodology developed here.

## **Disciplines**

Engineering | Systems Engineering | Transportation Engineering

# Skip-Stop Operation as a Method for Transit Speed Increase

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**I**NCREASE of transit speeds is one of the most effective ways of increasing the attractiveness of transit for urban travel. While surface transit in particular suffers from low speed, the desirability of higher speeds is not limited to it. Rapid transit has adequate speed for short to medium-distance trips in urban areas. However, for longer trips, particularly when there is a competing freeway facility, the requirement for speed is rather high. Since many station spacings are adopted on the basis of area coverage, high operating speed of the trains often cannot be achieved. Thus, typical lines of urban rapid transit with average interstation spacings of approximately one-half mile have only limited length on which their speeds are satisfactory; for distances longer than, typically, 5-7 miles, they often become too slow. This is becoming an increasing problem with the spatial spread of cities.

This article<sup>1</sup> describes the main alternative solutions to this problem and then focuses on the skip-stop operation, presenting

1. The author wishes to express his gratitude to the Urban Mass Transportation Administration for its partial sponsorship of this research through the Transportation Studies Center, University of Pennsylvania (Grant DOT-UT-253-URT-8(70)). Assistance of Messrs. Edson Tennyson, Deputy Secretary for Area and Local Transportation, Commonwealth of Pennsylvania and Frank Berdan, Jr., Planning Director of SEPTA in providing the data on Philadelphia rapid transit operations are also gratefully acknowledged.

a methodology for its analysis and evaluation of its applicability. Although the article discusses rail services, the basic aspects of the problem are common for any technology. For example, there are a number of bus services for which skip-stop service could be considered utilizing the methodology developed here.

#### THE ALTERNATIVE SOLUTIONS

##### *Multitrack Operation*

*Express-Local Service.* The best way to offer fast service to long-distance riders as well as good service to the corridor by short interstation spacings is to provide express and local service on more than two tracks. New York City has a number of lines which provide express service on two tracks and local service on the other two tracks. Provision of only three tracks can also provide such service, if the third track is used for express trains in the peak direction. In addition to New York, Chicago and Philadelphia have had both services. However, the cost of the additional tracks is very high and there are few cases in which they can be economically justified.

*Rapid Transit and Suburban Railroad.* In those cities which have suburban railroads serving the same corridors as rapid transit (each has two tracks), the railroads serve the farther-out areas, while rapid transit, with frequent stations, provides coverage for the inner area. Examples of this arrangement are found in New York, Chicago, London, and Paris. Most other cities do not have these two types of services, so rapid transit must satisfy both requirements—speed and area coverage.

##### *Two-track Operation*

*Longer Interstation Spacings.* Considerable use of automobiles for access to stations has decreased the importance of frequent stations in suburban areas. Therefore, new rapid transit systems in Cleveland, Philadelphia (Lindenwold) and San Francisco have very long interstation spacings (up to 3–5 miles or 5–8 kilometers). This type of service, however, still has the problem that it does not adequately serve the whole corridor through

which the line passes. Also, the stations create excessive concentrations of automobile traffic, negatively affecting the immediate surroundings of those stations.

The question is then whether it is possible to satisfy both the speed and the area coverage requirements on a two-track facility utilizing operational methods such as different stopping schedules for different trains.

*Express-Local Service.* Some systems (Chicago and Philadelphia's Lindenwold Line) operate express-local service on two tracks by dispatching an express train after a long headway and a local train immediately after it. This service provides the advantages of fast and undisturbed ride for long-distance riders, but it results in uneven headways and can be used only when a line is operating considerably below its capacity (headways longer than minimum).

*Zonal Service.* Some systems (e.g., New York) also utilize zonal service for commuter railroad services. With this operation the first of a group of trains runs nonstop through, for example, stations 2-9 and stops at stations 10, 11, 12, and 13, where it terminates. The following train runs nonstop to the sixth station and then stops at each station through the ninth, where it turns back, while the last train serves stations 2-5. This type of service results in higher average speed and lower fleet size requirements, but it drastically reduces frequency of service at each station and also does not provide for travel between the different zone stations. It is, therefore, applicable only for commuter railroads in the areas where a great majority of passengers travel to one central point.

*Skip-Stop Service.* Skip-stop operation has been used with considerable success in Chicago and Philadelphia. This is the sole method by which the speed of urban transit lines with only two tracks can be increased and high frequency of service can be maintained. The purpose of this article is to describe and evaluate this type of operation. On the basis of the analysis, conclusions will be drawn as to the cases in which this type of operation is superior to the standard operation in which all trains stop at all stations.

