Estimating the adequacy of a metro network

George Yannis[a,*] , Angeliki Kopsacheili[b], Panayiotis Klimis[c]

ABSTRACT

The objective of this research is a preliminary examination of metro rail network extensiveness versus city's needs aiming to assist the estimation of the adequacy of a metro network. This paper concentrated on comparing "mature" metro systems in several large European cities, based on a selection of indicators relating metro network characteristics (A, B, C) to city's characteristics (D, E, F). A methodology exploiting these macroscopic characteristics in a strategic planning context was developed, and a combination of related indicators is proposed. This methodology is applied for the estimation of the degree of adequacy of current Athens metro network in relation to the city's needs. Findings indicate that Athens metro network cannot be yet characterized as adequate and specific proposals are made, in terms of future network extensions, in order for the Athens metro network to reach the metro network coverage of other European cities. These proposals served as the initial reference point in a more sophisticated planning process for Athens metro system future development that outlined a future metro network of 8 lines, 220 km with 200 stations, setting in this way long-term targets for the main city transport infrastructure, in order to mobilize the necessary resources and avoid infrastructure development conflicts.

[a] National Technical University of Athens, School of Civil Engineering, Department of Transportation Planning and Engineering, 5 Iroon Polytechniou Str., Zografou Campus, Zografou-Athens, GR-15773, E-mail: geyannis@central.ntua.gr
* Corresponding Author
[b] ATTIKO METRO S.A, Mesogeion Aven. 191-193, Athens, GR-11525, Greece, E-mail: akopsacheili@ametro.gr
[c] *ATTIKO METRO S.A, Mesogeion Aven. 191-193, Athens, GR-11525, Greece, E-mail:* pklimis@ametro.gr

Subject Heading list:

- Transportation networks
- Urban areas
- Urban development
- Methodology
- Decision making
- Data analysis
- Evaluation
- Efficiency

INTRODUCTION

With urban road congestion at saturation levels in all major European cities, together with considerations for environmental issues and the lack of physical space in general, rail-based transit systems development is increasingly gaining political support (Knowles, 1996) and all recent national and international policies in most European countries continuously outline the need to decision makers for adopting urban rail-based solutions as an answer to urban mobility problems (Aravantinos, 2007; Yannis et al., 2009; Yu et al., 2011; Batsos and Tzouvadakis, 2011).

Simultaneously, several scientists claim that the future of cities' infrastructure can only be underground, singling out in this way metro systems from other rail-based transit systems (Ronka et al., 1998; Aravantinos, 2002; Kaliampakos and Benardos, 2008). Nowadays, more (or less than) 50 European cities currently have metro networks (metrobits.org, 2009;

urbanrail.net, 2009) ranging from large to small networks, completed or with future extensions planned, and plenty more are planning to follow this paradigm since their demographic, economic, environmental and social factors demand the provision of competitive rapid transit. Therefore, metro system development in European cities is expected to increase further in the near future, despite serious concerns related to the considerable funding effort associated to them (Mackett and Babalik-Sutcliffe, 2003; De Jong et al., 2010).

Bridging the funding gap for future metro network extensions is probably the biggest challenge most European cities have ever faced, including the city of Athens, due to the scarcity of funding sources. After all, this challenge could be an opportunity to develop for a well coordinated and integrated urban transport planning system (Edwards and Mackett, 1996), to ensure efficiency and adaptation of city's needs. It is increasingly recognised that that metro systems' expansion not only serves better the developed urban areas but also brings development to less populated and less developed urban areas.

This paper explores the aforementioned challenge by formulating a methodology exploiting macroscopic characteristics in a strategic planning context (Ortuzar and Willumsen, 2011), easily applicable and able to cope with the usual situation of limited availability and/or quality of data existing in the strategic level of planning. More specifically, a methodology estimating the potential for metro development according to basic city's needs is proposed. The proposed methodology is grounded on a macroscopic review and comparison of the extent of metro development in other urban areas with "mature" and successful metro systems, in order to provide an easy, useful and quick-response planning tool, on a strategic level.

The starting point of this paper presents the methodological approach that consists of two basic stages:

(a) Identification of successful and “mature” metro rail networks in Europe - following specific criteria of networks’ necessity, “maturity” and success - and examination of their basic characteristics (i.e. length, number of lines, stations etc.), which express the extensiveness of each system, based on available data collected, and identification of indicators for the analysis;

(b) Analysis of indicators, starting with the development of all indicators relating basic metro network characteristics to city’s main characteristics (i.e. size, population, density etc.) and continuing with statistical analysis.

