Novel Methodological Approach to Transit Network Analysis: Application to Tel Aviv Metropolitan Area

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Analysis of changes in spatial structure of transit lines represents a serious mathematical and computational problem, one that has not been resolved by existing models and transportation software. An original methodology to enable quantitative analysis of spatial characteristics of transit networks is presented. A set of criteria is developed, and practical experience of the technique is presented as developed for the Tel Aviv metropolitan area.

The Tel Aviv metropolitan area is a contiguous urbanized region with a transit system based on two large, privately owned and operated bus cooperatives with over 200 lines. In 1993 this system was serving a metropolis of 2 million people, 400,000 of whom resided in the core city of Tel Aviv. Historical allocation of bus routes preserved for many years a segregation of the intrametropolitan "Dan" company from the intercity operator "Eged." However, the urbanization process overflowed to the fringes of the region, the spread of the built-up area has blurred the border between intercity and intracity transit. Development of the transit network (TN) has not followed an organized pattern with systematic planning, and this has led to inefficient route structure, with many lines running along the same major corridors and most ending at the central bus station. Today Tel Aviv's TN is characterized by line duplication and levels of service that do not attend to the public's needs.

The contracts that each company has with the Transport and Finance ministries determine the service level, fares, and subsequent government subsidy; in most instances, the municipalities are not involved in transportation planning. Reorganization of the TN generally would be initiated by the bus companies themselves but would require official approval from the Ministry of Transport before going into effect. However, the government has little information and lacks adequate tools to evaluate proposed changes. It has operated on an intuitive and experimental instead of quantitative basis. This situation worsens when service modifications by both companies are introduced for the same area. In such a case, the transit authority also has to choose which proposition to approve. Present policy for route allocation forces compensatory balancing between the companies even though that means unnecessary duplication of Tel Aviv's TN.

Any change to the current situation is bound by a regulatory process and public scrutiny and encounters political pressure to preserve current economic conditions and government subsidies to the operators. Government regulation is based on maintaining a fine economic balance between the cooperatives. Structural change to TN, although economically and socially justifiable, could disturb this stability. Therefore, only marginal changes and not a system improvement have been acceptable. The novel method of TN analysis presented in this paper is based on research undertaken for the Ministry of Transport to facilitate the decision making in TN planning and development.

METHODS FOR TRANSIT NETWORK ANALYSIS

Existing methods for TN analysis are diverse, ranging from rule of thumb guidelines to computer packages. All such methods fall into one of two groups according to Nes et al. (*1*): evaluation methods for a predefined TN and construction methods for new TN design. Evaluation is a necessary element of any construction procedure, so construction methods also employ appropriate evaluation subroutines, see Baaj and Mahmassani (*2*). If planning a local improvement or comparing a limited number of alternatives it is sufficient for planners to perform the evaluation stage only. Evaluation and construction methods can be divided into three subgroups: (*a*) descriptive (based on a simplified calculation of performance measures and a good portion of intuition for TN design), (*b*) heuristic (usually allows user intervention at crucial points of TN design, but performs computerized evaluation of performance and marginal TN improvements), and (*c*) formal (mathematical optimization of TN).

Axhausen and Smith (*3*) have presented a comprehensive review of TN optimization algorithms. Practically all of them consist of three main steps: (*a*) initial TN construction (or input), (*b*) route development (by link addition and deletion), and (*c*) selection of optimum route set. Optimization methods for TN design are classified according to whether both main variables, routes and frequencies, are to be included (*1*). A new algorithm was developed that includes three stages: (*a*) route generation, (*b*) analysis procedure, and (*c*) route improvement (*2*). Summarizing the more than 20-year history of TN optimization, the work by Baaj and Mahmassani (*2*) lists difficulty of formulation, nonlinearity and nonconvexity [see also (*4*)], combinatorial explosion for a large TN, multiobjective nature [see also (*5*)], and difficulty of formalization of spatial layout of routes as problematic areas.

Combinatorial explosion is predetermined by the nature of a transit line that can be represented as a combination of links whose number is multiplied with an increasing number of nodes. Taken together with nonlinearity and nonconvexity, this practically prohibits application of optimization methodology for TN design in large cities. All of existing effective algorithms (*1,2,6–14*) have been applied successfully for relatively small TNs made

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up of not more than 100–250 nodes. A fairly schemative representation of TN in Tel Aviv metropolitan area requires about 2,000 nodes.

The problem of size is closely connected to the formalization of the spatial layout of routes. Frequency allocation to a given set of routes presents a particular problem that can be successfully resolved by using optimization techniques (*15–17*). It is spatial configuration of transit lines (layout of routes) that generates the most cumbersome set of decision-making variables and complicates both evaluation and construction stages of TN analysis.

In a descriptive approach, the planner visually defines the form of TN development. This can be strengthened by use of any evaluation tool. Certain planning guidelines are suggested, based on interviews with transit agencies over a broad spectrum of U.S. and Canadian cities (*18*). Schneider and Smith (*19*) proposed a complete concept for redesigning urban TN (a transit-center-based approach). Alternative route configurations determined by practical considerations were evaluated (*20*). Criteria for TN design suggested by Giannopoulos (*21*) include minimal demand, straightness of lines, and avoidance of overlapping. These practical guidelines give valuable information on basic structural features of an analyzed (designed) TN that, transformed into quantitative measures, can be used as input into an optimization procedure, ensuring integration of formal and intuitive planning techniques.

LEVELS OF TRANSIT NETWORK ANALYSIS

Several levels of detail for TN analysis are possible (Table 1). The first level deals with spatial configuration of TN. A major weak-

TABLE 1 Levels of Transit Network Analysis

Level	Scope	Core of Evaluation	Core of Construction
Line Spatial Configuration	Route Layout, Stop Spacing, Service type, Frequency, Traffic Constraints, Transit Facilities (Vehicle type, Number), Speed	Transit Operation Simulation[a], then Transit Performance Indicators Calculation (including Transit System Cost)[a]	Alternative Networks Development under Coverage or other Service Standard Conditions[b], Systemwide Network Optimization
Trip Distribution	Travel Demand for Transit (+ as above)	Transit Assignment with Fixed Demand[a], Transit Performance Indicators Calculation (including Transit System Cost and Level of Service)[a]	Alternative Networks then Development under Demand with Service Standard Conditions[b], Systemwide Network Optimization
Mode Interaction	Total Travel Demand, Alternative Modes (+ as above)	Modal Split[b] (Multimodal Assignment[a]), Diverted Demand Definition, then Transportation Performance Indicators Calculation (including Transport System Cost and Level of Service)[a]	Alternative Networks Development by Different Scenarios[c]
Linkage with Land-Use	Population Employment and Activity System (+ as above)	Trip Generation and Distribution Sensitive to Transit Accessibility[b], Derivative Demand Definition, then Modal Split[b] (Multimodal Assignment[a]), then Transportation Performance Indicators Calculation (including Transport System Cost, Level of Service and other Social Benefits[c])	Alternative Networks Development by Different Scenarios

a - Implemented Applicapable Software
b - Prospective Software
c - First Attempts to Formulation

ness of such an approach is obvious: TN will not directly follow the demand.

For this reason, routing based on road network calculations (e.g., the shortest path between predetermined terminals) is recognized as ineffective, even for initial route skeleton construction (*3*). In later proposed algorithms, special assignments (''expanded'' or ''first and second'' shortest path) of the demand matrix on the road network (*2*) were applied. Also, account must be taken of the approximate character of the demand matrix. If the demand matrix has been obtained by a trip survey, it will be biased toward existing transit corridors. If demand has been estimated by means of modeling (trip generation and distribution), it could likely be abstract and not sensitive to TN alternatives.

