MACROSCOPIC REVIEW OF METRO NETWORKS IN EUROPE AND THEIR ROLE IN THE CITY DEVELOPMENT

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ABSTRACT

This paper brings into focus the metro rail network extensiveness versus city's needs based on a set of meaningful indicators resulted from research and analysis of successful and "mature" metro rail networks in Europe. On that purpose, a set of selected indicators relating metro network elements and main city characteristics are developed. Subsequently, these indicators are applied in order to estimate the degree of adequacy of Athens metro network according to city's needs. Once the adequacy of Athens's metro network is formulated, specific proposals are presented concerning the network length, as well as the respective number of metro stations, that Athens should develop in the long-run in order to serve citizens' transportation needs for the next decades.

Key words: *metro rail, urban transport planning, city development, indicators*

1. 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, metro rail development is increasingly gaining political support and all recent national and international policies in most European countries continuously suggest to decision makers to adopt metro-based solutions to urban mobility problems. Several scientists claim that the future of cities' infrastructure can only be underground. About 50 European cities currently have metro networks (metrobits.org website, urbanrail.net website) large or small, either completed or with future extensions planned, and plenty 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 Europe is set to increase further in the future, contrary to the often-expressed view that fewer metro systems will be developed due to the considerable funding effort that their introduction requires.

This contradiction is probably the biggest challenge for further metro network development in most European cities, including the city of Athens, due to the scarcity of funding sources, and thus this challenge should become the initiative for a well coordinated and integrated urban transport planning, to ensure an efficient metro system development, according to city's needs.

The purpose of this paper is to explore the aforementioned challenge by formulating a methodology that estimates the potential for metro development according to the city's needs, through macroscopic review and comparison of the extent of metro development in other urban areas with "mature" and successful metro systems, in order to provide a useful and quick-response planning tool, on a strategic level.

The starting point (section 2) 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 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;

(b) 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.

In section 3 of this paper, the selected indicators are applied comparatively with the respective indicators of Athens 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 that 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.

In the conclusions section, the methodology as well as the application results are discussed.

2. METHODOLOGICAL APPROACH

2.1. 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 **demography 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.

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. 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 (Grava, 2002).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 (Antero 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 (Antero 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 on one street is 2000 passengers per hour max; tram/light rail begins from 500 passengers per hour per line up to 9000, when a metro line is already uneconomical to operate below 2500 passengers per hour (Antero 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 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.

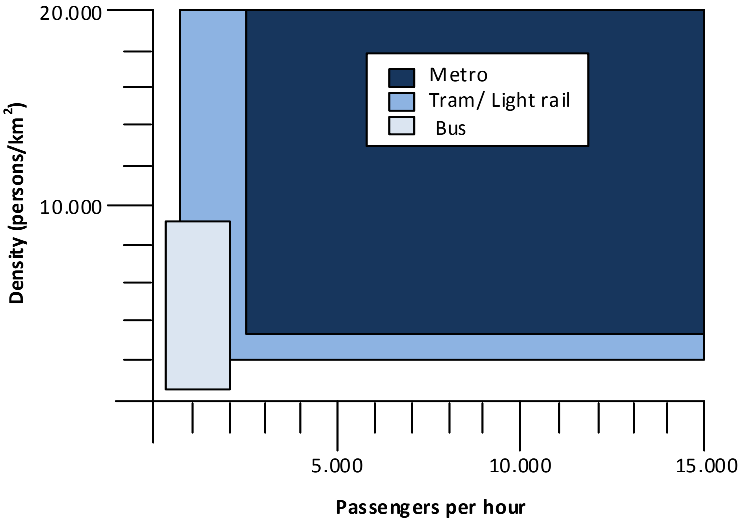

Figure 1. Operating conditions of different public transport systems (Antero Alku, 2007).

Data on cities' population size and spread, network structures and basic elements as well as network operational characteristics was obtained from various sources such as 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. 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.

Table 1. Cities and metro networks basic characteristics

City	Population (*mio inhabitants*)	Area (*km²*)	Density (*person/km²*)	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*

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

These indicators, mostly taken from the sector literature (Kansky, 1963, Vaughan, 1990, Vuchic, 1991, Vuchic and Musso, 1991, Gatusso and Miriello, 2005) 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.

