
Comparative Measures for Transit Network Performance Analysis
Author(s): Young-Jae Lee
Source: *Journal of the Transportation Research Forum*, Vol. 47, No. 3 (Public Transit Special Issue 2008), pp. 149-170
Published by: Transportation Research Forum
Stable URL: http://www.trforum.org/journal

Comparative Measures for Transit Network Performance Analysis

by Young-Jae Lee

This paper discusses existing measures for the analysis of transit network performance and develops new measures that use a comparative approach to examine the efficiency of transit network configuration. Most measures in transit planning and operating are estimated by the transit system itself, but because transit competes with other transportation modes, comparative measures are necessary to attract more transit riders.

This paper introduces two measures: the Degree of Competitiveness and the Degree of Circuity. While these measures examine performance for each zone-to-zone travel, simple average and weighted average are also introduced to evaluate the entire transit network.

INTRODUCTION

Optimal planning and operation are the two most important components for successful transit agencies. However, optimal planning and operation for transit are difficult to determine. Because of the complexity of transit planning, it is nearly impossible to set eventual optimal plans at the very beginning of the process. So, although initial planning processes are always developed, feedback with measures related to the transit operation and planning should be adopted to improve planning and operation as well, after the certain period of operation.

Measures to determine transit operation show how to diagnose current transit operations and make future planning more efficient. For those reasons, setting and developing measures is always important for transit agencies.

Transit performance measures can be classified in two ways. One way is through input/output measures. For most transit planning and operation, data are either related to the inputs or the outputs. Components for transit planning and operation are all input measures. Route length, headway, fare, and capacity are in this category as well. Data related to the performance of the transit agency are classified as output measures. This category includes efficiency ratio and utilization ratio (including revenue and person-km, etc.).

The other way to classify the measures is based on performance points of view. Measures used for transit planning and operation are related to transit users, transit agencies and society [Transit Cooperative Research Program 2003]. Some measures are in one of those parties, and some of them are in two or three of those parties.

This research discusses and develops comparative measures to diagnose current planning and operation in more efficient ways. The first part of the paper thoroughly discusses auto and transit travel time, which are the existing comparative measure. Since travelers always compare the available travel modes for their trips using their travel times and costs, measures that show the relationship between auto travel time and transit travel time are very useful. These measures will show the competitiveness of the transit service. In the second part of the paper, measures that compare the current transit networks and the potential shortest travel time transit networks are developed. If the size of the demand is big enough to provide high frequency for any route, this comparison shows how much the transit network can potentially be improved.

Those measures are good not only for the passengers, but also for the transit agencies. Passengers want to know how good and fast their transit travels will be, and agencies rely on those numbers for planning. More positive measures indicate more demand, more revenue, better service and higher frequencies in the future. These measures and the concepts behind these measures are not totally new, but they are systematically structured and mathematically developed in detail in this paper.

BACKGROUND

Transit Network Configuration

Transit network configuration is one of the most important components in determining the level of service for passengers and the key for operational efficiency. However, optimizing the transit network configuration has always been one of the most difficult tasks for the transit industry.

One of the primary reasons for the difficulty in optimizing transit network design is the complexity of designing transit network configurations. Because of this complexity, most transit networks have been designed with intuition and experience. Another complexity is the difficulty in changing current network configurations. Although recent studies have shown how to optimize a transit network, it is difficult for transit agencies to complete changes at once due to the confusion that may be caused.

Therefore, it is recommended that modest changes in schedules or the transit network be explored, rather than drastic changes to the transit network configuration. Once a transit network is designed, user travel time can't be improved drastically by other changes.

Transit Travel Time Characteristics [Lee 1998]

As mentioned, this study looks for measures that use auto and transit travel times as inputs for the transit system. To analyze transit travel time, it is necessary to analyze the components of transit travel time. Characteristics of transit differ from those of private transportation. Some of the advantageous characteristics of transit travel are the avoidance of driving and owning or taking care of a car. However, there are also disadvantages. Transit is usually operated on fixed routes, while private transportation users can choose their routes. Transit users must follow a schedule, while private transportation users can control their schedules. While private transportation users can drive from their homes, transit users must go to the station to use transit. And sometimes if the journey doesn't end at the destinations, many transit users must make transfers to complete their trips. These transit disadvantages involve components of travel time for transit users.

Fixed routes are related to in-vehicle travel time as described as the first disadvantage of the transit travel. While private transportation users choose paths involving minimum travel time, transit users must use fixed routes that are typically indirect. Although transit users can choose the route involving the least amount of travel time when alternative routes are available, additional in-vehicle travel time is usually required compared to auto transit travel time because of the circuity of transit routes.

The given schedule influences users' waiting time – the second disadvantage of transit travel. While private transportation users do not have waiting time, transit users have waiting time at the station. This is usually dependent on the service frequency of transit.

The additional trip from origin to station and from station to destination is related to access and egress distance and time – the third disadvantage of transit travel. The location of the station is the major factor that affects this disadvantage.

The final disadvantage of transit travel is the potential for a necessary transfer in a trip. This disadvantage necessitates access time to the transfer station, waiting time at the transfer station and an additional fare charge if necessary. Mainly due to operators' constraints, transit services cannot provide direct services from all origins to all destinations, so transfers between certain origins and certain destinations are unavoidable. The existence of transfers depends on the transit network configuration. The amount of transfer time penalty is dependent on the service frequency of the transfer route. Thus, the transfer disadvantage is directly related to the other disadvantages.

To make an efficient transit system, transit network design must consider and minimize these disadvantages. For a given mode and level of service, it is not possible to minimize every component of travel time because these components are closely related to each other, and there are trade-offs among them. To optimize a transit network, it is recommended that relationships among components be considered and then each component be optimized. Especially, routing, which decides in-vehicle travel time, and scheduling, which decides waiting time, should both be considered simultaneously at the sketch level to minimize total travel time in the transit network. Users' in-vehicle travel time and waiting time are basically determined when the corridor of each route is chosen because corridors determine the basic number of passengers. Then, each route can be specified and improved through changing details after designing a big picture of the transit network.

Relationship Between Routing and Scheduling

Total transit travel time is computed as the sum of the travel time components. There are many considerations for determining those components, but routing and scheduling are the major factors. Routing determines in-transit travel time and access/egress time (by station location). It also determines whether transfer is required for a certain trip. Scheduling has a close relationship with waiting time and transfer time, if there is a transfer. Without scheduling information, average waiting time is half of the headway. While waiting time with scheduling information does not have a definitive relationship with headway, it clearly moves to the same direction as headway. Although the difficulty of coordinating them means that they are usually planned separately, routing and scheduling should be considered together.

The relationship between routing and scheduling comes from the scheduling process. Scheduling is affected by many concerns, such as maximum policy headway and fleet size. However, the most important input for the scheduling process is demand size. As shown in Equation 1, to prevent an overcrowded situation, frequency should be linearly related with the demand. This means that demand for a certain route decides its frequency [Vuchic et al. 1976, Cedar and Israeli 1998].

$$(1) \qquad f_D = \frac{V_{MLS}}{C_v \cdot \alpha},$$

where

f_D = Frequency which satisfies the demand size
V_{MLS} = Volume on the maximum load section;
C_v = Vehicle capacity;
α = Load factor.

Depending on the routing, demand for a certain route is basically determined because of two reasons. One reason is, assuming the condition with fixed transit demand, that the amount of demand picked up by the route is decided depending on routing. The other reason is that routing determines the in-vehicle travel time and that in-vehicle travel time affects transit demand. The more efficient the transit route is, the more share transit can have from the general demand for the trip. Because of these reasons, although routing and scheduling are separate and different processes, routing affects and generally determines scheduling.

Under fixed transit demand, a route collects more riders if it is circuitous, resulting in higher frequency and shorter headway. However, there is a trade-off with circuitous routing. Although it can provide shorter waiting time due to shorter headway and higher frequency, it requires longer in-transit travel. Increasing directness reduces in-transit travel time under the assumptions of a single mode, but it requires more routes and lower frequency for each route due to less demand for each route. Obviously, lower frequency results in longer headway and eventually longer waiting time.

Demand Size and Circuity of the Network

The overall shape of transit network configurations can be classified into three types [Lee 1998] – directly connected networks with a greater numbers of routes; networks with fewer routes, which are circuitous; and networks that require transfers due to fewer directly connected routes. Demand size is one of the main considerations in determining the type of the transit network. When demand is low, providing many routes with direct connection is not efficient because the frequency of each route is low, resulting in longer waiting times. Direct connection is the better choice when demand is sufficient because networks can still provide short headway with many direct routes.

Transit networks with transfers share characteristics with networks that have circuitous routes. Frequencies are high as compared to directly connected networks due to the smaller number of routes, but in-vehicle travel time is still short due to the direct connection. However, because it requires transfer, transfer time exists in total travel time. If the network has circuitous fewer routes, waiting time is short due to the higher frequency, but in-vehicle travel time is longer due to circuitous routing.

