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RESEARCH ARTICLE

The Effect of the Size of Traffic Analysis Zones on the Quality of Transport Demand Forecasts and Travel Assignments

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Abstract

In this work we have studied the selection criteria for traffic analysis zones and the effects of their size and number on the model's forecasting capabilities. To do so we have focused on the corridor of İstanbul's Kadıköy-Kartal Metro Line and evaluated the consistency of demand forecasts and travel assignments versus actual measurements under different sizes of the Traffic Analysis Zones (TAZ). Significant improvements in model accuracy were observed by decreasing the zone size. Specifically, studying the public transport network assignments for the metro line when increasing the number of traffic analysis zones from 540 to 1,788 the root mean square error (RMSE) of forecasted vs. actual station-based counts was reduced by 23%. Subsequently, the study used population density and employment density as independent variables for the determination of the optimal radius for the 1,788 zone area, and applied an exponential regression model. Appropriate model parameters were derived for the above case study. The regression model resulted in R^2 values over 0.62.

Keywords

transportation model, traffic analysis zones, travel demand forecast, travel assignments

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1 Introduction

Transportation infrastructure, systems and investments underpin the growth, prosperity and vitality of communities and cities [1]. Transportation infrastructure and systems, however, are under increasing pressure in many cities around the world, where rising expectations for comfort and independent travel have increased the use of private vehicles. The resulting increase in traffic congestion has prompted cities to seek solutions supported by travel demand forecast models. These models allow a systematic review of how travel requirements change under different assumptions and are used by relevant authorities to demonstrate the feasibility and economic success of transportation investments. Since decision making relies in the fidelity of modeling, authorities constantly seek to improve their transport modeling infrastructure. Four-step models have emerged as effective and popular tools based on their straightforward information and operational requirements.

Some limitations of four-step models, however, have also prompted the development and initial application of activity-based models [2]. It should be noted that the transition from trip-based modeling to activity-based modeling is characterized by significantly increased data requirements, increased computational times, and implementation difficulties especially in large areas. Bao et al. in [3] have investigated the minimum field size, at which activity-based modeling can be applied in order to obtain reasonable computational times. The study discussed testing the suitability of the radii of the TAZ, when trip based modeling is used in areas where data requirements of activity based models cannot be met.

In the current study, the original 540 TAZ of Istanbul have been divided into smaller areas (zones) and the related effect on model consistency is examined. By dividing Istanbul's neighborhoods, which are the smallest administrative areas of the city, we were able to identify areas with similar land use characteristics, and enhanced the infrastructure of the demand prediction model, which now comprises 1,788 TAZ.

The remainder of this paper is organized as follows. In Section 2, demand forecasting models are examined and trip-based and activity-based models are discussed. Section 3 overviews the existing transport model of Istanbul, discusses its enhancement from 540 to 1788 TAZ, and how highway and public transport networks have been organized within the new zone structure. In Section 4, assignment results for the Kadıköy-Kartal-Pendik Metro Line using the 540 and 1788 zone structures are compared and model consistencies are assessed. In Section 5 we propose an appropriate functional that estimates the suitable traffic zone size using population and employment variables; this functional may be useful for regions with similar land, population, and transport characteristics as those in Istanbul. Section 6 presents the conclusions of the study.

2 Demand forecasting models

Transport models estimate demand and travel patterns based on a series of inputs and assumptions. The latter relate to key population activities, activity location and timing, and access options [4]. Both Trip-Based Modeling and Activity-Based Modeling methods have been proposed for trip demand forecasting models, as overviewed below.

2.1 Trip-based modeling

Trip-based demand forecasting models are also referred to as four-step demand forecasting models. The fundamental modeling concepts were introduced by Manheim [5] and further elaborated by Florian et al.

The main ideas underpinning the four-step demand forecasting model are presented in Figure 1. The basic element and input of this model is the traffic analysis zone-based database obtained from household surveys and demographic indicators [6]. The model is based on the geometric structure of the TAZ and the demographic data of these TAZ. Demographic data are generated on the basis of residents and households per TAZ. Other inputs include the road and public transport networks.

Using demographic information related to the TAZ, in the first step of the modelling process trip production and attraction models are established per TAZ. In the second step, a travel distribution model, such as a gravity model, is used to estimate a) the allocation of the trips produced by each zone among all other zones, and b) the origin zones of the trips attracted by each zone [7]. In the third step the types of modes (automobile, pedestrian, public transport, bicycle, etc.) used to perform the forecasted trips are estimated. For this purpose, *individual* or *aggregate* models are used The model's last step is the network assignment phase, which is an iterative process that provides the obtained matrix and network times.

