ROLE AND ORGANIZATION OF TRANSFERS IN TRANSIT NETWORKS

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1. TRANSFER AS AN ELEMENT IN TRANSIT NETWORK DESIGN

Passenger transfers among transit lines involve certain "resistance", because they cause some delay and require passenger orientation and walking between vehicles on different lines. Therefore it is sometimes believed that transfers are undesirable and that they should be avoided whenever possible.

The fact is, however, that transit networks with many transfer opportunities offer passengers much greater selection of travel paths than networks with disconnected lines which involve no transferring. In addition, the more transferring is performed, the greater is network efficiency, because each line can be designed optimally for its physical conditions, volume and character of demand. Consequently, when transfers are planned correctly, the resistance for passengers can be easily outweighed by the benefits transfers bring with respect to line alignments, schedules and, eventually, in better services offered. Passenger transfers among lines thus represent an important element of transit travel.

The importance of transfers has been clearly demonstrated by the fact that most successful large transit networks, such as Munich, Toronto and Washington, rely on extensive intermodal and intramodal transfers. Network integration through transfers includes functional design of lines, optimal layout of transfer stations, and coordinated scheduling and information.

This paper presents a systematic classification and analysis of transfers, including methods for scheduling and some aspects of station layout which minimize transfer time and distance, major elements of resistance to transferring.

2. CLASSIFICATION OF TRANSFERS BY HEADWAY LENGTH

As the basic model, passenger transfers occur when two or more transit lines intersect or terminate at the same point. On each line transit units (TUs - common designation for one or more vehicles travelling as a coupled unit) operate at fixed, uniform headways (intervals). Time delays caused by transferring depend on the lengths and relationships of headways on intersecting lines.

If, for a general analysis, lines are classified into those with short headways (generally, ≤ 10 min) and those with long headways (>10 or >15 min), transfers among them, listed in Table 1, have the following characteristics.

Cases A and B: **short-to-short and long-to-short headway**, respectively. Transferring from any line, with short or long headway, to a line with short headway, involves short transfer times. There is no need for any special schedule coordination at transfer points.

Case C: **short-to-long headway.** Reverse transfers to those in Case B, i.e. from a trunk to feeder lines with long headways, may involve long transfer times. The waiting times vary from very short ones to those close to the long headway on the feeder line to which passenger is

Destination line / Originating line	Short headway	Long headway
Short headway	Case A Always short, convenient	Case C Varies greatly Information about connecting runs required
Long headway	Case B Always short, convenient	Case D Variable depending on headways: (1) Equal and simultaneous - all transfers convenient (TTS) (2) Equal but not simultaneous - convenient if coordinated (3) Different - impossible to coordinate; long transfer times

Table 1. Transfer times between lines with short and long

transferring. Thus the degree of inconvenience varies randomly. This uncertainty can be eliminated when schedules for all lines are provided to passengers, so that each passenger can plan his/her trip and take the TU on the trunk line which connects with his particular feeder with minimum delay.

Case D: **long-to-long headway.** Transfers between two lines with long headways can be classified into three subcases based on the relationship of headways on the two lines.

Case D_1: **long-to-long, equal headways**, synchronized, with overlapping standing times. TUs from the connecting lines arrive at the same times and stand for a few minutes to allow exchange of passengers. Thus, easy and convenient transfers are provided for in all directions.

Case D_2: **long-to-long, equal headways**, but no overlap standing times. TU arrivals on two connecting lines are always in the same time sequence. It is possible to make convenient transfers from one line to another (M to N), but not in the opposite direction (N to M).

Case D_3: **long-to-long, different headways.** No coordination is possible. Transfer times are random and can approach the longest headway.

Table 1 presents a summary review of characteristics of individual types of transfers classified by headways of origin and destination lines. It shows that transferring from any line to one with short headways is always convenient (Cases A and B); transferring to a line with long headways varies from very convenient in Case D_1, to very inconvenient with different headways, Case D_3. Coordination of schedules is not necessary in Cases A and B, but it is very important in Cases C, D_1 and D_2.