The selected indicators are then applied comparatively with the respective indicators of Athens’s metro network, in order to estimate its degree of adequacy according to city's needs. Once the adequacy is formulated specific proposals are presented concerning the network length, as well as the respective number of metro stations that Athens should develop in order to serve citizens’ transportation needs.

It is needless to say that the methodology presented and applied in this paper does not substitute the need for full-scale long-term transportation planning studies (4-steps transport model), especially in complex urban environment and with a variety competitive transportation networks, but it can be applied in conjunction with the above studies, as an initial step, in order to investigate the potential for metro development. The final metro development will subsequently be evaluated through the transportation modelling process. It can also provide a quick estimate for the “ultimate” metro development required in a city with a non-mature metro network in the very long-run (even beyond the 15 or 20 years planning horizons usually adopted in transportation planning studies), or in case that the full scale transport study is not feasible.

Finally, the conclusions are presented.

METHODOLOGICAL APPROACH

Metro networks selection

In order to ensure systematic selection of the networks for analysis, three specific criteria were defined, based on relevant literature, in order to gradually conclude with a representative sample of metro networks: demography, network structure and system’s success.

Since the ultimate purpose of this paper is to provide a useful planning tool for future metro development in large urban areas, like the city of Athens, the **demographic criterion** (**C_1**) serves the selection of cities with population size big enough to justify cities’ characterisation as large urban areas. According to the Urban Audit of DG- Regional Policy (EC, 2008) cities with large urban areas are the ones having a population of more than 750.000 persons in the urban zone.

Clearly, notwithstanding all the cities being major European cities, there are various differences across them nevertheless they are all considered to be at a similar –and advanced- stage of urbanisation (high population, high density, increased economic growth/ high income compared to other cities in each country) struggling all the same with traffic congestion, demanding at the same time efficient, reliable and qualitative public transport. These cities' urban structure is the dominant factor for determining, even better ensuring the effectiveness (else usage) of urban public transport (Kockelman, 1995; Kronenberg, 2011), especially rail. To this end population was considered a safe choice for the demography criterion measurement.

The **network structure criterion** (**C_2**) was selected in order to exclude metro systems of "temporary situation", else the non-completed, else non-"mature", metro networks. Out of all possible metro network structures, such as single line, radial network, grid, circle line, peripheral loop, and parallel lines, metro systems of a single line were excluded, since in most cases they are considered a temporary situation, with the expectation that construction will continue on the other legs (Grava, 2002).

Cities with large urban areas do not usually share with similar characteristics. Most large cities are typically very tightly built in the city centres while others are not, thus having much less buildings and population per area. For this reason not all public transport systems are suitable for each one of them. Population density is the key factor for choosing the right public transport system for a city. What is suitable for tightly built and populated areas with limited free physical space – like metro systems- is too massive and expensive in others that might be served efficiently by tram/light-rail (Stone et al., 1992; Alku, 2005). As shown in Figure 1, cities with population density less than 3.200 person/km^2 should rather base their public transport system on other modes (Alku, 2007). In Figure 1, is also notable that the operation capacity of the trams/light rail systems (on-street) as well as buses does not overlap the metro's operation capacity. A bus systems capacity is 2.000 passengers per hour max; tram/light rail begins from 500 passengers per hour per line up to 9.000, when a metro line is already uneconomical to operate below 2.500 passengers per hour (Alku, 2007). Therefore the **success criterion (C_3)** is **population density vs. operation performance of a metro network line to be more than the efficient minimums**.

It is noted that the success, as well as, the purpose of a metro system, as any transit system, is to respond as best as possible to city's transportation needs. This is not always easy to measure. Ideally, a metro system should cater for most of the transportation needs as described by the respective Origin/Destination (O/D) pairs (Bruno et al., 2002), which was rather impossible to be done for all metro networks in European cities. For this reason, it was preferable to use simpler measures like population density vs. operation performance.

Insert Figure 1 about here

Data on cities' population size and spread, network structures and basic characteristics as well as network operational features was obtained from various sources such as official websites, census reports, research projects and papers (OECD, 2006; UITP, 2007; ESPON, 2007; EC, 2008; UN, 2008; metrobits.org, 2009; urbanrail.net, 2009). Once compiled, the collected data was subjected to a validation process to ensure that the information available was comparable and any erroneous entries were removed from the database. Following examination of the final database, the application of the aforementioned three criteria, led to the identification of 15 systems, out of the 50 European cities with metro networks, presented in Table 1, along with Athens's system.