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

- 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)
- 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)
- Served surface (S, *km*^{2}): it 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).
  $S = ST \bullet (\pi \bullet R^2) - [(S_1 \cap S_2) \cup (S_2 \cap S3) \cup ...]$ (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 (a station that its geographic position is in the zone between the city centre and the suburbs) and it is equal to the area of a circle with radius equal to 500m (that is according to the literature the largest distance accepted on average by a walker to access to a generic metro station).
  - S_1, S_2 ..etc., are the surfaces served by stations 1, 2..etc.
- 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)

2.2. Analysis of indicators

The indicators proposed in the previous section 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/km²*	Access density (A_d) *stations/km²*	Served surface (S) *km²*	Spatial Accessibility (A_s) *km²*	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

Sometimes, information given by an indicator on the characteristics offered by the networks is contrasting (Gatusso and Miriello, 2005). 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 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 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. Different regression types among the indicators were examined (linear, logarithmic, exponential, polynomial etc.) Figures 2(a), (b), (c), (d) and (e) show graphically the regression type (trend line), for each pair of indicators, with the highest R^2.

Based on the results of statistical analysis, almost all the indicators of Table 2 have been chosen, except one that is Served surface. As it can be seen in Figure 2(e) 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

The rest indicators present 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, they 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.

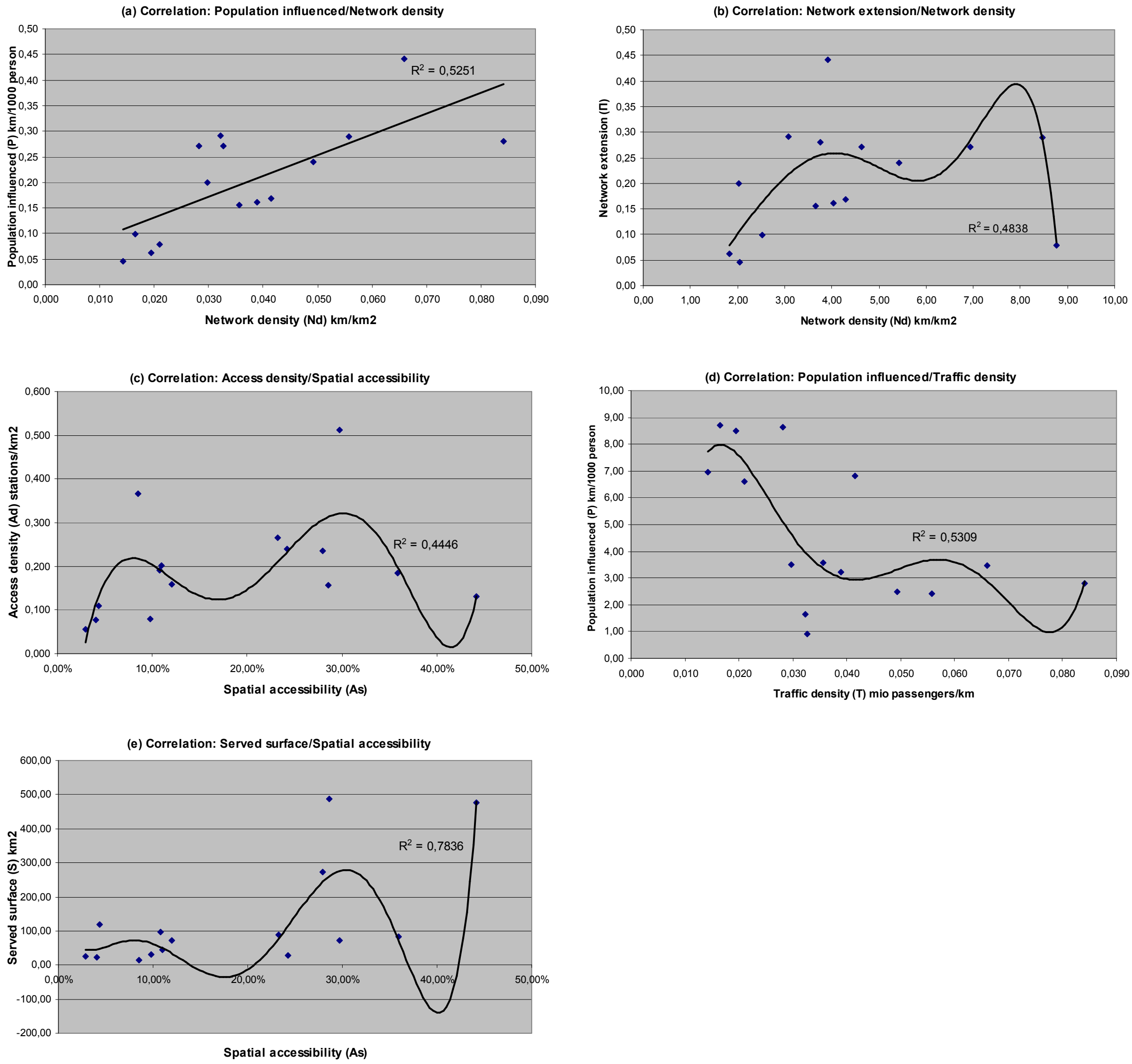

Figure 2. Correlations

3. 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 (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's metro network indicators were computed and compared with the selected indicators of previous section, as it is shown in Figures 3(a) and (b) and 4(a), (b), (c) and (d).