## DESCRIPTION OF SKIP-STOP OPERATION

Skip-stop operation, compared to standard operation on a time-distance diagram in Figure 1, is obtained by classifying stations along a line into three groups: *A*, *B*, and *AB*. Alternative trains stop at *A* and *AB* and at *B* and *AB* stations, respectively. Thus, at *A* and *B* stations stops only every other train (alternative ones), while at *AB* stations all trains stop.

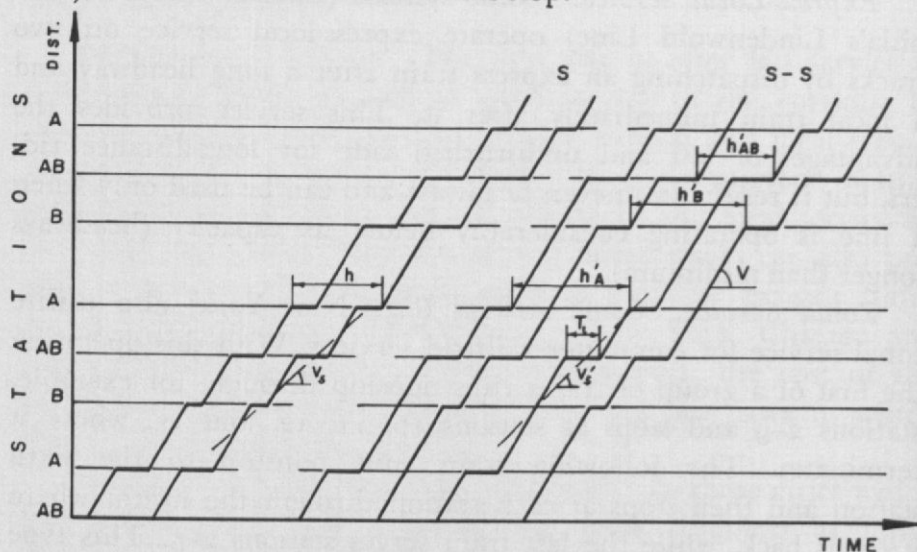


Figure 1. Standard (S) and Skip-Stop (S-S) Operation

Stations *A* and *B* are selected with the following considerations: (1) they should be the stations with the smallest numbers of passengers; (2) the total number of passengers at *A* and those at *B* stations should be similar to maintain even loading of *A* and *B* trains; and (3) the number of *A* and *B* stations should be the same to maintain uniform headways at *AB* stations. Finally, there should be as few consecutive stations as *A-B* pairs as possible, to minimize the number of station-to-station links which cannot be traveled without reversing.

There is practically no investment necessary for this service since the only change which has to be made is to provide designations of *A* and *B* stations and trains, and give the corresponding information to the public.

## SKIP-STOP VS. STANDARD OPERATION

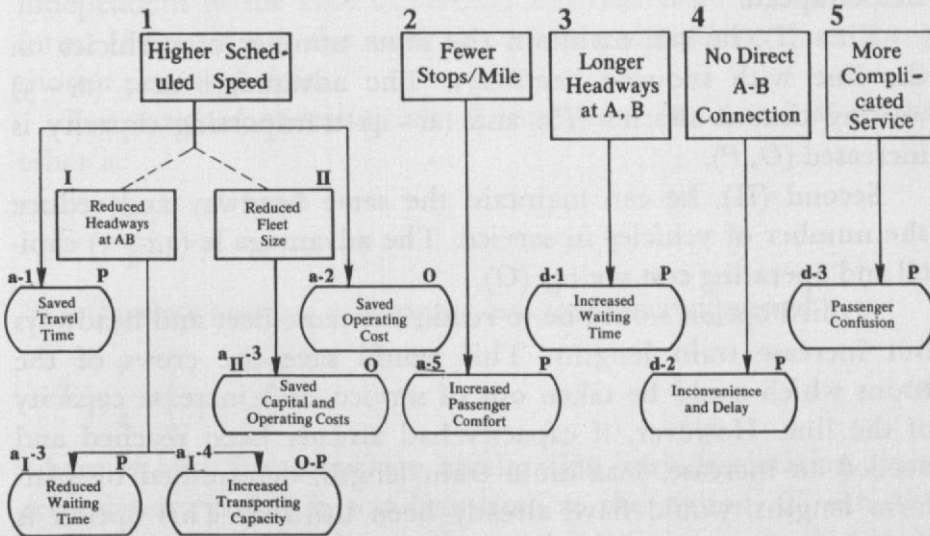


Figure 2. Characteristics of Skip-Stop Operation

*Skip-Stop versus Standard Operation*

The characteristics of skip-stop compared with standard operation and the resulting relative advantages and disadvantages are listed and evaluated here. Figure 2 shows them schematically: rectangular boxes show operational differences; boxes with rounded sides contain advantages (*a*) and disadvantages (*d*) of skip-stop operation, as they affect the two "parties": passengers (*P*) or operator (*O*).