METHODOLOGY

Comparative Measures – Degree of Competitiveness and Degree of Circuity

In this research, two comparative measures are developed. These two measures, “Degree of Competitiveness” and “Degree of Circuity,” compare the performance of auto and transit and evaluate potential transit network performance. The primary comparisons in this research are the travel times of the different cases.

The Degree of Competitiveness (DOCO) shows comparisons between auto and transit travel times. This measure shows how transit service is competitive with automobiles for each origin-destination trip.

The Degree of Circuity (DOCI) measures how much the transit service or network configuration can be improved. In general, if transit ridership increases, optimality of the transit network becomes higher with more direct connections between origin-destination pairs [Lee 1998]. With this idea, the Degree of Circuity provides data that show how circuitous the current transit network is compared to the hypothetical transit network with the possible shortest connections.

While it is rather simple to estimate auto travel time, estimating transit travel time is more complex due to its components. Because of the various travel time components of transit, transit users can consider travel time in two different ways: total transit time and in-transit travel time. Total transit time includes waiting time and considers complete door-to-door travel time. Waiting time can be determined by considerations other than demand size. When the headway is long and the schedule information is provided, waiting time may not be estimated from headway and frequency. As a result, this travel time can be distorted by the length of waiting time when the transit network is evaluated.

In-transit travel time, which excludes waiting time, is transit travel time after boarding. This measure includes waiting time, which is stochastic among all the components of travel times and represents the transit network configuration better than total transit travel time. However, in-transit travel time does not include the relationship between routing and scheduling, and it may not represent the overall performance of the transit system.

Access and egress times do exist in transit trip and total transit travel time, but they are excluded from this paper for simplicity. If necessary, certain fixed values can be added as well.

With two kinds of transit travel times defined, auto travel time and transit travel time are compared. This comparison is referred to as the Degree of Competitiveness. The Degree of Competitiveness (DOCO) is a measure designed to show how much additional travel time the transit network requires when compared to auto travel time. If transit travel time is identical to auto travel time, its DOCO is zero.

As stated earlier, two types of competitiveness can be considered with two kinds of transit travel time. These two types of competitiveness are "Total Travel Time Degree of Competitiveness" and "In-Vehicle Travel Time Degree of Competitiveness." The Total Travel Time Degree of Competitiveness (TTTDOCO) compares auto and transit door-to-door travel times and shows how competitive the transit system is. The In-vehicle Travel Time Degree of Competitiveness (ITTDOCO) compares auto and transit in-vehicle travel time. Since waiting time is not included in the comparison and auto travel follows its shortest paths, ITTDOCO shows how direct the transit network configuration is. Equations 2 and 3 show the TTTDOCO and ITTDOCO for an individual user or a certain origin-destination, respectively.

$$\text{(2)} \qquad \text{Individual TTTDOCO [\%]} = 100 \bullet \frac{\Delta t_T + t_t + p}{\min t_a},$$

$$\text{(3)} \qquad \text{Individual ITTDOCO [\%]} = 100 \bullet \frac{\Delta t_i + t_t + p}{\min t_a},$$

where

Δt_T = Additional total travel time (difference between real total travel time of transit and shortest time of auto);

Δt_i = Additional in-vehicle travel time (difference between real in-vehicle travel time of transit and shortest travel time of auto);

t_t = Transfer time;

p = Transfer penalty;

$\min t_a$ = Auto shortest path travel time.

The Degree or Circuity (DOCI) shows how much additional travel time is required by the current transit network as compared to the directly connected hypothetical transit network. This is due to the indirect connection of the current transit network. Just as there are two types of DOCO, there are two types of DOCI.

The "Total Travel Time Degree of Circuity" (TTTDOCI) compares the real door-to-door travel times of the current transit system and the potential minimum transit travel time. This assumes that the potential minimum transit travel time is estimated with no waiting time and the shortest connected in-vehicle travel time. TTTDOCI shows how much the transit system can be ultimately improved.

The other type of DOCI is called "In-vehicle Travel Time Degree of Circuity" (ITTDOCI). It compares the current in-vehicle travel time of transit and potential shortest in-transit travel time. Since potential shortest in-travel time comes from the directly connected transit network, and waiting time is not included in the comparison, ITTDOCI shows how direct the transit network configuration is. Equations 4 and 5 show the TTTDOCI and ITTDOCI for an individual user or a certain origin-destination, respectively.

$$\text{(4)} \qquad \text{Individual TTTDOCI [\%]} = 100 \bullet \frac{\Delta t_T + t_t + p}{\min t_i},$$

(5) Individual ITTDOCI [%] = $100 \bullet \frac{\Delta t_i + t_t + p}{\min t_i}$,

Where

Δt_i = Additional in-vehicle travel time (difference between real in-vehicle travel time and in-vehicle travel time of potential transit shortest path);

t_t = Transfer time;

p = Transfer penalty;

$\min t_i$ = In-vehicle travel time of potential transit shortest path.

Those measures, two DOCOs and two DOCIs, can be presented for each origin-destination trip as shown in the equations and for the whole network.

To estimate measures for the entire network, simple average and weighted average can be used to consider demand. Simple average does not count demand for each zone-to-zone. Without consideration of the demand size, these measures represent competitiveness or circuity of the transit network with the same weight for each origin-destination. Equations 6 and 7 show two simple Degrees of Competitiveness for the total travel time and in-vehicle travel time. Equations 8 and 9 show simple Degree of Circuity. In the equations, *n*(*n*-1) is used instead of n^2 as the denominator for the simple average because it is assumed there is no intra-zonal trips.

Weighted averages consider the demand size of each zone-to-zone. The weighted averages show how efficiently the transit network is designed to meet the demand and how well the transit network provides better service to origin-destination with higher demand. This is shown in Equations 10 through 13.

(6) Simple average TTTDOCO ***[%]*** = $\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(TTTDOCO)_{ij}}{n(n-1)}$,

(7) Simple average ITTDOCO ***[%]*** = $\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(ITTDOCO\ )_{ij}}{n(n-1)}$,

(8) Simple average TTTDOCI ***[%]*** = $\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{individual(TTTDOCI)_{ij}}{n(n-1)}$,

(9) Simple average ITTDOCI ***[%]*** = $\sum_{i\ 1}^{n}\sum_{j\ 1}^{n} \frac{individual(ITTDOCI\ )_{ij}}{n(n\quad 1)}$,

(10) Weighted average TTTDOCO ***[%]*** = $\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(TTTDOCO)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}}$,

(11) Weighted average ITTDOCO [%] =
$$\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(ITTDOCO)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}},$$

(12) Weighted average TTTDOCI [%] =
$$\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(TTTDOCI)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}},$$

(13) Weighted average ITTDOC [%] = 100
$$100\,\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} \cdot individual(ITTDOCI)_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij}},$$

Where

n = number of zone;
D_{ij} = demand from zone i to zone j.

Shortest Path Algorithm and Transit Route Choice Model

The inputs defined in Equations 2-13 should be required to estimate the Degree of Competitiveness and Degree of Circuity. Those inputs – demand size, link travel time and transfer time – can be surveyed or easily estimated. However, the real travel time of auto and transit and potential shortest travel time of the transit should be found and computed through the algorithms. This section discusses algorithms to find shortest auto paths, shortest transit travel paths (with and without waiting time) and potential shortest transit travel paths.