Spatial configuration can be thought of as a self-defining basis of a TN. A basic framework for TN development that cannot be completely formalized is most naturally expressed at this level. Such analysis, which can be performed without a data-taking demand component, is capable of reasonable TN evaluation and can be useful, especially in a preliminary stage in which a large number of solutions is to be reduced to a limited alternative pool. An unknown demand matrix can to a certain extent be substituted by coverage indicators on the basis of service standards per capita or employee. A number of packages can be applied for this task (*22,23*), but existing approaches have concentrated more on passive performance estimators than on TN weakness identification.

The second level is based on a known transit demand matrix. The core of the evaluation is a transit assignment procedure that allows trip distribution by lines and further estimation of transit system cost and components of level of service. The algorithm implemented in the IANO package (*13*) uses an assignment procedure at the last stage of line recombination. The EMME/2 package has a transit assignment module that can simulate the operation of a large TN. Another variant of transit assignment has been proposed (*2*). Transit assignment today is the most accessible tool for planning practice that is useful for comparison of TN alternatives under a fixed demand condition. Trip distribution is placed second to spatial configuration as a planning tool. The capability of existing software for TN construction is extremely limited by TN size.

The third level gives a new facet for substantiation of planning decisions, namely, possible diverted demand from private car to public transport as a result of level of service improvement (assuming total travel demand is fixed). The VOLVO package (*12*) suggested estimation of TN improvement's impact on demand with an independent mode choice model. A deterrence function was borrowed from the simultaneous distribution–modal split model (*24*), which describes the relation between supply and demand (*1*). The conclusion was reached that an external modal split model should be applied iteratively with a TN optimization algorithm to ensure supply-demand equilibrium (*3*). The EMME/2 package has a macro-option of multimodal assignment as a combination of successive automobile and transit assignments, with a demand function incorporating mode choice attributes. The difficulty of running such a technique limits its practical use today.

The fourth level is achievable only in the long-term master-planning framework in which transport system development relates to regional land use. Such large-scale transit projects as a new LRT or subway, which can radically change the accessibility of an area, will inevitably influence activity patterns, including residential and employment choice, and will generate new (derivative) travel demand. However, for practical transit planning this approach is impossible.

PRINCIPLES AND CRITERIA FOR SPATIAL CONFIGURATION ANALYSIS

Table 2 presents criteria used in various approaches at the first and second levels of TN analysis. Among the most common are operational cost, fleet size, and route directness, which serves for initial skeleton construction in almost all TN optimization algorithms. Level-of-service estimators at spatial configuration level were often not formulated, leaving this to a trip distribution stage when travel time or the number of transfers can be estimated by transit assignment. The lack of measures of spatial configuration from the passengers' point of view precludes TN construction subroutines from producing a good starting TN in most of the algorithms (*3*).

A number of criteria have been introduced in descriptive approaches and recent formal models. Among these are area coverage and direct connection possibility. Two spatial characteristics have been formulated (*19*): location of focal points (transfer centers) and service type (e.g., express or collector), but they are in need of quantification. Route duplication is noted as significant for TN design quality (*18* and *21*). An empirical maximum acceptable level of route overlapping was estimated as 50 percent (*21*). Duplication was introduced into the route joining subroutine of the TN improvement algorithm (*2*).

Ridership measures (passenger-miles, passenger per length) are the most commonly used indicator of system effectiveness, after trip distribution by lines. Every planner wants first to ensure that a proposed line will get reasonable ridership. Two level-of-service indicators have been established (*3*): demand density (ratio of the number of trips with 0,1,2 transfers to the number of origin-destination pairs connected with 0,1,2 transfers) and time deformation (difference in travel time between an optimum TN and actual TN). Demand slices by number of transfers are also considered (*2*).

To incorporate different criteria on a uniform methodological platform, systemwide TN characteristics should be stressed. The criteria list must be completed by indicators of TN connectivity and supplementation of each line to others. In real TNs, where great importance is placed on transfers, searching for the most effective way to deliver passengers on all origin-destination pairs in the entire TN is suggested. The proposed approach is composed of previously applied criteria but concentrates more on TN spatial configuration. It is based on three chief criteria: (*a*) line duplication, (*b*) area coverage and transit accessibility, and (*c*) network integration.

Line duplication allows recognition of a similarity of lines. Duplication represents an undesirable factor that negatively affects bus occupancy and adds nothing to the level of service. Significant duplication among lines reveals poor TN design. Practically, a systemwide duplication check can be reduced to a sequential check of all pairs of lines in the TN. For this reason, only pair duplication is described.

Line duplication (D) is composed of three components: (*a*) route overlapping (DR), (*b*) service identity (DS), and (*c*) frequency surplus (DF). D is calculated as

$$D(\%) = \frac{DR(\%) \cdot DS(\%) \cdot DF(\%)}{100(\%) \cdot 100(\%)} \qquad (1)$$

TABLE 2 Criteria for Spatial Configuration Analysis (Existing Approaches)

	Spatial Configuration Only										Trip Distribution by Lines						
	System Cost					Level of Service					System Effect		Level of Service				
	1. Operational costs 2. Fleet size 3. Route Directness 4. Route Length 5. Route Duplication					6. Service standards 7. Area coverage 8. Direct connection 9. Focal points 10.Service Type					11.Line/link Ridership 12.Vehicle Occupancy		13. Travel Time 14. Waiting Time 15. No. of Transfers 16. Demand Density 17. Time Deformation				
Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Formal Methods																	
Axhausen,Smith			+	+			+				+		+		+	+	+
Baaj,Mahmassani		+			+	+	+	+			+	+	+	+	+	+	
Billheimer,Gray	+																
Dubois,Bell,Llibre		+	+								+		+				
Furth,Wilson											+			+			
Hasselstroem											+	+			+		
Hsu,Surti			+								+						
Jun,Schnaider	+	+									+			+			
Lampkin,Saalmans		+	+								+		+				
Mandl			+								+		+	+	+		
Marwah	+	+											+		+		
Nebelung			+					+									
Nes, Hamerslag,Immers		+					+		+		+				+		
Rea			+								+			+			
Rosello	+		+	+							+						
Scheele		+									+		+	+			
Sahling			+								+						
Sharp	+												+	+			
Silman, Barzily,Passy			+								+						
Sonntag								+			+						+
Descriptive Methods																	
Chua,Silcock							+										
Giannopoulos	+		+	+	+						+						
NCHRP69			+	+	+	+	+										
Schnaider,Smith		+		+		+	+		+	+	+		+	+			
Thelen,Chatterjee, Wegmann	+						+						+				

All components are scaled from 0 through 100 percent. Zero means full divergence and 100 percent indicates complete identity of lines. Route overlapping is calculated first by comparing lines with regard to mutual segments. If a sufficient level of overlapping is identified (more than 40 percent), service identity and frequency surplus are checked. Criterion (*D*) becomes 0 in a case of lines' divergence by one component at least, but tends to 100 percent only when all components do so.

Route overlapping (*DR*) is calculated as a weighted sum of line segment proximity coefficients (*DD*).

$$DR(\%) = \frac{\sum_i DD_{i,j(i)} \cdot W_i \cdot W_{j(i)}}{\sum_i W_i^2} \qquad (2)$$

where

i = segments of given line,
$j(i)$ = segment of original line most closed to segment i, and
$W(i)$ = segment weight.