The operational differences of skip-stop operation are:

1. scheduled speed is increased;
2. frequency of stopping is reduced;
3. headways at stations *A* and *B* are increased;
4. there is no direct connection between *A* and *B* stations; and
5. service is more complicated.

Characteristic 1 results in two direct advantages: first (a-1 on

Figure 2), passenger travel time on trains ( $P$ ) is reduced; and second (a-2), operating cost ( $O$ ) is reduced.

The operator has two basic options on how to utilize the increased speed.

First (I), he can maintain the same number of vehicles on the line with reduced headways. The advantages are: (a<sub>I</sub>-3) waiting time is shorter ( $P$ ); and (a<sub>I</sub>-4) transporting capacity is increased ( $O, P$ ).

Second (II), he can maintain the same headway and reduce the number of vehicles in service. The advantage is (a<sub>II</sub>-3) capital and operating cost saving ( $O$ ).

A third option would be to retain the same fleet and headways but increase train lengths. This would save the crews of the trains which could be taken out of service, and increase capacity of the line. However, if capacity had already been reached and needed an increase, maximum train length, determined by platform lengths, would have already been utilized. This option is therefore not common and will not be further analyzed.

Option II is most common. In cases when capacity of the line is reached, it is the only feasible option. Characteristics 2-5 result, respectively (in sequence), in: (a-5) increased passenger travel comfort ( $P$ ); (d-1) increased waiting times at  $A$  and  $B$  stations ( $P$ ); (d-2) inconvenience and delay due to transferring of some passengers ( $P$ ); and (d-3) some potential confusion ( $P$ ).

The above-listed advantages and disadvantages will now be analyzed. The quantitative ones will be based on a model of a line: its length (one-way) is  $L$  and it is  $n + 1$  stations ( $n$  interstation spacings). Other basic designations are defined in the List of Symbols appended to this article. All factors which change when the skip-stop operation is introduced (such as speed, headway, number of vehicles, etc.), will be designated with a prime sign (') added to the original symbol. All times are in minutes, distances in miles, and speeds in miles per hour.

Since the advantages of the skip-stop operation depend heavily on the length of headways (and thereby indirectly on passenger volumes), its evaluation may vary for different periods of



the day. The analysis will therefore be based on hourly values. The assumption will be that the number of passengers boarding and alighting from the trains during that hour at each station is independent of the type of service, and that train arrival is uniform. If this is not the case, the analysis should be done for a shorter period of time.

For standard operation travel time from one terminal to the other is:

$$T_s = \frac{60L}{V} + nT_i; \quad (1)$$

$T_i$  is the time loss due to stopping at one station, expressed by:

$$T_i = \frac{V}{2} \times \left( \frac{1}{A} + \frac{1}{B} \right) + t_s, \quad (2)$$

where  $A$  and  $B$  are average acceleration and deceleration rates, respectively, and  $t_s$  is standing time at the station.  $T_i$  can also be easily found experimentally on the line by measuring train travel time between two fixed points with and without one stopping between them.  $T_i$  is the difference between these two times. It is assumed here that this time interval is constant, although it is somewhat shorter when the train does not reach the maximum speed  $V$  on an interstation spacing. The scheduled speed  $V_s$  and cycle time  $T$  are, respectively:

$$V_s = \frac{60L}{T_s} \text{ and } T = 2(T_s + t_t), \quad (3, 4)$$

$t_t$  being the average of the two terminal (including recovery) times. The headway is:

$$h = \frac{T}{N} = \frac{2}{N} \times \left( \frac{60L}{V} + nT_i + t_t \right), \quad (5)$$

$N$  being the number of trains (vehicles) on the line. The transporting capacity of the line can be expressed through capacity of trains,  $C_t$ , and frequency of service  $f$  (veh./hr.):

$$C = C_t \times f = \frac{60C_t}{h}. \quad (6)$$

*Speed Increase*

With the skip-stop operation, the train travel time changes to:

$$T'_s = T_s - kT_l, \quad (7)$$

$k$  being the number of  $A$ - $B$  pairs. The new scheduled speed,  $V'_s$  is expressed by (3),  $T'_s$  substituting for  $T_s$ . The new cycle time is:

$$T' = T - 2kT_l; \quad (8)$$

the headways at  $AB$  stations under Policy I are reduced to:

$$h'_{AB} = \frac{T'}{N} = h - \frac{2kT_l}{N}; \quad (9)$$

with Policy II the headways at  $AB$  stations do not change. At  $A$  and  $B$  stations the headways, under both policies, become:

$$h'_A = h'_B = 2h'_{AB}. \quad (10)$$

All changes in passenger travel times can now be analyzed together.