3. TIMED TRANSFER SYSTEM (TTS)

As shown in Table 1, the only way to provide for instant transfer between two or more lines with long headways is to schedule them so that station standing times of TUs on different lines coincide or at least partially overlap. Operation of two or more lines with such schedules is called Timed Transfer System (TTS). The locations at which the synchronized meetings occur are called transit centers or focal points of the TTS network.

The simplest example of a TTS system is a unifocal network, or a set of lines meeting - terminating or passing through - at a single transit center. A TTS schedule must be such that all the lines operate with the same headway. This, so-called pulse headway, should preferably have a value divisible in 60 minutes, so that the meeting times repeat themselves every hour. To schedule simultaneous meetings of TUs, each line terminating at the center should have the same (pulse) headway, or the same ratio between its cycle time and number of TUs. The relationship among one-way line length L, frequency of service f, cycle speed V_c and the number of TUs in operation N is expressed by the following equation:

$$N = (2L * f)/ V_c$$

Figure 1 shows the layout and graphical schedule for a transit line which has transit centers with TTS operation at both terminals. As the diagram shows, the synchronized lines may have different lengths: line 11 is longer than 12 and 13, but it has a higher operating speed, so that cycle times of all three lines are the same.

TTS can also be used for closed networks, but locations of transit centers must be selected so that pulse headways on all lines connecting them are equal. An example of a closed, trifocal network is shown in Fig. 2. The figure shows positions of buses for operation which has simultaneous meetings at the three centers. Two buses operate on all lines with cycle times T and one bus on the lines with cycles of 0.5T.

In a broader sense, operation of two or more transit lines with simultaneous meetings of vehicle at regular intervals (headways) is used on many different systems. Metro lines sometimes have meetings with simultaneous transfers at headways as short as 3-5 minutes, as will be shown in section 5.1. In some cities night ("owl") transit services operating with one hour headways have scheduled meetings at a central location of the transit network. However, the most common application of the TTS operation is found in suburban areas where bus lines operate at long headways, typically 15 or 20 minutes (or multiples of these). Transit centers may be unimodal: buses meet around an island which may have convenience store, waiting areas, etc.; they exchange passengers, and leave 4-5 minutes later. In many cities (Edmonton, Portland) introduction of a TTS network has resulted in upgrading of an uncoordinated set of lines into an integrated network of bus services with easy transfers among the lines. The TTS-based schedule often requires a slightly greater number of TUs (in the order of 10-15%) and therefore involves higher costs, but it offers a much better service and generates greater ridership and revenue.

Finally, intermodal TTS centers are often organized at stations of regional rail lines. Feeder buses are scheduled to arrive a few minutes before the train and leave a few minutes after its departure from the station. TTS is not used for metro lines which operate with short headways because they are not necessary and they would cause uneven loadings of trains.

