Connectivity Index for Systemwide Transit Route and Schedule Performance

TENNY N. LAM AND HARRY J. SCHULER

The services of a public transportation system are represented by its routes and schedules. The level and quality of service are, in part, determined by the ability of the route and schedule structure to serve the transportation needs of a service area. The concept of connectivity has been proposed for measuring how well the routes and schedules are integrated with respect to various transportation objectives within a framework of spatial-activity patterns. This study was undertaken to develop a methodology for determining the connectivity of the routes and schedules of an entire public transit system that serves a part or the whole of the service area. The objective is to use connectivity indicators as quantitative tools in the evaluation of service-delivery strategies. An investigation of the graph-theoretical connectivity by computer simulation found the mean of the reciprocals of the trip lengths of a representative sample of trips to be a good connectivity indicator. This indicator ties together the degree of connectiveness with the level of network development. It also offers a consistent picture of the level, as well as the quality, of connections offered by the route and schedule network structure.

The objective of the study is to introduce a methodology for defining and measuring network connectivity (1) for the purpose of evaluating transit system design and transit performance. The formulation provides a standard framework for evaluating problems of transit system performance on the basis of connectivity. The relevance of this line of inquiry lies in the overall importance of quality-of-service measures in assessing both the efficiency and effectiveness (2) of resource deployment and system design from a management or planning perspective.

In transit management practices, level-of-service measures are difficult to develop. First, there are many factors related to service quality (e.g., walking distance to transit stops, waiting time, travel time, and number of destinations served) that make it a multidimensional construct. Second, a transit system consists of many different routes. The extent to which the routes are integrated (to accommodate for transfers with a minimum of inconvenience) determines many of the service qualities of the transit system. Third, public transportation must be designed to serve peoples' needs. Perceptions of a transit system are influenced directly by individuals' use of the system and indirectly by the marketing program of the system operator. Because the perceived quality of service would likely not be the same to each individual engaged in travel, an analysis of the degree of network connectivity associated with fixed-route transit is a challenging research problem.

PROBLEM DEFINITION

Transit connectivity, defined as "the ability of a transportation network to provide the maximum number of origin-and-destination trip pairs through the optimal integration of routes, schedules, fare structures, information systems, and modal transfer facilities" (3), may serve as a valuable framework. This basic definition encompasses many of the considerations associated with the traveler's decision to use or not to use public transportation.

In modern transit management practices, quantitative information is required to develop evaluation tools that are necessary to assess system performance (4). In this context, connectivity is one of several measures useful for this purpose. However, it may be unrealistic and impractical to evaluate system performance on the basis of connectivity on any scale other than a relative one. As a relative measure of system performance, connectivity can provide useful information on alternative resource deployment and alternative system design. On an absolute basis, system comparisons would be controversial because of the uniqueness of environmental factors, route conditions, and operating characteristics that are uniquely associated with each transit system. Transit operators should realize these problems in order to render connectivity a meaningful role in management applications.

The basic managerial use of connectivity is as a standard against which a transit system might be compared. Deviant properties of the system would then be likely candidates for detailed examination. Connectivity measures may also be developed for performance characteristics. For example, one may consider connectivity as the percentage of potential or targeted trips that are served by the transit system with specific trip-time and distance performance measures. As one varies the performance specification, the connectivity indicators would also change. Because the performance level to be used is purely subjective, a continuous depiction of system performance with respect to the specification would allow the application of the base information to a number of potential situations. The approach eliminates the use of subjective value constraints in the application phase.

Other areas of potential use include evaluating route performance (both existing and proposed new routes) and periodic monitoring of transit operations on the basis of public investment in transit and derived benefits. Minimum standards for the continuation of service can be established and linked to route performance. In this manner, changing demand for transit service could be evaluated and the decision to continue or discontinue service could be internalized in the evaluation process.

