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Topological evolution of a metropolitan rail transport network: The case of Stockholm

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ABSTRACT

The structure of transport networks is the outcome of a large number of infrastructure investment decisions taken over a long time span. Network indicators are widely used for characterizing transport network topology and its performance as well as provide insights on possible developments. Little is known however on how rail bound public transport networks and their network indicators have evolved into their current form. This study conducts a longitudinal analysis of the topological evolution of a multimodal rail network by investigating the dynamics of its topology for the case of Stockholm in 1950–2025. The starting year marks the opening of the metro system while the end year is set to mark the completion of the current development plan. Based on a compilation of network topology and service properties, a year-on-year analysis of changes in global network efficiency and directness as well as local nodal centrality were conducted. Changes in network topology exhibit smooth long-term technological and spatial trends as well as the signature of top-down planning interventions. Stockholm rail network evolution is characterized by contraction and stagnation periods followed by network extensions and is currently undergoing a considerable densification, marking a shift from peripheral attachment to preferential attachment.

1. Introduction

Public transport networks constitute an important infrastructure in many metropolitan areas and are often considered critical infrastructure (e.g. Homeland Security, 2010). Public transport networks are developed over a long time span alongside land-use developments. Mass rapid services in the form of urban rail lines started with the introduction of steamed trams in the late 19 century and then rapidly expanded with tram, metro, commuter train and light rail. Investments in urban rail networks are expensive and complicated and are therefore considered strategic and long-term commitments with urban rail lines functioning as a backbone. This study conducts a longitudinal analysis of the topological evolution of a multimodal public transport network by investigating the dynamics of its topology for the case of Stockholm in 1950–2025.

The form and structure of public transport networks has been a subject of considerable research. In the last few years, an increasing number of studies have examined the properties of networks worldwide using network science indicators. Lin and Ban (2013) provide a review of applications of complex network theory in the transport domain. While these studies provide better understanding of the characteristics of public transport networks, there is lack of knowledge on how networks evolve until they arrive at their currently observed state. Knowledge on how public transport networks and their respective indicators have evolved over time can be insightful when considering infrastructure investments and identifying whether future development mark a continuation or break away with respect to topological trends.

The urban rail network is clearly not a ‘self-organizing’ system as its planning, construction and to a lesser extent its operations are subject to centralized decision making. Nevertheless, network extension decisions are often the outcome of interactions between a large number of players that pursue their interests rather than a unified planning process. A diverse set of stakeholders stemming from multiple co-existing political levels and interests, successive planners and policies that their influence changes over time, and, geographical coverage of multiple authorities, all of which have an influence on how the network develops. Investments in new rail sections and stations where a travel demand is expected results from a continuous and long process. The discontinuation of a service or even the removal of tracks can also occur, albeit less common. Therefore, the term *network evolution* is used

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in this study rather than *network growth* but the usage of this term does not imply a bottom-up self-organizing governing principle.

The objective of this study is to quantitatively analyse the evolution of a public transport network over a long period as well as its projected further development by examining changes in its topology. Sun et al. (2015) argue that the lack of longitudinal data hinders understanding and evaluating how network and urban mobility evolve. The lack of research on public transport network evolution arguably stems from the difficulty to obtain data on historical network topologies. Data on historical developments of urban public transport networks is not readily available and data compilation for long time spans pose a significant challenge in performing such an analysis. Network data, including distances and timetables, for each year from 1950 to 2025 was acquired for the purpose of this study for the case study network of the metropolitan rail transport network of greater Stockholm. The main contributions of this study are:

- Revealing the evolution of a multi-modal complex network designed by multiple actors over a long time span (75 years)
- Investigating how network extent, density and directness using network science indicators change over time
- Analysing the relation between changes in network structure, nodal centrality and travel distance and travel time metrics
- Identifying patterns and transition points in network evolution and their relation to planning policies, urban developments and operations

The results of the study provide for the first time to the best of the author knowledge empirical evidence on the evolution of a metropolitan rail network developed over a long time.

The remainder of this paper is organized as follows: The following section reviews the literature on public transport network topology and transport network evolution. Section 3 presents the topological indicators used in analysing the networks. The case study of Stockholm is described in Section 4, followed by the results and discussion in Section 5. Section 6 concludes with the implications of the study findings and directions for further research.

