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USING ACCESSIBILITY MEASURES IN TRANSIT NETWORK DESIGN

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Abstract. Transit planning scenarios may lead to the different Objective Function (OF) values since each scenario has different transit travel times, frequencies and fleet sizes. Change on those variables leads to the different accessibility values for each route set. Therefore, the actual performance of a route set may be unforeseen since the accessibility values are out of evaluation criteria. This study tries to generate techniques, which handle the relation between accessibility and transportation in the scope of public transit. The accessibility measures, which have direct relation with land use and transportation, are utilized in transit route set decision. Accessibility measures have been utilized in the decision-making process of transit network design. Conventional OFs, which are used to determine the most effective route sets are combined with accessibility based OFs and the decision-making process of transit network design is strengthened. In this context, the effects of accessibility measures in decision-making process of transit network design have been represented on an 8-node example transit network. The results showed the accessibility measures could effectively improve the planners' decision accuracy.

Keywords: transit network design; potential accessibility; utility-based accessibility; spatial interaction; transit assignment; multi-criteria decision-making.

Introduction

Spatial interaction between land use and transportation is an ever-developing concept since the literature about the scope is not fully formed yet (Geurs, Ritsema van Eck 2001). Accessibility is a vital parameter of land use and transportation interaction, however it is still evolving. Concept of accessibility has gained importance since it may be utilized in several stages of transportation planning in which the conventional paradigms have lost their efficiency. Transit network design problem, which directly affects the urban accessibility level, is a significant part of transportation planning. Public transportation systems are presented in most of the cities in the world, either conceived as a service that should be provided to the inhabitants as a tool for urban planning or as business of private companies (Cancella *et al.* 2015).

Accessibility is a significant issue, which has been used in many fields such as transportation and urban planning. Accessibility as a concept may be defined and measured in several methods by several researchers. Accessibility index is defined as the ease of people to reach the desired facilities, products and activities (Bhat *et al.* 2000). It has a considerable potential for the application in travel demand models since it is focused on the main purpose and expected utility of transportation activities. The mostly used definitions for the accessibility are; the potential of opportunities for interaction (Hansen 1959), the ease with which any land-use activity can be reached from a location using a particular transport system (Dalvi, Martin 1976), the freedom of individuals to decide whether or not to participate in different activities (Burns 1979) and the benefits provided by a transportation/land-use system (Ben-Akiva, Lerman 1979). Even if there are several studies regarding the definition of the accessibility; the basic spine of the concept is similar in terms of components, measures and perspectives (Gulhan *et al.* 2013). Land-use, transportation, temporal and individual components are the main elements of accessibility components that planners utilize and specify as an origin for getting into accessibility measures (Geurs, Ritsema van Eck 2001). Infrastructure-based, person-based, Utility-Based Accessibility (UBA) and the Potential Accessibility (PA) measures have been improved to determine the performance of accessibility (Geurs, Van Wee 2004).

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The previous transit-oriented studies have considered the accessibility measures as the methodology and perspective while it is possible to utilize as an efficiency indicator (Pitot *et al.* 2006; Benenson *et al.* 2010; Curtis 2011; Mavoa *et al.* 2012). Measuring the efficiency of transit performance is essential since it enables planners to evaluate and compare the success of individual operators (Costa, Markellos 1997). Additionally, possible effects of a change on the transit system may not be reflected by merely evaluating conventional indicators and it may cause inaccurate decisions (Gulhan *et al.* 2014). Thus, it is important to measure the level of accessibility provided by public transit alternatives in order to support the decision-making process of the public transit planning (Lei, Church 2010).