Insert Table 1 about here

As soon as the selection of metro networks was completed, the identification of indicators for further analysis followed.

These indicators, based on sector literature (Kansky, 1963; Vaughan, 1990; Vuchic, 1991; Vuchic and Musso, 1991; Newman and Kenworthy, 1991; Navarre and Caralampo, 1992; Biebert et al., 1994; Black et al., 2002; Jeon and Amekudzi, 2005; Gatusso and Miriello, 2005; Derrible and Kennedy, 2010, ASCE, 2009) relating metro network characteristics (technical and operational) to city's main characteristic (demographic), are useful to verify each network's capability to serve its respective territory and to make comparative analysis of networks while working in different urban contexts. The indicators finally used are a mixture of existing as well as new, allowing to meet the paper objectives.

Based on the available data, presented in Table 1, and on the aforementioned literature the indicators initially chosen for computation are:

a. Population influenced

Population influenced (P, *km/person*) is the ratio between network length (L) and the reference territory population (P_u, *person*) that is basically city's population located in the reference territory surface (S_u, km^2) that is city's urban area. $P = L/P_u$ (1)

b. Network extension

Network extension (Π) is the ratio between network length (L) and the network diameter (D), where network diameter (D, *km*) is the length of the shortest route connecting the farthest stations of the network. $\Pi = L/D$ (2)

c. Network density

Network density (N_d, km/km^2) is the ratio between network length (L) and the reference territory surface (S_u, km^2) that is basically city's urban area. $N_d = L/S_u$ (3)

d. Access density

Access density (A_d, *stations/*km^2) is the ratio between number of stations (ST) and the reference territory surface (S_u, km^2) that is city's urban area. $A_d = ST/S_u$ (4)

e. Served surface

Served surface (S, km^2) is equal to the territory extension where network is attractive and it is computed by multiplying the number of stations with the average range of influence of each station (R, km^2) minus the surfaces counted several times (else, the overlap areas of stations' ranges of influence). $S = ST \bullet (\pi \bullet R^2) - [(S_1 \cap S_2) \cup (S_2 \cap S3) \cup \ldots]$ (5)

S_1, S_2, etc. are the surfaces served by stations 1, 2 etc., while average range of influence (R, *km*^{2}) is a standard range indicating the largest distance accepted on average by a walker to access to a “generic” metro station. A “generic” station is a station that its geographic position is in the zone between the city centre and the suburbs. For a station in the city centre the distance accepted on average by a walker is much shorter than 500m while for a station in the suburbs can be much longer. The proper way to calculate the served surface would be to assign weights (0,5 to stations in the city centre, 1,5 to stations in the suburbs and 1 to stations in the intermediate zone) to stations’ range of influence according to stations’ geographic position but since this would require GIS mapping of all metro networks analysed it was impossible to be done in the framework of this research. Therefore, assuming that each network’s stations are distributed almost equally among the three zones of city centre, suburbs and in between, we chose the generic type of station.

f. Spatial accessibility

Spatial accessibility (or network covering degree) (A_s) is the ratio between the served surface (S, *km*^{2}) and the reference territory surface (S_u, *km*^{2}), that is basically city’s urban area. $A_s = S/S_u$ (6)

g. Traffic density

Traffic density (T, *passengers/km*) is the ratio of annual (usually) network ridership (RD) per km of line. $T = RD/L$ (7)

Analysis of indicators

The indicators proposed in the previous section were computed for the 15 selected metro networks and are presented in Table 2.

Sometimes, information given by an indicator on the characteristics offered by the networks is contrasting (Gatusso and Miriello, 2005; Derrible and Kennedy, 2010). For example, high range of influence is, on the one hand, a positive factor since it indicates a greater level of territorial covering; on the other hand, it indicates a greater level of difficulty for users who will have to walk, on average, a longer distance to reach a station. At the same time different indicators may supply information of the same kind. That is why a set of data statistical analyses has been elaborated in order to identify possible correlations and conclude to the most representative and meaningful indicators for application and eliminate the redundant ones.