In a public or quasi-public organization such as transit, evaluating public spending or investment is becoming increasingly important (5). Frugality is rapidly becoming a watchword in government appropriations. This consciousness with regards to the investment of public funds gave rise to the transportation system management (TSM) philosophy introduced originally in the 1970s. Consistent with the objectives of TSM, periodic monitoring of transit operations on the basis of connectivity can be linked to public spending in order to establish a return on investment in terms of overall performance. The potential exists to develop an approach that can make the evaluation of system performance more effective.

STUDY APPROACH

Two levels of transit connectivity are addressed. The first is the degree of connections between urban spatial locations provided by the transit network. For example, the degree of connections can be measured by the number of employment opportunities or locations accessible to transit from a particular residential address or by the number of homes that are within reach of a major shopping center by public transportation. This may be looked at from the point of view of mathematical graph theory. The connections between the spatial points may represent the idealized transit lines or they may represent point-to-point accessibility via the transit system. Transit connectivity expressed within a graph or network context is traditionally known as accessibility. Usually, accessibility means the ability provided by a transportation system to a person at a particular place such that he or she may go to other places that serve his or her needs. To what extent a transit system provides members of the community with accessibility would be one basis of evaluating transit system effectiveness. A transit network with many well-planned and coordinated lines would enable individuals within the service area to use public transportation to satisfy most of their mobility needs; therefore, such a transit system is well connected. On the other hand, a transit operation that has only a small number of disjointed lines would be poorly connected. An evaluation of the spatial configuration of transit service to different places within the service region can hence be made on the basis of some aggregated and weighted accessibility measures. One may expect that system accessibility measures would be strongly related to graph-theory-type connectivity indicators. A discussion of the graph-theory approach can be found in the literature (6-16).

A network of links and nodes, however, does not reflect the quality of service offered to users and potential users. It does not show the travel time, waiting time, walking distance, number of transfers, and transfer time. These user-oriented attributes can greatly affect user and community perceptions of the system's performance, ridership, and management policies. More significantly, a network representation fails to recognize the importance of system planning and the design of the route and schedule structure that are so essential for the efficient deployment of the often limited transit resources in order to maximize the system objectives. To take into consideration the route and schedule influence on the level of service offered to the users, a second level of transit connectivity indices needs to be introduced.

In order to look at transit connectivity in the proper perspective, it is necessary to consider the total system and problem setting and the different levels of factors that influence the development of the transit network, routes, and schedules and the quality of the services rendered. The system and problem setting can be viewed as a set of overlaying strata. They are the geographical terrain; the spatial-activity structure; the transit network, routes, and schedule; and the trip characteristics.

Each stratum represents temporal and/or spatial characteristics. By superimposing one on another, the effect that each level has on connectivity can be envisioned. For example, an area with natural barriers that channels urban development along narrow corridors has a positive influence on transit network, routes, and schedules. Relatively frequent transit services are provided and good connectivity is obtained because of the linear nature of the development. A simple route would provide connections between all places. A small number of vehicles on this single route would provide a high level of service without any need for transfers. On the other hand, for an area where the terrain is flat and urban development spreads in all directions, an extensive network, route, and schedule structure is necessary in order to achieve good spatial connectivity between all places. An extensive network with complicated routes and schedules is required to provide connections between all places. Even with greater expenditures, the services may not be as good as that for the linear city because the trips are so diverse that few trips may share the same direct routes.

A comparison of the performance of the transit network, route, and schedule systems cannot be made without recognizing the differences in the underlying geographical and spatial-activity distributions. For example, implicit in a bus transit network is an underlying highway network. A bus transit network, for all practical purposes, is a subset superimposed on the highway network. The urban structure also mirrors the shape, form, and function of the highways, which blend together the collective effects of geographical terrain, spatial distribution of activities, and urban development forces. There is an intricate interrelationship between the performance of a transit system and the dominating influence of highways. It would be difficult, if not impossible, to isolate the effects of the highway system on the transit network and the performance of the transit system. The influence of other transportation modes is also embedded in the connectivity and the service quality of any one mode of interest.