2.2 Activity based modeling

Trips and activities are intrinsically related, since a trip connects two activities that define its purpose (e.g. home to/from school). A chain of trips, which possibly involves more than two activities, is a tour [8]. These concepts are fundamental in activity-based models, which attempt to describe activity decision making, location, and travel between activities [4]. They relate to the entire day of the traveler and generate tours [9]. An important aspect is the diversity of variable activities, including the location data, the time and the type of activity. Advantages of activity-based modeling include the emphasis on activities and not trips, which may better describe traveler behavior [10].

Several practical activity-based models have emerged recently [3]. However practical application is complex, and so are the related costs [2]. Several challenges are related to these models, including the size of the spatial data and the details of the network data. In addition, obtaining trip diaries entails certain difficulties, including the insensitivity of diaries to policies, their limited availability, as well as privacy issues [11].

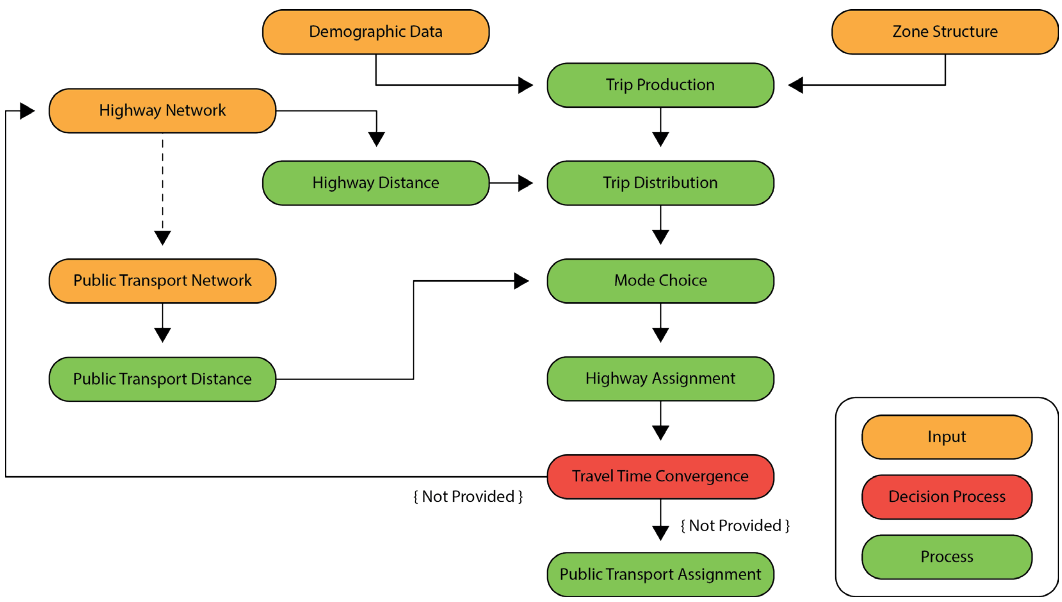

Fig. 1 Four-step model flow diagram

3 Setting up the model to investigate the effects of zone size

The original comprehensive demand forecasting model for İstanbul was developed by the İstanbul Technical University in 1997 [12] and covered the entire area of İstanbul Metropolitan Municipality (155 thousand ha at that time). Since then, the number of TAZ has been increased form the original 209 (related to 12,000 household surveys) to 451 (90,000 household surveys covering the entire province of 540 thousand ha), to 540 (160,000 household surveys in 2012). The latter structure sets the foundation for the current study.

3.1 Key data on traffic analysis areas of the current study

In the current study the 540 TAZ of the 2012 model were separated into smaller regions (resulting to 1,788 zones in total), independent of the administrative boundaries taking into account characteristics, such as land use structure, topographic conditions and accessibility. The work investigated the effects on model consistency and applicability.

It is emphasized that in transitioning from 540 to 1,788 TAZ, similarity in land use has been considered. Furthermore, the maximum radius is considered to be within walking distance in the urban area zones. For example, in the central district of Beyoğlu the average zone radius is 280 m, while in the non-central Başakşehir zone the average zone radius is 720 m. In general, the average TAZ radii in the central districts are less than 500 m. In the city's remote, almost rural districts, the radii are considerably higher. For example, the average radius is over 4.5 km in the rural province of Şile. The average radius in the entire city is around 733 m. In the 540 zone case the average zone area was 10 km^2. This decreased to 3 km^2 in the 1,788 zone case. Accordingly, the maximum zone size decreased from 319 km^2 to 188 km^2. Similarly, the average zone population decreased from around 26.000 to about 8.000, while average zone employment decreased from about 8.000 to 2.500. The zone with maximum employment included 220.000 employees in the original zone structure; now this number has decreased to 70.000.