*Passenger Travel Time* ( $a - 1, a_1 - 3, d - 1$ ). Two aspects of passenger travel time are important: how does the total travel time of all passengers change, and how is the time saving/loss distributed among passengers?

The total change in passenger travel time on the line consists of the changes in the time on trains and the changes in the waiting time at stations:

$$\Delta PT = \Delta PT_t + \Delta PT_w. \quad (11)$$

Considering time savings as positive (and increased time as negative), the change in the time on trains is:

$$\Delta PT_t = \frac{T_l}{2} \times \sum_{A,B} R_{A,B}, \quad (12)$$

$R_{A,B}$  being the sum of passengers on all trains passing through  $A$  and  $B$  stations. This number is divided by 2 because half of the passengers passing through, say, an  $A$  station, will be on  $B$

trains (assuming even loading) and save  $T_l$ . The other half, on  $A$  trains, will make the stop.

The waiting time in the stations changes by:

$$\Delta PT_w = \frac{h - h'_{AB}}{2} \times \sum_{AB} P_{AB} - \frac{h'_{A,B} - h}{2} \times \sum_{A,B} P_{A,B}, \quad (13-I)$$

$P_{AB}$  being the number of passengers boarding and alighting at  $AB$  stations,  $P_{A,B}$  the number of passengers boarding at  $A$  or  $B$  and those boarding at  $AB$ , but alighting at  $A$  or  $B$ . This equation holds for both policies, although for Policy II,  $h'_{AB} = \frac{1}{2} h'_{A,B} = h$ , so that it simplifies to:

$$\Delta PT_w = -\frac{h}{2} \times \sum_{A,B} P_{A,B}. \quad (13-II)$$

In most cases for which the skip-stop service would be considered the aggregate time saving,  $\Delta PT$ , would be considerable. However, that is not a sufficient reason for introduction of the service, since the distribution of the time savings may be quite uneven. Some passengers, suffering a considerable increase in travel time, might leave the system. It is necessary, therefore, to analyze the time savings and losses for individual groups of passengers.

Passengers boarding at one and alighting at another  $AB$  station are clearly only gaining: they have either the same or decreased headways, and increased travel speed on the line. The passengers boarding at  $A$  and  $B$  stations, however, have waiting time changed (increased) by

$$\Delta T_{w_{A,B}} = -\frac{h'_{A,B} - h}{2}, \quad (14)$$

while train travel time saving depends on the distance they travel, or more precisely, on the number ( $j$ ) of  $A-B$  pairs on the section of the line which they travel:

$$\Delta T_t = jT_l. \quad (15)$$

The passengers realize an overall saving in travel time if

$\Delta T_i > |\Delta T_w|$  (for their trips). Substituting (15) and (14) and then (10) and (9), with Policy I, passengers save time if

$$j > j_0 = \frac{h}{2T_i} - \frac{2k}{N}. \quad (16-I)$$

This expression is very simple to use for any given line. For example, if there are six pairs of *A-B* stations on a line,  $T_i$  is 0.75 minutes, and the number of trains in service is 20, the passengers at stations *A* and *B* would save time if they would travel over  $j$  *A-B* pairs defined as:

$$j > \frac{h}{1.5} - 0.6.$$

Thus, one can examine the distribution of time savings for any given headway, or any period of day. All trips satisfying inequality (16) realize a gain. Note that  $h$  is the *initial* headway, i.e., for standard operation. For Policy II the expression for  $j_0$  is:

$$j_0 = \frac{h}{2T_i}. \quad (16-II)$$

*Operating Costs (a-2).* Train operating costs will be lower in most cases, since the reduced number of stops per mile or per hour of operation reduces both the power requirements and the wear and tear on vehicles. Although no exact data on this item are available, an approximate value may be obtained by measuring the number of trains which can be taken out of service when the skip-stop operation is introduced. The savings in the operating costs are *at least* equal to the operating costs for the trains taken out of service. Cost of additional information for the skip-stop service is negligible.

*Transporting Capacity (a<sub>1</sub>-4).* Under Policy I the number of trains (vehicles) on the line is maintained constant, so that the capacity of the line increases due to the shorter headways by:

$$\Delta C = C' - C = 60C_t \times \left( \frac{1}{h'_{AB}} - \frac{1}{h} \right). \quad (17)$$

*Reduced Fleet (a<sub>II</sub>-3).* Under Policy II the headways are

retained without change for the skip-stop operation, so that, due to the decreased cycle time, the number of trains on the line can be reduced. The savings due to this reduction can be expressed as:

$$\Delta K = K \times \Delta N = K \times \left( \frac{T}{h} - \frac{T'}{h} \right) = 2K \frac{kT_i}{h}, \quad (18)$$

$K$  being the total (capital and operating) cost of a train per unit of time (day or year). It will be shown later that this saving can be very substantial.