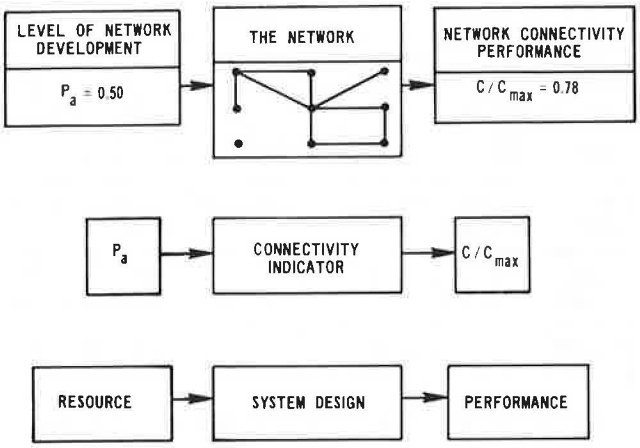
Transit connectivity must therefore be weighted by the trip patterns, although total ridership does not have a direct role on connectivity measures. Because transit demand is a function of many variables, including connectivity, the part of the total system demand that is subjected to the influence of system connectivity can serve as a basis for evaluating the performance of the transit network, routes, and schedule. Theoretically, connectivity, as a measure of how well the transit services are integrated through the coordination of routes, schedules, fare, etc., does not necessarily depend on demand. In reality, most transit operators cater to where existing or potential demand is the highest. The resulting transit system configuration reflects a great deal of the demand characteristics.

Transit operators have employed many different strategies in planning routes and schedules to effect the best services to the public. For example, take the use of timed transfer points. Timed transfer points are used to organize multiple nucleus radial routes such that maximum transit accessibility is provided for local collection and distribution and regional coverage with a relatively small number of simple routes. Although transfers may be required in such a network for many trips, there is a trade-off between short and coordinated transfers and areawide transit accessibility under the constraint of limited resources. Another example would be a highly directional commuter bus system that only provides accessibility between a limited number of spatial points but at a very good level of service for those who can use the system.

In addition to the four strata of system setting discussed previously, the key issues of community support, resource allocation, and management philosophy cannot be overlooked, especially in interpreting differences between systems. These issues, by themselves, do not enter into the measurement problem of connectivity, but the specification of the measures, the aggregation and sampling procedures for the data, and the interpretation of the indices depend on the policy viewpoints and the problem contexts.

The connectivity methodology developed here first ties resource input directly to system structure and system structure is then tied to performance outputs. In the form of a one-dimensional indicator, connectivity becomes a surrogate of resource input

Figure 1. Conceptual framework of network input and output and their relations with connectivity indicator.



and a surrogate of performance. In other words, the connectivity indicator is a reflection of both the level of input and the level of performance. In the sense of being a gross approximation of the characteristics of the overall system, connectivity is useful for comparing system alternatives between vastly different systems with respect to the quality of the route and schedule structure. Implicity embedded in the connectivity indicator should be a qualitative reflection of the level of system input and the level of system output. This concept is illustrated in Figure 1.

There have been many connectivity indicators proposed from graph and network theory points of view. Unfortunately, these indicators were found to be inadequate for the objective discussed here. Attention was given to the trip times as the focus of service quality. The travel time from origin to destination should be as short as practicable in the most extensively developed system with well-designed routes and schedules. Therefore, trip time is a good measure of the quality of the service in terms of mobility. However, the accessibility question must also be addressed. In other words, one cannot overlook the question of how well the transit services serve places--namely origins and destinations. The extent that places are connected by transit may be expressed in the form of the percentage of potential trip origin-destination pairs serviceable by transit. The primary focus of the study was on how to integrate these two level-of-service qualities that are determined by the route and schedule structure.

RESEARCH FINDINGS

Many network-connectivity indicators previously introduced have been examined with respect to their ability to represent the level of network development and system performance. System performance can be measured by both the directness of the route between an origin and a destination and the level of connectedness between all origins and destinations. None of the existing network-connectivity indicators offers a consistent picture among the level of resource input, number of links in the network, and output performance. Details of the investigation on graph-theory-related connectivity measures can be found elsewhere (17).