Coefficients and consequent route overlapping vary from 0 to 100 percent. The proximity coefficient for a particular segment of the original line gets the value 100 percent if an identical segment exists in the given line. Route overlapping is 100 percent only in the case of complete identity of all segments of given line with appropriate segments of the original line. Details of segment proximity (*DD*) and weight (*W*) estimation vary depending on objectives and data available. Comprehensive discussion on this issue can be found in a work by Cohen et al. (*25*).

In some cases, route overlapping derives from the road network structure. This occurs in southern Tel Aviv, where few possible entries predetermine overlapping for more than 70 routes connected CBD with the southern sector of the city. There are two possibilities for treatment of such enforced overlapping. The first suggests an additional multiplying coefficient for segment weight. The second assumes a permissible overlapping level. A permissible overlapping level for Tel Aviv has been set at 40 percent. Besides the CBD entrance, it reflects enforced overlapping in the central bus-station neighborhood.

Service identity (*DS*) is specified with regard to service type pairs. There are three main types of bus service: (*a*) direct (from origin to destination without intermediate stops), (*b*) express (intermediate stops only at key points), and (*c*) collector (all stops along line route are available). The classification is conventional, and it is possible to further differentiate types of service. The type of line service is specified as follows:

- 100 percent—full service identity (the same type),
- 50 percent—partial service similarity (direct or collector with express), and
- 10 percent—distinct kind of services (direct against collector).

The lines of service reflect a ridership that may "migrate" from one line to another. Detailed description of stop spacing could be a substitute for a service identity estimation. In that case, route overlapping includes service pecularities. Criterion *DS* is of importance for aggregate spatial description of routes and gives supplementary information on route overlapping. For example, an express line passing along a collector line should not be treated as completely duplicating.

Frequency surplus (*DF*) is defined as total frequency over a given maximum level divided by frequency of a given line. When ridership is unknown, the maximum level of frequency is defined a priori, for example, by a 5-min headway during the peak hours that yields (*DF*) values. The criterion depends largely on the maximum level defined. Taking a 3-min headway, one would obtain a concordance for lines both having 6-min headway as opposed to 80 percent surplus. It can also be calculated separately for peak and off-peak periods. Frequency surplus distinguishes between supplementary duplication of lines in the particular segment that needs frequency enhancement and real duplication that means useless bus trips. If transit assignment results are available, maximum reasonable frequency is calculated on the basis of passenger flows assigned but should not be less than a policy headway (15 to 30 min).

Area coverage and transit accessibility (Figure 1) reflect service scope and level for a given line or the TN as a whole. Coverage or accessibility improvement represents an advantage for a given line. Usually accessibility improvement is a main argument for a new line in an existing TN. Coverage reflects an aggregative relationship, "area-service," as accessibility represents a disaggregative relationship, "population-service," within the area unit. If the level of spatial aggregation is low (area unit size is comparable with walking time), coverage and accessibility indicate the same. If aggregation level is high (area unit size is much greater than walking time), accessibility is not defined. An intermediate level suggests a supplementary role: coverage represents aggregative parameters of area transit supply, whereas accessibility reflects internal parameters for each zone.

Coverage is based on a comparison of total parameters of TN with total parameters of the service area. There are two methods derived from two main quantitative characteristics of transit service: total frequency and number of lines (or total length). Total frequency is more usual for transportation planning. Line coverage is more suitable for land use or geographical study.

The frequency group is in turn divided into two types of coverage: nonoriented and oriented. For nonoriented coverage, a total frequency of all lines crossing the area unit is compared with unit travel demand factors (e.g., population and employees). This method is simple and practically available but not sensitive to trip directions. To take directionality into account, oriented coverage should be applied when total frequency and demand are compared for origin-destination pairs. Frequency is summed for all lines connecting a given origin and destination. Demand can be given by a trip matrix or estimated by travel potential (for instance, population and employees). Oriented coverage does not include transfers and is therefore also approximate. Line coverage is usually calculated as total line length/km^2 (transit density), but number of lines/km^2 is also of interest because it characterizes service multitude.

Accessibility includes two parameters: walking time or distance (formal accessibility) and total time, including walking, waiting, and riding to the most closed focal point in the TN (real accessibility to a wide service range). Transit planning usually is oriented to simple formal accessibility, assuming that any line fits travel demand direction. This appears reasonable for a radial or grid TN in which directions are obvious. A complex TN presents a problem for accessibility definition, because the closest line in origin can be useless for the passenger depending on destination. In such cases, the time to get to the closest focal point is more informative. A focal point can be defined as a node where at least

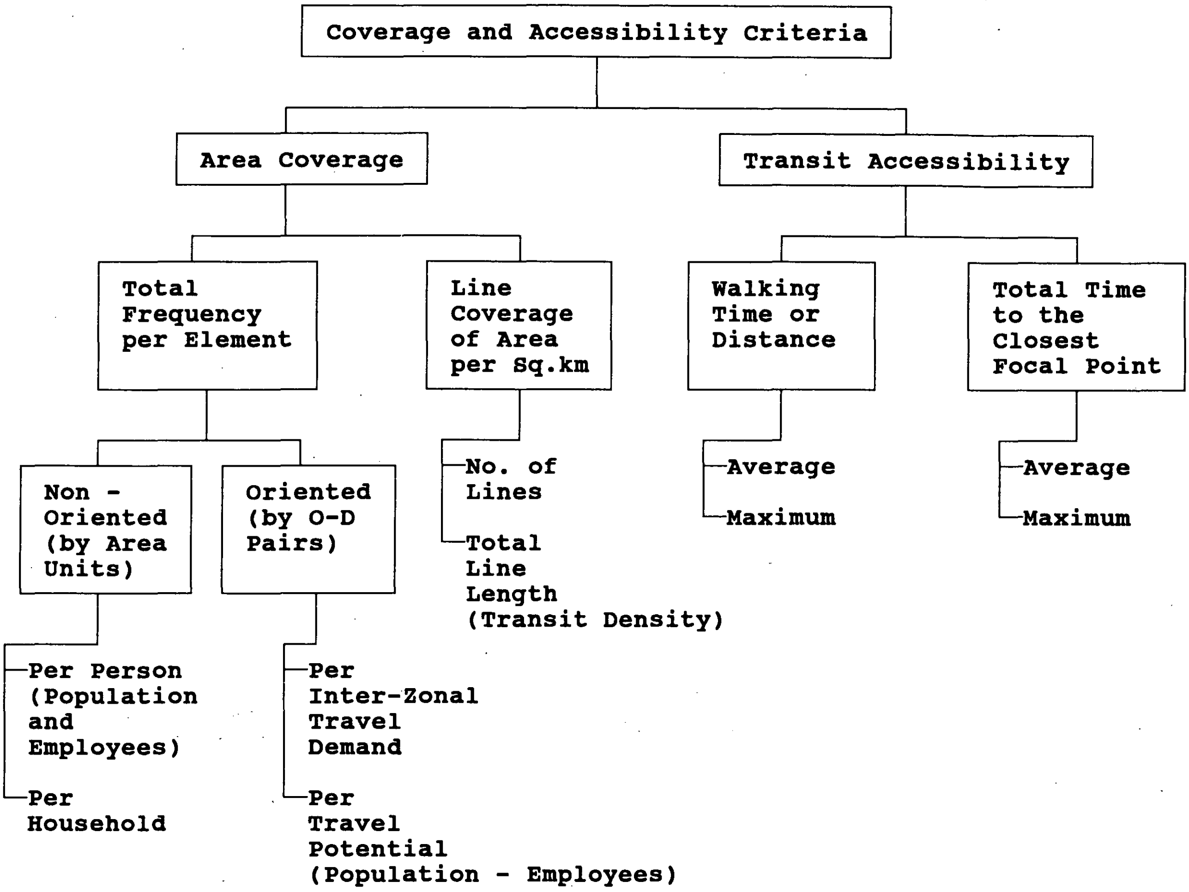


FIGURE 1 Classification of coverage and accessibility criteria.

three nonduplicative lines cross. Both parameters are estimated for each area unit. Later, two main summary principles can be involved: "average," which characterizes accessibility in a given region as a whole, and "maximum," which reveals the most problematic area units.