#### *Fewer Stops per Mile*

*Traveling Comfort (a-5).* Stopping a transit vehicle is undesirable for the passengers not only because of the delay; it also represents an interruption in their ride and affects them through deceleration-acceleration, opening and closing of doors, walking through the cars, etc. The significance of this interruption is not possible to measure in quantitative terms, but it has been observed that some passengers do not take the first train if it is local, but will rather wait for an express, although the latter will bring them to their destination later than the local. When the train does not stop, the passengers' impression is that the saving is actually considerably greater and more significant than the 30-60 seconds' reduction in travel time. The perceived benefits of not stopping are, therefore, an important advantage of the skip-stop operation.

#### *Connection between A and B Stations*

*Inconvenience and Delay (d-2).* With the introduction of the skip-stop operation, there is no direct connection between A and B stations, so that the passengers traveling between such stations suffer an inconvenience. Those traveling between distant A and B stations have to transfer from an A to a B train at an intermediate AB station. This involves certain discomfort and loss of time in the amount of  $h'_{AB}$ .

The passengers traveling between adjacent A and B stations cannot make those trips, unless they would travel past their station to the first AB station and then backtrack to their desti-

nation. This is highly inconvenient, and if the  $AB$  station has side platforms another fare payment may be necessary. In most cases such trips either do not exist or their number is quite negligible, since very few passengers travel very short distances on rapid transit. Yet, this factor should be considered in selecting  $A$  and  $B$  stations: many consecutive  $A$  and  $B$  stations should be avoided.

### *Complexity of Service*

*Passenger Confusion* ( $d - 3$ ). Skip-stop operation provides a somewhat more complicated service than the standard operation. Passengers must pay more attention to which train they take. This is an item of inconvenience, but in most cases it is not very significant if adequate information is given, particularly at the time such service is introduced for the first time. If the skip-stop operation is used only during certain times of the day, the information about it should be displayed more distinctly during those periods.

## METHODOLOGY FOR APPLICATION OF THE ANALYSIS

The preceding analysis can be utilized for a systematic examination of the advantages and disadvantages of skip-stop operation for any given situation, as well as for finding the optimal number of  $A$ - $B$  station pairs.

### *Steps in the Analysis*

The analysis consists of the following steps: data collection, planning decisions, data preparation, performance computations, and evaluation of alternatives.

*Data Collection.* This calls for obtaining operating data of the analyzed line:  $L$ ,  $T_s$ ,  $t_t$  (or  $T$ ),  $h$  (or  $N$ ),  $T_b$ ,  $C_t$  and  $K$  for the time period considered for skip-stop operation. Trip tables for the line—the number of trips from each to each station—for the studied period must be constructed. If the data for such a table do not exist (which is usually the case), all available data on the number of trips on the line should be collected.

*Planning Decisions.* The alternative skip-stop combinations

which are to be analyzed (e.g., with 2, 4, and 6  $A$ - $B$  pairs) should be selected. Which stations would be  $A$  and  $B$  in each alternative should be determined, as should whether Policy I or Policy II will be used.

*Data Preparation.* A "Performance Table" form like Table I will be needed. The Trip Table should be compiled (if not available) from the collected data. This is the only tedious process in the analysis; its basic steps are described in the subsequent example. The totals in the Trip Table, as explained in Table II, should be computed.

*Performance Computations.* The following should be computed for each of the studied alternatives:  $T_s$  by (1);  $V_s$  ( $V'_s$ ) by (3);  $T$  and  $T'$  by (4 and 8);  $h'_{AB}$  by (9) if Policy I, and  $N$  from (5) if Policy II is adopted. Also,  $j_c$  is found by (16),  $\Delta C$  by (17) and  $\Delta K$  by (18). Passenger time is computed in three

