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Macroscopic Review of Metro Networks in Europe and their Role in the City Development

G. Yannis, A. Kopsacheili and P. Klimis
Attiko Metro S.A.

ATTIKO METRO S.A.

Introduction

- Several scientist claim that the future of cities' infrastructure can only be underground, due to
  - urban road congestion is at saturation levels in all major European cities
  - considerations for environmental issues and the lack of physical space in general
- All recent national and international policies in European countries suggest to adopt metro-based solutions to urban mobility problems.
- Therefore, **Metro system development in Europe is set to increase further in the future, contrary to the considerable funding effort their introduction requires**.
- This contradiction is the biggest challenge for further Metro network development in most European cities, including the city of Athens, due to the scarcity of funding sources.

Scope & Outline

- **Scope** is to explore this challenge and estimate the potential for metro development according to a city's needs, through macroscopic review of "mature" and successful metro systems, providing as such a useful and quick-response planning tool, on a strategic level.
- **Outline**
  - **Methodological approach**
  - **Application of methodology** in order to estimate the degree of Athens's metro network adequacy according to city's needs.
    - 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.
  - **Conclusions**
    - the methodology as well as the application results are discussed.

Methodological approach

- Methodological approach, consists of two stages:
  - **Identification of successful and "mature" metro rail networks** in Europe -following specific criteria of networks' necessity, "maturity" and success - and examination of basic elements (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**;
  - **Analysis of indicators**, starting with the development of all indicators relating basic metro network elements to city's main characteristics (i.e. size, population, density etc.) and continuing with statistical analysis, aiming at **pointing out reference meaningful indicators for application**.

Metro networks selection

- 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 ($\mathbf{C_1}$),
  - Network structure ($\mathbf{C_2}$) and
  - System's success ($\mathbf{C_3}$)

Demography criterion

- 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 **demography criterion** 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 cities with large urban areas are the ones having a population of more than 750.000 persons in the urban zone.

Network structure criterion

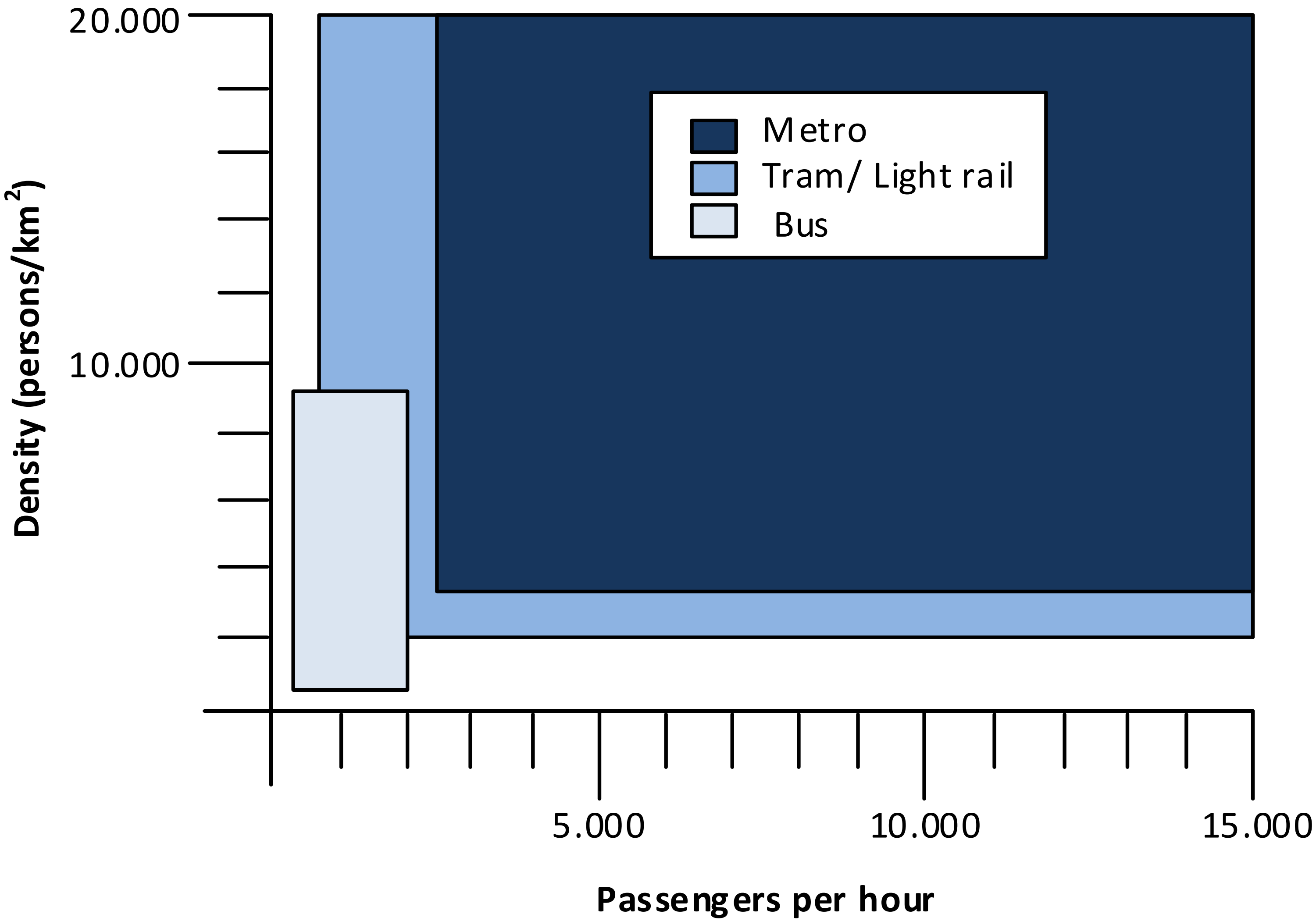
- The **network structure** was selected in order to exclude metro systems of "temporary situation", else the non-completed, else non-"mature", metro networks.