For total frequency per person, quantitative boundaries can be established in terms of low, standard, and surplus level of service (*25*). Improvement of coverage means reduction in the number of area units with low level of service. A growth in number of units with surplus service is not desirable.

Network integration can be viewed as different lines' consistency and allows recognition of the role of a given line in TN. It positively affects trip structure and level of service and balances between two contradictory objectives of TN design: direct connection and transfer convenience. Integration evaluation has two stages (Figure 2): (*a*) evaluation of given line characteristics and (*b*) evaluation of TN systemwide characteristics.

In the first stage, two subsets are involved: line crossing and line "exclusive addition to the TN integration." Crossing characterizes transfers to other lines. There are three pairs of parameters in the subset: (*a*) number of lines crossing the given line (*CL*), and the same for unduplicative lines only (*UCL*); (*b*) number of transfer points in the given line (*TP*), and the same for unduplicative lines only (*TPU*); and (*c*) minimum number of transfer points in the given line, which enables access to all crossing lines (*MTP*), and the same for unduplicative lines (*MTPU*) only.

Figure 3 presents a TN fragment. There are two compared lines (*A,B*) and five others (1–5). Number of crossing lines reveals an integration advantage for line *A*: *LC*(*A*) = 6; *LC*(*B*) = 2. Nevertheless, some of the lines crossing line *A* (1,5) duplicate it. A duplicative line usually presents no interest to transfer, because it has no (or few) additional destinations over the original line. To take this into account, the number of unduplicative crossing lines is of help. According to this parameter, the advantage of line *A* is not so appreciable: *UCL*(*A*) = 4 (without lines 1,5); *UCL*(*B*) = 2.

The second pair of parameters deals with transfer-point allocation. They are distinct from the number of crossing lines for two reasons. First, more than two lines can cross at one point (*b* for lines *A*,2,3,4). Second, two lines can cross each other several times. Usually, this occurs in duplicative lines, but not necessarily. Duplicative lines *A* and 1 have a list of transfer points *g*, *f*, . . ; unduplicative lines *A* and 2 also have transfer points *b* and *c*. The number of transfer points shows an advantage to line *A*: *TP*(*A*) = 12, *TP*(*B*) = 2. Most transfer points of line *A* are related to the duplicative lines *1* and *5*. Without them, the advantage of line *A* is less appreciable: *TPU*(*A*) = 3, *TPU*(*B*) = 2.

The third pair of parameters reflects transfer-point distinction. Two transfer points in the line are distinct if they have different crossing lines, as opposed to having the same lines. Practically, each line has a limited number of focal points that allow access to all crossing lines. This parameter is significant to line integra-

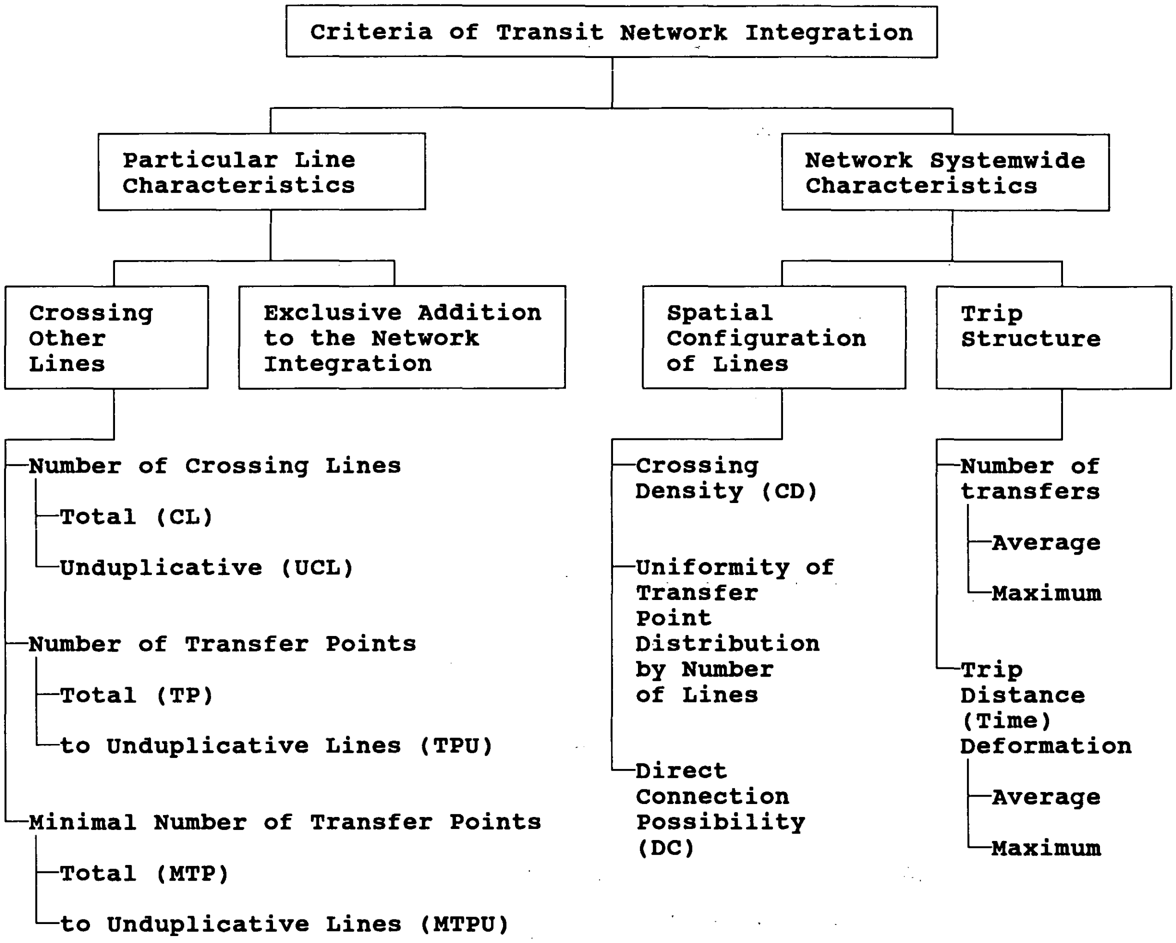


FIGURE 2 Classification of network integration criteria.

tion. It is similar for both given lines: $MTP(A) = 3\ (a,b,i)$, $MTP(B) = 2\ (a,m)$. Without duplication, equality of lines A,B is revealed: $MTPU(A) = 2\ (a,b)$, $MTPU(B) = 2\ (a,m)$.

In sum, two parameters (*UCL* and *MTPU*) can be viewed as most important in the subset. Simply by crossing parameters (*CL*, *TP*), line *A* has a significant advantage. Nevertheless, most of the advantages of line *A* should not be treated as real because they derive from the duplicative lines. More accurate analysis shows that line *B* is comparatively successful.

