Estimating the Adequacy of a Metro Network

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Abstract: The objective of this research is a preliminary examination of metro rail network extensiveness versus the 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, i.e., length and number of stations, to city characteristics, e.g., population and density. 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 the current Athens, Greece metro network in relation to the city's needs. Findings indicate that the Athens metro network cannot be yet characterized as adequate, and specific proposals are made in terms of future network extensions. 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 eight lines, 220 km, and 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. **DOI:** 10.1061/(ASCE)UP.1943-5444.0000114. *© 2012 American Society of Civil Engineers.*

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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 system development is increasingly gaining political support (Knowles 1996). All recent national and international policies in most European countries continuously outline the need for decision makers to 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 than 50 European cities currently have metro networks (Metrobits.org 2009; Urbanrail.net 2009), ranging from large to small networks and 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 with 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, Greece, due to the scarcity of funding sources. After all, this challenge could be an opportunity to develop a well-coordinated and integrated urban transport planning system (Edwards and Mackett 1996) to ensure efficiency and adaptation of the city's needs. It is increasingly recognized that metro systems' expansion not only serves the developed urban areas better 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) that is 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 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:

1. 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, and stations, which express the extensiveness of each system based on available data collected and identification of indicators for the analysis; and
2. Analysis of indicators starting with the development of all indicators relating basic metro network characteristics to the

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city's main characteristics, i.e., size, population, and density, 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 the 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 (four-step transport model), especially in a complex urban environment and with a variety of 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 modeling process. It can also provide a quick estimate for the ultimate metro development required in a city with a nonmature metro network in the very long run, even beyond the 15- or 20-year planning horizons usually adopted in transportation planning studies or in case 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: demographic, 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 a population size big enough to justify the cities' characterization as large urban areas. According to the Urban Audit of Directorate-General for Regional Policy (European Commission 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. Nevertheless, they are all considered to be at a similar and advanced stage of urbanization, e.g., high population, high density, and increased economic growth/high income, compared to other cities in each country; struggling all the same with traffic congestion; and demanding at the same time efficient, reliable, and qualitative public transport. These cities' urban structure is the dominant factor for determining or even better ensuring the effectiveness or else usage of urban public transport (Kockelman 1995; Kronenberg 2011), especially rail. To this end, the 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 a temporary situation or else the noncompleted or nonmature 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 similar characteristics. Most large cities are typically very tightly built in the city centers while others are not, thus having much fewer buildings and less 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 Table 1, cities with a population density of less than $3,800$ persons/km^2 should rather base their public transport system on other modes (Alku 2007). In Table 1, it is also notable that the operation capacity of the trams/light rail systems (on street) as well as the buses does not overlap the metro's operation capacity. A bus system's capacity is 2,000 passengers per hour maximum; tram/light rail begins with 500 passengers per hour per line up to 15,000 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 versus operation performance of a metro network line to be more than the efficient minimums.

The success as well as the purpose of a metro system as any transit system is to respond as best as possible to the 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 (OD) pairs, which was rather impossible to be done for all the metro networks in European cities. For this reason, it was preferable to use simpler measures like population density versus operation performance.

Data on cities' population size and spread, network structures, basic characteristics, and network operational features were obtained from various sources such as official websites, census reports, research projects, and papers [Organisation for Economic Cooperation and Development (OECD) 2006; International Association of Public Transport (UITP) 2007; European Spatial Planning Observation Network (ESPON) 2007; European Commission 2008; United Nations (UN) 2008; Metrobits.org 2009; Urbanrail.net 2009). Once compiled, the collected data were 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 2, along with Athens's system.

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; Giuseppe et al. 2002; Jeon and Amekudzi 2005; Gattuso and Miriello 2005; Derrible and Kennedy 2009; ASCE 2009) relating metro network characteristics (technical and operational) to the city's main characteristic (demographic), are useful to verify each network's capability to serve its respective territory and to make a comparative analysis of networks while working in different urban contexts. The indicators finally used are a mixture of existing as well as new, allowing for the paper objectives to be met.