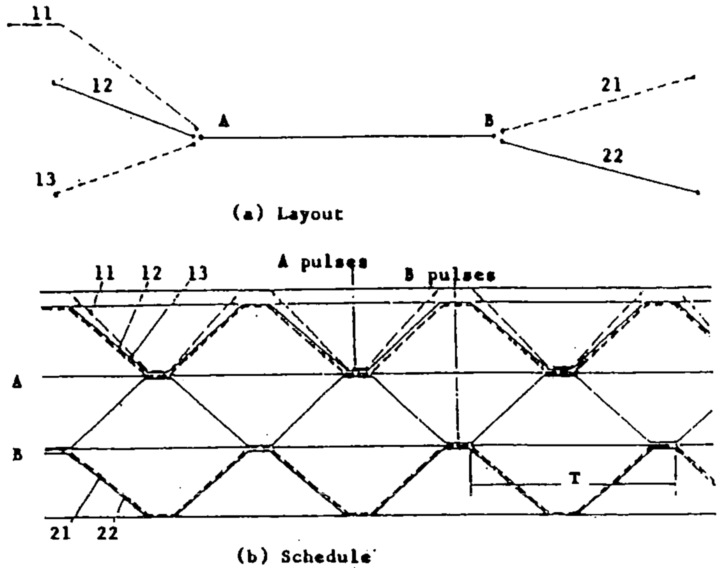


Figure 1. A trunk line with feeders and TTS at both terminals

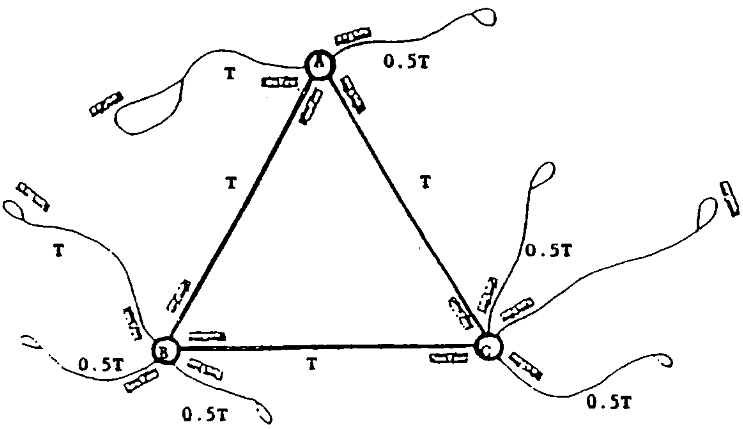


Figure 2. Trifocal transit network with TTS

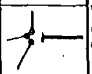
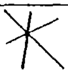
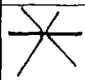
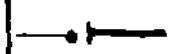
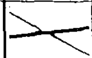
4. CLASSIFICATION OF TRANSFERS BY TYPE OF LINE

The number and character of transfers is influenced considerably by two aspects of the lines among which transfers take place. The first aspect is the relationship of each line to the transfer point: whether it terminates or passes through the transit center. With respect to this aspect, lines will be referred to as terminating (t_e) and through (t_t) lines. The second aspect is whether all lines are of similar nature (frequency, capacity, physical characteristics - mode), or one of them is a dominant or trunk line with considerably higher frequency, capacity and performance in general than any other line, while the others, with low frequency, represent its feeders with a collection/distribution function. This aspect of line type influences transferring patterns of passengers (i.e., many-to-many among equal lines, many-to-one and one-to-many between trunk and feeders).

Suburban bus lines meeting at different points often have a similar nature, while the feeder/trunk situation is typically found where suburban bus lines converge on a major radial line toward the central city. The trunk line may be rail or bus, but with much higher frequency than its individual feeders.

Table 2 presents descriptions and characteristics of transfers classified by the above defined aspects of transit line types. Three combinations of terminating and through lines, expressed in general terms ("N" routes), are

Table 2. Classification of transfers by types of lines

Case number	Number of lines: Terminating	Number of lines: Through	Transfer permutations	Similar lines/routes: Sketch	Similar lines/routes: Typical case	Similar lines/routes: Comment	Trunk with feeders: Sketch	Trunk with feeders: Typical case	Trunk with feeders: Comment
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	N_e	0	$N_e(N_e - 1)$		Many suburban lines terminating	Coordination between lines needed. TTS can be applied successfully.		Trunk line terminating with many feeders	Requires coordination in case of transfers among feeders (TTS)
2	0	N_t	$4N_t(N_t - 1)$		Any point with several intersecting transit lanes	TTS desirable, but causes delay of through passengers		Trunk line station where feeders intersect	TTS possible. Feeders' arrivals and departures "around" trunk's stopping.
3	N_e	N_t	$(N_e + 2N_t)^2 - (N_e + 4N_t)$		Many transit lines terminate or pass through	TTS desirable; easier to achieve than with case 2		Trunk line passes through where feeders intersect and/or terminate	
4	2	0	2		Terminal point of two suburban lines			Trunk line terminal with one feeder	
5	0	2	8		Intersecting point of any two transit lines			Trunk line station where a feeder intersects	
6	1	1	4		Point where one line terminates, another passes through			Trunk line passes through and feeder terminates	

given as Cases 1-3; the other three cases are with specific, small numbers of lines for clarity.

All the cases are described for two types of situations: for similar lines and for trunk-feeder relationship. Each case will be discussed here.