3.2 Revision of the links of the traffic analysis zones

Land use planning and transport planning are intrinsically related. This strong link is described by the '*land-use transport feedback cycle*', which captures the two-way interaction between the location of activities defined by land use, and transport that connects activity locations [13]. Thus, transport demand forecasting is strongly affected by land use characteristics that should be related to the TAZ. An additional basic issue in transport demand forecasting is the determination of the level of detail of the transportation network. This level of detail is directly related to the scale of the TAZ. It is necessary to establish a network structure to represent each zone's particular characteristics. The links (arcs) of the network's structure may represent movements over significant distances, as well as local movements over short distances. Links may be also differentiated as vehicle or walking links, based on the transport mode [5].

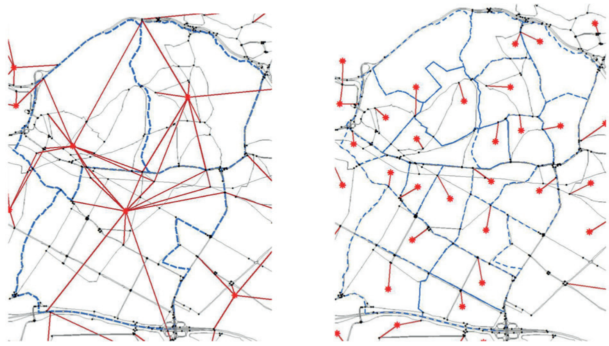

Fig. 2 Effect of refining traffic analysis zones on small roads and road connections

Table 1 Effect of change in traffic analysis zone size on connection links

Qualification Information	1,788 Traffic Analysis Zones	540 Traffic Analysis Zones
Number of Links	1,979	818
Total Length (km)	527.79	373.96
Minimum link length (m)	13.97	37.89
Maximum link length (m)	3,595.15	6,881.07
Average Link Length (m)	266.70	457.16

In the assignment model, centroid connector links should be added to represent the zonal traffic volumes starting from the zone's center and ending at the nearest transportation network point. The centroid connector links used for each TAZ vary depending on the scale. Figure 2 shows an example of how the connection links are shaped when a large-sized TAZ is divided into multiple TAZ of smaller size. In this case, the original TAZ is divided into nine smaller zones and the links are revised, resulting to a more representative access provided by a single link that connects each of the small traffic analysis zones to the refined network.

Within the scope of this study, all zones were examined in the same way and the links were revised accordingly. Table 1 presents key statistics regarding the links for the two cases. For the 1,788 TAZ case, the total link length is 528 km, increased from 374 km. The average link length has decreased from 457 m 267 m due to the more detailed structure.

The public transport network comprises surface transport, rail system and marine systems. Unlike the highway network assignment, the assignment matrix for the public transport network consists of journeys, not vehicles. Thus, it models the behavior of passengers, not public transport vehicles.

For the public transport network, in the 540 TAZ case a single point was defined per zone to represent the origin/destination of all passengers within the TAZ area. For the 1,788 zone case, each zone is added to the network with a link. The network has been developed in such a way to model public

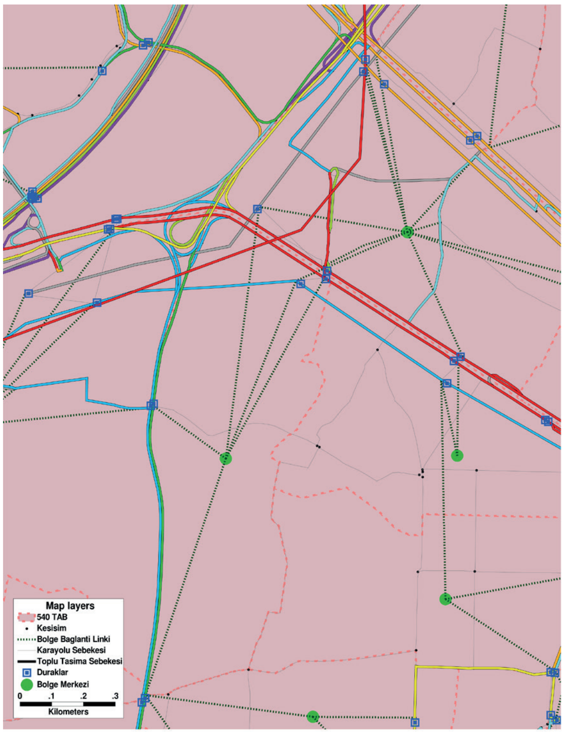

Fig. 3 Effect of refining traffic analysis zones on small roads and road connections

transportation routes, walking links, access and arrival links, and transfer links. Thus, it is expected to obtain more accurate results with respect to congestion at nodes and links that represent realistic city locations and system segments.

Figure 3 shows the structure of the public transport network within sample zones. Green points represent the zonal center of each TAZ. The zone boundaries are shown with red dashed lines. In order to provide access to different public transport routes from these centers, certain stops have been allocated and access links have been added to provide links between the centers and the related stops. Access links are shown with a green dashed line and stops are shown in blue squares. Each public transport route is shown in different colors and added to the road network. It is noted that the public transport network has more links than the road network.

