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16. Abstract

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One of the measures introduced in this paper is Degree of Competitiveness, which compares transit travel time and auto travel time. This measure illustrates how much additional transit travel time is required compared to auto travel. This compares how competitive the current transit system is to other transportation modes, mainly the auto system. Another measure is Degree of Circuity, which compares current transit travel time and potential shortest transit travel time. This measure shows how much additional transit travel time is currently required compared to the ultimate shortest transit travel time. It shows how direct the transit network is. Two different transit travel times, total travel time and total travel time after boarding, are used for further analysis.

While these measures examine the performance for zone-to-zone travel, two different types of average, simple average and weighted average, are also introduced to evaluate the entire transit network. These measures are tested with the example, and performance of measures and future research are discussed.

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DEVELOPING A METHODOLOGY

FOR TRANSIT NETWORK PERFORMANCE ANALYSIS

AND ITS APPLICATION

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ABSTRACT

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One of the measures introduced in this paper is Degree of Competitiveness, which compares transit travel time and auto travel time. This measure illustrates how much additional transit travel time is required compared to auto travel. This compares how competitive the current transit system is to other transportation modes, mainly the auto system. Another measure is Degree of Circuity, which compares current transit travel time and potential shortest transit travel time. This measure shows how much additional transit travel time is currently required compared to the ultimate shortest transit travel time. It shows how direct the transit network is. Two different transit travel times, total travel time and total travel time after boarding, are used for further analysis.

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1. INTRODUCTION

Optimal planning and operation are the most important components for successful transit agencies. However, optimal planning and operation for transit are difficult to be determined. 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, after the certain period of operation, is usually adopted to improve planning and operation.

Measures to determine transit operation show how to diagnose current transit operations and how to make the future planning efficient. Because of those reasons, setting and developing the measures are always important for transit agencies.

Measures are mainly related to either inputs or outputs for transit planning and operation. Since improving measures related to output is major interests of transit agencies, after checking the measures related to the output performance, agencies change their operational plans, which change their input measures, and improve output measures eventually.

In this research, input measures, which are related to transit network configuration, will be introduced and will show how they can work to improve output measures.

1.1 Measures for transit planning and operation

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

The other way to classify the measures is through objects for the measures. Measures used for the transit planning and operation are related to transit users, transit agencies, and/or society.

1.2 Objectives

This research develops new measures to diagnose current planning and operation in more efficient ways. Transit network configuration is one of the most important components for transit planning and operation, because many other planning and operation components depend on transit network configuration. In this research, new input measures related to transit network configuration and performance will be developed and suggested.

1.3 Scope of the Research

Originally, it was planned to collect input and output measures from the transit agencies, to check the relationship between input and output measures, and to show the higher relationship between output measures and newly developed input measures by this research using statistical analysis. Unfortunately, it was not possible to collect the necessary inputs to run the model to create measures, although many transit agencies have been contacted. Because of the difficulty in collecting data, this research will focus on the followings:

1. Introduction of newly developed measures
2. Process of determining the measures
3. Applying measures to the hypothetical cities

2. BACKGROUND CONCEPTS FOR THE RESEARCH

2.1 Relationship between Measures

Measures for the transit system evaluation are related to either one of three aspects: 1) users, 2) agency or 3) society. While most output measures, which are related to transit system performance, show the transit agency's aspects, input measures are usually related to users' and society's aspects.

Although interests of those parties may be different, they have relations and interact with each other. Most input measures make an impact on output measures, while output measures make an impact on input measures as well.

In most cases, improving input measures, such as headway, route length, etc., requires additional costs. Improved input measures improve most output measures except finance-related measures and some utilization measures.

2.2 Introduction to New Measures – Comparative Approach

In this research, comparative measures will be introduced. Most measures currently being used are produced solely by current transit planning and operation. However, because travel demand always compares the available travel modes, measures that can show the relationship between auto and transit travel are necessary. These measures will show the competitiveness of the transit service.

Also, current transit networks and potential shortest travel time transit networks are compared. This comparison shows how much transit network can be improved potentially, if the size of demand is big enough to provide high frequency for any route.

Among the many differences between auto and transit, travel costs are probably the most important concern for the demand. Travel time for each mode is the key component of travel costs. In this paper, measures, which compare travel times of two different modes, will be developed.

2.3 Transit Network Configuration

Transit network configuration is one of the most important components of 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 hardest tasks for the transit industry.