The studies about the transit network design problem are widely focus on determining frequencies, intervals and spaces. The researches about network design algorithms at 1960s and 1970s are given in detail by Axhausen and Smith (1984). Methods on determining bus routes (Hobeika, Chu 1979), synchronous design of frequencies and routes (Marwah *et al.* 1984), maximizing amount of trip by setting routes without transfer (Van Nes *et al.* 1988), generating optimum service plans at the level of sketch (List 1990) have been developed. Common approaches for the solution of the transit network design problem are GIS utilization (Ramirez, Seneviratne 1996), determining route choice and frequencies in the basis of genetic algorithms (Pattnaik *et al.* 1998; Bielli *et al.* 2002; Tom, Mohan 2003), and optimization of the interaction between bus service level and trip demand (Yan, Chen 2002). Transit network design models can be categorized as analytical and network models. Network models based on nodes and links do not require spatial data (Kuah, Perl 1989). However, analytical models require spatial data (Wirasinghe 1980; Wirasinghe *et al.* 1977; Kuah, Perl 1988; Chien, Schonfeld 1998; Chien, Yang 2000; Chien *et al.* 2001). Ibarra-Rojas *et al.* (2015) has reviewed the literature on the planning, operation, and control of the bus transport networks. The planning process involves every decision that should be taken before the operation of the system, and it is known as the Transit Network Planning (TNP) problem. Due to its complexity, TNP is commonly divided into the following sub-problems: transit network design, frequency/timetable setting, vehicle scheduling and crew planning. Note that the solution of those problems requires tactical, strategic and operational decision-making (Desaulniers, Hickman 2007).

Ceder (2007) states that there are two approaches for generating transit routes: for a set of routes or a small set of routes at a level of network. Those approaches generate several Objective Functions (OFs), which are procured by several perspectives and criteria that evaluate passengers, operations and relevance of society. Those perspectives and criteria have been created by Israeli and Ceder (1995), Ceder (2001, 2002) and Yin *et al.* (2005). There are mainly three perspectives: passengers, operator and community. Ceder (2007) defines four criteria while measuring the efficiency of a transit route: minimum waiting time for a passenger (passenger perspective), minimum empty seat/space time (operator perspective), minimum time difference from shortest path (passenger and community perspective) and minimum fleet size (operator perspective). It is also stated that the TNP problem may be dealt with different algorithms such as heuristic algorithms, integer-programming optimization, nonlinear programming using relaxation methods instead of enumeration of all possible covering scenarios. Note that the outcome of all algorithms is a set of a minimum number of routes that cover all Origin–Destination (O–D) pairs in the network.

Although both accessibility formulations and network design techniques have already been used before, there is still a significant gap in using accessibility measures in decision stages of transit network design. This study tries to make a contribution to the current state of the art on the decision level of transit network design by using accessibility measures as OFs in decision-making process. For that purpose, conventional OFs have been calculated and decision-making process is supported with PA and UBA measures. In the proposed methodology, optimal transit network design is determined by employing multi-criteria decision analysis between conventional and accessibility measures.

The general structure of the study has been organized as follows: the current transit features of the study network and methodology are defined in the first section. Accessibility and transit network design analyses are provided in the second section. Last section is the part for the general evaluations.

1. Methodology

This study tries to further extend the transit network design approach of Ceder (2007) by utilizing the PA and UBA measures. Transit network design process and accessibility measures have been integrated in an analytical process, which consists of six steps as given in Fig. 1.

As can be seen in Fig. 1 that transit demand between O–D pairs, terminals, nodes, links and the average travel times are initialized. Then the bus routes, which start from terminals are enumerated and the travel times of the shortest paths are calculated. At Step 1, several possible routes may be eliminated by using route lengths and travel time constraints in order to prevent excessive number of routes to be considered. Note that the demand is neglected at this stage.

At Step 2, possible route sets, which have to provide accessibility to each node, are generated. Note that the transit users may reach their destinations directly on a particular bus route or through a terminal to select a second route.

At Step 3, transit assignment is carried out to calculate passenger volumes on bus routes and minimum required service frequencies. Note that the demand is assigned on the transit routes with shortest travel time between the related O–D pairs. In other words, the transit users' strategy is established to minimize total waiting time at stops, transfers and in vehicles. After the assignment process, frequencies on routes are obtained. Then