Insert Table 2 about here

Different regression types among selected pairs of indicators were examined (linear, logarithmic, polynomial) (Cohen and Cohen, 1983) while the selection of pairs was based on common parameters influencing the indicators i.e. population influenced (passive voice?) was checked versus traffic density since both include the human factor. Table 3 summarizes the selected indicator pairs as well as the results of their statistical treatment. Based on these results almost all the indicators have been chosen, except for one that is Served surface. As it can be seen in Table 3 the high correlation ($R^2 \cong 0,79$) between Spatial accessibility and Served surface led to consider sufficiently indicative just one of them, that is Spatial accessibility, and to consider information coming from other as redundant.

Since the rest indicators presented no serious correlation among them so they were all chosen for further analysis. More analytically:

- *Population influenced*, *Network extension*, *Network density* and *Traffic density* indicators, are highly indicative for network's length influence (performance and width) and density. Thus, they were used to estimate the adequacy of network's kilometres.
- *Access density* and *Spatial accessibility*, are highly indicative for stations' influence and density. Thus they were used to estimate the adequacy of the number of network stations.

Insert Table 3 about here

APPLICATION

The city of Athens, with a population of 3,13 million spread over an urban area of 411 km^2, has currently a metro network of 3 lines, 52 km length with 51 stations (47 if transfer stations are counted once), 21 of which are underground. In order to estimate Athens's metro network degree of adequacy, according to city's needs, Athens metro network indicators were computed and compared with the selected indicators of previous section.

Obviously, these comparisons prove that Athens's metro network cannot be yet characterised as adequate since its respective indicators are well below the statistical average. In order for the Athens's metro network to be considered as adequate, its respective indicators should raise at least above the statistical average and if possible close to the statistical maximum, according to the ratios between the indicators' statistical averages and maximums values of Athens metro network indicators, as presented in Table 4. In the latter mentioned case, Athens's metro network could be considered as adequate if its length varied at least between 115 -255 kms and the number of stations from 65 to 140 respectively.

Insert Table 4 about here

Comparing the efficiency, else the success, of transport systems between similar cities is an issue that has already been addressed by several research works. However, most of these works have remained very qualitative in their approach or quantitative at a very generic level, since quantitative analysis in the field is confronted to two big limitations: defining a synthetic indicator of the market size at the city level and making this indicator operational (Newman and Kenworthy, 1991; Navarre and Caralampo, 1992; Biebert et al., 1994). In this framework and at this preliminary level of analysis reaching the statistical mean was considered a rather reasonable objective.

The above results were used as the initial reference point for a more sophisticated planning process for Athens's metro system future development that taking into consideration land-use and employment density forecasts as well as mobility trends of the city, outlined a future metro network (presented in Figure 2) of 8 lines, 220 km with 200 stations (175 if transfer stations are counted once). This network is expected to cover almost 85% of

Athens’s urban area. The priority of construction of the 8 Lines, as resulted from the sophisticated planning process, is reflected at the Lines numbering, meaning that the U-shaped Line (Line 4) is the first to be developed and the Ring Line (Line 8) will be the last. In such a “spider web” metro network the Ring line is designed to reduce the number of passengers travelling to the centre but its construction only makes sense if several radius Lines pre-exist.

This future Athens’s metro network is considered in the proposed “New Master-Plan of Athens and Attica Region, 2010-2030”, aiming in this way at an efficient metro system development. The final tuning of lines alignment and stations’ location will be finally determined in a full-scale transportation planning study that is currently under elaboration. The funding of its construction is foreseen also by earmarking revenues of motorways tolls, under the principle of “polluter pays” (the polluting cars pay for the “green” metro).

Insert Figure 2 about here

CONCLUSIONS

This paper attempts to examine the metro rail network extensiveness versus city's needs, based on a set of specially selected indicators resulted from research and analysis of successful and “mature” metro rail networks in Europe, taking into account that metro systems' expansion not only serves better the developed urban areas but also brings development to less populated and less developed urban areas.

The success of a metro system, as of any transit system, is to respond at least adequately to city's transportation needs. This is not always easy to measure. Ideally, the future development of a successful transit system, especially in complex urban environment with a variety competitive transportation networks, should be a result of a full scale transportation planning study based on 4-step transport model. However, it is also essential for any city, that long-term targets for the main city transport infrastructure are early set, not only for motivating the society and mobilising the necessary resources but also for avoiding infrastructure development conflicts (e.g. roadway underpasses and underground parking stations may seriously obstruct the construction of underground metro lines and stations.).