One of the main reasons of optimizing transit network design is the complexity of designing transit network configuration. Because of this complexity, most transit networks have been designed with intuition and experience.

Another reason is the difficulty in changing current network configuration. Although recent researches enable to optimize transit network, it is hard for transit agencies to complete changes at once, due to the confusion that it may cause.

Because of these reasons, rather than changing transit network configuration drastically, other elements, such as scheduling and/or modest changes in transit network, are recommended to improve the level of service. Once transit network is designed, user travel time can be hardly improved drastically by other changes.

2.4 Transit Travel Time Characteristics [1]

As mentioned, this study looks for measures that use travel times of auto and transit as inputs. In order 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. Among the characteristics, there are some advantages, such as the absence of the need to own and take care of cars, to drive etc. However, there are also disadvantages, as well. First, transit is usually operated on fixed routes, while private transportation users can choose their routes. Second, transit users must follow a schedule, while private transportation users can control their schedules. Third, transit users must go to the station to use transit, while private transportation users can drive from their homes. Fourth, transit users sometimes need to transfer. These disadvantages of transit involve components of travel time for transit users as shown in Figure 1.

The first disadvantage, fixed routes, is related to in-vehicle travel time. While private transportation users choose their minimum travel time paths, transit users must use fixed routes, which are not usually direct for many trips. Even though transit users can choose their minimum travel time route when alternative routes are available, usually additional in-vehicle travel time is required compared to auto transit travel time due to the circuity of transit routes.

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

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

The fourth disadvantage is the need to transfer. It includes access time to the transfer station, waiting time at the transfer station, and an additional fare charge if necessary. Mainly due to operator's 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.

In order to make an efficient transit system, transit network design which considers and minimizes these disadvantages is necessary. 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. In order to optimize a transit network, it is recommended that relationships among components be considered and then each component optimized. Especially routing, which decides in-vehicle travel time, and scheduling, which decides waiting time, should be considered simultaneously to minimize total travel time in the transit network at the sketch level. Basically, users' in-vehicle travel time and waiting time are determined when the corridor of each route is chosen, because corridors determine the basic number of passengers. Each route can be improved through changing details after designing a big picture of the transit network.

2.5 Relationship between Routing and Scheduling

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

The relationship between routing and scheduling comes from the scheduling process. Scheduling is affected by many concerns, such as maximum policy headway, fleet size, etc.

However, the most important input for the scheduling process is demand size. As shown in Equation 1, in order to prevent an overcrowded situation, frequency should be linearly related, which means demand for a certain route mainly decides its frequency. [2, 3]

$$f_D = \frac{V_{MLS}}{C_v \cdot \alpha}, \qquad [1]$$

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 fixed transit demand, that the amount of demand picked up by the route is decided depending on routing. The other reason is, depending on routing, that the demand for the transit travel is changed. The more efficient the transit route is, the transit can have more share 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 the fixed transit demand, a route collects more demand if it is circuitous, and it results in higher frequency and shorter headway. However, there is a trade-off from the circuitous routing. Although it can provide shorter waiting time due to the shorter headway and higher frequency, it requires longer in-transit travel time as shown in Figure 2. Under the assumptions of a single mode, increasing directness results in shorter in-transit travel time although it requires more routes and lower frequency for the each route due to less demand for the each route. Obviously, lower frequency results in longer headway, and eventually, longer waiting time.

2.6 Demand Size and Circuity of the Network

Overall shape of transit network configuration can be mainly classified in three types [1]. Networks with greater number of routes, which are directly connected, networks with less number of circuitous routes, and networks with less number of directly connected routes, so transfers are required. One of main considerations to determine the type of the transit network is demand size. With small demand size, providing many routes with direct connection is not efficient, because frequency of each route would be low. To avoid long waiting time due to low frequency, with small demand size, other types are preferable. However, when the demand is high enough, direct connection would be the better choice, because with many routes, networks can provide short headway.

Transit networks with transfers have the similar characteristics of networks with circuitous routes. Because of the smaller number of routes, frequencies are high compared to the directly connected network, yet the in-vehicle travel time is short due to the direct connection. However, because it requires transfer, transfer time exists in total travel time. So, in some sense, the network with transfer has similar characteristics with the network with circuitous routes in terms of decreased number of routes, higher frequency and longer travel time after boarding – longer in-vehicle travel time by circuitous routes and transfer time by routes with transfer.