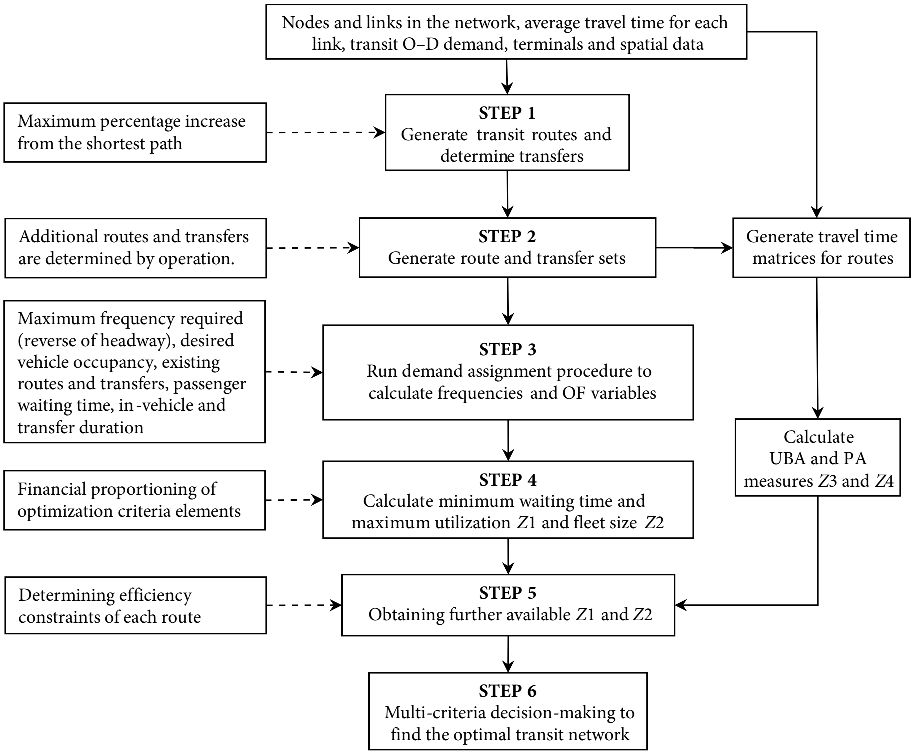

Fig. 1. Flowchart of the proposed transit network design approach

the passenger volumes and frequencies are used to calculate the OFs.

At Step 4, two OFs are defined: *Z*1 represents total waiting time and utilization of transit users, *Z*2 is the fleet size. *Z*1 consist of five different OFs. The first one is the total waiting time to be minimized as a user perspective as given in Eq. (1):

$$\min a_1 \sum_{i,j\in N} WT(i,j), \qquad (1)$$

where: a_1 is fiscally equivalent of one hour waiting time.

The second objective tries to minimize the amount of unused seats as an operator perspective as given in Eq. (2):

$$W_r = \frac{1}{2F_r}, \qquad (2)$$

where: W_r represents passenger waiting time on route *r*; F_r represents the vehicle frequency on route *r*.

Formulation of the third objective is given in Eq. (3):

$$\sum_{i,j\in N} WT(i,j) = \sum_{r\in R}\frac{1}{2F_r}\left(\sum_{i,j\in N_r} d_{ij}^r + \sum_{i,j\in N_{tr}} d_{ij}^{tr} a_{tr}^r\right), \qquad (3)$$

where: *R* represents transit route set; *r* is specific route; N_{tr} is node set on the transfer path *tr*; N_r is the node set in route *r*; d_{ij}^r is the travel demand between *i* and *j*; a_{tr}^r is a binary variable that indicates whether transfer *tr* moves through route *r* or not; d_{ij}^{tr} is the travel demand between *i* and *j* along the transfer path *tr*.

Meanwhile, if $a_{tr}^r = 1$ then *tr* transfer exists on route *r*, otherwise there is not any transfer on route *r*.

The fourth objective is given in Eq. (4):

$$EH_r = \left(\max(L_r, F_{\min}, d_o)\right)t_r - \sum_{i,j\in N} PH(i,j), \qquad (4)$$

where: L_r represents maximum passenger load on route *r*; F_{min} is the minimum required frequency; d_o is desired occupancy in each vehicle (loading standard); t_r is total travel time on route *r*.

Eq. (5) represents the last objective of *Z*1 that represents the proximity to the shortest path:

$$\sum_{i,j\in N} DPH(i,j) = \sum_{i,j\in N} PH(i,j) - \sum_{sp\in S}\sum_{j\in N_{sp}} d_{ij}^{sp} t_{ij}^{sp}, \qquad (5)$$

where: d_{ij}^{sp} represents the transit demand between *i* and *j* along the shortest path; t_{ij}^{sp} is the average travel time of the shortest path between *i* and *j*; *S* is the set of all shortest paths; N_{sp} is the cluster of nodes which takes place on the shortest path *sp*.