3.3 Network assignment

In the highway network assignment phase, the entire network has been reorganized as described above and the connections have been arranged to serve the smaller zones. The goal is to obtain more precision in the assignment results.

Figure 4 shows the comparison of the road network assignment results between the 540 and 1,788 zone cases. The right side of the Figure shows the assignment of three zones for the 540 zone case, while the left side of the Figure shows the assignment of the same three zones (now divided into 21 zones) for the 1,788 zone case. The first of the three zones has been divided into 6 sub-zones, the second into 8 sub-zones, and the third into 7 sub-zones. The load produced by each zone was examined separately and loaded onto the network.

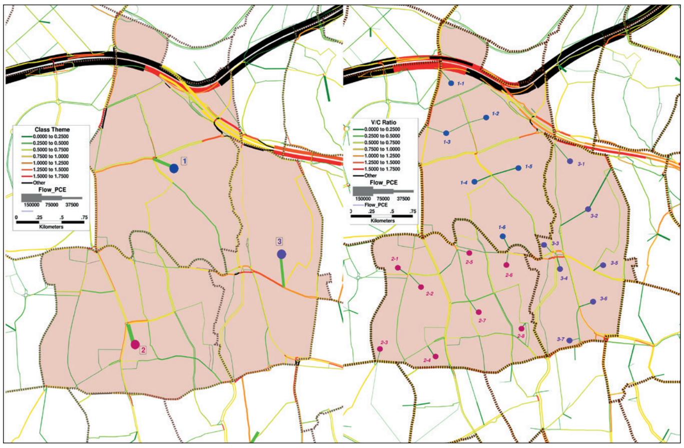

Fig. 4 Comparison of road assignment results for the 540 and 1788 zones

In the road network assignment of the 540 zone case, the gross zone linkage resulted in higher than actual demand within each of the three zones, since each linkage carries increased load and the other roads in the zone remain empty. When the 3 zones are increased to 21, the load is distributed across the network, since the latter comprises more connection links representing more accurately the actual network, especially near the network entry points. This has resulted in distributing the load over the entire network and has prevented the creation of artificial bottlenecks caused by the less detailed network.

To further illustrate the changes between the 540 and 1,788 TAZ cases, consider zone 1 of Figure 4 with the related zonal center. The general modeling principle has been followed, according to which all activities are represented at the same point. In this case, the area of zone 1 is over 3 km^2 and the distance between the north and south of the zone is about 2 km. When this zone is divided into 6 sub-zones, using land use and stronger field representations, appropriate access routes have been selected for each zone so that the single outflow has now been distributed across the entire network. A similar approach for zones 2 and 3 has resulted in model results closer to the actual passenger behavior.

The benefit of refining TAZ is also evident by the reduction in the value of the sum of the matrix diagonal that is loaded on the network during network assignment. Although, as expected, the grand sum of all matrix elements remains invariant in both cases, the sum of the diagonal elements of the matrix for public transport journeys has declined from 12% to 4%. This corresponds to 8% of journeys that could not be reflected by the network of the 540 TAZ.

Table 2 Annual boardings of the Kadıköy-Kartal Metro Line

Year	Number of Passengers (1000)
2012	13,127
2013	49,105
2014	70,420
2015	82,679

4 Influence of traffic analysis zone size on demand estimates for Kadıköy-Kartal-Pendik Metro Line

The Kadıköy-Kartal Metro Line started operating in 2012. Its initial length was 21.7 km, and reached 26.5 km with the extension of the Kaynarca-Tavşantepe section delivered in October 2016. The line serves 19 stations and runs parallel to the D-100 highway, which is the most important road backbone of the Anatolian side of Istanbul. Table 2 shows the annual boardings of the line since its start of operations.

The public transport network consists of the route segments (links) and public transport stops (nodes) that form the public transport routes (lines). Public transport assignment procedures predict the route choices of public transport trips on the basis of different attributes of the public transport network. Some of the more critical attributes are:

- Supply of public transport services as defined by the capacity of the public transport vehicle and its corresponding frequency
- The estimated cost of using public transport services (i.e. the average fare for a trip)
- The generalised impedance of travel by public transport, which is a function of the in-vehicle time, the time spent for reaching a public transport stop, waiting, transferring from one route to another, the fare, as well as comfort and convenience, public perception of the quality and reliability of each mode.

Since public transport assignment algorithms have many combinations, the configuration of the network must be set up in order to allow for all these combinations. The model estimates ridership, loadings, boardings and alightings, transfers, and a wealth of performance measures (see [14]).