3. METHODOLOGY

3.1 Comparative Measures – Degree of Competitiveness and Degree of Circuity

In this research, comparative measures, which compare the performance of auto and transit and evaluate potential transit network performance, are developed. The main comparison in this research is travel times of different cases.

One type of measures shows comparison between auto and transit travel times. This measure shows how transit service is competitive with auto, and shows which origin-destination trips are inferior to transit travel. This type of measure is called Degree Of Competitiveness (DOCO).

The other type of measures shows how much transit service or network configuration can potentially be improved. In general, if transit demand becomes higher, optimality of transit network becomes higher with more direct connections between origin-destination pairs [1]. With this idea, this type of measures provides how circuit the current transit network is compared to the hypothetical transit network with possible shortest connections. They are called Degree of Circuity (DOCI).

Although estimating auto travel time is rather simple, estimating transit travel time is much more complex due to its components. Because of various travel time components of transit, transit travel time can be considered in two different ways by the transit users. One is total transit travel time including waiting time. Although this measure considers complete door-to-door travel time, when the transit network is evaluated, this travel time can be distorted by the length of waiting time, which can be determined by many other considerations other than demand size. Also, waiting time may not be directly estimated from headway and frequency, when the headway is long and the schedule information is provided.

The other is in-transit travel time only including transfer time, which is transit travel time after boarding. This measure excludes waiting time, which is stochastic among all the components of travel times. This measure represents the transit network configuration better than the one with waiting time. However, this measure does not include the relationship between routing and scheduling, and it may not represent overall performance of the transit system.

Although access and egress times exist in transit trip and total transit travel time, in this paper, they are excluded for simplicity reason. However, if necessary, certain fixed value can be added as well.

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

Two types of competitiveness can be considered with two different kinds of transit travel time as defined previously. One is called “Total Travel Time Degree of Competitiveness (TTTDOCO)”, which compares door-to-door travel times of auto and transit. This shows how competitive the transit system is. The other is called “In-vehicle Travel Time Degree of Competitiveness (ITTDOCO)”, which compares in-vehicle travel time of auto and transit. This shows how direct the transit network configuration is, since waiting time is not included in the comparison, and auto travel follows its shortest paths. Equations 2 and 3, respectively, show the Total Travel Time Degree of Competitiveness and In-vehicle Travel Time Degree of Competitiveness of an individual user or a certain origin-destination.

Individual TTTDOCO [%] = $100 \cdot \frac{\Delta t_T + t_t + p}{\min t_a}$, [2]

Individual ITTDOCO [%] = $100 \cdot \frac{\Delta t_i + t_t + p}{\min t_a}$, [3]

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.

Degree of Circuity (DOCI) shows how much additional travel time is required by the current transit network compared to the directly connected hypothetical transit network, because of indirect connection of the current transit network. Just like DOCO case, there are two types of DOCIs.

One is "Total Travel Time Degree of Circuity (TTTDOCI)", which compares real door-to-door travel times of the current transit system and the potential minimum transit travel time, assuming that the potential minimum transit travel time is estimated with no waiting time and shortest connected in-vehicle travel time. This one shows how much the transit system can be ultimately improved. The other is called "In-vehicle Travel Time Degree of Circuity (ITTDOCI)", which compares current in-vehicle travel time of transit and potential shortest in-transit travel time. This shows how direct the transit network configuration is, since potential shortest in-transit travel time comes from the directly connected transit network, and waiting time is not included in the comparison. Equations 4 and 5, respectively, show the Total Travel Time Degree of Circuity and In-vehicle Travel Time Degree of Circuity of an individual user or a certain origin-destination.

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

$$\text{Individual ITTDOCI [\%]} = 100 \cdot \frac{\Delta t_i + t_t + p}{\min t_i}, \qquad [5]$$

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.

For estimating measures for the entire network, there are two ways by how to consider its demand, simple average and weighted average. One is simple average, which 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, and Equations 8 and 9 show simple Degree of Circuity.

Weighted average considers the demand size of each zone-to-zone. These measures show how efficiently transit network is designed to meet the demand, and how well the transit network provides better service to origin-destination with higher demand. They are shown in Equations 10 through 13. $n(n\text{-}1)$ is used instead of n^2 as the denominator for the simple average because it is assumed that there is no intra-zonal trips.

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

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

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

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

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

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

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

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

Where

n = number of zone;

D_{ij} = demand from zone i to zone j.