- More analytically, 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.

System's success criterion

- The success criterion was chosen as **population density vs. operation performance of a metro network line to be more than the efficient minimums** (Figure 1).
  - Cities with large urban areas are not all with similar characteristics. Some are very tightly built some 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.

Figure 1. Operating conditions of different public transport systems



System's success criterion (cont.)

- It should be noted here, 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.

Metro networks selected

- Data on cities' population size and spread, network structures and basic elements as well as network operational characteristics was obtained from various sources
  - official websites, census reports, research projects and papers (metrobits.org website, urbanrail.net website, UITP, 2007, EC, 2008, ESPON, 2007, UN, 2008, OECD, 2006).
- 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.
- Then the application of the 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.

Table 1. Cities and metro networks basic characteristics

City	Population (mio inhabitants)	Area (km^2)	Density (person/km^2)	Network				
				Length (kms)	Stations		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

** With transfer stations counted once*

*** Urban area of Athens*

Indicators identification

- Indicators, mostly taken from the sector literature are relating metro network elements (technical and operations) to city's main characteristic.

- Such indicators are useful to verify each networks capability to serve its respective territory and to make comparative analysis of networks while working in different urban contexts.
  - **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)

Indicators identification *(cont.)*

- **Network extension** (Π) is the ratio between network length (L) and the network diameter (D): $\Pi = L/D$ (2)
  - **Network diameter** (D, *km*) is the length of the shortest route connecting the farthest stations of the network:
- **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 city's urban area: $N_d = L/S_u$ (3)
- **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)

Indicators identification *(cont.)*

- **Served surface** (S, km^2): it is equal to the territory extension where network is attractive. It is computed by multiplying the number of stations with the circle area of a radius equal to 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).

$$S = ST \bullet \left(\pi \bullet R^2\right) - \left[\left(S_1 \cap S_2\right) \cup \left(S_2 \cap S3\right) \cup \ldots\right] \quad (5)$$

  - **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 (varying from 500m for central stations to 1km for stations located in the suburbs)
  - S_1, S_2 ..etc., are the surfaces served by stations 1, 2..etc.

