Transport Policy 32 (2014) 88–95

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Graph-theoretic evaluation support tool for fixed-route transport development in metropolitan areas

Theodore Tsekeris[a,*], Anastasia-Zoi Souliotou[b]

[a] Centre of Planning and Economic Research (KEPE), Amerikis 11, 10672 Athens, Greece
[b] EDESTA-INREV, Department of Arts and Image Technologies, University of Paris VIII, France

ARTICLE INFO

Available online 1 February 2014

Keywords:
Public transport
Network design
Evaluation
Graph theory
Urban planning

ABSTRACT

This paper presents a graph-theoretic analysis for supporting the evaluation of alternative fixed-route public transport development plans in metropolitan areas. Several indicators grounded on the theory of graphs and network science are suggested and calculated for evaluating prospective developments of the fixed-route transport system in the Athens metropolitan area, which includes the metro, tram and suburban railway. The comparative static analyses of past and scheduled line extensions and planned line constructions generally show the tendency of the system towards small-world networking with scale-free characteristics, which implies increasing scale economies and reliance on a few large transfer stations. The results suggest that policy-makers can choose the option of constructing a semi-circumferential line in the middle (compared to the end) of the system development process, in order to trade investment cost for increased levels of service and robustness.

1. Introduction

Fixed-route public transport systems, particularly subway or metro systems, are widely recognized as a type of transport infrastructure that can sustainably accommodate urban growth needs and address the increasing problems of traffic congestion and environmental degradation. Nonetheless, due to the considerably high cost of constructing, operating and maintaining the specific infrastructure, special attention should be given to the location of passenger stations and their interconnections within the network at different stages of the system development. Traditional approaches in handling these issues rely on (static) optimization procedures, within the framework of transit network design (van Nes, 2002; Guihaire and Hao, 2008) which primarily aims at minimizing travel time and, possibly, some measure of its variance. However, it has been recognized that, in reality, the structure of urban public transport networks is rather counter-intuitive, due to its intrinsic topological characteristics and other factors such as local development patterns, area coverage and operating costs (von Ferber et al., 2009; Roth et al., 2011). In addition, they evolve and organize themselves through usually uncoordinated decisions taking place over time. The proper timing and coordination of investment decisions may considerably enhance the anticipated benefits of public transport development projects into the overall urban economy. Especially, the fixed-route public transport systems are of crucial importance for the resilience (Cox et al., 2011; Zemp et al., 2011) and the scalability (Bornholdt and Schuster, 2002) of urban operations, in the sense that they help cities to 'work on all scales' and (re)build a fractalistic character so as to attain long-term strategic goals.

The use of computational tools and metrics from the graph theory and network science provides a sound methodological framework for investigating the self-organizing features and dynamic properties of fixed-route public transport networks. Such relevant measures as average path length, network diameter and density, clustering coefficient and robustness (see Section 2) are critical for both the sustainable and resilient planning of public transport systems. Their consideration typically corresponds to the final states of systems that have reached a sufficient level of maturity, in terms of the connectivity between stations and lines.

From the methodological point of view, the main purpose of the paper is to demonstrate how a set of simple graph-theoretic measures can be used for the plausible quick-response evaluation of alternative network design options, rather than to suggest a complete framework of a cost-benefit type of analysis. In contrast with other studies in the existing literature (see Section 2), it performs a comparative static analysis to examine the implications of these measures for the continuous planning and on-going evaluation of a large fixed-route public transport system, that of the Greater Area of Athens in Greece. From the policy perspective, the present analysis can offer a decision-support mechanism for prioritizing and scheduling public transport investments according

* Corresponding author. Tel.: +30 210 3676371.
E-mail address: tsek@kepe.gr (T. Tsekeris).

0967-070X/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tranpol.2014.01.005

to a set of policy objectives. A principal question that is addressed here concerns the potential benefits of constructing a semi-circumferential line at the mid-stage of the system development process, compared to the end stage, as has been originally considered in the existing urban master plan.

As far as the organization of the paper is concerned, Section 2 reviews and describes the metrics of the network analysis of fixed-route transport systems, in accordance with the graph theory. Section 3 presents the different (current, scheduled and planned) stages of the development of the fixed-route public transport system in Athens. Section 4 reports and discusses the results of the empirical analysis of the study. Section 5 concludes and provides policy implications of the study findings.

2. Network analysis of fixed-route transport systems

The increasing availability of geosimulation and network analysis software tools has facilitated the development and application of various metrics for measuring connectivity properties and other topological aspects in transport systems. The graph-theoretic analysis of transport networks was originally implemented for highways (Garrison, 1960). During the last two decades, numerous applications are encountered in various other types of transport networks, including large urban arterial street (Jiang and Claramunt, 2004; Porta et al., 2006; Xie and Levinson, 2007), railway (Sen et al., 2003), maritime (Veenstra et al., 2005), airline (Xu and Harriss, 2008; Wang et al., 2011) and express-logistics (Yang et al., 2009) networks. These graph-theoretic studies of large-scale transport systems have contributed to the better understanding of the complex interrelationships of their structural components and their evolution, and have enhanced the processes of planning, designing and operating them.