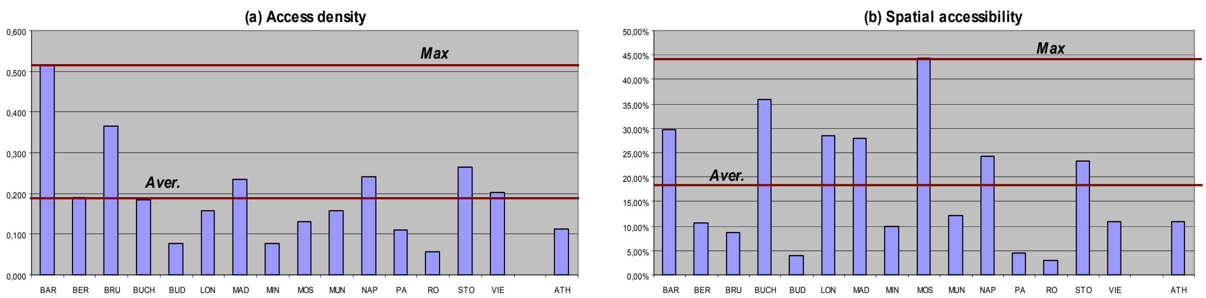

Figure 3. Comparative analysis of indicators – adequacy of network stations.

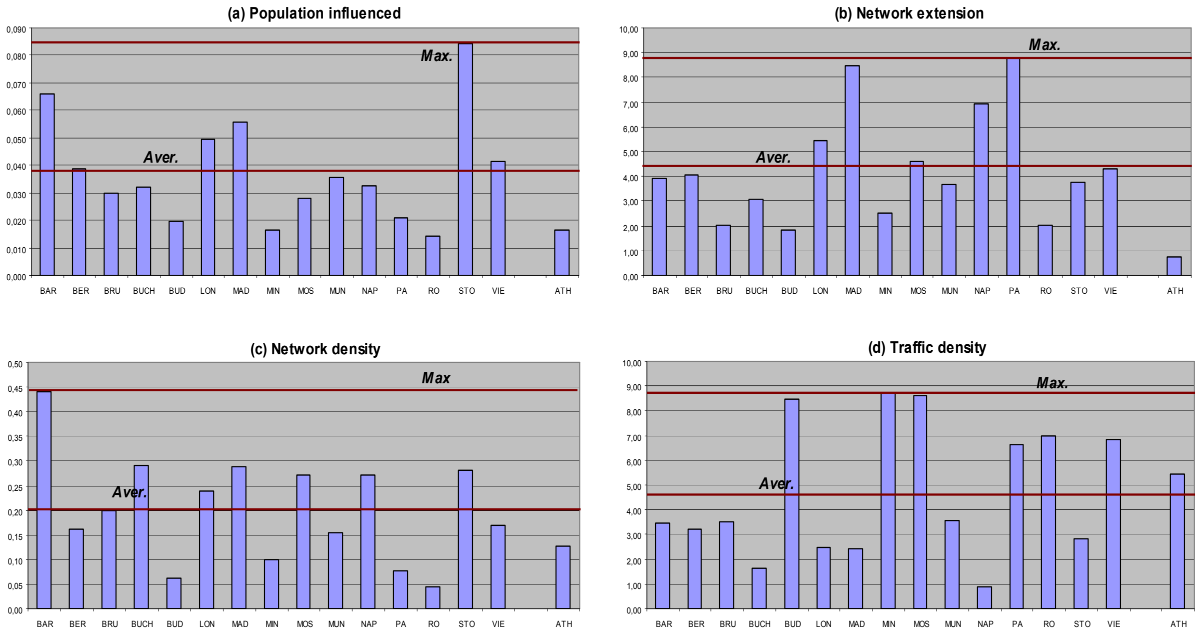

Figure 4. Comparative analysis of indicators – adequacy of network length.