Exclusive addition to the TN integration, *ANI*, represents a given line's contribution to transfer-point variety. First, interim calculations must be made, including the total number of TN transfer points (*TPN*) and focal points (*TPNF*), and the same without the given line (TPN^0,$TPNF^0$). Then line-exclusive addition to the number of transfer points (ΔTP) and focal points (ΔTPF) are calculated:

$$\Delta TP = TPN - TPN^0; \quad \Delta TPF = TPNF - TPNF^0 \tag{3}$$

After that the final calculation should be made.

$$ANI = \frac{(\Delta TP + \Delta TPF)}{TPN} \tag{4}$$

A line is considered significant for TN integration if it generates original transfer points or new focal points. If a line provides neither additional transfer points nor focal transfer points, it means that the line crosses others only in existing focal points. Normally, line-exclusive addition to the TN integration should be comparable with the total number of lines. For a TN including 100 lines, an average level of *ANI* can be defined as 1 percent. A line that has more than 1 percent addition can be viewed as especially important.

At the second stage, two subsets are involved: spatial configuration and trip structure indicators. A TN configuration is related to the spatial structure of the region. There are three criteria in the subset: crossing density (*CD*), uniformity of transfer point distribution, and direct connection (*DC*).

Crossing density indicates TN connectivity. It is calculated as a number of TN transfer points divided by a number of regional area units (*AU*).

$$CD = \frac{TPN}{AU} \tag{5}$$

Figure 4 presents typical TN patterns. Crossing density (*CD*) reveals an advantage of grid and shortcoming of radial and polycentric form, which allows limited possibility of transfer. How-

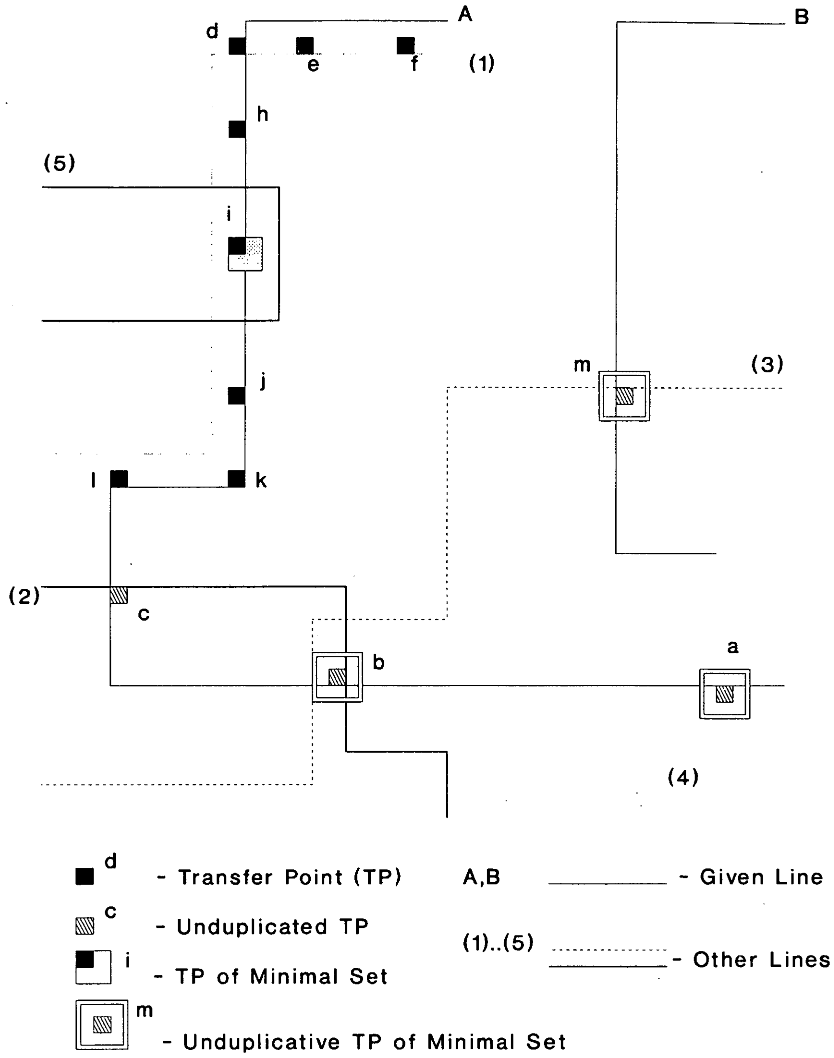


FIGURE 3 **Line crossing in transit network.**

ever, they are recognized as the most economical. A directionally oriented form is attractive in a case of oriented demand, but at the same time it is the most expensive. The TN in Tel Aviv is mixed, but all forms can be revealed. The Eged subnetwork is mostly radial, centered at the Tel Aviv central bus station. The Dan subnetwork in the northern part of Tel Aviv has a grid form, but in the southern part it is close to a directionally oriented form. Crossing density is of help for TN connectivity estimation as a whole. Approximate values of *CD* are 40 percent and more for tied TN (grid), 20 to 40 percent for mixed, and less than 20 percent for radial.

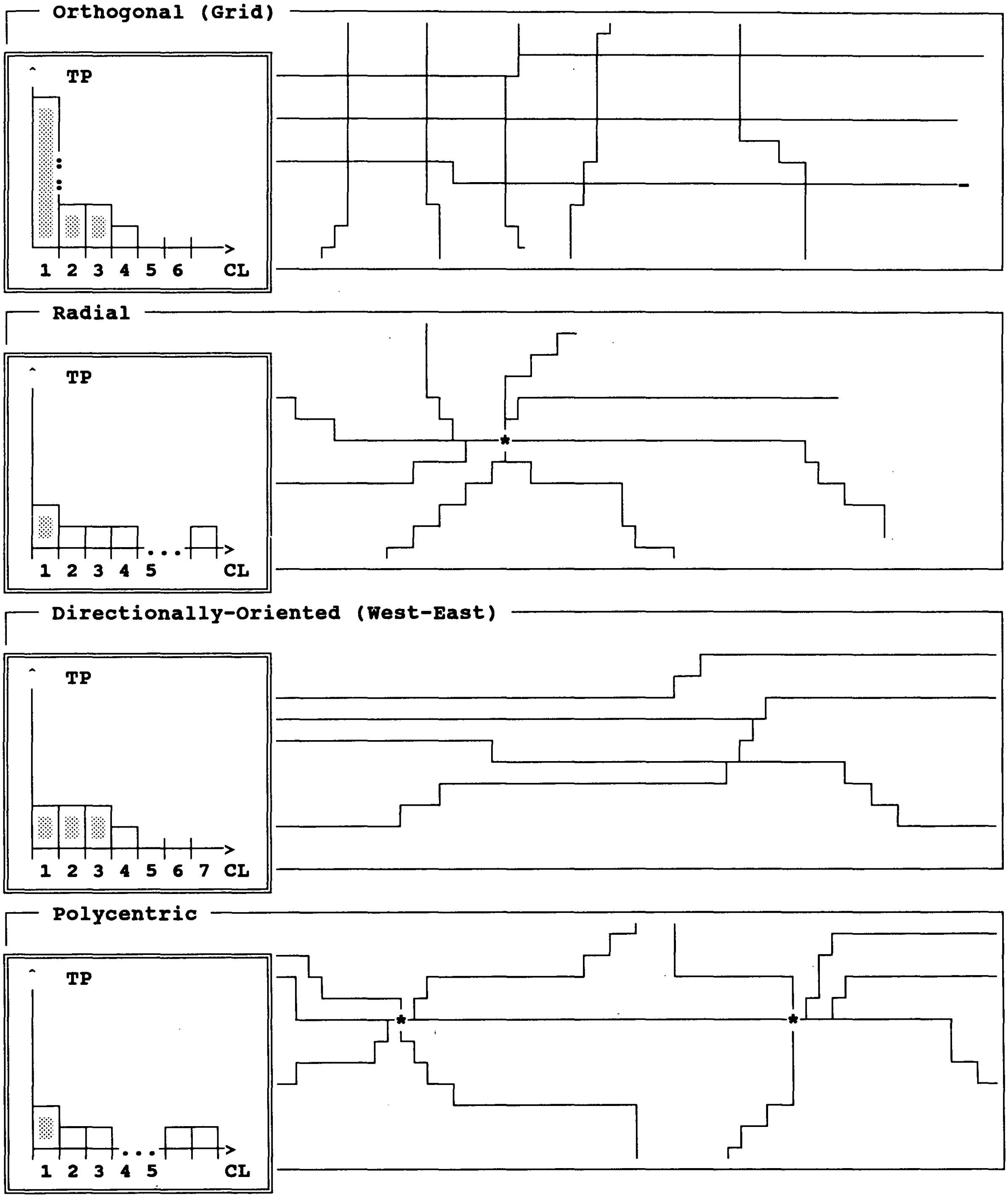
Because crossing density does not differentiate between ordinary and focal transfer points, radial TN (with wide center including a few area units) and a directionally oriented TN may have the same CD value. To distinguish between them, uniformity of transfer point distribution is of help (Figure 4). A Grid TN has the most uniform distribution (no focal points), and a radial TN has one dominant central point. Uniformity can be seen as a positive factor of TN integration.