Figures 5, 6 and 7 show the model infrastructure for the 540 TAZ case along the Kadıköy-Kartal Metro Line in Istanbul. Figures 8, 9 and 10 show the model arrangements made for the 1,788 zones. As the size of the zones decreases, both the length of the connection links, representing accesses, and the number of linking links of each zone have decreased. Walking speed is assumed as 6km/h on highways; it is allowed to walk on road network except on railway systems, TEM expressway, bridges, tunnels and maritime lines.

For the public transport network assignment in the 1,788 case, the transport network has been revised and network assignments have been rearranged versus the 540 zone case in order to address all aforementioned components (zonal centers, connection links, transfer links).

Table 3 shows the results of the assignment for the 1.788 and 540 zone cases for the Kadıköy-Kartal Metro Line. As it can be seen from the Table, the 1.788 zones case provides a significant advantage, especially in Acıbadem, Göztepe, Küçükyalı, Huzurevi and Gülsuyu stations.

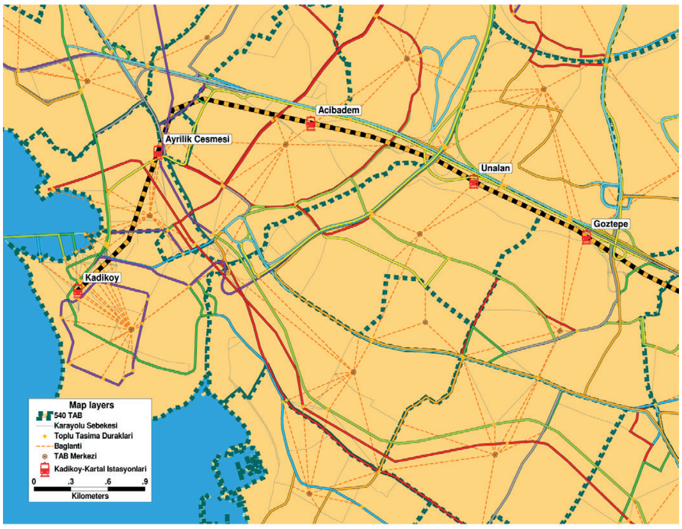

Fig. 5 The model infrastructure of the Kadıköy-Kartal Metro Line between Kadıköy-Göztepe stations in TransCAD: The 540 zones case

Fig. 6 The model infrastructure of the Kadıköy-Kartal Metro Line between Yenisahra-Küçükyalı stations in TransCAD: The 540 zones case

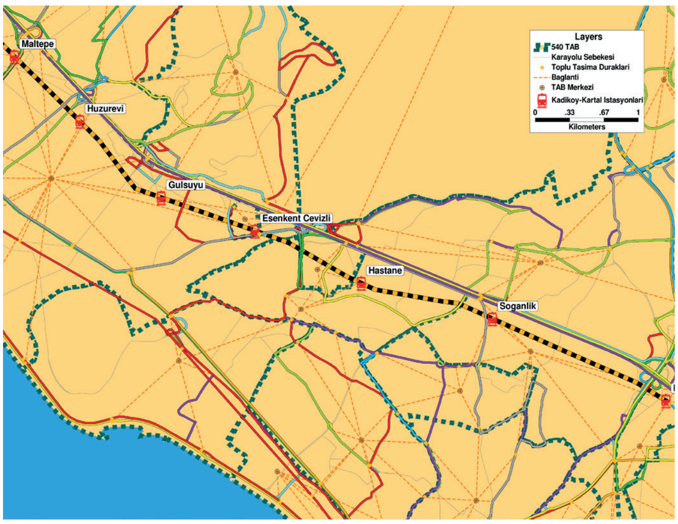

Fig. 7 The model infrastructure of the Kadıköy-Kartal Metro Line between Maltepe-Kartal stations in TransCAD: The 540 zones case

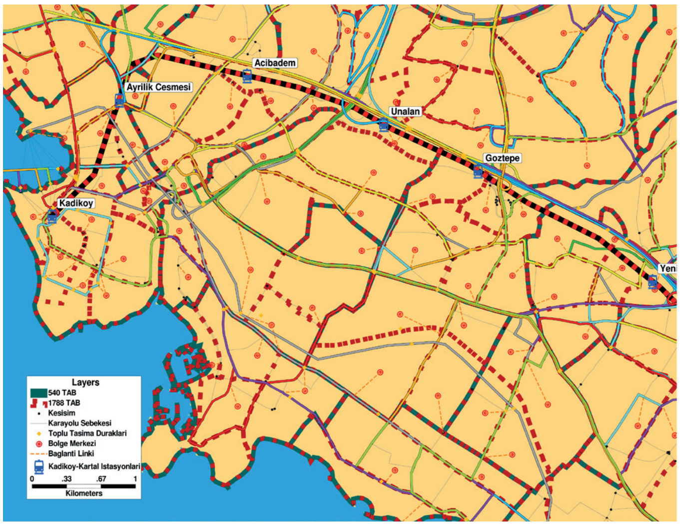

Fig. 8 The model infrastructure of the Kadıköy-Kartal Metro Line between Kadıköy-Göztepe stations in TransCAD : The 1,788 zones case