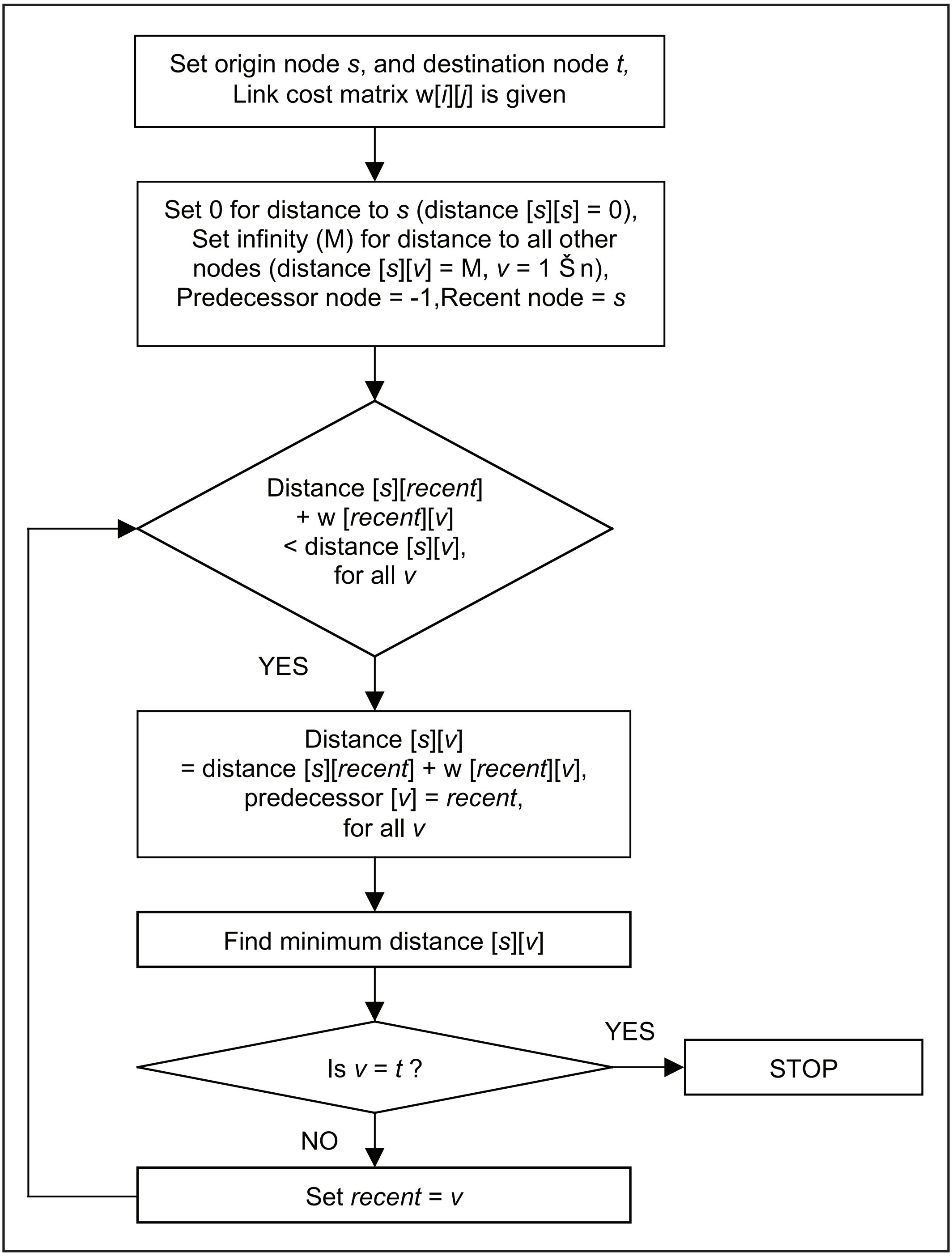
Shortest Path Mode for Auto Travel. Auto travel time assumes that users find the shortest auto travel paths. With this assumption, auto travel time can be estimated using the shortest path algorithm. This theory is well known and has been developed by many scholars including Moore [1957], Dijkstra [1959] and Dantzig [1966]. Moore's algorithm is modified for this procedure and is shown in Figure 1. The flowchart for Moore's algorithm shows the shortest path from the origin node [*s*] to the destination node [*t*].

With input of link length, link cost or travel time, this algorithm searches the shortest path for every node-to-node trip as a set of sequenced nodes or links. As a result, minimum cost or travel time for each origin-destination is obtained.

These outputs can also be represented by α_{ij}^{st}, an indicator variable for the relationship between origin-destination and link usage. This variable has a value of either 0 or 1. If α_{ij}^{st} is 0, then link *i-j* is not used for the travel from origin-destination, *s* to *t*. If it is 1, then link *i-j* is used for the travel from *s* to *t*. This form of indicator variable requires a lot of computational memory, but it makes the algorithm simple [Sheffi 1985].

This shortest path algorithm provides the shortest path with the given fixed travel time. In reality, link travel time varies with the traffic volume, and this shortest path algorithm may not be adequate; however, estimating real travel time with real travel demand is very complicated and difficult.

Figure 1: Flowchart for the Shortest Path Algorithm



Transit Route Choice Model. For transit travel time, the algorithm for transit route choice should be defined first. While auto shortest path is definitive for the given origin and destination, transit shortest path has stochastic characteristics. Though there are many uncertainties in auto travel, and users can change their paths in the middle of travel, many users also decide their travel paths before they make the trips.

However, transit users often decide their travel paths at the station after the certain route of bus arrives, when they have multiple choices for their travels at the same station. So, if there are multiple competitive paths, finding shortest paths and assigning the volume on the paths are not definitive.

In this study, deterministic waiting time is used for estimating total travel time. Deterministic waiting time is half of the headway and maximum 10 minutes. As with auto travel, the shortest paths for transit travel can be found with deterministic waiting time.

Another concern for the transit route choice is the certain route's link availability and link usage for the certain trip. While α_{ij}^{st} is used as an indicator variable for the relationship between origin-destination and link usage for the auto shortest path algorithm, indicator δ_{ij}^{st}, which shows the usage of link of the certain route for the certain origin-destination, should be introduced for transit choice and model assignment. If link *i-j* in route *k* is used for the trip between *s* and *t*, then δ_{ij}^{st} is 1 and otherwise it is 0 [Lee 1998, Lee and Vuchic 2005]. Figure 2 shows the flowchart for transit route choice and assignment.

Because waiting time is not included in the process, the procedure becomes similar and simpler for the algorithm to find the shortest in-vehicle travel time for transit.

Potential Shortest Path for Transit Travel. As discussed previously, comparisons between auto network and transit network may not successfully show the effectiveness of current transit networks, because transit link travel time and auto link travel time are already different. While this comparison can show how competitive transit service is, the comparison itself does not show how much the current transit system can be improved.

To have an idea of how much the current transit network can be improved, comparison of the potential transit shortest paths may be more adequate. Potential transit shortest path can be found by using the auto shortest path algorithm with transit link travel time instead of auto link travel time. This potential shortest transit path is the hypothetical transit path, assuming that transit does not have fixed routes and can go anywhere with the shortest path.

EXAMPLE

The basic information for the following example comes from Rea's paper [Rea 1971] and Lee's dissertation [Lee 1998]. The example uses Rea's template network and Lee's suggested transit routes. Transit link travel time is modified, and some other inputs are added for this research. Figure 3(a) shows the template network, and Figure 3(b) shows scheduling information for the routes. Figure 3(c) shows the transit link travel time for transit. For simplicity's sake, auto link travel time is assumed to be 30% less than transit link travel time. Figure 3(d) shows the current demand for the transit, and auto demand is assumed to be five times more than transit demand.

The shortest path for auto can be found from the shortest path algorithm. Potential shortest transit paths can be found in the same way. As transit link travel times are proportionally estimated from the auto link travel times, the shortest paths for auto and potential shortest transit paths are identical. Table 1 shows the results of the shortest path algorithm, and Table 2 shows the potential shortest transit in-vehicle travel times. Since this example assumes auto link time is 30% less than transit link travel time, auto shortest travel time is, accordingly, 70% of those travel times.