Direct connection (*DC*) indicates the possibility to travel to a destination without transfer. It is calculated as the number of area unit pairs directly connected by at least one transit line (*DSP*) divided by the total number of pairs. The latter can be calculated as $AU \cdot (AU - 1)/2$, thus

$$DC = \frac{2 \cdot DSP}{AU \cdot (AU - 1)} \qquad (6)$$

Crossing density and direct connection are contradictory—the first suggests transfers, but the second avoids them. That reflects the contradictory objectives of TN design: to improve level of service and reduce costs. Direct connection reveals an advantage of a directionally oriented TN and a shortcoming of a radial or polycentric TN. Normally, the cost criterion yields the opposite result. The directionally oriented form is effective from different points of view when demand is oriented. For example, in southern Tel Aviv, 80 percent of trips are south-north oriented as a result of the spatial structure of population and employment.

Trip structure summarizes the effectiveness of TN design. Two criteria should be noted: the number of transfers and trip distance or time deformation. Deformation is calculated as trip distance (time) on TN divided by trip distance (time) by shortest path



Legend: TP - Number of Transfer Points
CL - Number of Crossing Lines

FIGURE 4 Typical transit networks and transfer point distribution.

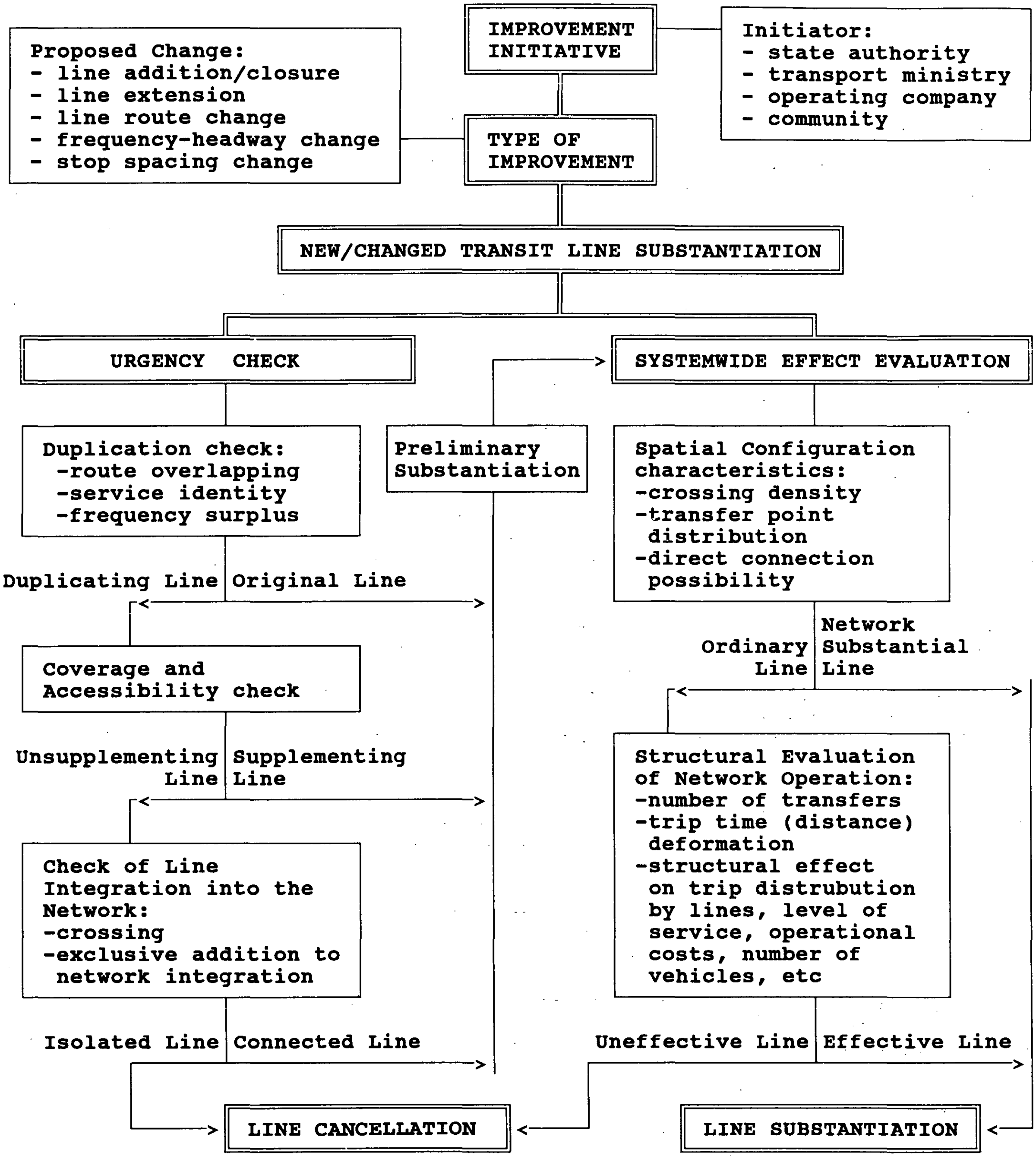


FIGURE 5 Decision-making framework for transit network improvement.

(minimum time) on the road network. These two criteria inevitably contradict under real constraints. Commonly, TN needs a sufficient level of transfers to supply directness of trips. Direct connection for most origin-destination pairs is too expensive. Any proposal that improves one of these criteria without worsening the other is of interest.

Both criteria should be checked as an average TN value and maximum value for particular origin-destination pair. Average parameters are useful to transit planning; however, a decision that is good systemwide may prove extremely inconvenient for particular passengers. This problem is usual for regions combining urban settlements with rural areas. Direct connection for a pair of rural zones will not be effective systemwide, and feeder lines to appropriate urban settlements yield at least two transfers and trip distance (time) deformation for these passengers.