Eq. (6) is the lower function:

$$\sum_{i,j\in N} PH(i,j) = \sum_{r\in R}\sum_{i,j\in N_r} d_{ij}^r t_{ij}^r + \sum_{tr\in TR}\sum_{ij\in N_{tr}} d_{ij}^{tr} t_{ij}^{tr}, \qquad (6)$$

where: d_{ij}^{tr} is the transit demand between *i* and *j* along the transfer path *tr*; t_{ij}^{tr} is the average travel time between *i* and *j* on transfer path *tr* and on route *r* (includes transfer penalties); t_{ij}^r is the average travel time between *i* and *j* on route *r*; d_{ij}^r is the transit demand between *i* and *j* on route *r*; *TR* is the set of all transfer paths.

Optimization criteria are represented from the point of passengers, operator and the society. At this stage, two OFs are evaluated as *Z*1 and *Z*2. *Z*1 function consists of waiting times, empty seat hours and lower level variables of shortest paths. Transit network design problem has been established those two OFs as the minimization of $Z1$ and $Z2$. The OF used for a single group is given in Eq. (7):

$$Z1 = a_1 \sum_{i,j\in N} WT(i,j) + a_2 \sum_{r} EH_r + a_4 \sum_{i,j\in N} DPH(i,j). \quad (7)$$

OFs for comparison are given in Eqs (8) and (9):

$$Z1 = a_1 \sum_{i,j\in N} WT(i,j) + a_2 \sum_{r} EH_r + \sum_{i,j\in N} (a_3 PH(i,j) - a_4 DPH(i,j)); \quad (8)$$

$$Z2 = FS. \quad (9)$$

In Eq. (8), $PH(i, j)$ represents passenger-kilometres between i and j $(\forall i, j \in N)$ (it is defined as the travel time of passengers in vehicle on hourly basis; measures the time spent between two nodes). $DPH(i, j)$ represents the shortest path difference in passenger-kilometres. $WT(i, j)$ is the waiting time between nodes i and j $(\forall i, j \in N)$ (defined as the time which passengers spend on the bus stops between two nodes). EH_r is the empty seat hours on route r (defined as the unused seats and represents the unused capacity in vehicles). FS represents the fleet size (amount of vehicles used for transit service), a_k represents fiscal coefficient or the other proportions in the form of k = 1, 2, 3, 4.

Operation interests are evaluated in three perspective as fleet size, empty-seat hour and length of routes. Primarily, fleet size is the most significant operation perspective OF of $Z2$ represents the fleet size. Consequently, as the fleet size get decreased the general efficiency increase in the algorithm. Increasing vehicle quantity inclines a purchase or a hire cost, thus operation interest is about minimizing the total vehicle quantity.

Length of routes may be considered as the second lower objective. Mentioned objective is provided in the section of route generation. The maximum deviation from the shortest path is α – 0.4. It means that no route length or portion of it can exceed its associated shortest travel time by more than 40%. Operation expects to decline its fuel costs, salaries, working times and vehicle aging.

At Step 5, the minimum $Z1$ and $Z2$ values are searched among the route sets and $Z3$ and $Z4$ values, which represent the PA and UBA measures, are calculated. PA is expressed as the total PA values of all zones as given in Eq. (10):

$$PA = \sum_i A_i = \sum_i \sum_j \frac{D_j}{d_{ij}^{\gamma}}, \quad (10)$$

where: A_i (ha/min) represents the accessibility measure to opportunities D_j of zone i; d_{ij}^{γ} is the impedance factor between i and j and γ is the parameter, which represents the impedance of the distance.

UBA values are calculated for all cases by using Eq. (11):

$$UBA = \sum_i A_i = \sum_i \frac{1}{\beta} \ln \sum_j \frac{D_j}{e^{\beta c_{ijm}}}, \quad (11)$$

where: A_i represents the accessibility for the n individual in zone i, at transportation mode m, with a cost c_{ijm}. It can also be defined as the achieved utility from opportunities D_j at zone j.

The sixth step of the methodology involves investigating the most efficient route sets by utilizing multi-objective evaluation of transit network design decisions using OF pairs. Thus, policy makers may take incisive decisions by analysing the correlation between $Z1$ and $Z2$. With addition of $Z3$ and $Z4$ functions, public welfare may be better reflected in decision-making process of transit planning.

2. Transit Network Design Analyses

In this section, the proposed transit network design approach is applied to the study network which is illustrated based upon the one used by Ceder (2007). The layout of the 8-node bus network is given in Fig. 2.