Table 1. Operating Conditions of Different Public Transport Systems

Preferred transportation mean	Density (persons/km^2)	Passengers per hour	Minimum service interval (min)
Bus	1,000–9,500	<2,000	30
Light rail	2,000–20,000	500–15,000	20
Metro	>3,800	>2,500	10

Note: Data from Alku (2007).

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Table 2. Cities' and Metro Networks' Basic Characteristics

City	Population (millions of inhabitants)	Area (km^2)	Density (persons/km^2)	Network				
				Length (km)	Stations		Lines	Annual ridership (millions)
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	1,014
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	2,529
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	1,410
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

Note: Numbers in the parentheses are total number of stations with transfer stations counted once.

Based on the available data presented in Table 2 and on the aforementioned literature, the indicators initially chosen for computation are:

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

$$P = \frac{L}{P_u} \tag{1}$$

2. 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:

$$\Pi = \frac{L}{D} \tag{2}$$

3. 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 the city's urban area:

$$N_d = \frac{L}{S_u} \tag{3}$$

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

$$A_d = \frac{ST}{S_u} \tag{4}$$

5. Served surface (S; km^2) is equal to the territory extension where the 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 or else the overlap areas of the stations' ranges of influence:

$$S = ST \bullet (\pi \bullet R^2) - [(S_1 \cap S_2) \cup (S_2 \cap S3) \cup \cdots] \tag{5}$$

The variables, e.g., S_1 and S_2, are the surfaces served by the stations, e.g., 1 and 2, while average range of influence (R; km^2) is a standard range indicating the largest distance accepted on average by a walker to access a generic metro station. A generic station is a station with a geographic position in the zone between the city center and the suburbs. For a station in the city center, the distance accepted on average by a walker is much shorter than 500 m, while for a station in the suburbs, it can be much longer. The proper way to calculate the served surface would be to assign weights, i.e., 0.5 to stations in the city center, 1.5 to stations in the suburbs, and 1 to stations in the intermediate zone, to the stations' range of influence according to the stations' geographic position but since this would require geographic information system (GIS) mapping of all metro networks analyzed, 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 the city center, suburbs, and in between, the generic type of station was chosen.

6. 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 the city's urban area:

$$A_s = \frac{S}{S_u} \tag{6}$$

7. Traffic density (T; passengers/km) is the ratio of annual (usually) network ridership (RD) per kilometer of line:

$$T = \frac{RD}{L} \tag{7}$$

Analysis of Indicators

The indicators proposed in the previous section were computed for the 15 selected metro networks and are presented in Table 3. Sometimes information given by an indicator on the characteristics offered by the networks is contrasting (Gattuso and Miriello 2005; Derrible and Kennedy 2009). 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

Table 3. Computed Indicators

City	Population influenced (P) (km/1,000 persons)	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) (%) (km^2)	Traffic density (T) (millions of passengers/km)
Athens	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
Standard deviation	0.02	2.20	0.11	0.12	157.05	12.87	2.71
Standard error	0.005	0.57	0.03	0.03	40.55	3.32	0.70

Note: Athens is not included in the calculation of minimum, maximum, average, standard deviation, and error.

statistical analyses has been elaborated in order to identify possible correlations, conclude to the most representative and meaningful indicators for application, and eliminate the redundant ones.

Different regression types among selected pairs of indicators were examined (linear, logarithmic, and polynomial) (Cohen and Cohen 1983), while the selection of pairs was based on common parameters influencing the indicators, i.e., population influenced was checked versus traffic density since both include the human factor. Table 4 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, which is served surface. As can be seen in Table 4, the high correlation ($R^2 \cong 0.79$) between spatial accessibility and served surface led to a consideration sufficiently indicative of just one of them, which is spatial accessibility, and to consider information coming from the other as redundant.