A TN for a metropolitan area can be recognized as acceptable if the averge number of transfers is no more than 40 percent (20 percent shows an excellent pattern) and less than 5 percent of passengers experience two or more transfers. Both distance and time deformation are of interest. Time can be thought of as an ultimate service indicator, but it is affected by road congestion. Thus, trip distance deformation is a more direct indicator of TN design.

TABLE 3 Summary Report for Transit Line Substantiation (Extension of Line 8)

Evaluation Stage/Step	Scope	Criterion	Value			Conclusion (ª - before, º - after)
			Before	After	%	
1. Substantiation	28 lines "Eged" 20 lines "Dan"					Unsubstantial lineª Additional Substantiationº
1.1. Duplication over 40%	- || -	No. of duplicative lines	4	4	0%	Duplicative lineª Reduced Duplication with some lines but increased Duplication with some othersº
	Line 18 "Dan"	Route overlapping	59%	42%	-29%	
		Service identity	100%	100%	0%	
		Frequency surplus	100%	100%	0%	
	Line 42 "Dan"	Route overlapping	51%	-	-100%	
		Service identity	100%	-	-100%	
		Frequency surplus	0%	-	0%	
	Line 85A "Eged"	Route overlapping	49%	55%	12%	
		Service identity	100%	100%	100%	
		Frequency surplus	0%	0%	0%	
	Line 85 "Eged"	Route overlapping	48%	53%	10%	
		Service identity	100%	100%	0%	
		Frequency surplus	0%	0%	0%	
	Line 83A "Eged"	Route overlapping	-	43%	+100%	
		Service identity	-	100%	+100%	
		Frequency surplus	-	0%	0%	
1.2. Coverage	28 lines "Eged" 20 lines "Dan" 59 traffic zones	No. of served zones uncluding:	59	59		Non-Supplementing lineª No additional coverageº
		- surplus level of service	4	4	0%	
		- standard level of service	45	45	0%	
		- low level of service	10	10	0%	
1.3. Integration	28 lines "Eged" 20 lines "Dan"					
- Line	- || -	No. of crossing lines	37	46	+24%	Connected lineª Additional connectionº
		No. of undupl. cross. lines	33	42	+27%	
		No. of transfer points	43	54	+26%	
		No. of tr.p. to undupl. lines	43	54	+26%	
		Min. no. of trans. points	5	6	+20%	
		Min. no. of tr.p. to und. l.	5	6	+20%	
		Addition to Integration	0.5%	0.5%	0%	
- Network Spatial Configuration	- || -	Crossing density	51%	53%	+4%	Network substantial lineª Additional substantialityº
		Transfer point distribution				
		- 2 crossing lines	32	35	+9%	
		- 3 crossing lines	24	26	+8%	
		- 4 crossing lines	14	13	-7%	
		- 5 and more crossing lines	16	17	+6%	
		Direct connection possibility	41%	46%	+12%	

(Continued on next page)

TABLE 3 *Continued*

Evaluation Stage/Step	Scope	Criterion	Value			Conclusion (ª - before,º - after)
			Before	After	%	
- Trip Structure	- || -	Average no. of transfers	1.32	1.30	-2%	Uneffective lineª Additional effectº
		Maximum no. of transfers	2	2	0%	
		Average distance deformation	1.24	1.23	-1%	
		Maximum distance deformation	2.68	2.66	-1%	
		Average time deformation	1.18	1.17	-1%	
		Maximum time deformation	2.60	2.55	-2%	
		Trips distrubution by lines:				
	Line 8	No. of boardings	263	711	+170%	
		Average occupancy ratio	0.12	0.24	+100%	
		Maximum occupancy ratio	0.26	0.53	+104%	
	Line 83A	No. of boardings	633	398	-37%	
		Average occupancy ratio	0.35	0.20	-43%	
		Maximum occupancy ratio	0.86	0.45	-48%	
2.Allocation to Companies						"Dan" lineª Line open to competitionº
2.1.Integration within Subnetworks	28 lines "Eged" (+line 8)	No. of crossing lines	14	21	+50%	Line more connected with subnetwork "Dan"ª Line equally connected with subnetworks "Eged" and "Dan"º
		No. of undupl. cross. lines	12	19	+58%	
		No. of transfer points	38	48	+26%	
		No. of tr.p. to undupl. lines	38	48	+26%	
		Min. no. of trans. points	3	4	+33%	
		Min. no. of tr.p. to und. l.	3	4	+33%	
		Addition to Integration	5.4%	8.1%	+50%	
	20 lines "Dan"	No. of crossing lines	19	19	0%	
		No. of undupl. cross. lines	16	16	0%	
		No. of transfer points	43	53	+23%	
		No. of tr.p. to undupl. lines	43	49	+14%	
		Min. no. of trans. points	3	3	0%	
		Min. no. of tr.p. to und. l.	3	3	0%	
		Addition to Integration	2.7%	9.2%	+241%	
2.2.Subnetworks Structure	28 lines "Eged" (+ line 8)	Crossing density	42%	43%	+2%	Ordinary line for "Dan" subnetworkª Equally substantial line for "Eged" and "Dan" subnetworksº
		Transfer point distribution:				
		- 2 crossing lines	40	43	+8%	
		- 3 crossing lines	19	16	-16%	
		- 4 crossing lines	2	5	+150%	
		- 5 and more crossing lines	2	2	0%	
		Direct connection	29%	35%	+21%	
	20 lines "Dan"	Crossing density	25%	30%	+20%	
		Transfer point distribution:				
		- 2 crossing lines	13	18	+38%	
		- 3 crossing lines	5	7	+40%	
		- 4 crossing lines	6	6	0%	
		- 5 and more crossing lines	5	5	0%	
		Direct connection	21%	24%	+14%	

DECISION MAKING FRAMEWORK FOR TRANSIT NETWORK DEVELOPMENT

Figure 5 presents a decision-making framework for TN improvement in a real planning environment. The starting point is an initiative for change from one party. Potential changes may range from line opening or closure to change of line characteristics. Any change can be expressed ultimately as inserting new lines or (if necessary) discontinuing service on existing lines. There are two stages of substantiation: (*a*) urgency check and (*b*) systemwide effect evaluation.

Urgency check enables line estimation without the cumbersome procedure of trip structure analysis. It will become increasingly relevant in a longer term when travel demand is unknown and can only be approximated. Urgency check involves three sequential steps: duplication, coverage and accessibility, and line integration into TN. As a result of first step, the line can be defined either as original (its route has no mutual segments with existing lines, its type of service is different from service provided by other lines, its frequency gives reasonable addition to a total frequency of existing lines) or as duplicating. After the second step, the line can be recognized either as supplementing (if it serves new area previously unserved or improves transit accessibility in a particular area) or as unsupplementing. At the third step, the line can be qualified either as connected (if it has a number of TN-important transfer points) or as isolated.

The line is considered preliminarily substantiated in the case of a positive result from at least one of the checks. A preliminary substantiated line is subjected to systemwide effect evaluation. There are two steps here: (*a*) spatial configuration, and (*b*) structural evaluation of TN operation. As a result of the first step, the given line gets a status either as a network substantial line (significant for TN operation for a strong relationship with other lines) or as an ordinary line (limited by its own operational sphere). The second step is the final one in the decision-making process. A transit assignment with a defined demand matrix should be used. At this stage such TN performance indicators as trip redistribution by lines, level of service, and operational cost are available. As a result, the line can be defined either as effective (it attracts sufficient ridership, its introduction leads to a level of service improvement within an acceptable cost range) or as ineffective.