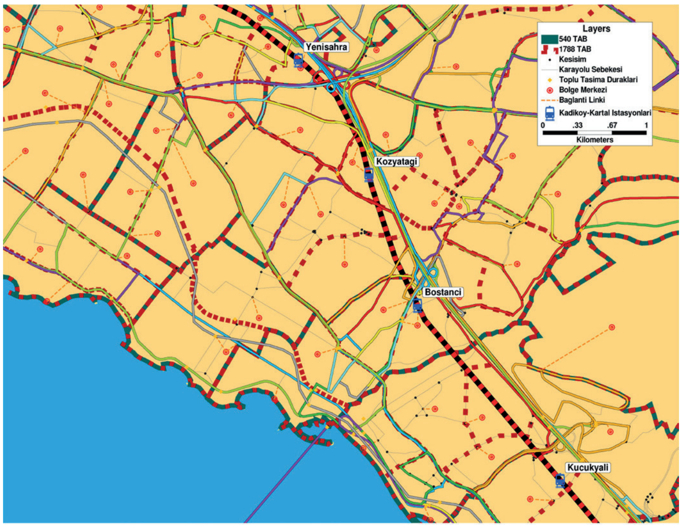

Fig. 9 The model infrastructure of the Kadıköy-Kartal Metro Line between Yenisahra-Küçükyalı stations in TransCAD: The 1,788 zones case

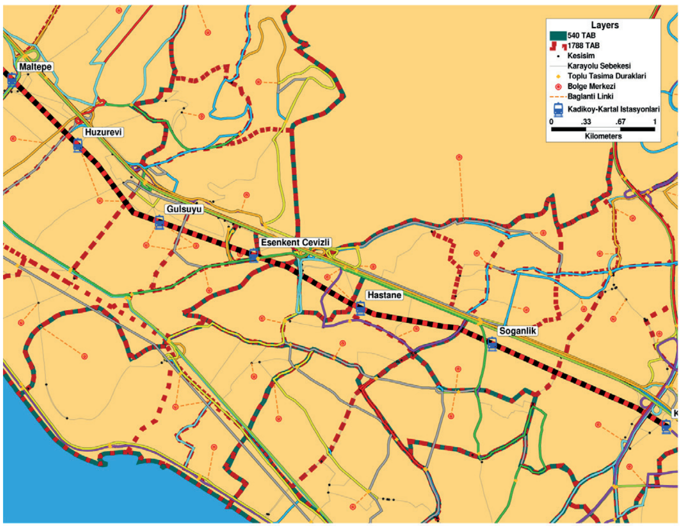

Fig. 10 The model infrastructure of the Kadıköy-Kartal Metro Line between Maltepe-Kartal stations in TransCAD: The 1,788 zones case

Table 3 Comparison of model results for Kadıköy-Kartal Metro Line with different zone size

Station Name	Actual	1788 Region	540 Region
Kadıköy	41,852	24,205	26,385
Ayrılıkçeşme	39,362	40,372	40,776
Acıbadem	6,833	5,477	12,518
Ünalan	21,139	24,630	23,581
Göztepe	9,819	9,042	25,180
Yenisahra	9,869	10,574	13,950
Kozyatağı	19,042	14,671	22,681
Bostancı	17,305	19,596	21,457
Küçükyalı	9,991	9,802	16,794
Maltepe	12,462	18,160	17,997
Huzurevi	7,625	6,365	851
Gülsuyu	5,377	5,421	16,755
Esenkent Cevizli	7,998	10,152	5,512
Hastane	9,021	9,567	13,785
Soğanlık	8,906	7,640	10,785
Kartal	29,178	17,826	23,021
TOTAL	255,779	233,502	292,030

Table 4 Correlation values between actual measurements and the model results for the 1,788 and 540 zone cases for the Kadıköy-Kartal Metro Line

M4	Actual	1,788 Zones	540 Zones
Actual	1.00	0.87	0.77
1,788 Zones	0.87	1.00	0.82
540 Zones	0.77	0.82	1.00

The One-Way Anova test was applied to examine whether there exists a statistical difference between the methods used in the assignment and the actual value. To do so, it is necessary to look at the correlation obtained using the model and the actual measured value. For both cases, i.e. "1,788 Zones" (t = 0,376; p = 0,71 > 0,05) and "540 Zones" (t = 0,613; p = 0,55 > 0,05), the difference between the model values and the actual value is not statistically significant.