Figure 2: Flowchart for Transit Route Choice

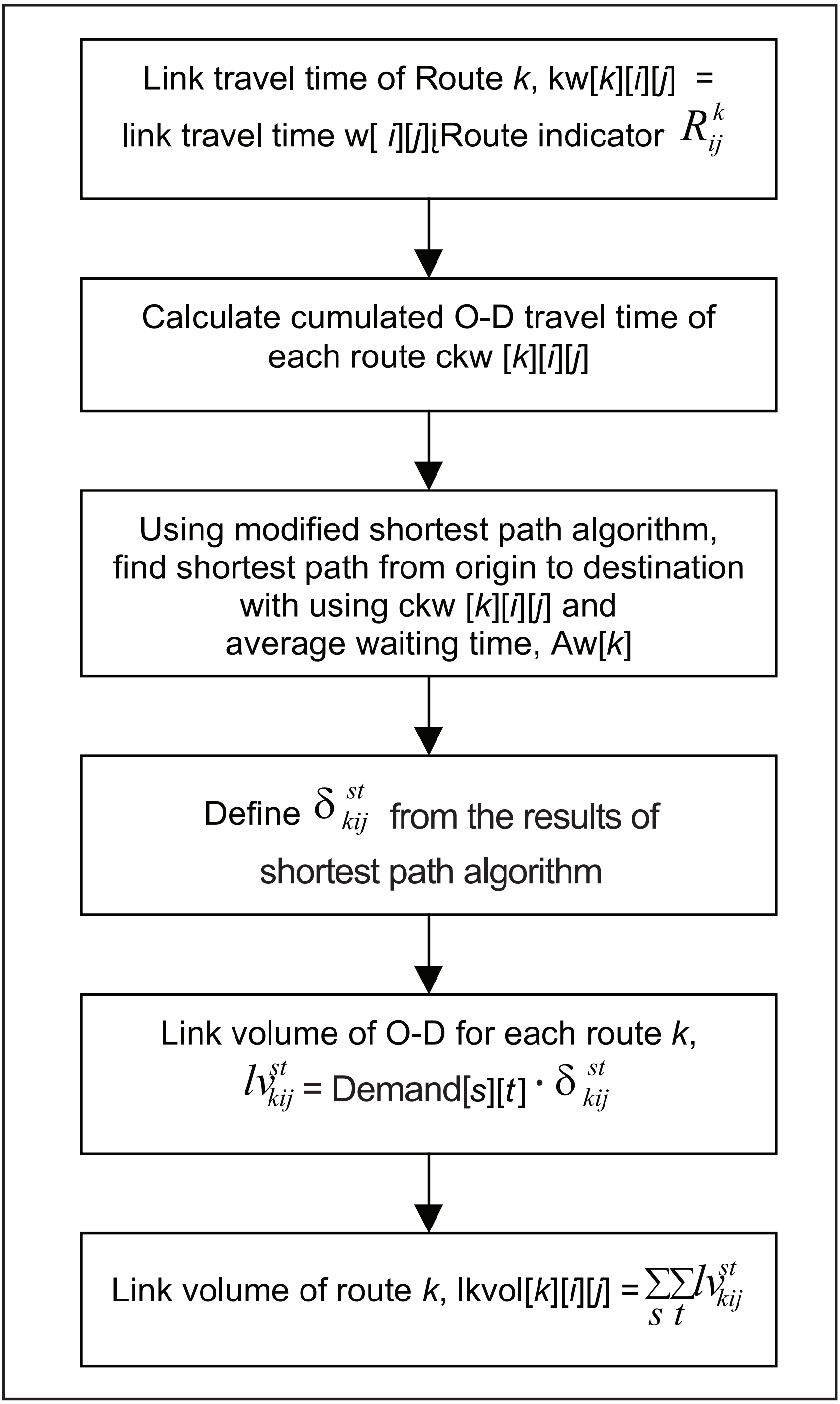
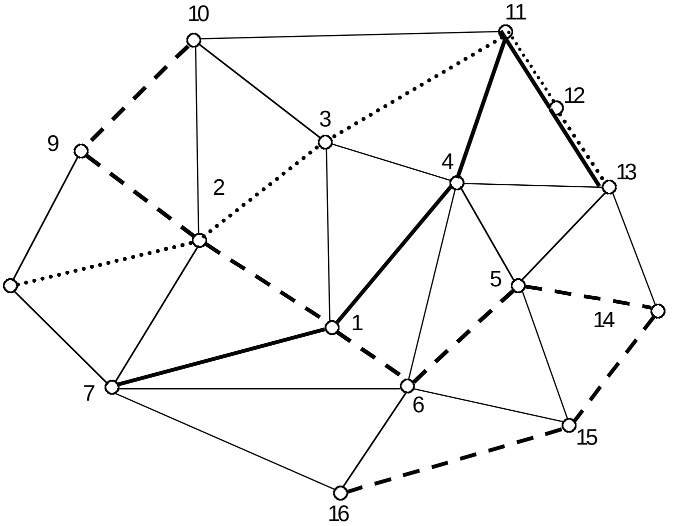


Figure 3: Information for the Example



(a) Template Network for the Example

(b) Scheduling Information for the Example

Route	Configuration	Frequency (bus/hr)	Headway (min)	Average waiting time (min)
#1	7-1-4-11-12-13	8	7.5	3.75
#2	10-9-2-1-6-5-14-15-16	12	5	2.5
#3	8-2-3-11-12-13	5	12	6

(c) Transit Link Travel Time for the Example

(min)

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	0	5 9	6 95	5 9	0	2 8	6 2	0	0	0	0	0	0	0	0	0
# 2	5 9	0	5 0	0	0	0	7 1	6 2	5 0	5 55	0	0	0	0	0	0
# 3	6 95	5 0	0	5 0	0	0	0	0	0	5 0	6 2	0	0	0	0	0
# 4	5 9	0	5 0	0	5 0	7 1	0	0	0	0	5 7	0	6 95	0	0	0
# 5	0	0	0	5 0	0	5 0	0	0	0	0	0	0	5 9	7 45	5 7	0
# 6	2 8	0	0	7 1	5 0	0	8 35	0	0	0	0	0	0	0	6 2	5 0
# 7	6 2	7 1	0	0	0	8 35	0	5 9	0	0	0	0	0	0	0	6 95
# 8	0	6 2	0	0	0	0	5 9	0	4 4	0	0	0	0	0	0	0
# 9	0	5 0	0	0	0	0	0	5 9	0	5 0	0	0	0	0	0	0
# 10	0	5 55	5 0	0	0	0	0	0	5 0	0	9 05	0	0	0	0	0
# 11	0	0	6 2	5 9	0	0	0	0	0	9 05	0	2 8	0	0	0	0
# 12	0	0	0	0	0	0	0	0	0	0	2 8	0	2 8	0	0	0
# 13	0	0	0	6 95	5 9	0	0	0	0	0	0	2 8	0	7 45	0	0
# 14	0	0	0	0	7 45	0	0	0	0	0	0	0	7 45	0	6 2	0
# 15	0	0	0	0	5 9	6 2	0	0	0	0	0	0	0	6 2	0	8 45
# 16	0	0	0	0	0	5 0	6 95	0	0	0	0	0	0	0	8 45	0

Figure 3: Information for the Example (continued)

(d) Origin-Destination Demand for the Example

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	0	5	5	5	5	5	1	1	1	1	1	1	1	1	1	1
# 2	30	0	20	30	20	20	10	10	10	10	10	10	10	10	10	10
# 3	30	20	0	30	20	20	10	10	10	10	10	10	10	10	10	10
# 4	5	5	5	0	5	5	1	1	1	1	1	1	1	1	1	1
# 5	30	20	20	30	0	20	10	10	10	10	10	10	10	10	10	10
# 6	30	20	20	30	20	0	10	10	10	10	10	10	10	10	10	10
# 7	40	10	10	40	10	10	0	5	5	5	5	5	5	5	5	5
# 8	40	10	10	40	10	10	5	0	5	5	5	5	5	5	5	5
# 9	40	10	10	40	10	10	5	5	0	5	5	5	5	5	5	5
# 10	40	10	10	40	10	10	5	5	5	0	5	5	5	5	5	5
# 11	40	10	10	40	10	10	5	5	5	5	0	5	5	5	5	5
# 12	40	10	10	40	10	10	5	5	5	5	5	0	5	5	5	5
# 13	40	10	10	40	10	10	5	5	5	5	5	5	0	5	5	5
# 14	40	10	10	40	10	10	5	5	5	5	5	5	5	0	5	5
# 15	40	10	10	40	10	10	5	5	5	5	5	5	5	5	0	5
# 16	40	10	10	40	10	10	5	5	5	5	5	5	5	5	5	0

Table 1: Shortest Paths for Auto and Potential Shortest Paths for Transit

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	1-2	1-3	1-4	1-6-5	1-6	1-7	1-2-8	1-2-9	1-2-10	1-4-11	1-4-11-12	1-4-13	1-6-15-14	1-6-15	1-6-16
# 2	2-1	-	2-3	2-3-4	2-1-6-5	2-1-6	2-7	2-8	2-9	2-10	2-3-11	2-3-11-12	2-3-11-12-13	2-1-6-15-14	2-1-6-15	2-1-6-16
# 3	3-1	3-2	-	3-4	3-4-5	3-1-6	3-2-7	3-2-8	3-2-9	3-10	3-11	3-11-12	3-11-12-13	3-4-5-14	3-4-5-15	3-1-6-16
# 4	4-1	4-3-2	4-3	-	4-5	4-6	4-1-7	4-3-2-8	4-3-2-9	4-3-10	4-11	4-11-12	4-13	4-5-14	4-5-15	4-6-16
# 5	5-6-1	5-6-1-2	5-4-3	5-4	-	5-6	5-6-7	5-6-7-8	5-6-1-2-9	5-4-3-10	5-4-11	5-13-12	5-13	5-14	5-15	5-6-16
# 6	6-1	6-1-2	6-1-3	6-4	6-5	-	6-7	6-7-8	6-1-2-9	6-1-2-10	6-4-11	6-5-13-12	6-5-13	6-15-14	6-15	6-16
# 7	7-1	7-2	7-2-3	7-1-4	7-6-5	7-6	-	7-8	7-8-9	7-2-10	7-1-4-11	7-1-4-11-12	7-1-4-13	7-6-15-14	7-6-15	7-16
# 8	8-2-1	8-2	8-2-3	8-2-3-4	8-7-6-5	8-7-6	8-7	-	8-9	8-9-10	8-2-3-11	8-2-3-11-12	8-2-3-11-12-13	8-7-6-15-14	8-7-6-15	8-7-16
# 9	9-2-1	9-2	9-2-3	9-2-3-4	9-2-1-6-5	9-2-1-6	9-8-7	9-8	-	9-10	9-10-11	9-10-11-12	9-10-11-12-13	9-2-1-6-15-14	9-2-1-6-15	9-8-7-16
# 10	10-2-1	10-2	10-3	10-3-4	10-3-4-5	10-2-1-6	10-2-7	10-9-8	10-9	-	10-11	10-11-12	10-11-12-13	10-11-12-13-14	10-2-1-6-15	10-2-1-6-16
# 11	11-4-1	11-3-2	11-3	11-4	11-4-5	11-4-6	11-4-1-7	11-3-2-8	11-10-9	11-10	-	11-12	11-12-13	11-12-13-14	11-4-5-15	11-4-6-16
# 12	12-11-4-1	12-11-3-2	12-11-3	12-11-4	12-13-5	12-13-5-6	12-11-4-1-7	12-11-3-2-8	12-11-10-9	12-11-10	12-11	-	12-13	12-13-14	12-13-5-15	12-13-5-6-16
# 13	13-4-1	13-12-11-3-2	13-12-11-3	13-4	13-5	13-5-6	13-4-1-7	13-12-11-3-2-8	13-12-11-10-9	13-12-11-10	13-12-11	13-12	-	13-14	13-5-15	13-5-6-16
# 14	14-15-6-1	14-15-6-1-2	14-5-4-3	14-5-4	14-5	14-15-6	14-15–6-7	14-15-6-7-8	14-15-6-1-2-9	14-13-12-11-10	14-13-12-11	14-13-12	14-13	-	14-15	14-15-16
# 15	15-6-1	15-6-1-2	15-5-4-3	15-5-4	15-5	15-6	15-6-7	15-6-7-8	15-6-1-2-9	15-6-1-2-10	15-5-4-11	15-5-13-12	15-5-13	15-14	-	15-16
# 16	16-6-1	16-6-1-2	16-6-1-3	16-6-4	16-6-5	16-6	16-7	16-7-8	16-7-8-9	16-6-1-2-10	16-6-4-11	16-6-5-13-12	16-6-5-13	16-15-14	16-15	-