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

- Population influenced, network extension, network density, and traffic density indicators are highly indicative for the network's length influence (performance and width) and density. Thus,

Table 4. Statistical Analysis Results

y	x	Best fit curve (equation)	Slope/s (a)	y-intercept (b)	R^2
Network density (ND)	Population influenced (P)	Linear	4.052	0.0509	0.5251
Network density (ND)	Network extension (Π)	Polynomial (fifth 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 accessibility (AS)	Access density (AD)	Polynomial (sixth degree)	a_1:5,485 a_2:4,057.6 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 (fifth degree)	a_1:3E + 08 a_2: −7E + 07 a_3:6E + 06 a_4: −242,917 a_5:4,236.9	18.044	0.5309
Spatial accessibility (AS)	Served surface (S)	Polynomial (sixth degree)	a_1:3E + 07 a_2: −3E + 07 a_3:2E + 07 a_4: −3E + 06 a_5:273,458 a_6: −10,340	179.27	0.7836

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Table 5. 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 indicator	0.017	1.31	0.13	0.114	10/97	5/46
Indicator average	0/038	4/36	0/20	0/197	18/49	4/69
Indicator maximum	0.084	8.76	0.44	0.512	44.18	8.71
Ratio of						
Indicator average/ATH	2.3	3.3	1.6	1.7	1.7	0.9
Indicator maximum/ATH	5.1	6.7	3.5	4.5	4.0	1.6
Average value of ratios						
Indicator average/ATH	**2.2**				**1.3**	
Indicator maximum/ATH	**4.9**				**2.8**	

they were used to estimate the adequacy of the network's kilometers.

- Access density and spatial accessibility are highly indicative for the stations' influence and density. Thus, they were used to estimate the adequacy of the number of network stations.

Application

The city of Athens, with a population of 3.13 million spread over an urban area of 411 km^2, currently has a metro network of three lines, 52 km in length, with 51 stations or 47 stations if transfer stations are counted once, 21 of which are underground. In order to estimate the Athens metro network degree of adequacy according to the city's needs, the Athens metro network indicators were computed and compared with the selected indicators of the previous section.

Obviously, these comparisons prove that Athens's metro network cannot be yet characterized as adequate since its respective indicators are well below the statistical average. In order for the Athens metro network to be considered as adequate, its respective indicators should be raised at least above the statistical average and if possible close to the statistical maximum according to the ratios