A new indicator was developed in this study. This indicator is the harmonic mean trip time for a representative sample of trips. When different experimental networks were examined under this indicator, it showed the expected correlations between the input and output measures. Suppose there are n trips that are representative of the travel within the service region of the transit system. Each trip is identifiable by its origin O_i and its destination D_i. In a fully developed network it can be assumed that potentially a large number of routes should be available, such that every origin-destination pair in the service region is served by the system at some standard rate of service in terms of frequency and overall trip speed. For the n trips in the representative sample, the trip times can be determined under this hypothetical fully developed system. If T_i is the trip time (weighted or unweighted for access time, waiting time, on-board time, and transfer time) of the ith trip in the sample between O_i and D_i in the fully developed system, the harmonic mean is given by the following:

$$\bar{T} = 1/(1/n)[(1/T_1) + (1/T_2) + \ldots + (1/T_n)] \quad (1)$$

Most networks, however, are much less developed than the hypothetical fully developed case. Therefore, for the same n trips in the sample, the actual travel time for trips i will be much longer than T_i. Let the actual trip time for trip i between O_i and D_i be denoted by t_i. A harmonic mean $\bar{t}$ of the actual trip time can be calculated as follows:

$$\bar{t} = 1/(1/n)[(1/t_1) + (1/t_2) + \ldots + (1/t_n)] \quad (2)$$

The connectivity indicator, which is the normalized reciprocal harmonic mean trip length, or R, is given by $R = \bar{T}/\bar{t}$. Because $\bar{T}$ is for the ideal case of full development, the actual trip time t_i is at best equal to the ideal trip time T_i and would be longer for most trip, i.e., $t_i \geqslant T_i$. As a result, $\bar{t} \geqslant \bar{T}$ and $0 \leqslant R \leqslant 1$. If R is equal to 1, the system is ideal. However, if trip i in the sample cannot be served by the system, we assume the actual trip time to be infinite, i.e., $t_i = \infty$. This also reflects the quality level of the transit service. When the travel time is long (in some poorly connected case this can be many hours or days), the reciprocal $1/t_i$ is small and contributes little to the harmonic mean. In the extreme case, when $t_i = \infty$, $1/t_i = 0$. For example, if there are five trips in the sample, let their ideal trip times be 25, 5, 16, 8, and 35 min. The harmonic mean $\bar{T}$ of the ideal trip times is as follows:

$$\bar{T} = 1/(1/5)[(1/25) + (1/5) + (1/16) + (1/8) + (1/35)] = 10.96 \text{ min} \quad (3)$$

Suppose for the actual network the second and fourth trips are not connected and the actual trip times are 25, ∞, 20, ∞, and 40 min. The harmonic mean $\bar{t}$ of the actual system is as follows:

$$\bar{t} = 1/(1/5)[(1/25) + (1/\infty) + (1/20) + (1/\infty) + (1/40)] = 43.48 \text{ min} \quad (4)$$

The resulting connectivity indicator R is then

$$R = \bar{T}/\bar{t} = 10.96 \text{ min}/43.48 \text{ min} = 0.25 \quad (5)$$

If the actual trip times for the five trips are 26, 60, 20, 45, and 35 min instead,

$$\bar{t} = 1/(1/5)[(1/26) + (1/60) + (1/20) + (1/45) + (1/35)] = 32.07 \text{ min} \quad (6)$$

and

$$R = 10.96 \text{ min}/32.07 \text{ min} = 0.34 \quad (7)$$

In the extreme case when no transit service is

Figure 2. Network connectivity performance C/C_{max} plotted versus level of network development P_a.

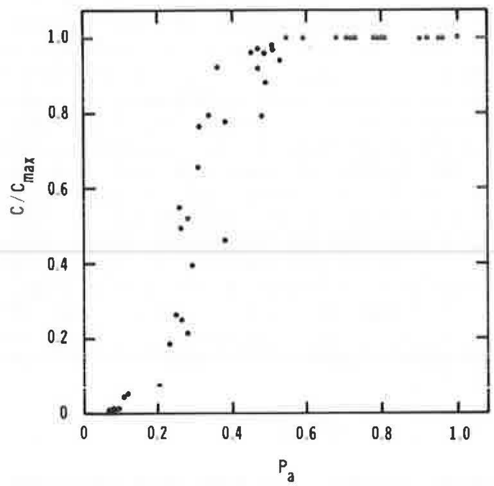


Figure 3. Relation between reciprocal normalized harmonic mean of trip lengths and level of network development P_a.