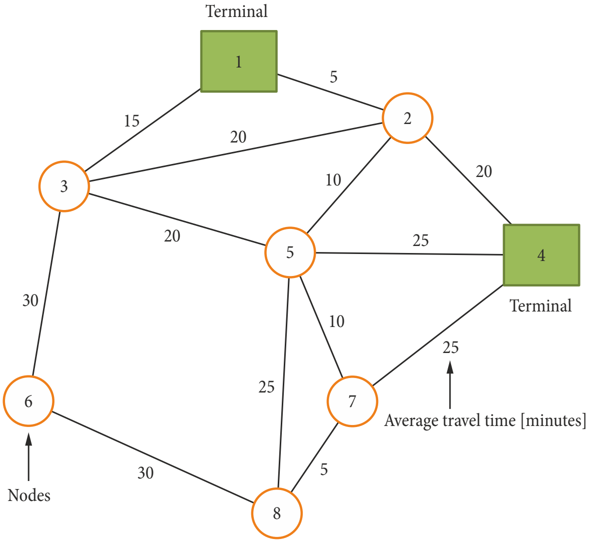

Fig. 2. Layout of the study network (Ceder 2007)

In the study network, the nodes have been accepted as centroids, consequently transit demand between nodes represent the travel demand between zones. Total transit demand for the network is given in Table 1.

Table 1 indicates that the sixth and eighth zones attract higher demand. The first and fourth nodes are considered as terminals. Average travel times between nodes are given in Table 2.

Table 1. Demand between the nodes [person] (Ceder 2007)

Nodes	1	2	3	4	5	6	7	8
1		80	70	160	50	200	120	60
2			120	90	100	70	250	70
3				180	150	120	30	250
4					80	210	170	230
5						250	40	130
6			Symmetrical				130	120
7								70
8								

Table 2. Average travel times between nodes [min] (Ceder 2007)

Nodes	1	2	3	4	5	6	7	8
1		5	15					
2	5		20	20	10			
3	15	20			20	30		
4		20			25		25	
5		10	20	25		35	10	25
6			30		35			30
7				25	10			5
8					25	30	5	

By following the flowchart given in Fig. 1 for the proposed approach, some detailed illustrative steps are provided as:

Step 1: all possible routes for the transit network have been enumerated under several assumptions and constraints (Ceder 2007). A travel in other words a route has been accepted as valid only if it starts from a terminal. Maximum distinction from the shortest path has been accepted as 40%, which means α has been determined as 0.4. Relevant routes after elimination, accessible nodes and travel times for mentioned routes are showed in Table 3.

Step 2: alternative route sets have been generated to obtain $Z1$ and $Z2$ functions which have been given in Eqs (8) and (9). As a matter of fact, each route set is a unique scenario. A route set may consist of all possible routes. Consequently, maximum number of routes in a route set has been limited to six and the transfers have been neglected. Note that the route sets have to provide access to each node in the network. By evaluating emphasized constraints, 19538 route sets have been obtained for study transit network. If the amount of nodes increase in a network then the amount of route sets have a major increase. In such cases, Ceder (2007) has been proposed several optimization techniques

Step 3: assignment of transit demand has been carried out to calculate the number of passenger journeys occur on the bus routes. Note that the demand is assigned on transit routes with shortest travel time between the related O–D pairs. Vehicle capacity in the network has been accepted as $d_o = 50$. Passenger-load profile has been generated for each route and vehicle frequencies have been obtained from those passenger-load profiles.

Step 4: Lower level variables of $Z1$ have been accepted as $a_k = 1$ and $k = 1, 2, 3, 4$. At the calculation of $DPH(i, j)$, travel times for private car mode between nodes have been used. Pre-defined travel times are given in Table 4.

$Z1$ values have been calculated for each possible route and their values are given in Table 5.

$Z1$ values have been found by gathering PH_r, DPH_r, WH_r, and EH_r which are found for each route. Minimum fleet sizes, in other words, $Z2$ values have been found for all routes. Maximum load, frequencies and empty-seat hour have been calculated. PH_r and DPH_r values have been found.

Minimum frequencies have been obtained by dividing the load of maximum demands to vehicle capacities after calculation of $Z1$ function values. Afterwards, minimum fleet size values, in other words $Z2$ values, have been. Due to fleet size cannot be a fractional number, vehicle quantities have been finalized to nearest integer values. The 10 most efficient $Z1$ values with fleet size is given in Table 6.