Indicators identification *(cont.)*

- **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)

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

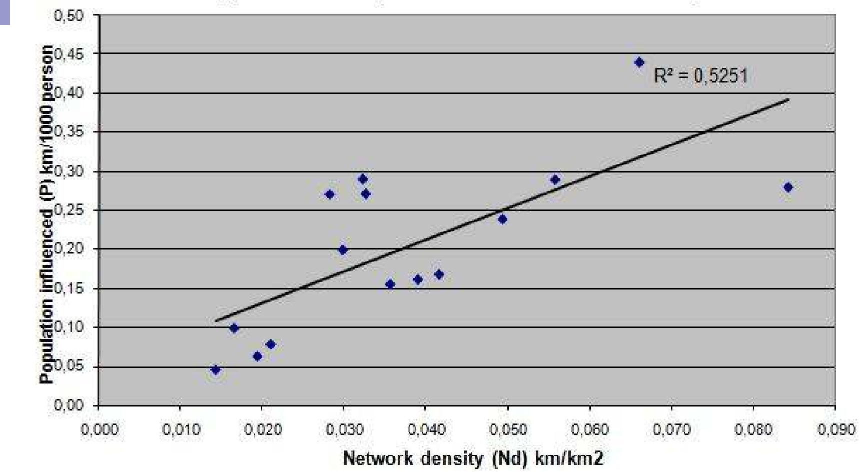
The indicators proposed were computed for the 15 selected metro networks and are presented in Table 2.

Table 2. Computed Indicators

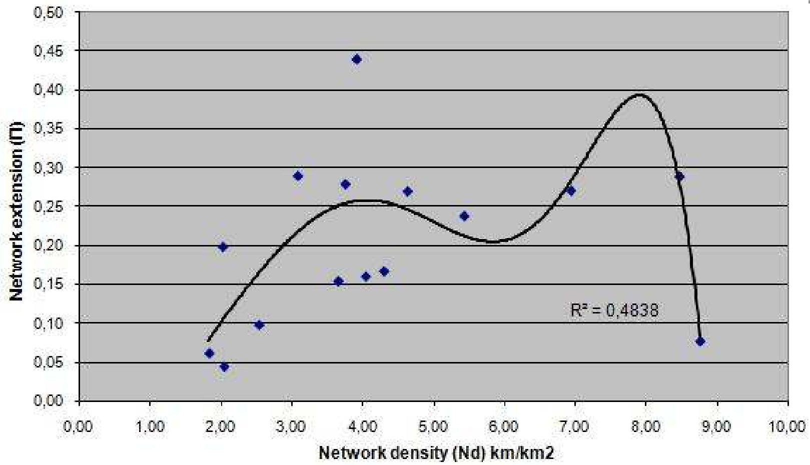
City	Population influenced (P) km/1000 person	Network extension (Π)	Network density (N_d) km/km^2	Access density (A_d) stations/km^2	Served surface (S) km^2	Spatial Accessibility (A_s)	Traffic Density (T) (mio passengers/km)
Barcelona	0,066	3,91	0,44	0,512	71,94	29,73%	3,46
Berlin	0,039	4,04	0,16	0,191	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

Analysis of indicators

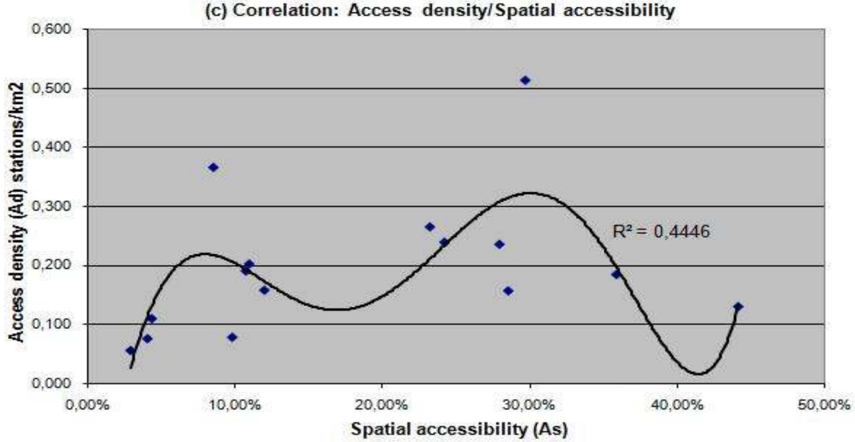
- Information given by an indicator on the characteristics offered by the networks is contrasting
  - i.e. high range of influence is, on the one hand, a positive factor since it indicates a greater level of territorial covering; on the other hand, it indicates a greater difficulty level for users who 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 (regression 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 (*figures next*).