Table 4 shows the correlation matrix for the Kadıköy-Kartal Metro Line. The correlation value is close to 1, indicating a strong relationship. Furthermore, the results of both models are highly compatible with the measured actual values. However, the correlation value corresponding to the 1,788 zones case is 0.87 while the value for the 540 zones case is 0.77. A correlation value increase of 13% was achieved in the 1,788 zones case.

The comparison of the actual measurements and the model values is also shown graphically in Figure 11. In the ideal case the model values would be equal to the actual measurements, and, thus, all points of Figure 11 would be on the line y = x (slope = 1). For the 540 zones case, the R^2 value for the regression line is 0.596, while it increased by 0.16, reaching 0.756 for the 1,788 zones case. Furthermore, the slope of the regression line for the 540 zone case is 0.62, while the slope in the 1,788 case improves to 0.71. An extensive regression study using reasonable models, exponential, logarithmic, etc., indicated that

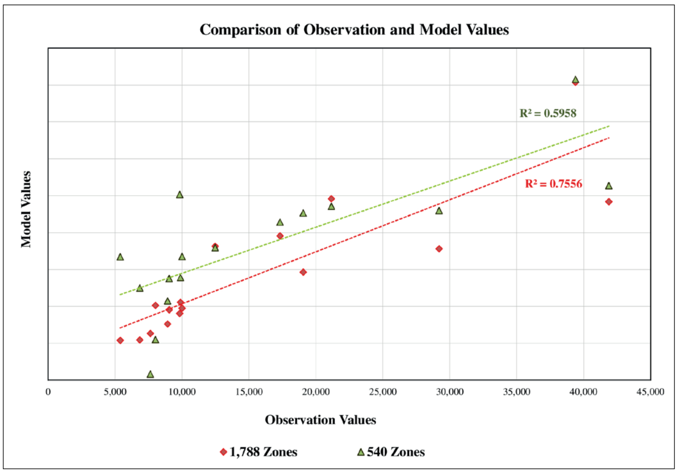

Fig. 11 Comparison of observations and model values for 1,788 and 540 zones

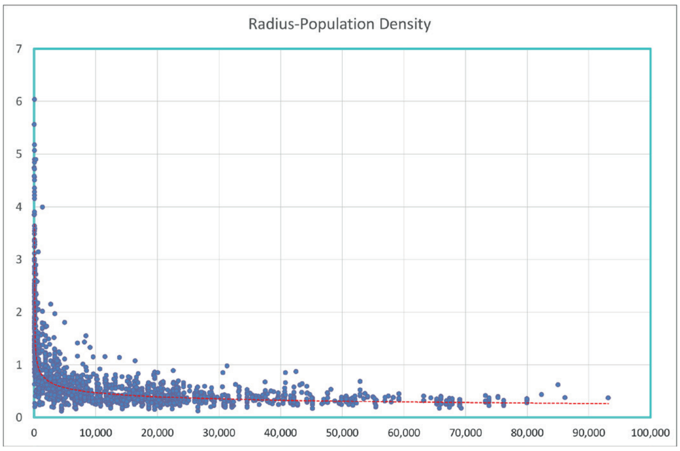

Fig. 12 Relationship between zonal radius and populatioon density

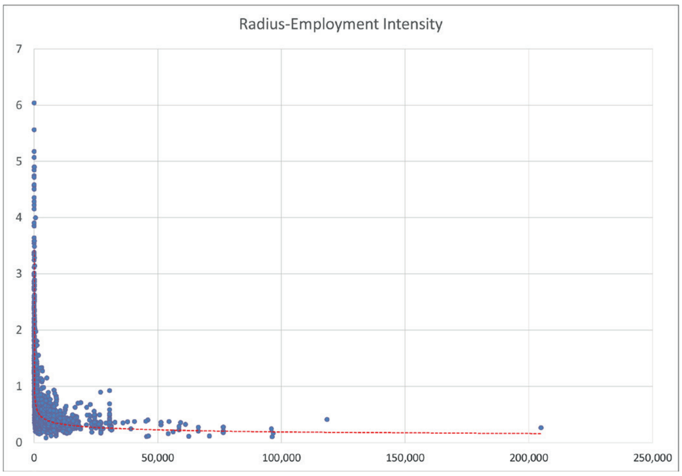

Fig. 13 Relationship between zonal radius and employment density

although the fit improves (in terms of R^2) for certain models, the improvement is not considerable. This indicates the robustness of the linear model in both cases.

Table 5 compares the errors between the actual measurements and the results of the two models using the mean square root (RMSE) method. It is seen that the RMSE value for the Kadıköy-Kartal Metro Line is lower for the 1,788 zones case. The analysis was based on station-based boarding measurements.