3.2 Shortest Path Algorithm and Transit Route Choice Model

In order to estimate the Degree of Competitiveness and Degree of Circuity, inputs, which were defined in the Equations 2 through 13, should be required. Among those inputs, demand size, link travel time, and transfer time can be surveyed or easily estimated, however, real travel time of auto and transit, and potential shortest travel time of the transit should be found and computed through the algorithm. This section discusses algorithms to find shortest auth paths, shortest transit travel path (with waiting time and without waiting time) and potential shortest transit travel paths.

3.2.1 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[4], Dijkstra[5], and Dantzig[6]. Moore [4]'s algorithm was modified for this procedure, and its flowchart, which finds shortest path from the origin node [*s*] to the destination node [*t*], is shown in Figure 3.

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, and as results, its cost or travel time for each origin-destination is obtained.

These outputs can also be represented by α_{ij}^{st}, which is an indicator variable for the relationship between O-D and link usage. These variables have a value of either 0 or 1. If α_{ij}^{st} is 0, then link *i-j* is not used for the travel from O-D, *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 algorithm simple. [7]

This shortest path algorithm provides the shortest path with the given fixed travel time. However, link travel time is varied with the traffic volume, so the shortest path algorithm may not be adequate, but if used link travel time is surveyed real travel time, then it can be concluded that the results of this shortest path algorithm reflect the real shortest auto travel path and travel time.

3.2.2 Transit Route Choice Model

First, for transit travel time, algorithm for transit route choice should be defined. While auto shortest path is definitive for the given origin and destination, transit shortest path has stochastic characteristics. Although there are many uncertainties in auto travel and users can change their paths in the middle of travel, users can decide their travel path before they make the trips. However, transit users often decide their travel paths at the station after the certain route of bus comes, when they have a multiple choice for their travels at the same station. So, if there are multiple competitive paths, of which total travel times are within a headway of the longer travel time path, finding shortest paths and assigning the volume on the paths are not definitive.

Many route choice and transit volume assignment models have been introduced, and for this study, deterministic waiting time, which is half of the headway and maximum 10 minutes, is used for estimating total travel time. With deterministic waiting time, just like auto travel, shortest paths for transit travel can be found.

Another concern for the transit route choice is link availability for the certain route and link usage for the certain trip. While α_{ij}^{st} is used as an indicator variable for the relationship between O-D and link usage for the auto shortest path algorithm as discussed, for transit route choice model and assignment, indicator δ_{kij}^{st}, which shows the usage of link of the certain route for the certain O-D, should be introduced. If link *i-j* in route *k* and if it is used for the trip between *s* and *t*, then δ_{kij}^{st} is 1 and otherwise it is 0 [1,8]. Figure 4 shows the flowchart for transit route choice and assignment.

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

3.2.3 Potential Shortest Path for Transit Travel

As discussed previously, comparison between auto network and transit network may not effectively show the effectiveness of the current transit network, since transit link travel time and auto link travel time are already different. Although this comparison can show how competitive the transit service is, the comparison itself does not show how much the current transit system can be improved.

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

4. EXAMPLE

The basic information for the example comes from Rea's paper [9] and Lee's dissertation [1]. 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 5-(a) shows the Template network and Figure 5-(b) shows scheduling information for the routes. Figure 5-(c) shows the transit link travel time for transit. Auto link travel time is assumed 30 percent less than transit link travel time for simplicity. Figure 5-(d) shows the current demand for the transit, and auto demand is assumed five times more than transit demand.

Shortest path for auto can be found from the shortest path algorithm. Also, potential shortest transit paths can be found in the same way. Because 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. Auto shortest travel time would be 70 percent of those travel time, accordingly, since auto link time is assumed to be 30 percent less than transit link travel time for this example.

Table 3 shows the real shortest transit paths, which is found using the transit route choice model with the given transit network information in Figure 5. It also shows O-D in-transit travel time including transfer time and total transit travel time.