TABLE I—PERFORMANCE OF ALTERNATIVE OPERATING SCHEMES, MARKET-FRANKFORD LINE, P.M. PEAK HOUR \*

	Standard Operation	Skip-Stop		
		S-0	S-3 (3 Pairs)	S-6 (6 Pairs)
$V_s$ (m/h)	20.6	21.6	22.8	23.2
$T$ (min.)	86	82	78	(77) 78
I: $N = 43$				
$h_{AB}$ (min.)	2	1.91	1.81	1.81
$\Delta PT_t$ (hr./day)	—	354	765	870
$\Delta PT_{w_{AB}}$ (hr./day)	—	21	41	39
$\Delta PT_{w_{A,B}}$ (hr./day)	—	-16	-46	-54
$\Delta PT$ (hr./day)	—	359	760	855
$j_c$	—	1.5	1.4	1.3
$\Delta C$ (persons)	—	750	2250	2250
II: $h_{AB} = 2$ min.				
$N$	43	41	39	39
$\Delta PT_t$ (hr./day)	—	354	765	870
$\Delta PT_{w_{A,B}}$ (hr./day)	—	-18	-57	-67
$\Delta PT$ (hr./day)	—	336	708	803
$\Sigma P_{A,B}$	—	1077	3392	4036
$j_c$	—	1.7	1.7	1.7
$\Delta K$ operations (\$/yr.)	—	240,000	480,000	480,000
$\Delta K$ investment (\$/yr.)	—	100,000	200,000	200,000
$\Delta K$ total (\$/yr.)	—	340,000	680,000	680,000

\*  $L = 13.05$  m.

$T_t = 36$  sec. = 0.6 min.

$t_t = 5$  min.

$T_s = 38$  min.

TABLE II—EXPLANATION OF THE TRIP TABLE FOR ANALYSIS OF ALTERNATIVE SERVICES \*

To	From	$O_W$	$J$	$K$	$L$	$M$	$N$	$O_c$	$O$
$D_e$				$D_{Ke}$	$D_{Le}$				
$J$			$S_{Je}$						
$K$		$O_{Kw}$	$S_{Jw=O}$	$S_{Kw}$	$S_{Ke}$		$R_{Le}$	$O_{Ke}$	$O_K$
$L$		$O_{Lw}$			$S_{Lw}$	$S_{Le}$		$O_{Le}$	$O_L$
$M$									
$N$									
$D_W$				$D_{Kw}$	$D_{Lw}$				$O=D$
$D$				$D_K$	$D_L$			$D=O$	

\* J-N — station designations

O, D — originating and destination passengers, respectively.

e, w — eastbound and westbound, respectively.

S — total number of passengers in trains leaving respective station.

R — number of passengers traveling through a station.

Examples:  $O_{Ke}$  — number of passengers traveling from station K eastbound.  $S_{Lw}$  — number of passengers in trains leaving station L westbound.

Note that the number of passengers leaving K is equal to the number leaving J minus destinations at K plus origins at K:

$$S_{Ke} = S_{Je} - D_{Ke} + O_{Ke}$$

Number of passengers traveling through L is equal to the passengers leaving K minus destinations at L or to passengers leaving L minus origins at L:

$$R_{Le} = S_{Ke} - D_{Le} = S_{Le} - O_{Le}$$

steps for the more common Policy II; for Policy I the procedure is very similar as follows:

1. Use equation (12). The sum of passengers for that equation,  $\sum_{A,B} R_{A,B}$  is obtained from the Trip Table through application of the formula for R, given in Table II, to all A and B stations, and then summing them up.

2. Increased waiting time at A and B stations should be computed by (13-II). The sum of the affected passengers is simply the total of all passengers boarding trains at A and B stations



(in both directions), found in the last column of the Trip Table.

3. Find the total time saved by subtracting the increased waiting from the reduced travel time.

4. Estimate how many passengers traveling between  $A$  and  $B$  stations were affected and how they were affected (adding  $h_{AB}$  to their travel time, which can be easily computed; or impossible to make the trip). If significant, correct the time savings estimates and write the number of affected passengers.

*Evaluation of Alternatives.* All the major differences among the alternatives are consolidated in the Performance Table. Due to the fact that it is extremely difficult to bring the various items in the table to a common denominator (value of time would be particularly difficult to handle), and that many other local factors must often be also included in considerations, it is suggested that the planning engineer evaluate the alternatives by observing simultaneously the following items:

$V'_s$ : in addition to the time savings, the increased speed makes the service more attractive for new passengers;

$\Delta PT$ : total time savings of passengers, although relatively small for each individual, often represent a major social benefit;