Consequently, the methodology presented in this paper can be used as the initial step and be applied in conjunction with full scale transportation planning studies, in order to investigate the potential for metro development that will subsequently be evaluated through the transportation modelling process. Furthermore, it can provide a quick estimate, on a strategic level, for the "ultimate" metro development required in a city with a non-mature metro network in the very long-run (even beyond the 15 or 20 years planning horizons usually adopted in transportation planning studies), or in a case that the full scale transportation planning study is not feasible. Finally, it can also be used in case of other transport modes networks i.e. light rail. In this case the three criteria developed in the first step of the methodology will probably lead to a different group of cities to be analysed, while the same indicators can be applied in the second step.

The results of the methodology were initially evaluated through a more sophisticated planning process for Athens's metro system future development, in combination with land-use and employment density forecasts as well as mobility trends of the city; this initial evaluation showed that methodology presented can provide results to serve as reference point for a more sophisticated planning process. Nonetheless, methodology's results will be finally validated through a full scale transportation planning study that is currently under elaboration, aiming in this way at a gradual and efficient, and according to Athens's needs, metro system development.

REFERENCES

Alku, A. (2005) “Modern Light Rail basics.” Position Paper.

Alku, A. (2007). *Let's take Light Rail – The new Era of Public Transport*, Anria Publishing Ltd, Finland.

Aravantinos, A. (2002). “Dynamics and planning of the city centers for the following decades - towards centralised or decentralised schemes?” *Aeixoros - Texts of Urban Planning, Planning and Urban Development*, 1(1), 6-29.

Aravantinos, A. (2007). *City Planning - For a Sustainable Development of Urban Space*, Symmetria ed.

American Society of Civil Engineers (2009). *Report Card for America’s Infrastructure*.

Batsos, D., Tzouvadakis, J. (2011). “New Metro System as a Catalyst for Successful Planning Interventions in Athens.” *Journal of Urban Planning and Development (ASCE)*, 137 (1), 49-55.

Biebert, A., Massot, M.-H., Orfeuil, J.-P. (1994). “Prospects for daily mobility.” *Transport Reviews* , 14 (4), 321-340.

Black, J. A., Paez, A., Suthanaya P. A. (2002). “Sustainable Urban Transportation: Performance Indicators and Some Analytical Approaches.”, *Journal of Urban Planning and Development (ASCE)*, 128 (4), 184-209.

Cohen, J., Cohen, P. (1983). *Applied multiple regression/correlation analysis for the behavioral sciences (2nd edition)*, Hillsdale.

De Jonga, M., Mua, R., Steada, D., Mab, Y.,Xib, B. (2010). “Introducing public–private partnerships for metropolitan subways in China: what is the evidence?” *Journal of Transport Geography*, 18(2), 301-313.

Derrible, S., Kennedy, C. (2009). “Network Analysis of World Subway Systems Using Updated Graph Theory.” *Transportation Research Record*, 2112, 17-25.

EC-DG of Regional Policy, Unit D2 Urban Actions (2008). *Urban Audit-Database*, European Commission (EC).

Edwards, M., Mackett, R.L. (1996). “Developing new urban public transport systems: An irrational decision-making process.” *Transport Policy*, 3(4), 225-239.

ESPON (2007). “Study on Urban Functions.” *Project 1.4.3, Final Report, Chapter 3*. European Spatial Planning Observation Network, European Commission (EC).

Gattusso, D., Miriello, E. (2005). “Compared Analysis of Metro Networks Supported by Graph Theory.” *Networks and Spatial Economics*, 5, 395–414.

Giuseppe, B., Gendreau, M., Laporte, G. (2002). « A heuristic for the location of a rapid transit line.” *Computers & Operations Research*, 29, 1-12.
Grava, S. (2002). *Urban Transportation Systems*, McGraw-Hill.

Hellenic Ministry for the Environment, Physical Planning and Public Works (2009). *New Master-Plan of Athens and Attica Region, 2010-2030*, Hellenic Ministry for the Environment, Physical Planning and Public Works.

Kaliampakos, D., Benardos, A. (2008). “Underground space development: Setting modern strategies.” *Proc. 1st Int. Conf. Underground Spaces*, 2008, The New Forest, UK, WIT Press, Southampton.