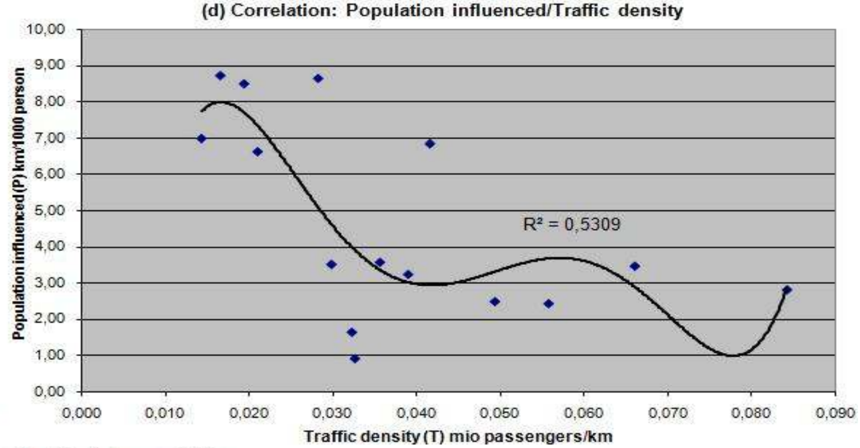
(a) Correlation: Population influenced/Network density



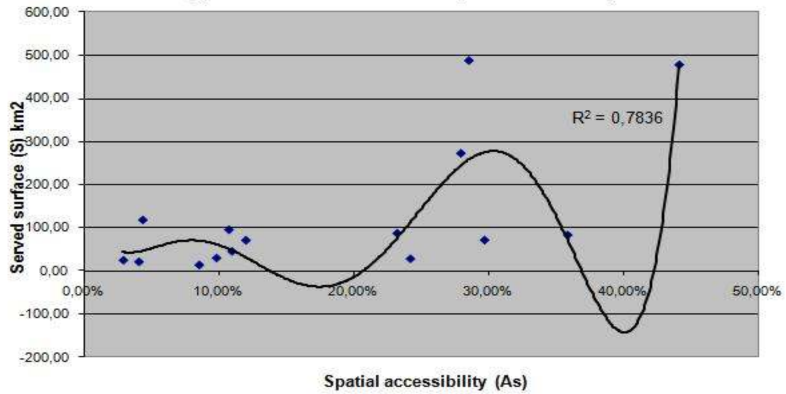
(b) Correlation: Network extension/Network density



(c) Correlation: Access density/Spatial accessibility



(d) Correlation: Population influenced/Traffic density



(e) Correlation: Served surface/Spatial accessibility

Selected Indicators

- Based on the results of statistical analysis, almost all the indicators of Table 2 have been chosen, except one that is Served surface.
  - The high correlation ($R^2 = 0,79$) between Spatial accessibility and Served surface led to consider sufficiently indicative just one of them, that is Spatial accessibility.
- The rest indicators present no serious correlation among them so they were all chosen for further analysis.
  - *Population influenced*, *Network extension*, *Network density* and *Traffic density*, 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 network's stations number.

Application

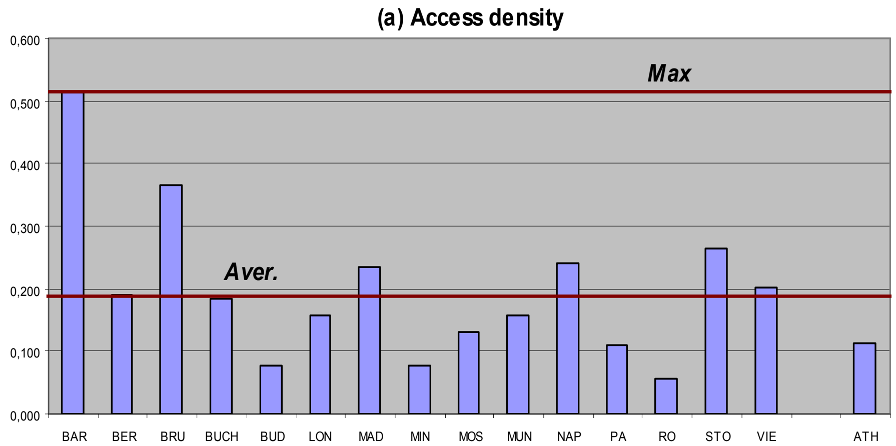
- Athens city, with a population of 3,13 million spread over an urban area of 411 km^2, has currently a metro network of 3 lines, 52 km length with 51 stations.