Table 2: Potential Shortest Travel Time by Transit

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	5.9	6.95	5.9	7.8	2.8	6.2	12.1	10.9	11.45	11.6	14.4	12.85	15.2	9.0	7.8
# 2	5.9	-	5.0	10.0	13.7	8.7	7.1	6.2	5.0	5.55	11.2	14.0	16.8	21.1	14.9	13.7
# 3	6.95	5.0	-	5.0	10.0	9.75	12.1	11.2	10.0	5.0	6.2	9.0	11.8	17.45	15.7	14.75
# 4	5.9	10.0	5.0	-	5.0	7.1	12.1	16.2	15.0	10.0	5.7	8.5	6.95	12.45	10.7	12.1
# 5	7.8	13.7	10.0	5.0	-	5.0	13.35	19.25	18.7	15.0	10.7	8.7	5.9	7.45	5.7	10.0
# 6	2.8	8.7	9.75	7.1	5.0	-	8.35	14.25	13.7	14.25	12.8	13.7	10.9	12.4	6.2	5.0
# 7	6.2	7.1	12.1	12.1	13.35	8.35	-	5.9	10.3	12.65	17.8	20.6	19.05	20.75	14.55	6.95
# 8	12.1	6.2	11.2	16.2	19.25	14.25	5.9	-	4.4	9.4	17.4	20.2	23.0	26.65	20.45	12.85
# 9	10.9	5.0	10.0	15.0	18.7	13.7	10.3	4.4	-	5.0	14.05	16.85	19.65	26.1	19.9	17.25
# 10	11.45	5.55	5.0	10.0	15.0	14.25	12.65	9.4	5.0	-	9.05	11.85	14.65	22.1	20.45	19.25
# 11	11.6	11.2	6.2	5.7	10.7	12.8	17.8	17.4	14.05	9.05	-	2.8	5.6	13.05	16.4	17.8
# 12	14.4	14.0	9.0	8.5	8.7	13.7	20.6	20.2	16.85	11.85	2.8	-	2.8	10.25	14.4	18.7
# 13	12.85	16.8	11.8	6.95	5.9	10.9	19.05	23.0	19.65	14.65	5.6	2.8	-	7.45	11.6	15.9
# 14	15.2	21.1	17.45	12.45	7.45	12.4	20.75	26.65	26.1	22.1	13.05	10.25	7.45	-	6.2	14.65
# 15	9.0	14.9	15.7	10.7	5.7	6.2	14.55	20.45	19.9	20.45	16.4	14.4	11.6	6.2	-	8.45
# 16	7.8	13.7	14.75	12.1	10.0	5.0	6.95	12.85	17.25	19.25	17.8	18.7	15.9	14.65	8.45	-

Table 3 shows the real shortest transit paths, which were found using the transit route choice model and the given transit network information in Figure 3. It also shows origin-destination in-transit travel time, including transfer time and total transit travel time.

Table 4 details the various measures for individual origin-destination pairs. Auto shortest travel time, potential transit in-vehicle travel time, real shortest in-vehicle travel time, and real shortest travel time are taken into consideration for each origin-destination. Obviously, ITTDOCI shows the lowest values of all four measures, and those with total travel time of transit and auto shortest travel time show the highest values. It is also clear that ITTDOCO shows lower values than TTTDOCO, and ITTDOCI shows lower values than TTTDOCI because in-transit travel time is shorter than total transit travel time. Additionally, ITTDOCO is higher than ITTDOCI because auto travel time is shorter than potential shortest travel time. TTTDOCO is higher than TTTDOCI for the same reason.

Table 5 shows the overall network measures for all four cases discussed. Measures for the transit network can be shown with simple average and weighted average. Both are shown for four cases, and weighted averages are less than simple averages for this example. This shows that the transit network of the example is well designed because origin-destination with higher demand is served with higher efficiency and a lower Degree of Circuity.

CONCLUSION

In this paper, measures that show the competitiveness and indirectness of the current transit system are introduced. Degree of Competitiveness (DOCO) compares additional transit travel time with auto travel time to show how competitive the current transit system is. Degree of Circuity (DOCI) compares additional transit travel time with potential shortest transit travel time to show how much the current transit system can ultimately be improved. Each measure is dependent on in-vehicle travel time and total travel time for defining transit travel time. Since transit network design is one of the most complicated processes in transit planning and requires many feedback procedures, these measures can improve the feedback process.

Although the values of the measures from real transit systems would greatly help the decision process, the relationships between the measures can also give some clues for transit system improvement.

Individual measures can show which origin-destination service is poor. Obviously, the one with a higher value of measures has poor service. With a trip demand matrix, these measures can show whether the origin-destination with high priority (higher demand) has better service, i.e., more direct connection and more competitive service. It is desirable that the origin-destination pair with higher demand has more direct connections and more competitive services to compete with autos in terms of travel time. If a certain origin-destination with high demand has a higher DOCO and/or DOCI, then the efforts to provide better service should be followed in the next planning process.

Measures for the network represent overall transit network performance. The difference between simple average and weighted average shows how well the origin-destination trips with heavier demand are considered. The lower the weighted average, the better the transit network is designed. If a transit network is not well designed, weighted average measures will be higher than simple average measures.

In the future, measures from real transit systems can be estimated, and the overall efficiency of the transit system can be better evaluated. Though a lower DOCO and DOCI with total travel time of transit representing the good performance of the current transit system – because optimal transit network configuration is greatly related to demand size [Lee 1998] – the estimation of satisfactory values of the measures through real agencies is needed to evaluate whether the transit system performance and network configuration with given demand size is proper.

Measures with in-vehicle travel time do not include waiting time, and it is not always good to have lower values for those measures because optimal ITTDOCI depends on demand size. For example, low ITTDOCI may not be good for a system with small demand size, because longer headway is needed to achieve that – which may not be efficient.

The measures and the concepts discussed in this paper are not totally new, but, this paper systematically structures and mathematically develops them in detail.

Table 3: Real Shortest Travel Time by Transit Without and With Waiting Time

(min, min)