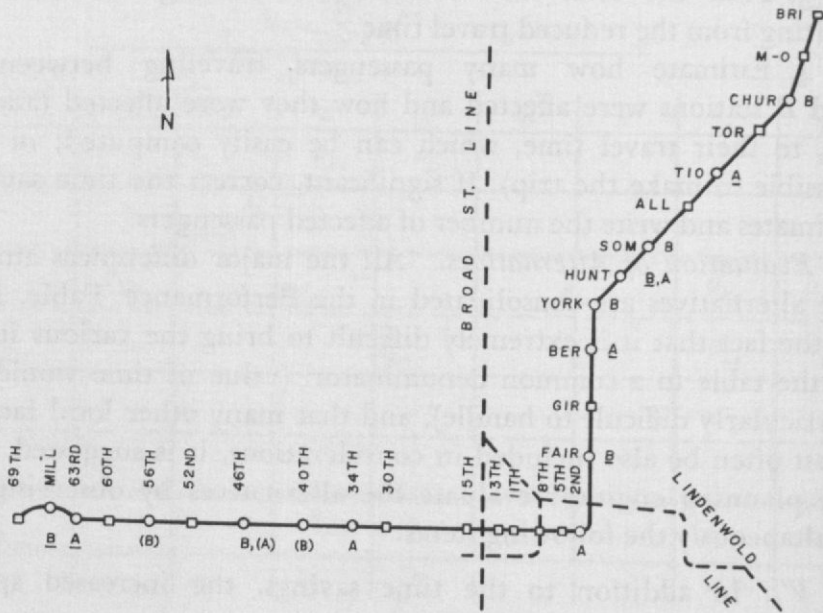
$j_c$ : if its value is high, the number of passengers negatively affected by the skip-stop operation may be significant; in many practical cases it is, however, quite negligible;

$\Delta N$  and  $\Delta K$ : savings in the number of required trains or cars represent a very direct cost reduction for the operator. If the analysis is made prior to a purchase of cars, the savings are not only in the operating but also in the investment costs.

The number of passengers affected negatively in different ways should be analyzed with particular attention. This should be given a greater relative weight than just the amount of time lost, number of additional transfers, etc.

#### *Example of Methodology Application*

The Market Street rapid transit line in Philadelphia, shown in Figure 3, was selected for application of the developed methodology. This line, 13.05 miles long with 28 stations, has had skip-stop operation (six  $A$ - $B$  station pairs) during the peak hours for



- A, B — Skip-stop Stations for 3-pair System  
 A, B — Additional Skip-stop Stations for 6-pair System  
 (A), (B) — Additional Stations for 7-pair System

Figure 3. Market-Frankford Rapid Transit Line in Philadelphia

over 10 years. The steps of analysis given in the preceding section were followed, and they will be briefly described here.

*Data Collection.* Operating data were readily available. They are given in Table I. Passenger counts were obtained from 1954, 1969-1971, as daily passengers for each station, hourly fluctuations for each station, and peak-hour train occupancies at the two maximum load points. No origin-destination data were available.

*Planning Decisions.* Standard operation was compared with three variations of skip-stop operation: three, six (the present operation), and seven A-B station pairs. Values of all elements were to be computed for both policies.

*Data Preparation.* Operating elements were computed and

introduced in the Performance Table, (Table I). The number of trains was computed for the assumed average headway ( $h = 2$  min.) and it may be slightly different from the number of trains really employed because of irregular schedules used in actual operation.

For the Trip Table the 1954 data, containing some valuable hourly fluctuation relationships, were corrected to 1970 through limited data on hourly passenger volumes for 1970 and the total ridership ratios. The total number of passengers entering all stations of the line during the P.M. peak hour was 14 percent of the daily volume, i.e., 29,017. This volume was distributed on station origins by the  $K$  (peak hour) factor for each station (corrected 1954 data), while their destinations were determined by the A.M. peak hour  $K$  factor for each station from the same data, since P.M. destinations corresponds to A.M. origins. A check of this derived Trip Table was made by comparing the obtained maximum occupancies with those counted on the line. Final balancing of the table was made on that basis.

This data manipulation was done with great care and it was time consuming. The second part, computation of the totals, is simple and, for larger tables, could easily be computerized.

*Performance Computations.* These computations followed exactly the procedure defined in the preceding section on methodology.

Cost assumptions were as follows: The total annual operating costs per car are estimated by SEPTA (transit operating agency) at \$42,000. Since this includes costs which would not be reduced by withdrawal of a train (such as track maintenance, station personnel), a conservative figure of only \$20,000 per car per year was used. The investment cost is based on the probable present purchase price of rapid transit cars of \$250,000, depreciated over 30 years.

The saving of the operating expenses for the vehicles not needed is realistic, since the peak requirement is the determinant for the fleet size. The capital cost would be saved, however, only at the time of the car purchase, or if the extra cars could be used for other lines.

For convenience, the costs are given in annual amounts, although passenger times shown are daily.

*Evaluation of Alternatives.* A number of interesting conclusions can be made from the obtained performance results:

1. Total passenger time saving is quite substantial. Although each person saves an *average* of only 1–2 minutes, for some passengers the time saving may be very significant.

2. Time saving is approximately proportional to the number of *A-B* pairs.

3. The low values of  $j_e$  ( $< 2$ ) indicate that a great majority of passengers would realize a net saving in time. The number of persons who cannot make their trips (between adjacent *A* and *B* stations) has been estimated to be in the range of 10–20, or less than 1 per 1000 passengers. Skip-stop, therefore, does not represent an undesirable operation for any significant number of passengers.