Kansky, K. (1963). “Structure of Transportation Networks: Relationships Between Network Geography and Regional Characteristics.” *Research Papers 84*, Department of Geography, University of Chicago.

Knowles, R.D. (1996). “Transport impacts of greater Manchester's metrolink light rail system.” *Journal of Transport Geography*, 4 (1), 1-14

Kockelman, K.M. (1995). “Which Matters More in Mode Choice: Density or Income?” *Institute of Transportation Engineers, Compendium of Technical Papers*, 844-867.

Kronenberg, T. (2011). *Demography and Infrastructure: National and Regional Aspects of Demographic Change*, Springer, February.

Mackett, R., Babalik Sutcliffe, E. (2003). “New urban rail systems: a policy-based technique to make them more successful.” *Journal of Transport Geography*, 11(2), 151-164.

Metrobits.org Website <http://www.metrobits.org>

Navarre, D., Caralampo, F. (1992). “Paris-Londres: Une comparaison des systèmes de transport.” *IAURIF & London Research Center*.

Newman, P., Kenworthy, J. (1991). “Transport and urban form in thirty-two of the world principal cities.” *Transport Reviews*, 11(3), 249-72.

OECD (2006). “Competitive Cities in the Global Economy.” *OECD Territorial Reviews*, Organisation for Economic Co-operation and Development.

Ortuzar, J. de D., Willumsen, L.G. (2011). *Modelling Transport (4th Ed.)*, John Wiley and Sons.

Ronka, K., Ritola, J., Rauhala, K. (1998). “Underground space in land-use planning.” *Tunnelling and Underground Space Technology*, 13 (1), 39-49.

Stone, J.R., Allen, J.D., Moerz, Z., Gardner, B. (1992). “Transit system evaluation: guideway bus vs. light rail transit.” *Journal of Advanced Transportation*, 26, 213-240.

UITP (2007). *Mobility in Cities Database* (CD-ROM), International Association of Public Transport.

UN Department of Economic and Social Affairs (2008). *World Urbanization Prospects* (2007 revision), United Nations.

Urbanrail.net Website <http://www. urbanrail.net >

Vaughan, R. (1990). “The Performances of Rectangular, Radial and Polar Base Network.” *Traffic Engineering*, 5.

Vuchic, V.R. (1991). *Urban Public Transportation—System and Technology*, Prentice-Hall.

Vuchic, V. R., Musso, A. (1991). “Theory and Practice of Metro Network Design.” *Public transport international*, 40 (3).

Yannis, G., Sykianaki, E., Bairaktari, S., Toleris, E., Theofilis, I., Kaperoni, P., Kopsacheili, A. (2009). “Urban Mobility Strategy for Greek Cities.” *Proc. 2nd Pan Hellenic Conf. on Urban Planning, Land Use Planning and Regional Development*, 2009, Department of Planning and Regional Development, University of Thessaly, Volos, Greece.

Yu J., Liu, Y., Chang, G.L., Ma, W., Yang, X. (2011). "Locating Urban Transit Hubs: A Multi-Criteria Model and Case Study in China" Journal of Transportation Engineering (ASCE), in press.

TABLES

Table 1. Cities and metro networks basic characteristics

City	Population (*mio inhabitants*)	Area (*km²*)	Density (*person/km²*)	Network			
				Length (*kms*)	Stations[a]	Lines	Annual Ridership (*mio*)
Athens	3,13	411	7.604	52	51 (47)	3	284
Barcelona	1,62	242	6.677	106,6	147 (124)	9	369
Berlin	3,70	892	4.148	144,1	192 (170)	9	466
Brussels	1,08	161,4	6.696	32,2	61 (59)	3	113
Bucharest	2,10	233	9.013	67,7	50 (43)	4	111
Budapest	1,70	525,2	3.241	33	42 (40)	3	280
London	8,28	1.706	4.850	408	268 (268)	11	1014
Madrid	5,10	980	5.204	284	281 (231)	13	690
Minsk	1,83	305,5	5.993	30,3	25 (24)	2	264
Moscow	10,38	1.081	9.605	292,9	177 (141)	12	2529
Munich	2,60	594,9	4.370	92,5	100 (94)	6	330
Naples	0,98	117	8.335	31,8	30 (28)	3	29
Paris	10,14	2.723	3.725	213	380 (300)	16	1410
Rome	2,73	852	3.200	39,0	49 (48)	2	272
Stockholm	1,26	377,3	3.331	105,7	104 (100)	3	297
Vienna	1,68	414,9	4.050	69,8	96 (84)	5	477