Node	# 1	# 2	# 3	# 4	# 5	# 6
# 1	-	1-2 (5 9, 8 4)	1-2, 2-3 (16 9, 19 4)	1-4 (5 9, 9 65)	1-6-5 (7 8, 10 3)	1-6 (2 8, 5 3)
# 2	2-1 (5 9, 8 4)	-	2-3 (5 0, 11 0)	2-1, 1-4 (15 55,18 05)	2-1-6-5 (13 7, 16 2)	2-1-6 (8 7, 11 2)
# 3	3-2, 2-1 (14 65, 19 4)	3-2 (5 0, 11 0)	-	3-11, 11-4 (15 65,21 65)	3-2, 2-1-6-5 (21 2, 27 2)	3-2, 2-1-6 (16 2, 22 2)
# 4	4-1 (5 9, 9 65)	4-1, 1-2 (14 3, 18 05)	4-11, 11-3 (17 9, 21 65)	-	4-1, 1-6-5 (16 2, 19 95)	4-1, 1-6 (11 2, 14 95)
# 5	5-6-1 (7 8, 10 3)	5-6-1-2 (13 7, 16 2)	5-6-1-2, 2-3 (24 7, 27 2)	5-6-1, 1-4 (17 45,19 95)	-	5-6 (5 0, 7 5)
# 6	6-1 (2 8, 5 3)	6-1-2 (8 7, 11 2)	6-1-2, 2-3 (19 7, 22 2)	6-1, 1-4 (12 45, 16 2)	6-5 (5 0, 7 5)	-
# 7	7-1 (6 2, 9 9)	7-1, 1-2 (14 65,18 35)	7-1, 1-2, 2-3 (25 6, 29 35)	7-1-4 (12 1, 15 85)	7-1, 1-6-5 (16 5, 20 25)	7-1, 1-6 (11 5, 15 25)
# 8	8-2, 2-1 (14 6, 20 6)	8-2 (6 2, 12 2)	8-2-3 (11 2, 17 2)	8-2, 2-1, 1-4 (24 25,30 25)	8-2, 2-1-6-5 (22 4, 28 4)	8-2, 2-1-6 (17 4, 23 4)
# 9	9-2-1 (10 9, 13 4)	9-2 (5 0, 7 5)	9-2, 2-3 (16 0, 18 5)	9-2-1, 1-4 (20 55,23 05)	9-2-1-6-5 (18 7, 21 2)	9-2-1-6 (13 7, 16 2)
# 10	10-9-2-1 (15 9, 18 4)	10-9-2 (10 0, 12 5)	10-9-2, 2-3 (21 0, 23 5)	10-9-2-1, 1-4 (25 55,28 05)	10-9-2-1-6-5 (23 7, 26 2)	10-9-2-1-6 (18 7, 21 2)
# 11	11-4-1 (11 6, 15 35)	11-3-2 (11 2, 17 2)	11-3 (6 2, 12 2)	11-4 (5 7, 9 45)	11-4-1, 1-6-5 (21 9, 25 65)	11-4-1, 1-6 (16 9, 20 65)
# 12	12-11-4-1 (14 4, 18 15)	12-11-3-2 (14 0, 20 0)	12-11-3 (9 0, 15 0)	12-11-4 (8 5, 12 25)	12-11-4-1, 1-6-5 (24 7, 28 45)	12-11-4-1, 1-6 (19 7, 23 45)
# 13	13-12-11-4-1 (17 2, 20 95)	13-12-11-3-2 (16 8, 22 8)	13-12-11-3 (11 8, 17 8)	13-12-11-4 (11 3, 15 05)	13-12-11-4-1, 1-6-5 (27 5, 31 25)	13-12-11-4-1, 1-6 (22 5, 26 25)
# 14	14-5-6-1 (15 25,17 75)	14-5-6-1-2 (21 15,23 65)	14-5-6-1-2, 2-3 (32 15,34 65)	14-5-6-1 1-4 (24 9, 27 4)	14-5 (7 45, 9 95)	14-5-6 (12 45,14 95)
# 15	15-14-5-6-1 (21 45,23 95)	15-14-5-6-1-2 (27 35,29 85)	15-14-5-6-1-2 2-3 (38 35,40 85)	15-14-5-6-1, 1-4 (31 1, 33 6)	15-14-5 (13 65,16 15)	15-14-5-6 (18 65,21 15)
# 16	16-15-14-5-6-1 (29 9, 32 4)	16-15-14-5-6-1-2 (35 8, 38 3)	16-15-14-5-6-1-2, 2-3 (46 8, 49 3)	16-15-14-5-6-1, 1-4 (39 55,42 05)	16-15-14-5 (22 1, 24 6)	16-15-14-5-6 (27 1, 29 6)

Table 3: Real Shortest Travel Time by Transit Without and With Waiting Time (continued)

(min, min)

Node	# 7	# 8	# 9	# 10	# 11	# 12
# 1	1-7 (6 2, 9 95)	1-2, 2-8 (18 1, 20 6)	1-2-9 (10 9, 13 4)	1-2-9-10 (15 9, 18 4)	1-4-11 (11 6, 15 35)	1-4-11-12 (14 4, 18 15)
# 2	2-1, 1-7 (15 85,18 35)	2-8 (6 2, 12 2)	2-9 (5 0, 7 5)	2-9-10 (10 0, 12 5)	2-3-11 (11 2, 17 2)	2-3-11-12 (14 0, 20 0)
# 3	3-2, 2-1, 1-7 (23 35,29 35)	3-2-8 (11 2, 17 2)	3-2, 2-9 (12 5, 18 5)	3-2, 2-9-10 (17 5, 23 5)	3-11 (6 2, 12 2)	3-11-12 (9 0, 15 0)
# 4	4-1-7 (12 1, 15 85)	4-1, 1-2, 2-8 (26 5, 30 25)	4-1, 1-2-9 (19 3, 23 05)	4-1, 1-2-9-10 (24 3, 28 05)	4-11 (5 7, 9 45)	4-11-12 (8 5, 12 25)
# 5	5-6-1, 1-7 (17 75,20 25)	5-6-1-2, 2-8 (25 9, 28 4)	5-6-1-2-9 (18 7, 21 2)	5-6-1-2-9-10 (23 7, 26 2)	5-6-1, 1-4-11 (23 15,25 65)	5-6-1, 1-4-11-12 (25 95,28 45)
# 6	6-1, 1-7 (12 75,15 25)	6-1-2, 2-8 (20 9, 23 4)	6-1-2-9 (13 7, 16 2)	6-1-2-9-10 (18 7, 21 2)	6-1, 1-4-11 (18 15,20 65)	6-1, 1-4-11-12 (20 95,23 45)
# 7	-	7-1, 1-2, 2-8 (26 8, 30 55)	7-1, 1-2-9 (19 6, 23 35)	7-1, 1-2-9-10 (24 6, 28 35)	7-1-4-11 (17 8, 21 55)	7-1-4-11-12 (20 6, 24 35)
# 8	8-2, 2-1, 1-7 (24 55,30 55)	-	8-2, 2-9 (13 7, 19 7)	8-2, 2-9-10 (18 7, 24 7)	8-2-3-11 (16 4, 22 4)	8-2-3-11-12 (19 2, 25 2)
# 9	9-2-1, 1-7 (20 85,23 35)	9-2, 2-8 (17 2, 19 7)	-	9-10 (5 0, 7 5)	9-2, 2-3-11 (22 2, 24 7)	9-2, 2-3-11-12 (25 0, 27 5)
# 10	10-9-2-1, 1-7 (25 85,28 35)	10-9-2, 2-8 (22 2, 24 7)	10-9 (5 0, 7 5)	-	10-9-2, 2-3-11 (27 2, 29 7)	10-9-2, 2-3-11-12 (30 0, 32 5)
# 11	11-4-1-7 (17 8, 21 55)	11-3-2-8 (16 4, 22 4)	11-3-2, 2-9 (18 7, 24 7)	11-3-2, 2-9-10 (23 7, 29 7)	-	11-12 (2 8, 6 55)
# 12	12-11-4-1-7 (20 6, 24 35)	12-11-3-2-8 (19 2, 25 2)	12-11-3-2, 2-9 (23 75, 27 5)	12-11-3-2, 2-9-10 (28 75, 32 5)	12-11 (2 8, 6 55)	-
# 13	13-12-11-4-1-7 (23 4, 27 15)	13-12-11-3-2-8 (22 0, 28 0)	13-12-11-3-2, 2-9 (24 3, 30 3)	13-12-11-3-2, 2-9-10 (29 3, 35 3)	13-12-11 (5 6, 9 35)	13-12 (2 8, 6 55)
# 14	14-5-6-1, 1-7 (25 2, 27 7)	14-5-6-1-2, 2-8 (33 35,35 85)	14-5-6-1-2-9 (26 15,28 65)	14-5-6-1-2-9-10 (31 15,33 65)	14-5-6-1, 1-4-11 (30 6, 33 1)	14-5-6-1, 1-4-11-12 (33 4, 35 9)
# 15	15-14-5-6-1, 1-7 (31 4, 33 9)	15-14-5-6-1-2, 2-8 (39 55,42 05)	15-14-5-6-1-2-9 (32 35,34 85)	15-14-5-6-1-2-9-10 (37 35,39 85)	15-14-5-6-1, 1-4-11 (36 8, 39 3)	15-14-5-6-1, 1-4-11-12 (39 6, 42 1)
# 16	16-15-14-5-6-1, 1-7 (39 85,42 35)	16-15-14-5-6-1-2, 2-8 (48 0, 50 5)	16-15-14-5-6-1-2-9 (40 8, 43 3)	16-15-14-5-6-1-2-9-10 (45 8, 48 3)	16-15-14-5-6-1, 1-4-11 (45 25,47 75)	16-15-14-5-6-1, 1-4-11-12 (48 05,50 55)

Table 3: Real Shortest Travel Time by Transit Without and With Waiting Time (continued)

(min, min)