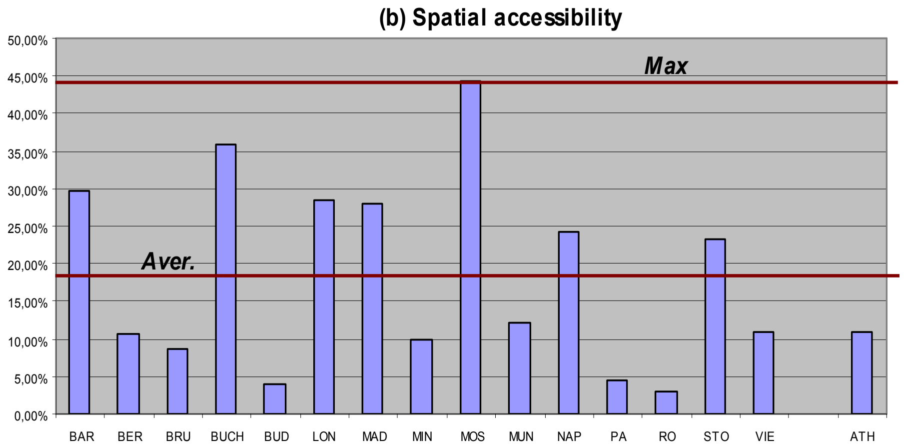
- In order to estimate Athens's metro network degree of adequacy, according to city's needs, Athens's metro network indicators were computed and compared with the selected indicators of previous section, as it is shown in figures next.

ΣΧΕΔΙΟ ΑΝΑΠΤΥΞΗΣ ΓΡΑΜΜΩΝ ΜΕΤΡΟ ΑΘΗΝΑΣ

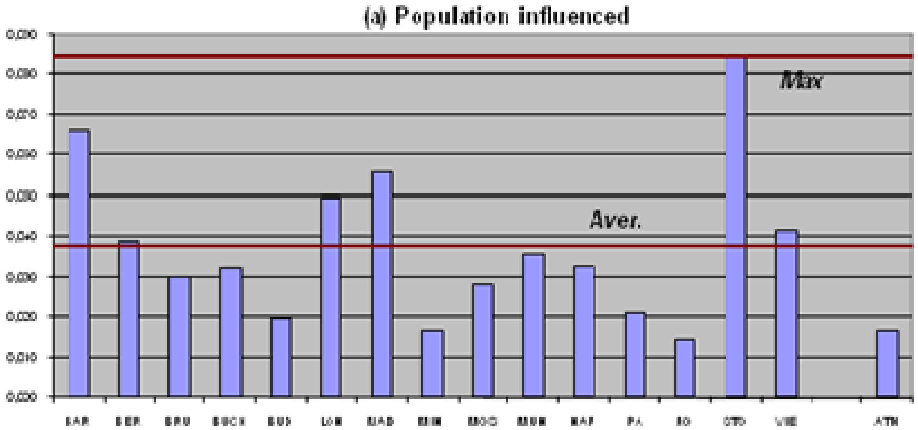
ΤΡΙΤΟ ΚΟΙΝΟΤΙΚΟ ΠΛΑΙΣΙΟ ΣΤΗΡΙΞΗΣ
ΜΕ ΤΗ ΣΥΓΧΡΗΜΑΤΟΔΟΤΗΣΗ ΤΗΣ ΕΛΛΑΔΑΣ ΚΑΙ ΤΗΣ ΕΥΡΩΠΑΪΚΗΣ ΕΝΩΣΗΣ
Υ.ΠΕ.ΧΩ.Δ.Ε.