Case 1 is the simplest. When all of the N_e lines coming to a transfer station terminate, the total number of transfer permutations among the lines k is:

$$k = N_e\ (N_e-1).$$

This type of station is the prime case for application of TTS to minimize passenger delays and integrate transit network. A typical example of this case is found where many suburban routes have a common terminal; they may be of similar nature (columns 5-7 in Table 2), or there can be the case of suburban low-frequency lines terminating at a trunk line terminal (columns 8-10). This case is found, for example, at most rapid transit terminals in Atlanta, Hamburg and Philadelphia.

In the latter case, trunk with feeders, application of TTS again greatly facilitates transfers among the feeders, but it creates uneven loadings on the trunk line. Due to its much shorter headways, many of the trunk line's TUs would meet no feeders, while a few would get passenger loads from all feeders. Therefore, TTS should be used only if transferring among feeders is substantial and, whenever possible, feeders should be divided into 2-3 groups which meet in staggered pulses. If this transferring is negligible, feeders should be staggered as much as possible to provide even loading on the trunk.

Case 4 represents the simplest numerical example of this type: two lines with a common terminus. The number of possible transfers is two: one from line A to B, and one from line B to A.

Case 2 represents transfer stations at which all N_t lines pass through. The total number of transfer permutations k is:

$$k = 4N_t(N_t-1).$$

This is a very large number. For only two intersecting lines (shown in Case 5) there are already 8 possible transfers. It is therefore highly desirable to organize a TTS among lines for which there is appreciable number of transferring passengers and which can have the same headways. However, since this transfer point is in the middle of both lines, it causes delay to all through passengers. To minimize that delay and prevent eventual loss of through passengers, it is very important to ensure short layover times through precise scheduling, reliable operation and convenient design of transfer points (short transferring distances).

Case 3 represents the most general situation: N_e terminating lines meet N_t through lines at a joint terminal. The number of possible transfers k among these lines given by the expression

$$k = (N_e + 2N_t)^2 - (N_e + 4N_t).$$

When all lines are terminating, Case 3 "collapses" into Case 1.

Case 6 in Table 2 shows the simplest situation of a transfer between a terminating and a through line: where only two such lines meet. There are only 4 possible transfers and coordination is best achieved if TUs on the terminating line arrive before and leave after TUs on the through line pass through. This condition is similar to the one where feeders intersect a trunk line (cases 2 and 5, columns 8-10), except that no additional delay is caused on either line by this scheduling: terminal time on the terminating line is used for "overlap" with the arrival on the through line.

5. STATION LAYOUTS AND SCHEDULES FOR TRANSFERS IN METRO SYSTEMS

Most transfer stations in metro systems have two or more lines crossing themselves at different levels. Since passengers must negotiate one or two flights of stairs, schedules of trains on different lines cannot be coordinated for simultaneous transfers. However, whenever geometry of line alignments allows, and particularly when large passenger volumes make fast and convenient transfers highly desirable, station layouts which allow across-the-platform simultaneous two-way transfers between trains should be planned. Several such cases are described in this section.

5.1 Simultaneous Transfers Between Weaving Lines

When alignments of two metro lines can be brought to intersect under a flat angle, tracks be "woven" as shown in Fig. 3. The two trains in each direction are then scheduled to operate with the same, simultaneous headways. The passengers are thus given the "ultimate" type of transfer, with minimum distance and no waiting.

Very successful applications of this type of station design are found in Hamburg. Three U-Bahn lines meet each other in pairs at three different stations of the network: Berliner Tor, Farmsen and Kelinghusen Strasse. This operation requires coordinated scheduling of all three lines, precise operations and schedule corrections at stations approaching these junctions. Experience shows that operation with 5-min. headways is easily synchronized, while 2.5-min. headways are somewhat less reliable. Ploschad Nogina station on the Moscow Metro also has this type of design.