Node	# 13	# 14	# 15	# 16
# 1	1-4-11-12-13 (17 2, 20 95)	1-6-5-14 (15 25,17 75)	1-6-5-14-15 (21 45,23 95)	1-6-5-14-15-16 (29 9, 32 4)
# 2	2-3-11-12-13 (16 8, 22 8)	2-1-6-5-14 (21 15,23 65)	2-1-6-5-14-15 (27 35,29 85)	2-1-6-5-14-15-16 (35 8, 38 3)
# 3	3-11-12-13 (11 8, 17 8)	3-2, 2-1-6-5-14 (28 65,34 65)	3-2, 2-1-6-5-14-15 (34 85,40 85)	3-2, 2-1-6-5-14-15-16 (43 3, 49 3)
# 4	4-11-12-13 (11 3, 15 05)	4-1, 1-6-5-14 (23 65, 27 4)	4-1, 1-6-5-14-15 (29 85, 33 6)	4-1, 1-6-5-14-15-16 (38 3, 42 05)
# 5	5-6-1, 1-4-11-12-13 (28 75,31 25)	5-14 (7 45, 9 95)	5-14-15 (13 65,16 15)	5-14-15-16 (22 1, 24 6)
# 6	6-1, 1-4-11-12-13 (23 75,26 25)	6-5-14 (12 45,14 95)	6-5-14-15 (18 65,21 15)	6-5-14-15-16 (27 1, 29 6)
# 7	7-1-4-11-12-13 (23 4, 27 15)	7-1, 1-6-5-14 (23 95, 27 7)	7-1, 1-6-5-14-15 (30 15, 33 9)	7-1, 1-6-5-14-15-16 (38 6, 42 35)
# 8	8-2-3-11-12-13 (22 0, 28 0)	8-2, 2-1-6-5-14 (29 85,35 85)	8-2, 2-1-6-5-14-15 (36 05,42 05)	8-2, 2-1-6-5-14-15-16 (44 05, 50 05)
# 9	9-2, 2-3-11-12-13 (27 8, 30 3)	9-2-1-6-5-14 (26 15,28 65)	9-2-1-6-5-14-15 (32 35,34 85)	9-2-1-6-5-14-15-16 (40 8, 43 3)
# 10	10-9-2, 2-3-11-12-13 (32 8, 35 3)	10-9-2-1-6-5-14 (31 15,23 65)	10-9-2-1-6-5-14-15 (37 35,39 85)	10-9-2-1-6-5-14-15-16 (45 8, 48 3)
# 11	11-12-13 (5 6, 9 35)	11-4-1, 1-6-5-14 (29 35, 33 1)	11-4-1, 1-6-5-14-15 (35 55, 39 3)	11-4-1, 1-6-5-14-15-16 (44 0, 47 75)
# 12	12-13 (2 8, 6 55)	12-11-4-1, 1-6-5-14 (32 15, 35 9)	12-11-4-1, 1-6-5-14-15 (38 35, 42 1)	12-11-4-1, 1-6-5-14-15-16 (46 8, 50 55)
# 13	-	13-12-11-4-1 1-6-5-14 (34 95, 38 7)	13-12-11-4-1, 1-6-5-14-15 (41 15, 44 9)	13-12-11-4-1, 1-6-5-14-15-16 (49 6, 53 35)
# 14	14-5-6-1, 1-4-11-12-13 (36 2, 38 7)	-	14-15 (6 2, 8 7)	14-15-16 (14 65, 17 15)
# 15	15-14-5-6-1, 1-4-11-12-13 (42 4, 44 9)	15-14 (6 2, 8 7)	-	15-16 (8 45, 10 95)
# 16	16-15-14-5-6-1, 1-4-11-12-13 (50 85,53 35)	16-15-14 (14 65,17 15)	16-15 (8 45, 10 95)	-

Table 4: Individual Measures for the Example

(a) In-vehicle Travel Time Degree of Competitiveness (ITTDOCO)

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	0 43	2 47	0 43	0 43	0 43	0 43	1 14	0 43	0 98	0 43	0 43	0 91	0 43	2 40	4 48
# 2	0 43	-	0 43	1 22	0 43	0 43	2 19	0 43	0 43	1 57	0 43	0 43	0 43	0 43	1 62	2 73
# 3	2 01	0 43	-	3 47	2 03	1 37	1 76	0 43	0 79	4 00	0 43	0 43	0 43	1 35	2 17	3 19
# 4	0 43	1 04	4 11	-	3 63	1 25	0 43	1 34	0 84	2 47	0 43	0 43	1 32	1 71	2 99	3 52
# 5	0 43	0 43	2 53	3 99	-	0 43	0 90	0 92	0 43	1 26	2 09	3 26	5 96	0 43	2 42	2 16
# 6	0 43	0 43	1 89	1 51	0 43	-	1 18	1 10	0 43	0 87	1 03	1 18	2 11	0 43	3 30	6 74
# 7	0 43	1 95	2 02	0 43	0 77	0 97	-	5 49	1 72	1 78	0 43	0 43	0 75	0 65	1 96	6 93
# 8	0 72	0 43	0 43	1 14	0 66	0 74	4 94	-	3 45	1 84	0 35	0 36	0 37	0 60	1 52	3 90
# 9	0 43	0 43	1 29	0 96	0 43	0 43	1 89	4 58	-	0 43	1 26	1 12	1 02	0 43	1 32	2 38
# 10	0 98	1 57	5 00	2 65	1 26	0 87	1 92	2 37	0 43	-	3 29	2 62	2 20	1 01	1 61	2 40
# 11	0 43	0 43	0 43	0 43	1 92	0 89	0 43	0 35	0 90	2 74	-	0 43	0 43	2 21	2 10	2 53
# 12	0 43	0 43	0 43	0 43	3 06	1 05	0 43	0 36	1 01	2 47	0 43	-	0 43	3 48	2 80	2 58
# 13	0 91	0 43	0 43	1 32	5 66	1 95	0 75	0 37	0 77	1 86	0 43	0 43	-	5 70	4 07	3 46
# 14	0 43	0 43	1 63	1 86	0 43	0 43	0 73	0 79	0 43	1 01	2 35	3 66	5 94	-	0 43	0 43
# 15	2 40	1 62	2 49	3 15	2 42	3 30	2 08	1 76	1 32	1 61	2 21	2 93	4 22	0 43	-	0 43
# 16	4 48	2 73	3 53	3 67	2 16	6 74	7 19	4 34	2 38	2 40	2 63	2 67	3 57	0 43	0 43	-

(b) Total Travel Time Degree of Competitiveness (TTTDOCO)

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	1 03	2 99	1 34	0 89	1 70	1 29	1 43	0 76	1 30	0 89	0 80	1 33	0 67	2 80	4 93
# 2	1 03	-	2 14	1 58	0 69	0 84	2 69	1 81	1 14	2 22	1 19	1 04	0 94	0 60	1 86	2 99
# 3	2 99	2 14	-	5 19	2 89	2 25	2 47	1 19	1 64	5 71	1 81	1 38	1 15	1 84	2 72	3 77
# 4	1 34	1 58	5 19	-	4 70	2 01	0 87	1 67	1 20	3 01	1 37	1 06	2 09	2 14	3 49	3 96
# 5	0 89	0 69	2 89	4 70	-	1 14	1 17	1 11	0 62	1 50	2 42	3 67	6 57	0 91	3 05	2 51
# 6	1 70	0 84	2 25	2 26	1 14	-	1 61	1 35	0 69	1 13	1 30	1 45	2 44	0 72	3 87	7 46
# 7	1 28	2 69	2 47	0 87	1 17	1 61	-	6 40	2 24	2 20	0 73	0 69	1 04	0 91	2 33	7 71
# 8	1 43	1 81	1 19	1 67	1 11	1 35	6 40	-	5 40	2 75	0 84	0 78	0 74	0 92	1 94	4 56
# 9	0 76	1 14	1 64	1 20	0 62	0 69	2 24	5 40	-	1 14	1 51	1 33	1 20	0 57	1 50	2 59
# 10	1 30	2 22	5 71	3 01	1 50	1 13	2 20	2 75	1 14	-	3 69	2 92	2 44	0 53	1 78	2 58
# 11	0 89	1 19	1 81	1 37	2 42	1 30	0 73	0 84	1 51	3 69	-	2 34	1 39	2 62	2 42	2 83
# 12	0 80	1 04	1 38	1 06	3 67	1 45	0 69	0 78	1 33	2 92	2 34	-	2 34	4 00	3 18	2 86
# 13	1 33	0 94	1 15	2 09	6 57	2 44	1 04	0 74	1 20	2 44	1 39	2 34	-	6 42	4 53	3 79
# 14	0 67	0 60	1 84	2 14	0 91	0 72	0 91	0 92	0 57	1 18	2 62	4 00	6 42	-	1 00	0 67
# 15	2 80	1 86	2 72	3 49	3 05	3 87	2 33	1 94	1 50	1 78	2 42	3 18	4 53	1 00	-	0 85
# 16	4 93	2 99	3 77	3 96	2 51	7 46	7 71	4 61	2 59	2 58	2 83	2 86	3 79	0 67	0 85	-