[a] Numbers in the parentheses are total number of stations with transfer stations counted once

Table 2. Computed Indicators

City	Population influenced (P) *km/1000 person*	Network extension (Π)	Network density (N_d) *km/km²*	Access density (A_d) *stations/km²*	Served surface (S) *km²*	Spatial Accessibility (A_s) *km²*	Traffic Density (T) *(mio passengers/km)*
Athens[a]	0,017	1,31	0,13	0,114	45,163	10,97%	5,46
Barcelona	0,066	3,91	0,44	0,512	71,94	29,73%	3,46
Berlin	0,039	4,04	0,16	0,191	95,88	10,75%	3,23
Brussels	0,030	2,02	0,20	0,366	13,80	8,55%	3,51
Bucharest	0,032	3,08	0,29	0,185	83,67	35,91%	1,64
Budapest	0,019	1,83	0,06	0,076	21,37	4,07%	8,48
London	0,049	5,43	0,24	0,157	487,59	28,57%	2,49
Madrid	0,056	8,47	0,29	0,236	274,09	27,97%	2,43
Minsk	0,017	2,53	0,10	0,079	30,03	9,83%	8,71
Moscow	0,028	4,63	0,27	0,130	477,63	44,18%	8,63
Munich	0,036	3,65	0,16	0,158	71,45	12,01%	3,57
Naples	0,033	6,94	0,27	0,239	28,35	24,23%	0,91
Paris	0,021	8,76	0,08	0,110	118,72	4,36%	6,62
Rome	0,014	2,04	0,05	0,056	24,87	2,92%	6,97
Stockholm	0,084	3,75	0,28	0,265	87,70	23,25%	2,81
Vienna	0,042	4,29	0,17	0,202	45,53	10,97%	6,83
Minimum	0,014	1,83	0,05	0,056	13,80	2,92%	0,91
Average	0,038	4,36	0,20	0,197	128,84	18,49%	4,69
Maximum	0,084	8,76	0,44	0,512	487,59	44,18%	8,71
St. Dev.	0,02	2,20	0,11	0,12	157,05	12,87%	2,71

St. Error	0,005	0,57	0,03	0,03	40,55	3,32%	0,70

[a] Athens is not included in the calculation of min., max., average, standard deviation and error.

Table 3. Statistical Analysis Results

y	x	Best fit curve (equation)	Slope/s (a)	y-intercept (b)	R-squared (r^2)
Network density (Nd)	Population influenced (P)	Linear	4,052	0,0509	0,5251
Network density (Nd)	Network extension (Π)	Polynomial *(5th degree)*	a_1: -0,0002 a_2: 0,0058 a_3: -0,0546 a_4: 0,2518 a_5: 0,6271 a_6: 0,9448	-0,5918	0,4838
Spatial Accesibility (As)	Access density (Ad)	Polynomial *(6th degree)*	a_1: 5485 a_2: 4057,6 a_3: 159,63 a_4: 761,86 a_5: 205,52 a_6: 19,275	-0,3799	0,4446
Traffic density (T)	Population influenced (P)	Polynomial *(5th degree)*	a_1: 3E+08 a_2: -7E+07 a_3: 6E+06 a_4: -242917 a_5: 4236,9	18,044	0,5309
Spatial Accesibility (As)	Served surface (S)	Polynomial *(6th degree)*	a_1: 3E+07 a_2: -3E+07 a_3: 2E+07 a_4: -3E+06 a_5: 273458 a_6: -10340	179,27	0,7836

Table 4. Desired (target) indicators for the city of Athens

	Network Length related indicators				Station Number related indicators	
	Population influenced	Network extension	Network density	Access density	Spatial Accessibility	Traffic Density
ATH Ind.	0,017	1,31	0,13	0,114	10,97%	5,46
Ind. Aver.	0,038	4,36	0,20	0,197	18,49%	4,69
Ind. Max.	0,084	8,76	0,44	0,512	44,18%	8,71
Ratio of						
Ind. Aver./ATH	2,3	3,3	1,6	1,7	1,7	0,9
Ind. Max./ATH	5,1	6,7	3,5	4,5	4,0	1,6
Av. value of ratios						
Ind. Aver./ATH		**2,2**			**1,3**	
Ind. Max./ATH		**4,9**			**2,8**	