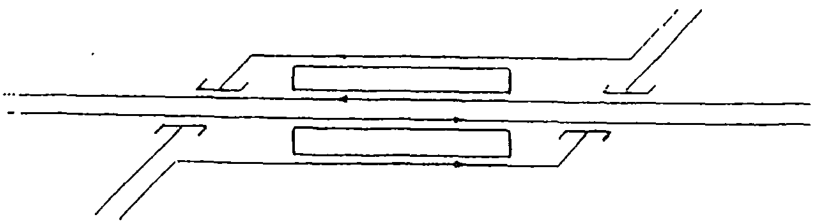


Figure 3. Interchange station for weaving lines with simultaneous transfer

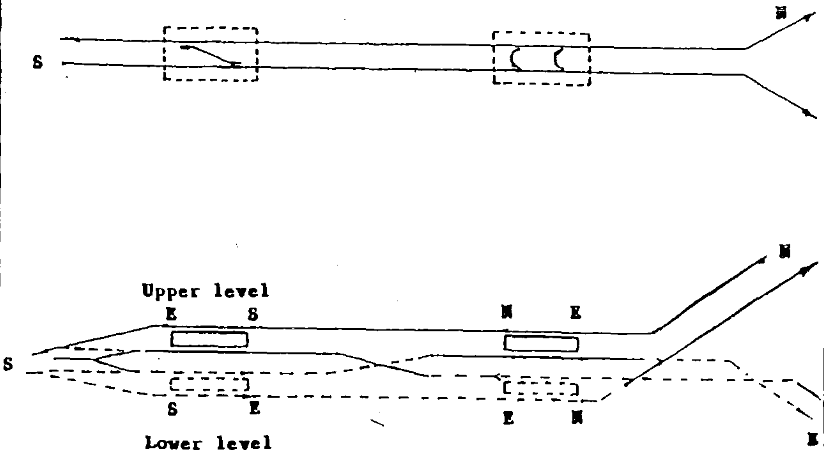


Figure 4. Two-station "Y" junction with across-platform transfers for all movements (Hong Kong)

5.2 Station Design for Transfers at "Y" Junctions

If an "Y"-shaped radial line is operated with the trunk continuing into one branch, while the other branch is disconnected, i.e. operated as a feeder, there are very heavy transfers at the convergence of the two lines. Such a case exists on the Hong Kong Metro: its main radial line from the CBD (Hong Kong Island) goes to Kowloon and then diverges into two lines. The trunk line continues to Tsuen Wan on the north (to be designated here N), while the line to Kwun Tong on the east (E) is operated as a feeder.

Since the majority of passengers from the E line travel toward CBD, but a certain volume also travels to the north, there are heavy passenger transfers between the E line and both directions of the N line at the "Y" junction. To provide for efficient transfers, an imaginative station layout was developed (Fig. 4).

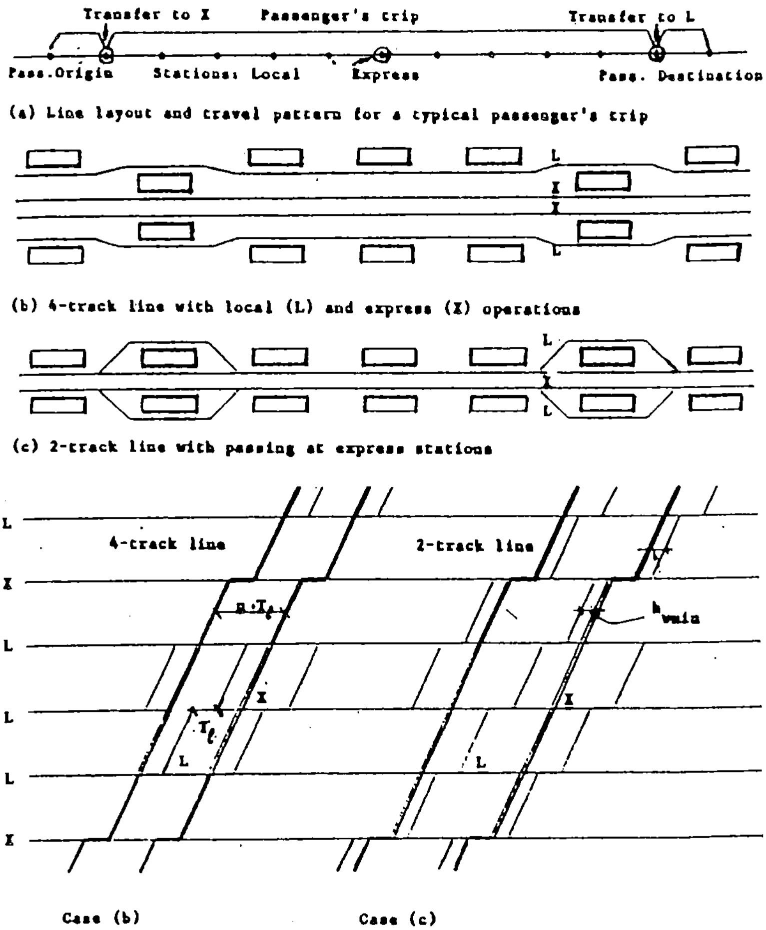
The two lines overlap on a section with two stations. The transfers between E and N in both directions take place at the northern station, where the two lines first meet. The two pairs of tracks between which this transfer takes place are "woven" around joint platforms on two levels. Two of the tracks then change levels, so that at the southern joint station the tracks for transfers between two southbound and two northbound trains are brought to two joint platforms, again on separate levels. Thus, all four sets of transfers - N-E, E-N, S-E and E-S - are organized across platforms, i.e. in the most efficient manner.