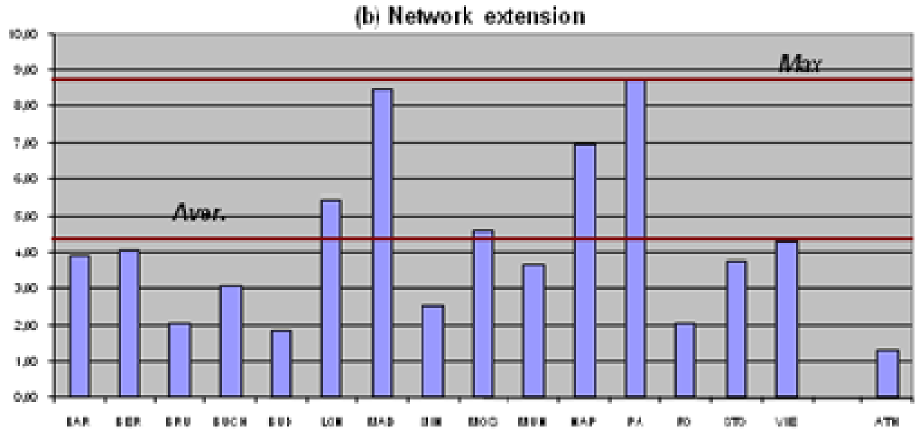
Comparative analysis of indicators – *adequacy of network stations*

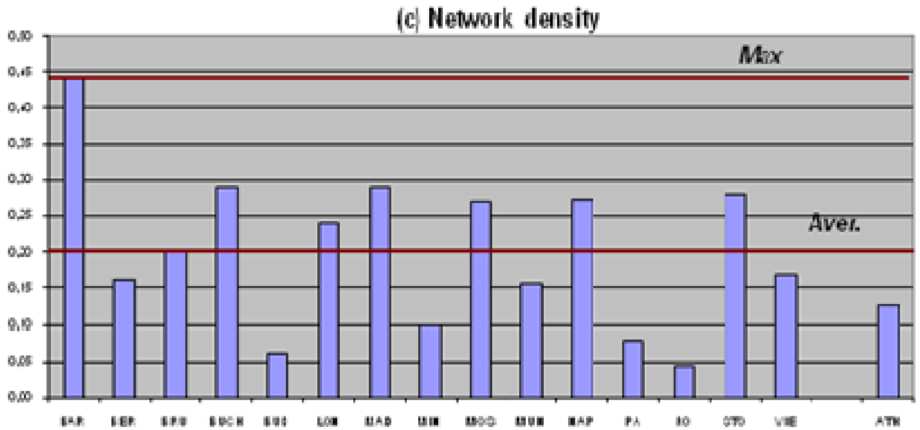




Comparative analysis of indicators – *adequacy of network length*







Application results

- As it is obvious, from these figures, Athens's metro network cannot be yet characterised as adequate since its respective indicators are well below the statistical average.