Table 4: Individual Measures for the Example (continued)

(c) In-vehicle Travel Time Degree of Circuity (ITTDOCI)

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	0 00	1 43	0 00	0 00	0 00	0 00	0 50	0 00	0 39	0 00	0 00	0 34	0 00	1 38	2 83
# 2	0 00	-	0 00	0 56	0 00	0 00	1 23	0 00	0 00	0 80	0 00	0 00	0 00	0 00	0 84	1 61
# 3	1 11	0 00	-	2 13	1 12	0 66	0 93	0 00	0 25	2 50	0 00	0 00	0 00	0 64	1 22	1 94
# 4	0 00	0 43	2 58	-	2 24	0 58	0 00	0 64	0 29	1 43	0 00	0 00	0 63	0 90	1 79	2 17
# 5	0 00	0 00	1 47	2 49	-	0 00	0 33	0 35	0 00	0 58	1 16	1 98	3 87	0 00	1 39	1 21
# 6	0 00	0 00	1 02	0 75	0 00	-	0 53	0 47	0 00	0 31	0 42	0 53	1 18	0 00	2 01	4 42
# 7	0 00	1 06	1 12	0 00	0 24	0 38	-	3 54	0 90	0 94	0 00	0 00	0 23	0 15	1 07	4 55
# 8	0 21	0 00	0 00	0 50	0 16	0 22	3 16	-	2 11	0 99	0 00	0 00	0 00	0 12	0 76	2 43
# 9	0 00	0 00	0 60	0 37	0 00	0 00	1 02	2 91	-	0 00	0 58	0 48	0 41	0 00	0 63	1 37
# 10	0 39	0 80	3 20	1 56	0 58	0 31	1 04	1 36	0 00	-	2 01	1 53	1 24	0 41	0 83	1 38
# 11	0 00	0 00	0 00	0 00	1 05	0 32	0 00	0 00	0 33	1 62	-	0 00	0 00	1 25	1 17	1 47
# 12	0 00	0 00	0 00	0 00	1 84	0 44	0 00	0 00	0 41	1 43	0 00	-	0 00	2 14	1 66	1 50
# 13	0 34	0 00	0 00	0 63	3 66	1 06	0 23	0 00	0 24	1 00	0 00	0 00	-	3 69	2 55	2 12
# 14	0 00	0 00	0 84	1 00	0 00	0 00	0 21	0 25	0 00	0 41	1 34	2 26	3 86	-	0 00	0 00
# 15	1 38	0 84	1 44	1 91	1 39	2 01	1 16	0 93	0 63	0 83	1 24	1 75	2 66	0 00	-	0 00
# 16	2 83	1 61	2 17	2 27	1 21	4 42	4 73	2 74	1 37	1 38	1 54	1 57	2 20	0 00	0 00	-

(d) Total Travel Time Degree of Circuity (TTTDOCI)

Node	# 1	# 2	# 3	# 4	# 5	# 6	# 7	# 8	# 9	# 10	# 11	# 12	# 13	# 14	# 15	# 16
# 1	-	0 42	1 79	0 64	0 32	0 89	0 60	0 70	0 23	0 61	0 32	0 26	0 63	0 17	1 66	3 15
# 2	0 42	-	1 20	0 81	0 18	0 29	1 58	0 97	0 50	1 25	0 54	0 43	0 36	0 12	1 00	1 80
# 3	1 79	1 20	-	3 33	1 72	1 28	1 43	0 54	0 85	3 70	0 97	0 67	0 51	0 99	1 60	2 34
# 4	0 64	0 81	3 33	-	2 99	1 11	0 31	0 87	0 54	1 81	0 66	0 44	1 17	1 20	2 14	2 48
# 5	0 32	0 18	1 72	2 99	-	0 50	0 52	0 48	0 13	0 75	1 40	2 27	4 30	0 34	1 83	1 46
# 6	0 89	0 29	1 28	1 28	0 50	-	0 83	0 64	0 18	0 49	0 61	0 71	1 41	0 21	2 41	4 92
# 7	0 60	1 58	1 43	0 31	0 52	0 83	-	4 18	1 27	1 24	0 21	0 18	0 43	0 33	1 33	5 09
# 8	0 70	0 97	0 54	0 87	0 48	0 64	4 18	-	3 48	1 63	0 29	0 25	0 22	0 35	1 06	2 89
# 9	0 23	0 50	0 85	0 54	0 13	0 18	1 27	3 48	-	0 50	0 76	0 63	0 54	0 10	0 75	1 51
# 10	0 61	1 25	3 70	1 81	0 75	0 49	1 24	1 63	0 50	-	2 28	1 74	1 41	0 07	0 95	1 51
# 11	0 32	0 54	0 97	0 66	1 40	0 61	0 21	0 29	0 76	2 28	-	1 34	0 67	1 54	1 40	1 68
# 12	0 26	0 43	0 67	0 44	2 27	0 71	0 18	0 25	0 63	1 74	1 34	-	1 34	2 50	1 92	1 70
# 13	0 63	0 36	0 51	1 17	4 30	1 41	0 43	0 22	0 54	1 41	0 67	1 34	-	4 19	2 87	2 36
# 14	0 17	0 12	0 99	1 20	0 34	0 21	0 33	0 35	0 10	0 52	1 54	2 50	4 19	-	0 40	0 17
# 15	1 66	1 00	1 60	2 14	1 83	2 41	1 33	1 06	0 75	0 95	1 40	1 92	2 87	0 40	-	0 30
# 16	3 15	1 80	2 34	2 48	1 46	4 92	5 09	2 93	1 51	1 51	1 68	1 70	2 36	0 17	0 30	-

Table 5: Summary of the Measures for the Network

Measures	Values
Simple In-vehicle Travel Time Degree of Competitiveness (ITTDOCO)	1.65 (165%)
Simple Total Travel Time Degree of Competitiveness (TTTDOCO)	2.18 (218%)
Simple In-vehicle Travel Time Degree of Circuity (ITTDOCI)	0.85 (85%)
Simple Total Travel Time Degree of Circuity (TTTDOCI)	1.23 (123%)
Weighted In-vehicle Travel Time Degree of Competitiveness (ITTDOCO)	1.53 (153%)
Weighted Total Travel Time Degree of Competitiveness (TTTDOCO)	2.09 (209%)
Weighted In-vehicle Travel Time Degree of Circuity (ITTDOCI)	0.77 (77%)
Weighted Total Travel Time Degree of Circuity (TTTDOCI)	1.16 (116%)

Acknowledgements

This research was funded by National Transportation Center at Morgan State University in Baltimore, MD. The author appreciates Dr. Andrew Farkas and Ms. Erica Johnson at the National Transportation Center for his contribution to the research and for her contribution to the editing.

References

Cedar, A. and Y. Israeli. "User and Operator Perspective in Transit Network Design." Paper No. 980267, 77th annual meeting of TRB, Washington, DC, January 1998.

Dantzig, G.B. "All shortest routes in a graph." Théorie des graphes, Proceedings of the International Symposium, Rome 1966, Dunod, Paris, (1966): 91-92.

Dijkstra, E.W. "A Note on Two Problems in Connection with Graphs." Numerische Mathematik 1, (1959): 269-271.

Lee, Young-Jae. "Analysis and Optimization of Transit Network Design with Integrated Routing and Scheduling." Dissertation (Ph.D). University of Pennsylvania, Philadelphia, PA, 1998.

Lee, Young-Jae and V. R. Vuchic. "Transit Network Design with Variable Demand." *Journal of Transportation Engineering*, 131(1), (2005): 1-10.

Moore, E.F. "The Shortest Path Through a Maze." Proceedings of an International Symposium on the Theory of Switching, Part II, pp. 285-292, Harvard University Press, Cambridge, MA, 1957.

Rea, J.C. *Designing Urban Transit Systems: An Approach to the Route-Technology Selection Problem*. No. UMTA-URT-49(70)-71-6, Urban Transportation Program, University of Washington, Seattle, WA, 1971.

Sheffi, Yosef. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1985.

Transit Cooperative Research Program. *A Guidebook for Developing a Transit Performance-Measurement System*. TCRP Report 88, TRB 2003.

Vuchic, V.R. et al. *Transit Operating Manual*. Pennsylvania Department of Transportation, University of Pennsylvania, Philadelphia, PA, 1976.

***Young-Jae Lee** is an associate professor in the Department of Transportation and Urban Infrastructure Studies at Morgan State University. Lee received his Ph.D. at the University of Pennsylvania, and his dissertation was about transit network design and analysis. Lee is considered a transit expert in the academic field and transit industry. He has published numerous papers in peer reviewed journals and presented at conferences, and he has been quoted in numerous papers as well. Among transit agencies, Lee participated in projects for the Maryland Transit Administration, the Southeastern Pennsylvania Transit Authority and San Francisco's Bay Area Rapid Transit.*