4. Policy I as compared with Policy II results in not very significantly higher time saving (less than 10 percent) and line capacity (3–10 percent). However, Policy II results in extremely significant operating and investment cost savings to the operator. Policy II is, therefore, considered more advantageous than Policy I.

5. The aggregate benefits from each of the three skip-stop alternatives are greater than their costs—compared with standard operation. Among the three, S-6 has significantly greater benefits than S-3, while S-7 does not offer any cost reduction over S-6. Its time saving is greater, but the number of people negatively affected is also increased. It is concluded, therefore, that the S-6 alternative, which is the one actually used in operation, is the optimal one.

#### CONCLUSIONS

Skip-stop operation represents an effective way of providing both good area coverage and satisfactory travel speed. Experience with it, so far limited to a few cities, has been very positive and its application should be considered for transit operations in many cities.

Introduction of skip-stop service is usually made on the basis of general estimates of its main positive and negative features. Methodology presented here offers a relatively simple and yet conceptually clear and computationally accurate way of evaluation of various types of skip-stop operations.

The main benefits from the skip-stop operation are reduced passenger travel time, increased traveling comfort, enhanced attractiveness of service for potential travelers due to the increased speed, and savings to the operator, all of which are often quite substantial. The main problems of skip-stop operation are decreased headways at *A* and *B* stations and some initial passenger confusion, which can easily be overcome.

Skip-stop operation is particularly effective on lines with many stations, since it can then offer significant speed increase. However, it can be introduced only when headways are short, so that the double headway at stations *A* and *B* is still acceptable. In most cases skip-stop could be readily introduced when headways are shorter than 3-4 minutes, since the new headways of up to 6-8 minutes would not be excessive. In some cases skip-stop may be desirable even for headways of 5-6 minutes if a significant number of skip-stop station pairs can be introduced, so that the increased waiting time is more than offset by reduced travel time for most passengers. In the example given with equation (16-I), for a headway of 6 minutes passengers traveling through four or more *A-B* pairs would realize greater saving in travel time than loss in waiting. For headways of 3 minutes passengers traveling over only two *A-B* pairs would already realize a net time saving. Consequently, one might expect that skip-stop service would result in benefits to users and operator far exceeding the inconvenience they would cause if it would be introduced, particularly during the peak hours, on a number of lines in New York (as shown by Vickrey<sup>2</sup>), Paris, Montreal, Hamburg, Berlin, Stockholm, Boston, and a number of other cities. Some cities with high-frequency light rail (e.g., San Francisco, Frankfurt, Cologne) or bus (several British cities) service could also benefit from skip-stop operation.

Transit planners should perform this analysis for new lines,

2. Vickrey, "Subway Capacity Potentials."

since its results may influence the number and locations of stations for planned lines. Instead of planning very few stations with long interstation distances, with the risk that additional stations must later be built at a very high cost, in many cases it would be better to provide more stations and maintain high speed by applying the skip-stop operation.

As rail systems progress toward full automation—and other automated systems are being considered—it is likely that frequency of service of modern transit systems, as well as their travel speeds, will increase. Such developments may greatly increase utilization of skip-stop and similar types of operation.

## APPENDIX: LIST OF SYMBOLS

<i>Symbol</i>	<i>Dimension</i>	<i>Definition</i>
$C$	per./hr.	Transporting capacity of line
$C_t$	persons	Capacity of train
$f$	trains/hr.	Frequency of service
$h$	min.	Headway
$j$		Number of skipped stations on a particular trip
$k$		Number of $A$ - $B$ station pairs on a line
$K$	\$/train/yr.	Total annual—capital and operating—cost of one train
$L$	miles	Length of line (one-way)
$n$		Number of interstation spacings on a line
$N$		Number of trains in service on a line
$P_{A,B}$		Number of passengers boarding trains at stations $A$ or $B$ during the studied time interval
$PT$	per./hr.	Passenger travel time
$R_{A,B}$		Number of passengers on the trains passing through stations $A$ and $B$ , respectively
$t_t$	min.	Average of the two terminal times
$T$	min.	Cycle (round trip) time on the line
$T_l$	min.	Incremental time loss per station (difference between travel time with and without stopping)
$T_s$	min.	Scheduled travel terminal-to-terminal time
$T_w$	min.	Waiting time at stations
$T_t$	min.	Travel time on trains
$V$	m/hr.	Maximum running speed

$V_s$  m/hr. Scheduled speed ( $L/T_s$ )  
, Designations of values for skip-stop operation

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