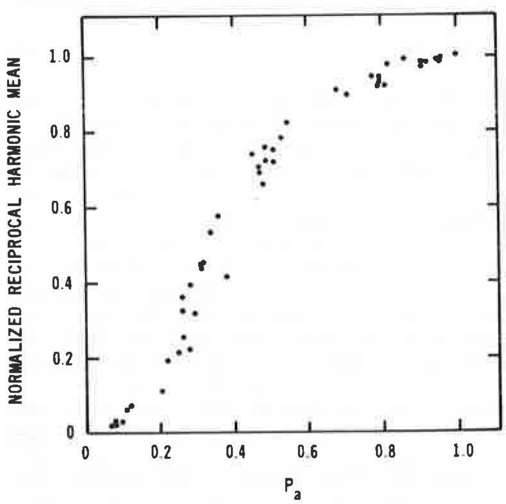
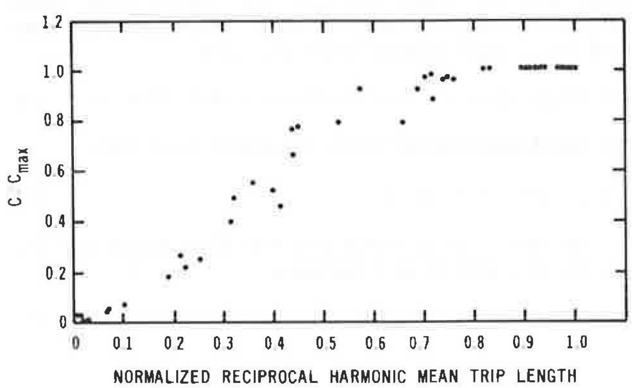


Figure 4. Correlation between network connectivity performance index C/C_{max} and reciprocal normalized harmonic mean trip length.



provided, the connectivity indicator R, so defined, is zero.

The results from the research experiments are shown in Figures 2, 3, and 4. Figure 2 shows the usual quantitative connectedness measure C/C_{max}, where C is the actual number of origin-destination pairs connected by the network, while C_{max} is the total number of origin-destination pairs in the sample. This indicator is related in Figure 2 to the level of network development P_a. The indicator P_a is the ratio of links between the actual system and the hypothetical fully developed system. One can see that as more and more links are provided, P_a increases. As P_a increases, the connectedness offered by the system also increases. However, the index C/C_{max} does not provide any insight into the quality of the connections. The relation between C/C_{max} and P_a is also undesirable because of its abrupt change in the middle range of network development, namely when $0.2 \leq P_a \leq 0.5$.

However, the normalized inverse harmonic mean of trip length R offers a much more smooth relation with P_a. As a result, a better differentiation between system performances is possible, as shown in Figure 3. Moreover, Figure 4 shows a very good relation between C/C_{max} and R. The result suggests that R is a very satisfactory indicator. Because trip length is used in this indicator instead of some abstract mathematical notions, the usual representation of system service by trip length (i.e., time) and the weights associated with the different components in trip length (or time) can be maintained. The weights developed from attitudinal and behavioral studies are useful to reflect the human perception of the quality of the transit services.

METHODOLOGY

There are two remaining problems that must be resolved in order to make the connectivity indicator--the normalized reciprocal harmonic mean trip time R--operational. One is the strategy for statistical sampling and another is on establishing some reference of the indicator to local geographical, highway system, and transit system conditions that are unrelated to the quality and performance of routes and schedules.