Especially regarding the metro and other fixed-route public transport networks in large urban areas, graph-theoretic models are capable of parsimoniously representing the main structural and functional properties of such systems. This paper employs a wide range of indices which can depict these properties, including the following:

(i) *Average Degree*, which is defined by the sum of all the degrees divided by the number of nodes (stations) in the network. The total degrees encompass the in-degrees (or row degrees), that is the number of links leading to a station from other stations, and the out-degrees (or column degrees), that is the number of links leading out of a station to other stations.

(ii) *Network Diameter*, that is the longest graph distance between any two nodes in the network; it indicates how far apart the two most distant stations are and, hence, the ease of access from one to the other.

(iii) *Graph Density*, which is defined by the ratio of the existing number of edges (links) to the total number of possible edges, including all possible linkages between stations in the network; it essentially measures how close the network is to completion (where it has all possible edges and the density equals to one).

(iv) *Modularity*, which provides a measure of the decomposability of the network, namely, its ability to be decomposed or partitioned into interconnected groups of nodes (neighboring stations). The community detection algorithm (Blondel et al., 2008) is implemented to calculate the modularity score.

(v) *Average Path Length*, that is the average network distance between all pairs of stations; its calculation relies on the result of a shortest path-finding algorithm.

(vi) *Clustering Coefficient*, C, which is expressed here by the degree of connectivity, $C=E/(3V-6)$, as originally introduced by Kansky (1963), where E denotes the number of edges and V the number of vertices (nodes or stations). The latter measure offers an overall indication of the clustering or level of development of the system, compared to its potential development: more developed transit networks tend to have shorter trip distances, i.e. higher clustering (and higher probability of a future linkage between two unconnected neighbors of a considered node). It is noted that the measure of the clustering coefficient essentially refers to the graph density for planar graphs, in contrast with the general definition of graph density which holds for non-planar graphs and is calculated here for comparison purposes among the different stages of the system development. In fact, the planar graph hypothesis is widely adopted for simplicity purposes from the early studies of the graph-theoretic analysis of transport networks and it provides a sufficient representation of the graph density in metro and rail networks. For this reason, the clustering coefficient is used here to denote the planar property of the fixed-route transport network, demonstrate changes in the network connectivity and capture the small-world properties of the system, in conjunction with the average path length.

(vii) *Robustness Index*, r, which denotes the ability of the system to successfully respond to failures/incidents and continue its operation to serve the demand between stations. Based on Derrible and Kennedy (2010), this index can be expressed as $r=(E-V_d+1-E_m)/V$, where V_d is the number of diatonic stations, including all transfer stations and termini or end-stations, and E_m is the number of diatonic (or multiple) edges, which connect the diatonic stations.

(viii) *Ratio of transfer stations to total number of stations* in the network.

(ix) *Scaling factor* ε, which assigns the scale-free property to the system. In accordance with Barabási and Albert (1999), if we take all stations V of a network and identify those that host one line, two lines and so on, and if the frequency plot decays following a power law, as defined by the relationship $f(\ell)\propto \ell^{-\varepsilon}$, then that network is referred to as scale-free, where the exponent ε is the scaling factor and ℓ is number of lines passing through a station. Such networks have plenty of monotonic stations (hosting only one line) and a few diatonic stations (hosting more than one line), as it usually happens in 'mature' public transport systems. By performing an ordinary least-squares (OLS) regression, the frequency function f takes the form $\ln(f(\ell))=-\varepsilon\ln(\ell)+\ln(\alpha)$, in which the factor ε is the slope and coefficient α is the intercept. The scale-free property can then be identified by such statistical measures as the magnitude of ε (large scale-free networks typically have a factor in the range $2<\varepsilon<3$) and the goodness-of-fit (R^2).

The above measures provide useful insights about different aspects of the conditions of serviceability and cost-effectiveness of a proposed public mass transit design plan. Hence, they can be used to define planning policy priorities and support the evaluation of the development of such a system. In particular, an increased average degree (ratio of total links to stations) and ratio of transfer stations to total stations are typically associated with higher investment cost. However, they relate to higher levels of service and network reliability, since they reflect a larger number of connections between stations and availability of paths between them. Increased graph density and clustering coefficient (connectivity between stations) as well as reduced network diameter and average path length imply a decrease in the travel time of users and improved reliability. The role of modularity on the performance of the system configuration is ambiguous, as it relies on the evenness (or the hierarchy) of nodes. In the case where the degree