With auto shortest travel time, potential transit in-vehicle travel time, real shortest in-vehicle travel time and real shortest travel time for each origin-destination, Table 4 shows the various measures for individual origin-destination pairs. Obviously, DOCI with in-transit travel time of transit and potential shortest transit travel time, which is ITTDOCI, shows the least values of all four measures and those with total travel time of transit and auto shortest travel time shows the highest values. Also, it is obvious that DOCO with in-transit travel time and auto shortest travel time, ITTDOCO, shows less values than those with total transit travel time and auto shortest travel time, TTTDOCO, and DOCI with in-transit travel time and potential shortest transit travel time, which is ITTDOCI, shows less values than those with total transit travel time and potential shortest transit travel time, which is TTTDOCI, because, in-transit travel time is shorter than total transit travel time. Also, the measure with in-transit travel time and auto shortest travel time, ITTDOCO, is higher than that with in-transit travel time and potential shortest transit travel time, ITTDOCI, because auto travel time is shorter than potential shortest transit travel time. The measure with total transit travel time and auto shortest travel time, which is TTTDOCO, is higher than that with total transit travel time and potential shortest transit time, TTTDOCI, because of the same reason.

Table 5 shows the overall network measures for all four cases discussed. As discussed, measures for the transit network can be shown in two different ways, one with simple average and the other with weighted average. Both are shown for four cases, and weighted ones are less than simple ones for this example. That shows 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.

5. CONCLUSION

In this paper, measures, which show how competitive and how indirect the current transit system is, were introduced. The measure called “Degree of Competitiveness (DOCO)” compares additional transit travel time with auto travel time, so it can show how competitive the current transit system is. The measure called “Degree of Circuity (DOCI)” compares additional transit travel time with potential shortest transit travel time, so it can show how much the current transit system can be improved ultimately. Each measure has two different cases depending on defining transit travel time, which are in-vehicle travel time and total travel time. Since transit network design is one of the complicated processes for transit planning and it requires many feedback procedures, these measures can improve the feedback process for transit planning.

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

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

Although auto travel time is always shorter than transit travel time in this example, in the real case, with mixed modes and transit priority, transit travel time for certain links can be faster than auto. In this case, DOCO can work better for the planning process, because it can show real competitiveness of the different modes.

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 less the weighted average is, the better the transit network is designed. If a transit network is not well designed, then weighted average measures can be higher than simple average measures.

In the future, if measures from real transit systems can be estimated, then overall efficiency of the transit system can be evaluated in the better way. Although a lower Degree of Competitiveness and Degree of Circuity with total travel time of transit show the good performance of the current transit system, since transit network configuration is greatly related to the demand size [1], in order to evaluate the current transit system performance and network configuration with given demand size, the standard for the measures from various real agencies is necessary. Measures with in-vehicle travel time of transit does not include waiting time, it is not always good to have lower values for those measures, because optimal In-vehicle Travel Time Degree of Circuity depends on demand size. For example, for the system with small demand size, low ITTDOCI may not be good for the system, because in order to achieve that, longer headway is necessary.

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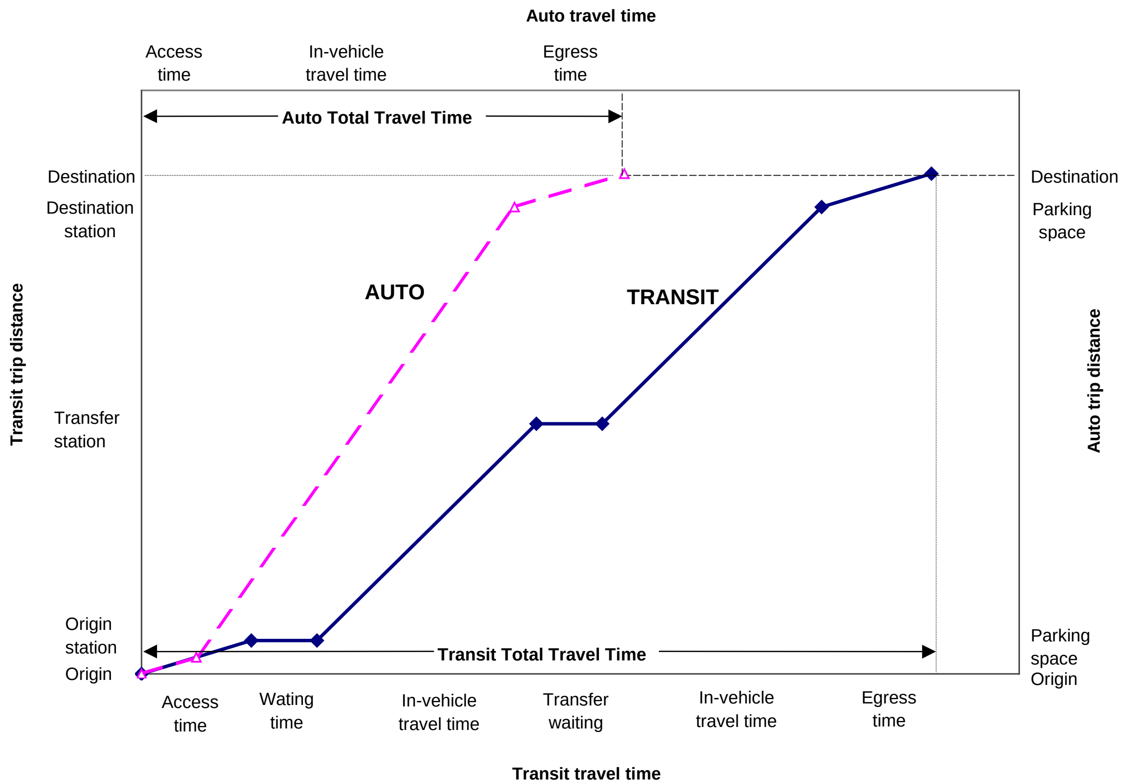