Definition of Study Area

The definition of the study area is a policy-oriented issue and is beyond the realm of the present research. However, some general discussion can be offered here as to how the definition of the study area may be addressed. If the policy question is on the service quality within the transit district at large, the study area should be the entire district. A study area so defined will yield a connectivity indicator that is broadly based from the point of view of the total community, independent of the marketing and operational strategies. Another definition of the study area is the effective service area, which may be the area covered within 0.25 mile on both sides of all transit routes. However, express routes should be defined with service areas that are within the actual or expected catchment basin of each station or terminal.

The distinction between total district area and effective service area does not pose any difficulty for the connectivity-measurement procedure developed here. Both spatial connectivity and within-system connectivity are measured. In general, system connectivity should integrate both. Therefore, the definition of the study area is not too critical.

More significant is the definition of the perimeter and the size of the total area. The exact definition is an administrative and policy matter and is not a technical issue.

Procedure for Developing Trip Samples

The basis of the connectivity indicator is the travel characteristics of the target population of the transit operation. The target population may consist of everyone in the metropolitan area or may consist of the potential and present users of the transit services or special subgroups. The special subgroups may be the patrons of particular land use types or particular social services or certain socioeconomic groups.

It is neither practical nor necessary to calculate the connectivity of the service offered to each and every trip of the entire target population. All of the required information can be obtained by evaluating the service to a small sample that represents the trip characteristics of the entire population. Statistical sampling is widely used in all kinds of surveys, in engineering and scientific studies, and in management practices. In transportation, almost all the information used in planning and analysis comes from samples of a very small number of individuals and trips. In home-interview surveys, the percentage of households included in the studies varies from 20 percent in small cities to about 2-3 percent in large metropolitan areas. Most transit surveys usually involve samples of less than 1000 individuals.

Within the context of the present study, two strategies may be used to develop the trip sample. Where there already exists an extensive travel survey conducted recently, the survey may be used. Depending on the connectivity indicator to be developed, the entire trip sample may be used if the travel time and travel distance are included in the survey. If only origins and destinations are available from the survey, travel times and distances may have to estimated. The estimation of travel times and distances is costly and time consuming and, therefore, only a small sample is practical.

Estimation of System Performance

Travel time on the transit system is used as the basic data for determining the connectivity indicator. For each of the trips in the sample it is necessary to measure the transit time, the distance between the origin and destination, and, if access time and waiting time are included, the estimation of the access and waiting time. The transit time should include all transfer times and number of transfers as well as walking time between transfer points. Previous studies have indicated that transit users place more weights on access times, waiting times, and transfer times than on the on-board times. By determining these separate time elements, proper weights can be assigned to them and a weighted total transit travel time may be determined.

For the connectivity measuring concept developed here, there is no need to set arbitrary cut-off criteria on whether a trip is effectively connected. The contribution of a long trip (even unrealistically long) can be readily incorporated. The longer the trip time is relative to average transit system performance, the less its value is in terms of spatial connectivity.

The determination of the travel-time elements is based on the origin, destination, and starting time of the trip. Knowing the input information, the travel time can be determined from transit system route maps and timetables. If more accurate information is required, the transit travel time, etc., can be actually measured by taking the actual ride. However, it is inconceivable that such a procedure is necessary unless the timetable information is very inaccurate. Occasionally, in the absence of trip-time information, the connectivity indicator can be measured in terms of route distance between the origin and destination of the trip. The distance information is useful to complement the time information, rather than in lieu of the time information.

The purpose of determining the transit route distance and the straight-line distance is to facilitate the development of the reference base necessary for making connectivity indices comparable for different transit operations. In the connectivity indicator, the reference base is the travel time on a hypothetical transit system that is fully developed. By fully developed, the average speed on the transit system without transfers is applied to the most direct highway route that connects the origin and destination of a trip in the sample. Therefore, it is necessary to determine the average transit system speed and the average highway speed. In addition to the ratio between transit route distance and straight-line distance, the ratio between automobile-route distance and the straight-line distance is also useful. This information may be obtained for the trips in the trip sample or independently. Actual field measurements may be used from standard transit and traffic travel-time studies. Or, where there exists an updated urban transportation planning analysis network, the information may be obtained from computer network analysis.