2. Literature review

The structure of transport networks in general, and public transport networks in particular has long been the subject of interest of researchers and planners. While networks could be classified in relation to idealized prototypes such as grid and radial structures, only recently research advances enabled the systematic quantification of network topological properties. This is largely driven by developments in network sciences which provided researchers with a useful toolbox with solid theoretical foundations in graph theory to examine transportation networks as reviewed by Lin and Ban (2013). This section is devoted to reviewing the literature on public transport network topology (2.1) and the evolution of transport networks (2.2).

2.1. Public transport topological analysis

Transport planners use a large variety of metrics to quantify networks in terms of the coverage, accessibility and connectivity that they yield. These metrics are based on principles adopted from graph theory and spatial analysis techniques (see Ducruet and Logo, 2013 for a review of these methodologies). These approaches analyse the performance of a given transport network rather than its underlying topological characteristics and often require detailed representation in Geographical Information Systems software for transportation applications. Another line of research by transport planners and geographers is concerned with creating a taxonomy of public transport network prototypes and analysing their common network structure characteristics (e.g. Vuchic, 2005). While such studies provide insights on the diversity of network structures and discusses descriptively how they grow over time, it does not quantify network characteristics and does not allow for a systematic analysis of their evolution or comparison.

Complex network theory has increasingly emerged as a new scientific paradigm for analysing and designing a wide range of systems including urban metabolisms, information and communication, social relations, as well as transport systems. In the case of the latter, the networks are embedded in a spatial-geographical system and the analysis is therefore typically concerned with a planar graph representation. There is a growing literature which applies complex network theory methods to analyse transport systems including road (Xie and Levinson, 2009), rail (Wang et al., 2009), urban public transport (von Ferber et al., 2009), air (Wang et al., 2011) and maritime (Ducruet, 2017).

The analysis of network topology indicators suggests that different types of network share common features. Two notable network classes are scale-free and small-world networks. A *scale-free* network is characterized by a node degree distribution that follows a power law, implying that there are many nodes with few connections and few nodes with many connections (Barabasi and Albert, 1999). Previous studies assert that there are many man-made and complex natural networks that are scale-free, including road and metro networks (Xie and Levinson, 2007; Derrible and Kennedy, 2011). A blueprint of a *small-world* network, which is neither a random graph nor an orderly planned graph, is a short path length and high clustering (Watts and Strogatz, 1998). While a scale-free structure is prominent for public transport networks when represented in L-space (i.e. nodes correspond to stations and links correspond to a service connecting consecutive stations), small-world has not been often observed when using the P-space representation (i.e. nodes correspond to stations and links correspond to the existence of at least one common line) (von Ferber et al., 2009; Sienkiewicz and Holyst, 2005; Lee et al., 2008).

Several studies analysed and compared the network topology of metro and urban rail systems across the world. von Ferber et al. (2009) describe different ways to represent a public transport network. Comparisons of indicators for networks worldwide were performed by Derrible and Kennedy (2010) and Zhang et al. (2013) for 32 metro and 30 urban-rail networks, respectively. The former proposed metrics for classifying networks based on their state, form and structure.

In the context of public transport, topological indicators have been most extensively used for analysing network vulnerability in case of link or node failure and for the identification of critical links. This research topic was investigated for 17 prototype network structures (Zhang et al., 2015), the world largest metro systems (Angeloudis and Fisk, 2006), 32 metro systems worldwide (Derrible and Kennedy, 2010), London and Paris (von Ferber et al., 2012), Nanjing (Deng et al., 2013) and Madrid (Rodriguez-Nunez and Garcia-Palomares, 2014). The results demonstrate that public transport networks vary in their capacity to absorb random and targeted attacks. The availability of cyclic paths which allow to perform detours and bypass a disrupted area in case needed contributes to network robustness. Cats (2016) enriched the topological analysis with travel demand distribution to evaluate the impacts of network extension plans on its robustness.

While network science is increasingly applied to the transport, and in particular public transport domain, many of these applications are performed without considering key network features. Dupuy (2013) asserts that by neglecting such features and the urban planning context, studies performed by scientists from other disciplines in the field of network geometry and urban railway systems provide very limited recommendations to network planners and thus obstruct potential implementations. Remarkably, only few studies have included information on travel impedance (e.g. distance or time), representing the public transport network as an unweighted graph. The analysis of topological indicators for non-weighted graphs is then based on counting links, questioning the value of often reported indicators such as network diameter (longest shortest path), average shortest path, node closeness

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