Figure 1 **Conceptual street transit travel time components compared to auto travel time**

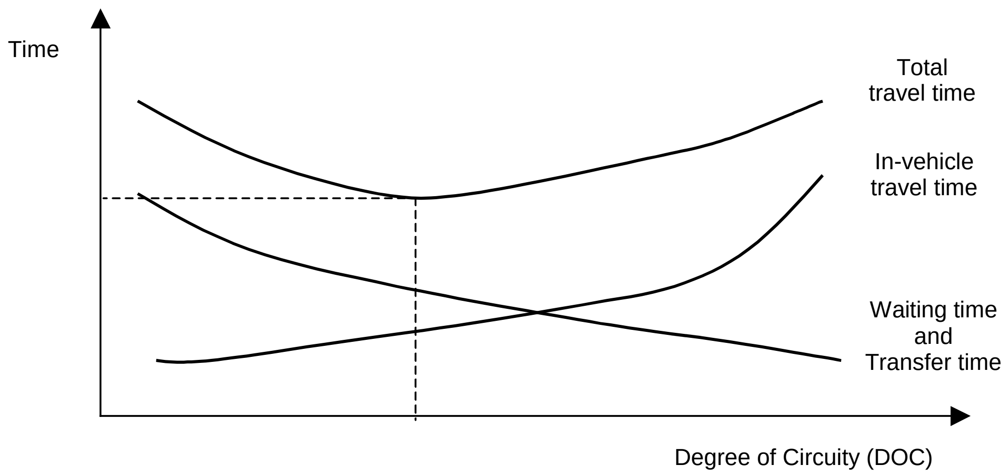


Figure 2 **Conceptual relationship between in-vehicle travel time and waiting time due to directness**