Calculation of Connectivity Index

Table 1 gives an example of the type of information for a sample of 30 trips. Of the 30 trips in the sample, 10 are not served by transit. For these trips, the transit travel time is infinite. The first step in the calculation is to compute the reciprocal of the harmonic mean by the formula

$$(\bar{t})^{-1} = (1/n) \sum_{i=1}^{n} (1/t_i) \tag{8}$$

where t_i is the total transit time in column 4 of the table.

For the example in Table 1,

$$\begin{aligned}(\bar{t})^{-1} &= (1/30)(0.74)\\ &= 0.024\,58\ (\text{min})^{-1}\end{aligned} \tag{9}$$

and $(\bar{t})$ = 40.68 min. In order to determine the reference base, the travel times of all the trips in a fully developed transit network are estimated. For the fully developed transit network, the direct route is assumed to be the shortest highway route. On this fully developed network, transit speed is assumed to be the route speed for those transit trips that are served. The route speed is given in column 9, which is determined from the on-board time and the transit-route distance. The on-board time is the total transit time minus the transfer time. Multiplying the average of column 9 to the highway-route distance in column 8, the value t_i is given in column 10 to represent the equivalent transit travel time over direct routes between the origin and destination over the fully developed transit network without transfers. The average route speed for the example is 17.35 mph. The reciprocal har-

Table 1. Example of transit performance data.

Trip No.	Origin	Destination	Total Transit Time (min)	Transit-Route Distance (miles)	Transfers No.	Transfers Time (min)	On-Board Time (min)	Highway Distance (miles)	Transit-Route Speed (mph)	Transit Time, Fully Developed Network (min)
1	2804	4710	-	-	-	-	-	16.8	-	58
2	3403	3401	-	-	-	-	-	3.2	-	11
3	1802	4714	103	18.2	2	35	68	13.0	16.1	45
4	3004	1501	5	2.6	0	0	5	2.8	31.2	10
5	2702	1803	5	1.45	0	0	5	1.5	17.4	5
6	1802	1508	70	4.8	1	55	15	3.5	19.2	12
7	2902	4401	48	10.7	1	5	43	5.9	14.9	20
8	3607	1303	99	22.45	2	20	79	11.1	17.1	38
9	2702	4302	57	13.7	2	8	49	9.4	16.8	33
10	1501	2102	35	6.65	1	10	25	6.7	16.0	23
11	4399	4705	56	10.0	1	6	50	5.1	12.0	18
12	1206	4711	-	-	-	-	-	4.9	-	17
13	1402	2501	49	11.7	1	13	36	8.0	19.5	28
14	2101	3501	51	12.8	1	10	41	11.4	18.7	39
15	3611	4702	25	5.0	1	1	24	4.7	12.5	16
16	4710	1207	-	-	-	-	-	6.7	-	23
17	1901	2908	-	-	-	-	-	2.3	-	8
18	1602	1706	-	-	-	-	-	5.6	-	19
19	1803	3601	-	-	-	-	-	18.0	-	62
20	2102	2903	-	-	-	-	-	13.2	-	46
21	4711	1402	101	21.2	2	30	71	14.5	17.9	50
22	5004	4803	-	-	-	-	-	7.9	-	27
23	1203	3901	73	17.5	2	13	60	10.9	17.5	38
24	3302	1603	73	14.4	2	20	53	6.1	16.3	21
25	4301	1801	103	19.25	2	35	68	12.1	17.0	42
26	3606	2807	49	11.4	1	5	44	7.5	15.6	26
27	4704	3403	39	7.45	1	10	29	3.0	15.4	10
28	2903	4711	46	8.3	1	10	36	8.2	13.8	28
29	2908	4706	-	-	-	-	-	2.7	-	9
30	5002	1302	42	11.8	1	10	32	6.4	22.1	22

monic mean of the t_i's in column 7 is as follows:

$$(\bar{T})^{-1} = (1/n)\,[\sum_{i=1}^{n} (1/t_i')]$$
$$= (1/30)(1.65)$$
$$= 0.054\,89\ (\text{min})^{-1} \quad (10)$$