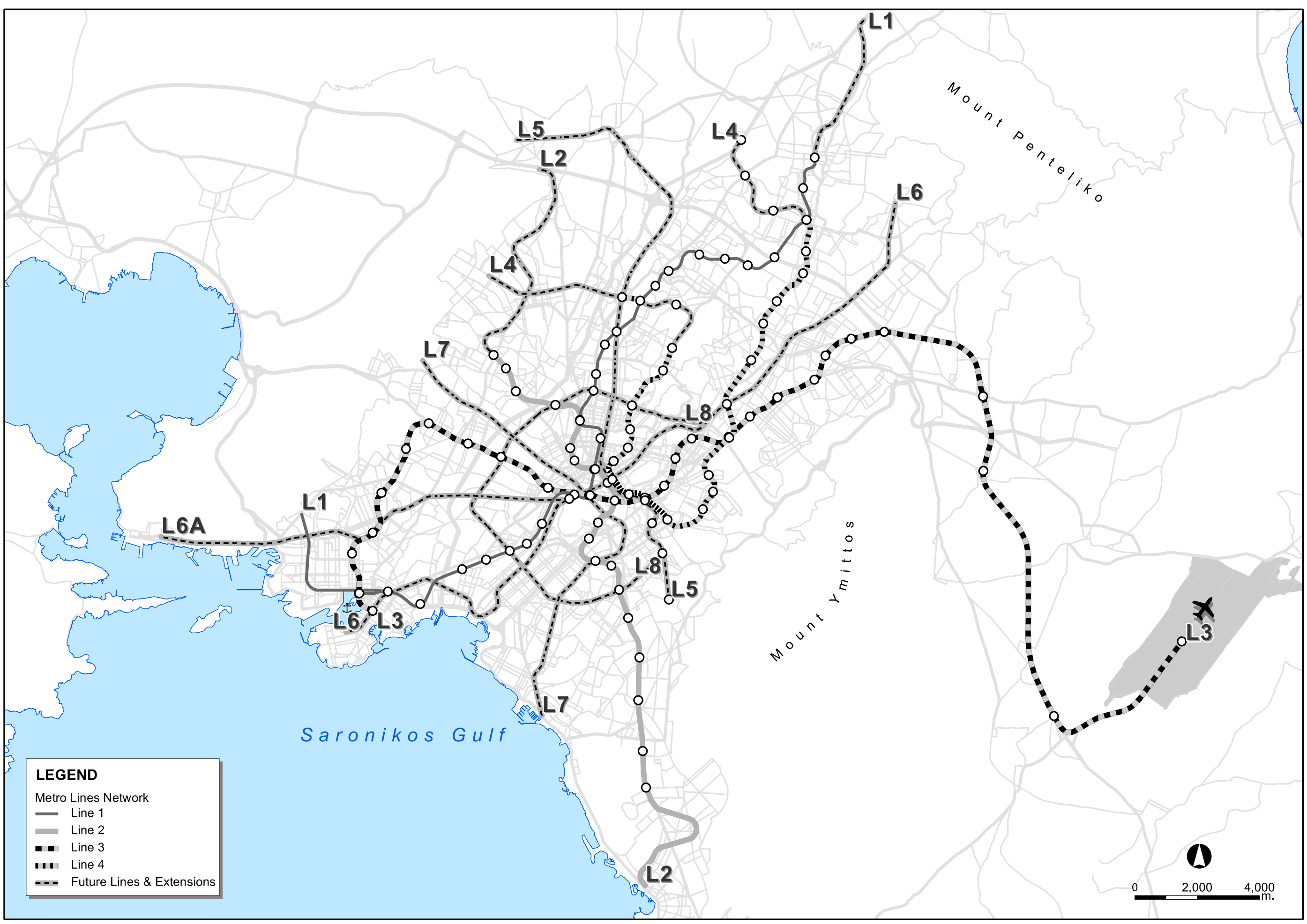

Fig. 1. Future Athens metro network

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between the indicators' statistical averages and maximum values of the Athens metro network indicators, as presented in Table 5. In the latter mentioned case, Athens's metro network could be considered as adequate if its length and number of stations varied at least between 115 and 255 km and from 65 to 140, respectively.

Comparing the efficiency or 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 by 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 takes into consideration land use and employment density forecasts as well as mobility trends of the city. A future metro network (presented in Fig. 1) of eight lines, 220 km, and 200 stations or 175 stations if transfer stations are counted once is outlined. This network is expected to cover almost 85% of Athens's urban area. The priority of construction of the eight lines, which resulted from the sophisticated planning process, is reflected at the line 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 traveling to the center but its construction only makes sense if several radius lines preexist.

This future Athens metro network is considered in the proposed *New Master-Plan of Athens and Attica Region, 2010–2030* (Hellenic Ministry for the Environment, Physical Planning and Public Works 2009), aiming in this way for efficient metro system development. The final tuning of line alignment and station 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 motorway tolls under the principle of polluter pays, i.e., the polluting cars pay for the green metro.

Conclusions

The objective of this research is a preliminary examination of metro rail network extensiveness versus the city's needs, aiming to assist in 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 to a city's characteristics. A methodology exploiting these macroscopic characteristics in a strategic planning context was developed, and a combination of related indicators is proposed.

The success of a metro system, as of any transit system, is to respond at least adequately to a city's transportation needs. This is not always easy to measure. Ideally, the future development of a successful transit system, especially in a complex urban environment with a variety competitive transportation networks, should be a result in a full-scale transportation planning study based on a four-step transport model. However, it is also essential for any city that long-term targets for the main city transport infrastructure are set early not only for motivating the society and mobilizing 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 modeling process. Furthermore, it can provide a quick estimate on a strategic level for the ultimate metro development required in a city with a nonmature metro network in the very long run and even beyond the 15- or 20-year 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 mode 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 analyzed, 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 the 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 the methodology presented can provide results to serve as a reference point for a more sophisticated planning process. Nonetheless, the 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, efficient, and according to Athens's needs metro system development.

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