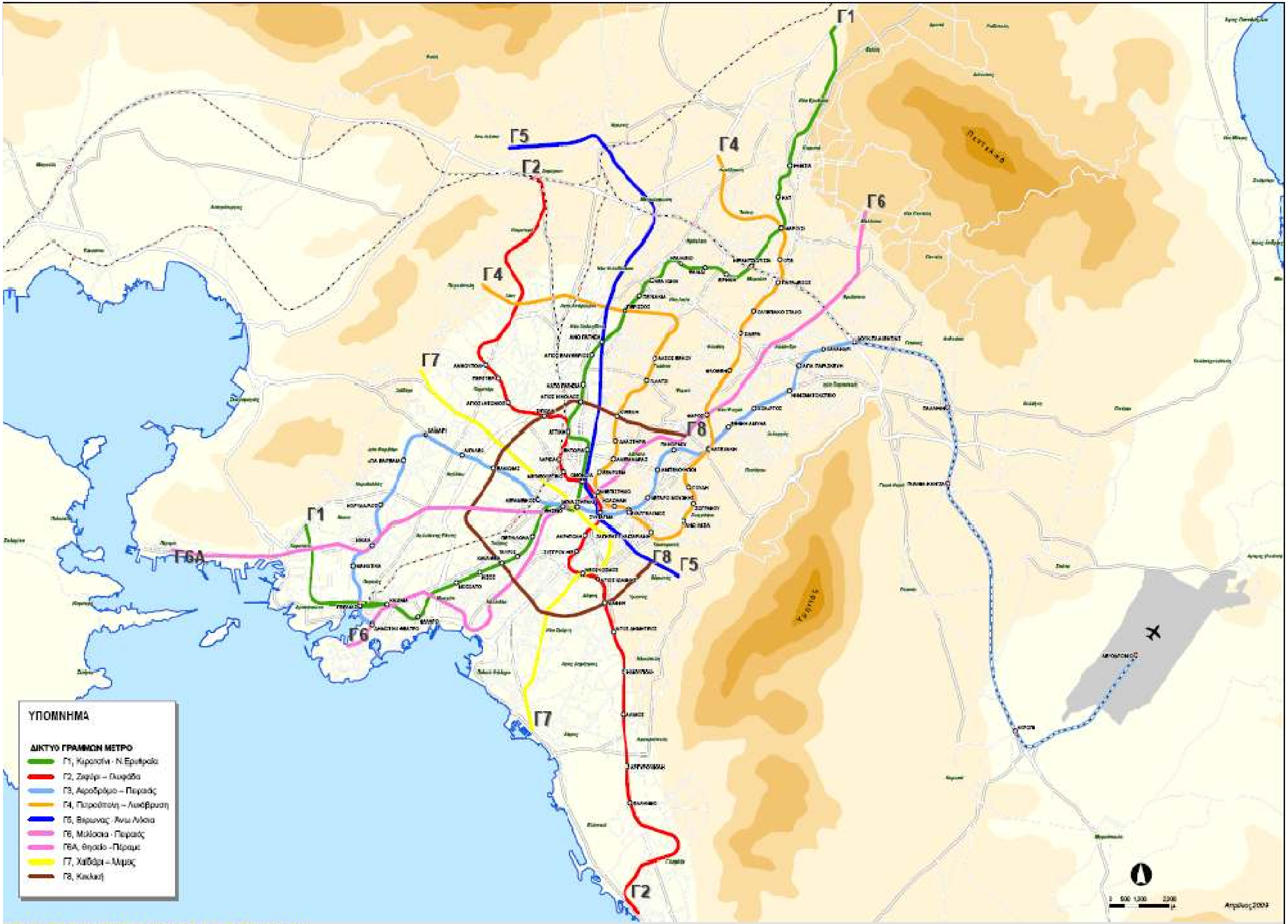
- In order for the Athens's metro network to be considered as adequate, its respective indicators should raise at least above the statistical average but below the statistical maximum, according to the ratios between the indicators' statistical averages and maximums with Athens's metro network indicators values, as presented in Table 3.

Table 3. Necessary metro network length and number of stations for the city of Athens

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

Future Metro network in Athens

- These 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 outlined a future metro network (*presented in Map next*) of 8 lines, 220 km with 200 stations, which is expected to cover almost 85% of Athens's urban area.
- This above Athens's metro network is included tentatively in the proposed "New Master-Plan of Athens and Attica Region, 2010-2030", aiming in this way at an efficient, and according to Athens's needs, metro system development.
- The fine tuning of lines alignment and stations' location will be finally determined in a full-scale transportation planning study that is currently under elaboration and its funding is foreseen by earmarking revenues of motorways tolls, under the principle of "polluter pays" (the polluting cars pay for the "green" metro).



ΡΥΘΜΙΣΤΙΚΟ ΣΧΕΔΙΟ ΑΤΤΙΚΗΣ
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ΜΕ ΤΗ ΣΥΓΧΡΗΜΑΤΟΔΟΤΗΣΗ ΤΗΣ
ΕΛΛΑΔΑΣ ΚΑΙ ΤΗΣ ΕΥΡΩΠΑΪΚΗΣ ΕΝΩΣΗΣ

Υ.ΠΕ.ΧΩ.Δ.Ε.

Conclusions – *on methodology*

- Ideally, the future development of a successful transit system, especially in complex urban environment with a variety of competitive transportation networks, should be a result of a full scale transportation planning study based on 4-step transport model.

- Nonetheless, 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.

Conclusions – *on the results*

- 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.

- 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, and they will be finally validated through a full scale transportation planning study that is currently under elaboration, aiming in this way at an efficient, and according to Athens's needs, metro system development.