and $\bar{T}$ = 18.22 min. By using the concept that the connectivity indicator is the ratio between the actual reciprocal harmonic mean transit time and the reciprocal harmonic mean transit time on a hypothetical fully developed network, the connectivity indicator R is given by R = $\bar{T}/\bar{t}$. For example, the connectivity index of the transit network that serves the 30 trips in the sample is as follows:

$$R = 18.22\ \text{min}/40.68\ \text{min} = 0.45 \quad (11)$$

CONCLUSIONS

The objective of this study is to develop operational indices to represent the ability of a transit system to connect urban places and the quality of service provided on the connections. Connectivity is related first to the structure and the level of development of the transit network. Then the connection between two points on the transit network is influenced by the coordination of the routes and schedule. The routes and schedule, in turn, are influenced by management policies on resource allocation and deployment.

The difficulty for developing connectivity indices lies in the many complex interacting factors involved in transit service delivery. There are great differences among the geographical, land use, highway, and user characteristics between regions. The indicators developed must, hence, incorporate other measures that could be used as references from which the actual performance of the network, routes, and schedule of the transit system can be measured. The resulting measurement should be realistic in representing subjective evaluation of the quality of connectivity, flexible in allowing different data-collection procedures to be used, and robust in its applicability to all systems.

In this study, the main focus is on identifying the contribution of transit system connectivity to the overall performance of how well urban-activity connections are served by transit. The study approach involves looking at the problem from the perspectives of graph theory, urban transportation planning models, and statistical sampling. Attempts were made to develop sets of measures that would reflect, as much as possible, transit connectivity viewed from both accessibility and level-of-service points of view. The evaluative and performance measures such as accessibility and quality of service are commonly used in almost every aspect of transportation planning. They reflect many important planning and management factors. Connectivity of the transit system's network, routing, and scheduling is only one of the factors. Care must be used in not confusing the evaluative and performance measures with connectivity measures, despite the fact that connectivity reflects the level of transit service.

A number of remaining questions need to be addressed before full implementation and application should take place. One question is the sensitivity of the indicator to sample size. This question can be readily resolved with a sensitivity analysis of the results with samples of different sizes for the same area. The next question is on how trip samples should be drawn with respect to different types of issues. Should spatial area or traffic zone be used as the trip sample base? Should the sample be based directly on a surveyed sample of trips or a sample of trips from available planning model information? Should 24-h trips be used or trips within some specific period of time? Should the trips be sampled for weekdays as well as weekends? Should transit trips be used or should all personal trips be used?

The sampling questions cannot be answered except within the specific context of a problem or issue to be addressed. When application is to be made, it is necessary to first detail the objectives of the application. What exactly is of interest within the policy and issue context? What role does the route and schedule play within the context? How does connectivity enter into the consideration? What would the indicators mean with respect to the issues? How should the indicators and the results be interpreted in answering the questions being addressed?

With respect to the application to be made, an interview with managers of each of the transit operations to be involved should be made to qualitatively determine the subjective impressions of those intimately knowledgeable of the systems. The calculated indices must also be correlated with the subjective impressions. The purpose of the indices is to provide a systematic basis of estimating and quantifying subjective impressions. Therefore, the indicators should correspond to the collective wisdom of the experts. A good correlation between the quantitative and subjective evaluations should adequately validate the methodology and the procedure. As a result, the connectivity indicator would then have the necessary credibility and acceptability for full implementation.

ACKNOWLEDGMENT

The study benefited from the participation of Wilfred W. Recker. Michael J. Uyeno and Behrooz Mohammadi assisted in much of the technical work.

The study was supported, in part, by an Urban Mass Transportation Administration technical study grant awarded to the State of California. The Institute of Transportation Studies, University of California, Irvine, performed the research with the Division of Mass Transportation, California Department of Transportation. The views expressed here are ours and not necessarily those of the University of California, the State of California, or the U.S. government.

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Publication of this paper sponsored by Committee on Bus Transit Systems.