Step 5: $Z1$ and $Z2$ values have been enumerated, afterwards $Z3$ and $Z4$ values are calculated. The minimum $Z1$ value is 10402 passenger-kilometre and it has been generated by route set 5, which includes the routes 6 and 34. The maximum $Z1$ value is 45600 passenger-kilometres and it has been generated by route set 19427, which includes the routes 23, 24, 27, 28, 29 and 32. $Z1$ function has been calculated for each route set and the 10 most efficient $Z1$ values are given in Table 7.

The 10 most efficient $Z1$ values are between 10000 passenger-kilometres and 13000 passenger-kilometres $Z1$ values for those route sets are 5, 1, 7, 2, 79, 11, 22, 303, 287 and 3.

In accessibility calculation process, each route set has been determined as a scenario. Each scenario has different accessibility values since each scenario has different travel time matrices. Passengers who travel between zones/nodes have to change terminals/routes, if there is no direct access to destination. Therefore, it is supposed that there is a different transportation mode apart from transit network between zones 1 and 4, which has a travel time of 5 minutes. Residential areas have been supposed and showed in Table 8.

Table 9 shows that areal sizes for zones verify between 100 ha and 456 ha. 10 most efficient PA and UBA values for route sets have been calculated and showed in Table 9.

The route set which provides the maximum PA is the route 6095 with 732 ha/min and the route set which provides the minimum PA is the route 3479 with 370 ha/min. Note that, accessibility values do not involve categoricalness and they are generated values for internal comparison since it is not significant to positive or negative. Table 9 indicates that PA values have more inherent distinction than UBA values. While PA values verify between 732 and 724, UBA values verify in a smaller interval. Accessibility values are index values and they are meaningful when they are compared with each other. Consequently, it is a regular circumstance for UBA values to be negative.

Step 6: Optimal design method of the proposed approach involves investigating the most efficient route sets by utilizing multi-objective evaluation of transit network design decisions using OF pairs. The purpose is to investigate the various alternatives for the most efficient ($Z1$, $Z2$) solution. Therefore, the decision-maker can decide whether or not to accept the proposed solution; for example, the decision-maker can see how much $Z1$ is increased by decreasing $Z2$ to a certain value, and vice versa (Ceder 2007). The trade-off between $Z1$ and $Z2$ is investigated using a two-dimensional graph given in Fig. 3.

Table 3. Possible routes in the study network (Ceder 2007)

Routes	Nodes						Travel time [min]
1	1	2					5
2	1	3					15
3	1	2	4				25
4	1	2	5				15
5	1	3	6				45
6	1	2	3	6			55
7	1	2	5	6			50
8	1	2	5	7			25
9	1	2	5	7	8		30
10	1	2	5	8			40
11	4	2	1				25
12	4	2					20
13	4	5	2	1	3		55
14	4	5	3				45
15	4	2	3				40
16	4	7	5	3			55
17	4	5	2	3			55
18	4	2	1	3			40
19	4	2	5	3			50
20	4	5					25
21	4	2	5				30
22	4	5	6				60
23	4	5	7	8	6		70
24	4	2	1	3	6		70
25	4	7	8	6			60
26	4	2	5	6			65
27	4	2	3	6			70
28	4	5	8	6			80
29	4	2	5	7	8	6	75
30	4	7	5	6			70
31	4	2	5	3	6		80
32	4	5	3	6			75
33	4	7					25
34	4	5	7	8			40
35	4	7	8				30

Table 4. Travel times for the private car mode between nodes [min]

Nodes	1	2	3	4	5	6	7	8
1		3	10	15	11	20	20	18
2	3		15	15	7	31	18	10
3	10	15		30	11	22	22	11
4	15	15	30		20	30	21	18
5	11	7	11	20		30	9	14
6	20	31	22	30	30		20	20
7	20	18	22	21	9	20		4
8	18	10	11	18	14	20	4	

Table 5. $Z1$ values for possible routes [passenger-kilometre]