Table 5 Measuring model consistency with the mean square root error (RMSE) method for Kadıköy-Kartal Metro Line

	RMSE values	
	1,788 Zones	540 Zones
M4 Metro Line	5,709	7,438

Table 6 Determination of radius of traffic analysis zone as a dunction of population density (Dependent variable = TAZ radius)

	Independent Variables		t	Sig.
	B	Standard Error		
Population Density	-0.259	0.005	-56.815	0,000
Constant	5.138	0.208	24.663	0,000

All aspects of the above analysis of the public transportation network assignment provide strong evidence that model results improve significantly by considering a TAZ size which corresponds to a living area that relates to walking distance (e.g. 500 m radius for central TAZ), and not using the area which is defined by the administrative city boundaries (as in the 540 zone case).

5 Determination of zone radius for traffic analysis zones

Regression analysis was used to measure the relationship between the optimum TAZ radius size versus population size and employment size . Based on the evidence of Figure 12 and Figure 13, the exponential function appears to best fit the relevant data, and, thus, it has been used in the regression model.

Zones with a population density close to zero were not included in the analysis, and the analysis was performed over 1,677 zones. Figure 12 shows the result of the analysis for the relation between the radius of the zone and population density. The analysis resulted in $R^2 = 0.658$, $F = 3{,}227.94$; $p < 0.01$, indicating a strong dependence of zone size on population density (see Table 6).

For the case considered, the most suitable equation providing the zone radius for population-intensive zone construction is the following:

$$Radius = 5.138 \cdot (Population\ Density^{-0.259}) \qquad (1)$$

Figure 13 shows the result of the analysis for the relationship between the zone radius and the intensity of employment. Zones with close to zero employment intensity were not included in the analysis, and the analysis was performed over 1,772 zones. The analysis resulted in $R^2 = 0.624$, $F = 2{,}933.347$; $p < 0.01$, indicating a strong dependence of zone size on employment density (see Table 7).

Table 7 Determination of the radius of the traffic analysis zone according to intensity of employment (Dependetn variable = Zone radius)

	Independent Variables		t	Sig.
	B	Standard Error		
Employment intensity	-0.245	0.005	-54.160	0,000
Constant	3.250	0.112	28.961	0,000

For the case considered, the most suitable equation providing the zone radius for employment-intensive zone construction is the following:

$$Radius = 3.250 \cdot (Employment\ Density^{-0.259}) \qquad (2)$$

The decision whether to use the population or density of employment depends on the characteristics of the area considered. Based on this decision the appropriate formulation is applied to determine the zone radius.

6 Conclusions and evaluation

All strategic transport models developed to date for İstanbul are trip-based models. In this paper we have studied whether it would be useful to improve the accuracy of the current model by dividing the TAZ into finer ones. Thus we have attempted to create zones by taking into consideration the unit that can meet the daily basic needs of people; that is, a walking distance of approximately 500 m in the more populated areas. Particular attention has been paid to maintaining a zone radius of 350 m in central areas. Thus, the original 540 TAZ were divided into 1,788 smaller zones and the effects on model consistency were examined.

To do so, the infrastructure of the demand prediction model has been reconstructed. The three most important components of this infrastructure are: The O-D matrix, road networks, and public transport networks. The effects of using smaller zonal structures for Istanbul on network assignment algorithms were examined. The case considered in this paper is the Kadıköy-Kartal Metro Line area. The consistency of the output of the demand forecasting model for the coarser and finer cases of TAZ along the metro line was analyzed and the resulting benefits were investigated.

To analyze the public transport network assignments for the Kadıköy-Kartal Metro Line for the 540 and 1,788 traffic analysis zonal cases, we used actual measurements of station-based boardings and compared them with the related model outputs for the two cases. The comparison was based on the mean square root error (RMSE) method. For the 1,788 TAZ, the error rate was reduced by 23% versus the 540 zones case. By examining the correlation matrix of the assignments corresponding to the two cases (1,788 zones and 540 zones) with the actual measured values, it was found that correlation increased from 0.77 (in the 540 zones case) to 0.87 (in the 1,788 zones case). R^2 value increased by 26% from 0.60 to 0.76.

Generally speaking, both models show a good representation of reality, but the case of smaller zones appears to provide significant improvements in model accuracy.

Population density and employment intensity were used as independent variables and the supersymmetric model was applied to determine the appropriate zone radius. Appropriate equations were determined to provide the zone radius (dependent variable) for the case examined. This related analysis yielded a 0.66 R^2 value for the population-intensive areas. For the employment-intensive areas, the R^2 value was found to be 0.62.

When selecting the most suitable relationship to calculate the radius of the zone, the characteristics of the zone should be considered. While population density is insufficient when determining the region radius for areas with high employment intensity, the density of employment is insufficient in the population-intensive areas. Both models are significant for the İstanbul demand forecasting model.

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