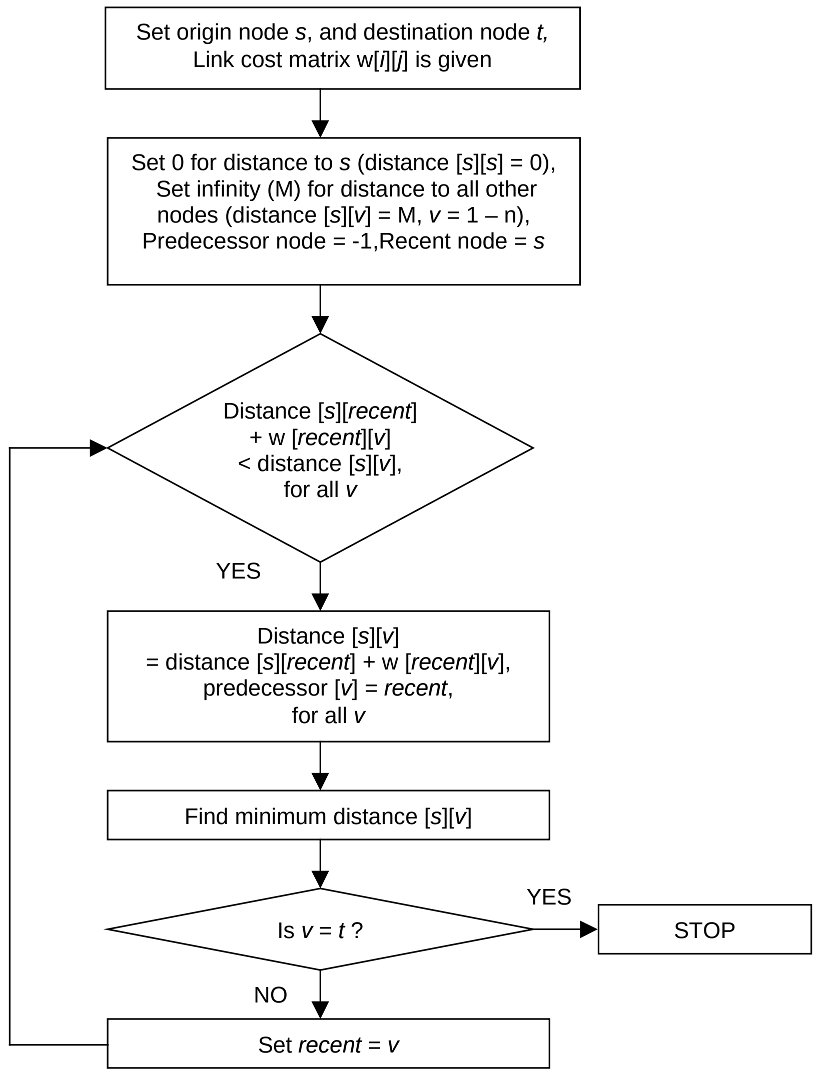


Figure 3 **Flowchart for shortest path algorithm.**

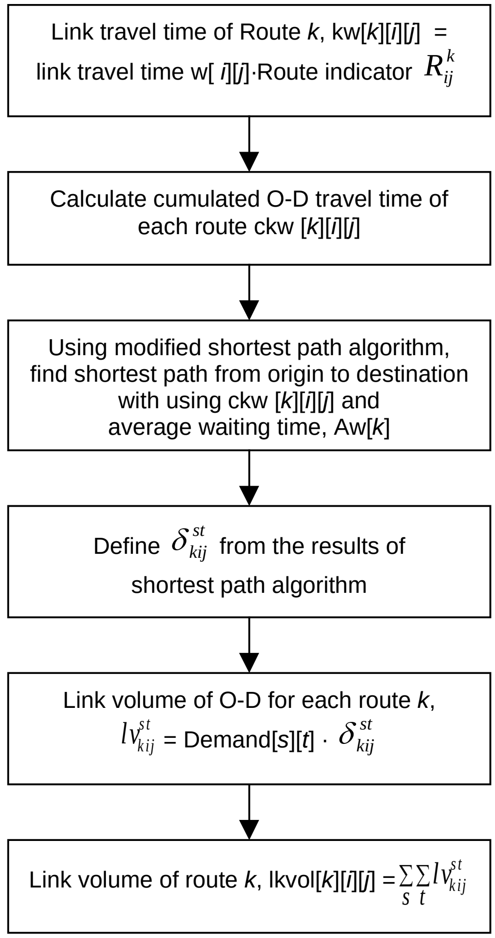
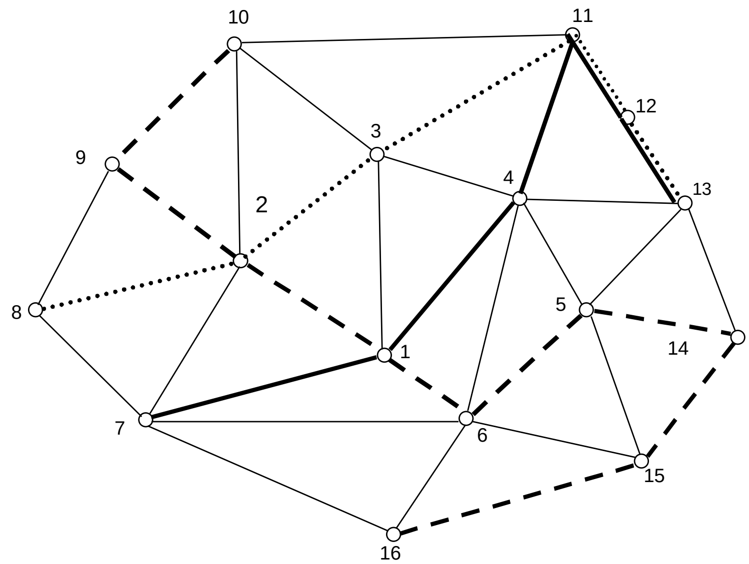


Figure 4 **Flowchart for transit route choice.**



(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

(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

Figure 5 **Information for the example.**

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 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)

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)

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	–

(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%)