Routes	$WT(i, j)$	EH_r	$DPH(i, j)$	$Z1$
1	3000	0	111	3111
2	3000	0	173	3173
3	3123	130	517	3770
4	4414	13	285	4712
5	3508	100	504	4112
6	3902	502	730	5134
7	4085	83	598	4766
8	4810	187	325	5322
9	4810	285	364	5459
10	4810	647	644	6101
11	4500	130	517	5147
12	3000	0	407	3407
13	4384	1593	953	6930
14	3394	1100	891	5385
15	3725	473	695	4894
16	4455	363	657	5475
17	3909	1237	957	6103
18	4586	830	691	6107
19	4107	980	977	6064
20	3000	0	495	3495
21	4107	233	581	4921
22	3414	1272	808	5494
23	3808	3017	854	7679
24	4586	2030	1021	7637
25	3909	893	538	5340
26	4107	887	894	5887
27	3725	1673	1026	6425
28	3505	3788	1134	8427
29	4389	2455	940	7784
30	4229	412	574	5214
31	4107	2180	1307	7594
32	3596	2830	1222	7648
33	3000	0	220	3220
34	3808	887	574	5269
35	3909	83	258	4250

Table 6. The 10 most efficient $Z1$ values with fleet sizes

Route sets	$Z1$ [passenger-kilometre]	$Z2$ [quantity]
	total	vehicle
5	10401.81	188
1	10957.34	140
7	11883.42	184
2	11896.08	148
79	12190.53	183
11	12270.93	185
22	12491.48	235
303	12787.48	266
287	12791.08	186
3	12811.81	188

Table 7. 10 most efficient $Z1$ values [passenger-kilometre]

Route sets	Routes						$Z1$ [passenger-kilometre]						Total $Z1$
	1	2	3	4	5	6	Route 1	Route 2	Route 3	Route 4	Route 5	Route 6	
5	6	34					5133	5269	0	0	0	0	10402
1	2	29					3173	7784	0	0	0	0	10957
7	9	27					5459	6424	0	0	0	0	11883
2	5	29					4112	7784	0	0	0	0	11896
79	2	7	35				3173	4766	4251	0	0	0	12191
11	13	25					6930	5341	0	0	0	0	12271
22	1	5	34				3111	4112	5269	0	0	0	12491
303	5	12	34				4112	3407	5269	0	0	0	12787
287	5	9	33				4112	5459	3220	0	0	0	12791
3	6	23					5133	7679	0	0	0	0	12812

Table 8. Residential areas in the network

Residential areas D [ha]							
1	2	3	4	5	6	7	8
125	320	144	456	124	222	100	147

As can be seen in Fig. 3 that the compromise solution can be found on the boundary, so-called Pareto front, between route sets 1 and 5, which are more feasible that the other transit network configurations (Coello Coello *et al.* 2007). At this point, route set 1 requires the smallest fleet for operation while route set 5 provides the minimum waiting time. Therefore, it may be useful to utilize accessibility measures $Z3$ and $Z4$ in order to determine the optimal transit network design. Geurs and Van Wee (2004) stated that the accessibility is a measure for the benefit of society which is represented by transit users. On the other hand, fleet size does not have a common intersection with accessibility measures. Therefore, the trade-off between $Z1$ and accessibility measures are given in Figs 4 and 5, respectively.

Fig. 4 shows that the route sets 5, 7, 79, 287, 289, 284, 279 and 6095 are on the Pareto front. Based on this trade-off, if the route set 7 is selected as the solution point, the accessibility increases about 11% while the transit users' benefit decreases about 14% in comparison with route set 5. Similarly, if the route set 6095 is selected as the solution point, the accessibility increases about 23% while the transit users' benefit decreases about 139%.

Table 9. 10 most efficient PA and UBA values for route sets

Route sets	$Z3$ [ha/min]								
	Zones								Total
	1	2	3	4	5	6	7	8	
6095	187	106	64	84	94	35	91	71	732
6419	187	106	64	84	94	35	91	71	732
12414	187	106	64	84	94	35	91	71	732
12743	187	106	64	84	94	35	91	71	732
13104	187	106	64	84	94	35	91	71	732
13283	187	106	64	84	94	35	91	71	732
13626	187	106	64	84	94	35	91	71	732
12933	186	106	66	84	96	34	90	70	731
13232	186	106	64	84	94	35	91	70	730
13259	186	106	64	84	94	35	91	70	730
	$Z4$ [ha/min]								
13173	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113035
6142	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113035
12461	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113035
13325	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113035
13331	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113035
13170	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113036
13415	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113059
13416	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113059
13161	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113059
13191	1.654	−0.141	−10.124	−0.155	−3.955	−24.322	−0.004	−0.395	−37.44113059