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	Access density	Spatial Accessibility	Traffic Density
ATH Ind.	0,017	0,76	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	5,7	1,6	0,9	1,7	1,7
Ind. Max./ATH	5,1	11,5	3,5	1,6	4,5	4,0
Av. value of ratios						
Ind. Aver./ATH		2,5			1,7	
Ind. Max./ATH		5,1			4,3	

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 outlined a future metro network (presented in Figure 5) 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).

4. CONCLUSIONS

This paper attempts to examine the metro rail network extensiveness versus city's needs, based on a set of meaningful indicators resulted from research and analysis of successful and "mature" metro rail networks in Europe.

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.

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. 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.

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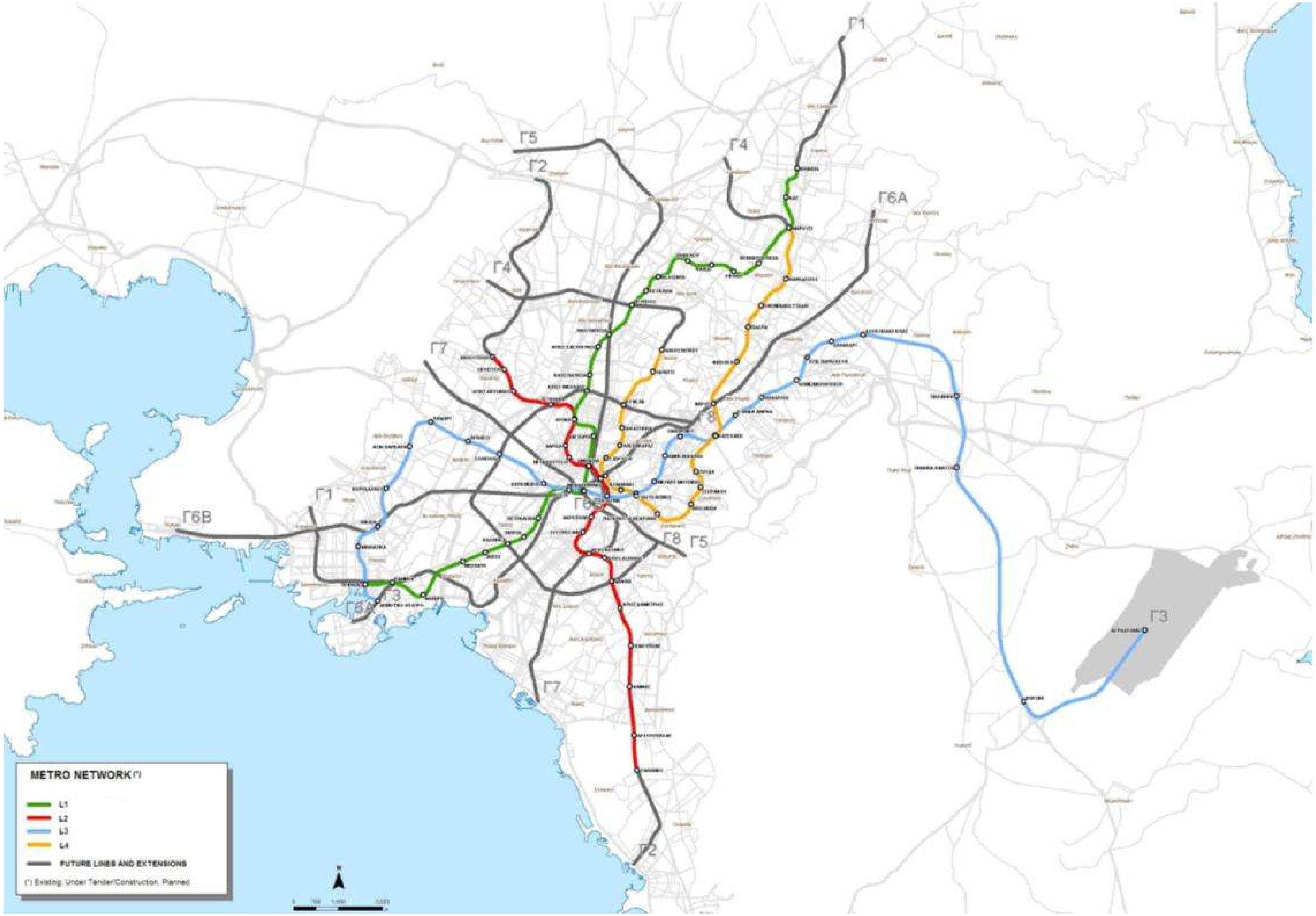

Figure 5. The future Athens metro network