5.3 Transfers between Express and Local Trains

Some large cities have metro and regional rail lines which provide local service (trains stop at all stations) as well as express service (trains stop only at major stations). Such services exist on rapid transit systems in several U.S. cities: New York (by far the most extensive), Chicago and Philadelphia have lines with such operation on four, exceptionally three or even two tracks. Several Japanese cities - Tokyo, Osaka and Kobe - also have such operations on their metro and regional rail systems.

The two most typical line designs for local/express operation, one on 4- and the other on 2-track line, are shown in Fig. 5. Sketch 5a shows the basic concept of this type of operation. A passenger who enters the line at a local station and travels a long distance can take a local train to the first express station, transfer to an express train for the largest portion of trip, then again transfers to a local train to get to a destination at a local station

Sketches 5b and 5c show track and station layouts for 4- and 2-track lines, respectively. On the 4-track line the headways of local and express trains are independent of each other, but ideal operation is when local trains are scheduled to stop simultaneously with expresses at every



(d) Graphical schedule of synchronized local/express operations

Figure 5. Station layout and schedule for local/express services with simultaneous transfers

express station, so that passengers can transfer without any waiting. On 2-track lines only this type of schedule synchronization can be operated because trains must pass each other at express stations. The difference between the two cases is shown in the time-distance diagram in sketch 5d: on 4-track lines the ideal schedule is achieved when the headways h for both, local and express lines, are equal to the sum of the times lost T_l by local trains for stopping at the n_1 local stations between the express stations:

$$h = n_1 * T_l.$$

On the 2-track lines local train must arrive in the express station first. Then an express arrives, exchanges passengers across the platform, and departs, followed by the local. Thus the local train's standing time is longer than that of express train by two headways between trains following each other on a line, $h_{w\ min}$. This service requires precise and reliable operation.

6. INCREASING ROLE OF TRANSFERS IN TRANSIT NETWORKS

Transit systems can be successful in attracting passengers and competing with private automobile only if they offer services as integrated, area-wide networks. Integration of different lines of the same mode (e.g., metro network or bus network), as well as intermodal integration can be achieved only if convenient and efficient transfers are provided for.

It has been shown that transfers must be carefully planned for most transit networks. One example are metro networks and stations which handle high service frequencies and large passenger volumes. Another - on the other extreme of transit services - is the TTS, which is primarily applicable to the services in suburban areas with low ridership volumes. However, many regional rail systems also successfully utilize the TTS concept. The importance of transfers is obvious from the fact that transit systems in cities which offer the best services, such as Boston, Calgary and Hannover, consist of multimodal networks relying heavily on transfers. Most cities with low levels of transit services, on the other hand, have minimal or no provisions for convenient transfers. Examples of inadequate services are found in many cities in developing countries, in some auto-based cities in North America (Houston, Phoenix), and, recently, in some British cities with deregulated, competing transit services.

Consequently, with efforts to improve transit services in many cities around the world, the importance of transfers in transit networks will increase further in the foreseeable future.

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