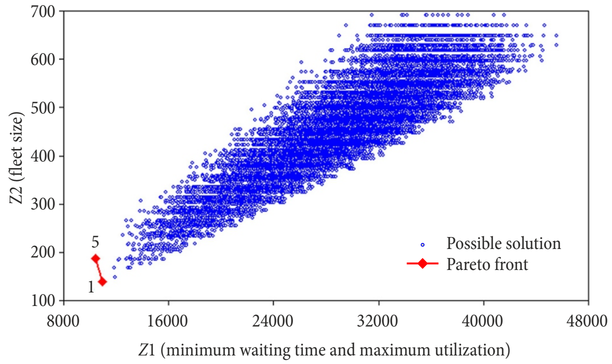

Fig. 3. The trade-off between *Z*1 and *Z*2

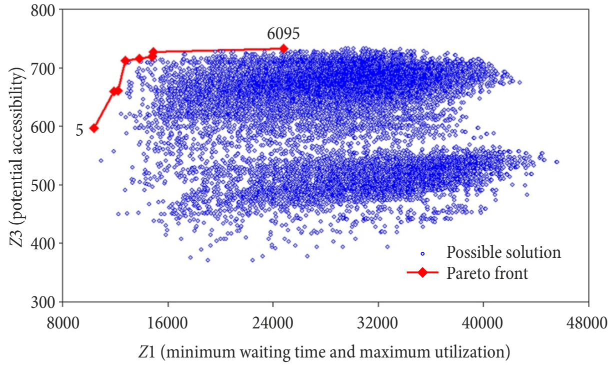

Fig. 4. The trade-off between *Z*1 and *Z*3

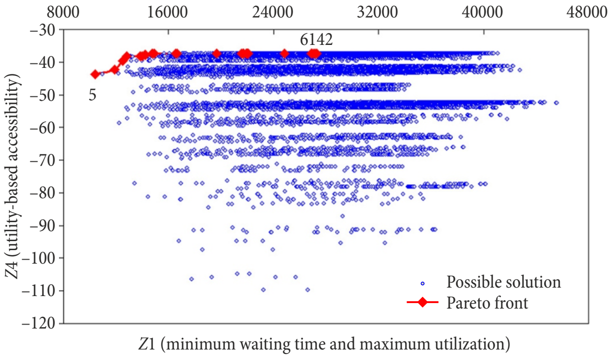

Fig. 5. The trade-off between *Z*1 and *Z*4

In Fig. 5, route sets 5, 7, 22, 287, 289, 81, 196, 255, 260, 279, 256, 1780, 4640, 6139, 6131 and 6142 are on the Pareto front. Based on this trade-off, if the route set 7 is selected as the solution point, the accessibility increases about 3% while the transit users' benefit decreases about 14% in comparison with route set 5. Similarly, if the route set 6142 is selected as the solution point, the accessibility increases about 14% while the transit users' benefit decreases about 162%. Therefore, the route set 5 may be considered as the best transit network configuration since all other Pareto solutions proportionally reduce transit users' benefit more than the gain in PA and UBA.

Conclusions

Using accessibility measures in transit network design leads a more comprehensive planning paradigm since spatial interaction values are introduced to general perspective. The reason is that, land use areas and travel times between the zones are participated into design process. In this manner, several transportation characteristics of cities may be utilized without overlooking.

This study aimed to make a contribution to the current state of the art of transit network design by using accessibility measures as OFs in decision-making process. In the proposed methodology, conventional OFs have been calculated and decision-making process is supported with PA and UBA measures. In this context, an example application was provided. Firstly, total travel time and fleet size were calculated on an 8-node example transit network. Pareto solutions for those conventional measures showed that the decision-maker had two route sets that the first one required the smallest fleet for operation while the second one provided the minimum waiting time. While the accessibility measures utilized for the solution, the results showed that the route set with minimum waiting time could be considered as the best transit network configuration since all other Pareto solutions proportionally reduce transit users' benefit more than the gain in PA and UBA.

In this study, the transit demand between the O–D pairs is assigned on routes with shortest travel time. Note that those routes were taken from a previous study. In future studies, a timetable-based assignment technique, where all transit services are taken into account with their precise departure and arrival times, may be adopted. Usually, adaptation of algorithms into real-world applications may require high computation times for most engineering optimization problems. However, proposed method did not require high computational efforts since the study network is a small-scaled area for a specific test application.

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