A line is substantiated in the case of a positive result at one of the stages: either it is substantial for TN or effective in itself. A line is otherwise canceled. For practical evaluation, a programming package has been developed by the Israel Institute of Transportation Planning and Research (*25*). Transit assignment is performed by the EMME/2 package, which is compatible with developed programs.

SUMMARY OF RESULTS

Final results for the evaluation indicate that the proposed modification will improve TN integration (Table 3). At present, line 8 is marked as over 40 percent duplication of four different lines. In addition, line 8 is not supplementary to transit coverage of the area under study. Therefore, the change would be beneficial to passengers and operator. Extension of a line to zones that are served by other lines results in a 24 percent increase in the number of crossing lines (from 37 to 46). Crossing density, however, does not increase much, showing only a 9 percent increase in the number of crossing lines with two or more lines. Direct connection possibility has increased by 12 percent as more destinations can be reached along the extended route of line 8. All these results indicate the value of the change to greater passenger mobility and accessibility.

By using a transit assignment, an increase of 170 percent in the number of boardings was observed, and the average occupancy ratio doubled. The findings demonstrate the attractiveness of the line to passengers. In a closed system with the fixed demand matrix that the authors use, any increased passenger boardings in one line will worsen other lines' levels of occupancy. It is beyond the scope of this research to present the effect of service quality on demand. Nonetheless, lines suffering as a result of service improvements in another line will usually have some level of duplication. In this case, most line boardings decreased slightly, with the exception of line 83A, which suffered a 37 percent decline in ridership. Although, it is not the line with the highest level of duplication, it suffered most. One of the reasons is that, whereas other lines had a relatively high level of duplication with line 8 before the change, line 83A had no duplication at all. As a result of the modification, lines 8 and 83A were competing on passenger ridership in the same areas, demand was split between them, and thus 83A was affected significantly.

The final analysis phase considers line allocation to companies. The basic rationale for picking one transit company over the other is a better line integration in existing companies' subnetworks and enhancement of their structure. In such case, passengers may benefit from improved service and the operator will benefit from improved operating costs. The area under study was specifically picked to test the model behavior in a case where both Dan and Eged are pushing for additional network expansion and neither is dominating. The result showed that although at present line 8 is run by Dan for justifiable reasons, after extension, TN can be allocated equally to both companies. This was the major reason Dan was pushing the Ministry to accept the proposed change and to give them a foot in the door to better market share. This is an example of how a policy-oriented approach can favor one operator.

REFERENCES

1. Nes, R. V., R. Hamerslag, and B. H. Immers. Design of Public Transport Networks. In *Transportation Research Record 1202*, TRB, National Research Council, Washington, D.C., 1988, pp. 74–83.
2. Baaj, M. H., and H. S. Mahmassani. An AI-Based Approach for Transit Route System Planning and Design. *Journal of Advanced Transportation*, Vol. 25, No. 2, 1991, pp. 187–210.
3. Axhausen, K. W., and R. L. Smith. Evaluation of Heuristic Transit Network Optimization Algorithms. In *Transportation Research Record 976*, TRB, National Research Council, Washington, D.C., 1984, pp. 7–20.
4. Newell, G. Some Issues Related to the Optimal Design of Bus Routes. *Transportation Science*, Vol. 13, 1979, pp. 20–35.
5. Jun, M., and J. B. Schneider. Designing Personal Rapid Transit (PRT) Networks. *Journal of Advanced Transportation*. Vol. 25, No. 3, 1991, pp. 247–268.
6. Lampkin, W., and P. D. Saalmans. The Design of Routes, Service Frequencies and Schedules for a Municipal Bus Undertaking: A Case Study. *Operations Research Quarterly*, Vol. 18, No. 4, 1967, pp. 375–397.
7. Silman, L. A., Z. Barzily, and U. Passy. Planning the Route System for Urban Buses. *Computers and Operations Research*, Vol. 1, 1974, pp. 201–211.
8. Hoidn, H. P. Busnetz von Aarrau. *Neukonzeption der Linien*. Institut fuer Operations Research der ETH Zuerich, Zuerich, Switzerland, 1975.

9. Rosello, X. An Heuristic Algorithm to Generate an Urban Bus Network. *Advances in Operations Research: Proceedings*. Elsevier, Amsterdam, the Netherlands, 1976.
10. Sonntag, H. Ein Heuristisches Verfahren zum Entwurf Nachfrageorientierter Linienfuerhrung im Oeffentlichen Personennahverkehr. *Zeitschrift fuer Operations Research*, Vol. 23, 1979, pp. B15–B23.
11. Dubois, D., G. Bell, and M. Llibre. A Set of Methods in Transportation Network Synthesis and Analysis. *Journal of the Operations Research Society*, Vol. 30, No. 9, 1979, pp. 797–808.
12. Hasselstroem, D. *A Method for Optimization of Urban Bus Route Networks*. Report 88-DH-03. Volvo Bus Corporation, Gothenburg, Sweden, 1979.
13. Mandl, C. *User Reference and Implementer Manual IANO-System*. Institutsarbeit 122. Institute for Advanced Studies, Vienna, Austria, 1979.
14. *Sommer Semester 1981: Linienplanung*. Seminar Verkehrswesen, Institutsnotiz.
15. Furth, P. G., and N. H. M. Wilson. Setting Frequencies on Bus Routes: Theory and Practice. In *Transportation Research Record 818*, TRB, National Research Council, Washington, D.C., 1981, pp. 1–7.
16. Hagberg, B., and D. Hasselstrom. *A Method to Assign Frequencies and Vehicle Types to Fixed Route Urban Public Transport Systems*. Volvo Transportation Systems, Gothenburg, Sweden, 1980.
17. Scheele, S. O. A Supply Model for Public Transit Services. *Transportation Research*, Vol. 14B, No. 3, 1980, pp. 133–146.
18. *NCHRP Synthesis of Highway Practice 69: Bus Route and Schedule Planning Guidelines*. TRB, National Research Council, Washington, D.C., 1980.
19. Schneider, J. B., and S. P. Smith. Redesigning Urban Transit Systems: A Transit-Center-Based Approach. In *Transportation Research Record 798*, TRB, National Research Council, Washington, D.C., 1981, pp. 56–65.
20. Thelen, K. M., A. Chatterjee, and F. J. Wegmann. Evaluation of Alternative Transit Routing Configurations in a Hypothetical Low-Density Area. In *Transportation Research Record 761*, TRB, National Research Council, Washington, D.C., 1980, pp. 53–56.
21. Giannopoulos, G. A. *Bus Planning and Operation in Urban Areas: A Practical Guide*. Avebury, 1989.
22. Rapp, M., and C. D. Gehner. Transfer Optimization in an Interactive Graphics System for Transit Planning. *Transportation Research Record 619*, TRB, National Research Council, Washington, D.C., 1976, pp. 27–33.
23. Douglas, G. B. Applications of Interactive Graphics in Urban Transit Analysis. In *Transportation Research Record 866*, TRB, National Research Council, Washington, D.C., 1982, pp. 18–24.
24. Wilson, A. G. The Use of Entropy Maximizing Models in the Theory of Trip Distribution, Modal Split and Route Split. *Journal of Transport Economics and Policy*, Vol. 2, No. 1, 1969, pp. 108–126.
25. Cohen, A., P. Vovsha, and T. Goodovitch. *Decision Support System for Planning and Development of Public Transport: An Application to Tel Aviv Metropolitan Area* (in Hebrew). The Israel Institute of Transportation Planning and Research, Tel Aviv, Israel, 1993.

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