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Topological Evolution of a Metropolitan Rail Transport Network: The Case of Stockholm

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Highlights:

- Longitudinal analysis of the evolution of multi-modal metropolitan network topology
- Revealing the evolution of Stockholm's rail infrastructure network in 1950-2025
- Investigating the development of network structure, density and impedance
- Same connectivity and accessibility in 2025 as in 1950 but for a greater area
- Identifying patterns and transition points in network evolution and their drivers

Keywords: Public Transport; Network Evolution; Topology; Rail; Infrastructure; Investments

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. In this study I conduct 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 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 Lugo 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 and betweenness centrality. Assigning link labels is essential for measuring the intended network coverage, node efficiency, location accessibility and interchanging flows, respectively.

2.2 Transport network evolution

The process in which networks evolve over time is an important aspect in the growing interest in network science. Nevertheless, most studies have focused on the topological analysis of networks in their current state. As stressed by Dupuy (2013), graph theory-based studies resulted with a static representation of the network, hindering the analysis of network development process. In their review of how network science has been integrated into the work of spatial scientists, Ducruet and Beauguitte (2014) concluded that research concerning the evolution and dynamics of networks using network science concepts and methods has remained surprisingly unexplored as most studies adopting a static approach. In line with Dupuy's arguments, some the of studies that have taken a dynamic perspective to network topology were performed by scientists from disciplines other than transport, in particular from physics and computer sciences, as reflected by the neglect of spatial elements in the analysis and interpretation.

In the absence of empirical data, several studies have simulated how transport networks may have evolved by specifying principles that may govern their development. Ash and Newth (2007) modelled the evolution of a simple grid network with links being added or removed in an iterative manner with network robustness measured in terms of average efficiency as the objective function. Xie and Levinson (2008) proposed an agent-based approach for simulating how road networks may develop if in each iteration roads that are not used as much were to be abandoned whereas heavily used roads would have been upgraded. Model results show that some networks had similar characteristics even though they have developed from very different initial types of networks. This was taken as an indication that transport networks possess robust properties that can emerge from the interplay between many different actors. While this approach may be useful for analysing the outcomes of alternative strategies, it lacks empirical underpinning and assumes a highly systematic and consistent network design approach.

Longitudinal infrastructure data is increasingly made available for road and heavy rail networks. This has led to a stream of empirical research in recent years into the development of these networks. The findings of these studies suggest that developments range from self-organizing patterns to a top-down planning signature, with most networks exhibiting a combination of the two. Both Strano et al. (2012) and Mohajeri and Gudmundsson (2014) identified two underlying mechanisms governing street network growth: expansion and densification. Strano et al. suggest that these are two development phases: an exploration phase where branches are built into areas previously not served by roads followed by a densification phase where the network became denser through the addition of links between already existing branches. Interestingly, the most important roads as measured by node betweenness centrality maintained their importance throughout the 200 years analysis period. Conversely, Barthélemy et al. (2013) in their analysis of how the street network of Paris evolved over more than 200 years observed a self-organized smooth growth and densification was penetrated by large-scale top-down planning. A similar pattern was found by Thevenin et al. (2016) in their analysis of the evolution of the French railway network over a century and also resonates with the findings of Erath et al. (2009) concerning the development of the Swiss road network between 1950-2005 where a period of systematic growth is followed by a stagnation. Top-down planning was found particularly important in the investigation of the changes in accessibility offered by the Chinese railway network by Wang et al. (2009) during the 20th century. They stress the strong political influence and the importance of central governmental policies in network development and its impacts on changes in accessibility and the generation of economic centres.

Research into the evolution of airline and shipping networks is facilitated by the recent availability of open data concerning their line operations. These highly dynamic networks are characterized by point-to-point line-based networks that develop at a continental or global scale and operate in a highly competitive setting. Airline traffic is highly market-driven and exercises strong fluctuations in response to changes in demand patterns as shown by Lin and Ban (2014) and Wang et al. (2014) for the air transport networks of the US in 1990-2010 and China in 1930-2012, respectively. Ducruet (2017) concludes from analyzing the dynamics of multi-layer maritime global flows that their evolution is highly path-dependent with the reinformcement of major hubs. The reinforcement of existing hubs - a growth pattern that tends to connect new nodes to nodes that already well-connected (also known as 'the rich getting richer' phenomenon) - will give rise to a scale-free network.

Few studies have discussed the development of metropolitan public transport systems using a network science approach. Based on a static analysis of three bus networks in China, Yang et al. (2014) concluded from the node degree distribution that network topology evolved through random network extensions, although the evolution of these network has not been directly investigated. Metro networks were found to share some common topological properties even when considering networks that have been constructed at different times and by different governmental structures. Derrible (2012) examined trends in how betweenness centrality changes in metro networks as a function of their size in terms of number of nodes (stations). He observed an exponentially increasing trend with larger networks having a much more distributed betweenness centrality suggesting a process of democratization where central nodes in larger networks obtain a smaller share of the total betweenness centrality compared to those in smaller network. This analysis did not however take travel times into account. The only study that to the best of the author's knowledge investigated the evolution of public transport network structure was conducted by Roth et al (2012) who investigated how fourteen metro networks around the world have developed over time. They observed that metro networks develop into a shape with a denser core surrounded by a circular line and branches extending from the core to suburbs, often through fork stations. The analysis by Roth et al. considered the unweighted graph, though discarding network distances or travel times and were therefore restricted to configurational metrics. An analysis limited to nodal accessibility was performed by Chen et al. (2014) who examined the rapid development of Guangzhou metro network in 1999-2011.

Complex network theory applications to public transport have resulted with a growing knowledge of the topological properties of public transport networks. Several studies have also modelled how public transport network may evolve over time based on certain growth principles. However, there is lack of knowledge on how public transport networks evolve in a context where investments in surface transport infrastructure span over long periods of time. This arguably stems from the difficulty of obtaining and compiling longitudinal data, partially attributed to corresponding organisational and technological changes. This study aims to extend the knowledge on how public transport topology evolves over time by empirically investigating the dynamics of the indicators presented in the following section.

3. Network topology indicators

L-space is used for representing the public transport network in this study. This graph representation is adopted in this study because it allows focusing on the availability of physical tracks which represent a long-term investment in infrastructure. Hence, the physical network infrastructure is defined by a directed graph $G(S,E)$, where the node set S represents rail stations, and the link (edge) set $E \subseteq S \times S$ represents rail segments connecting a pair of stations. The graph could be described as a $S \times S$ adjacency matrix, A, where each entry A_{ij} equals 1 if i and j are connected with a link and equals 0 if there is no direct connection. Each link $e \in E$ is a service-segment that may be operated by one or several public transport lines and induces a certain travel impedance. Link labels may correspond to link length, in-vehicle travel time or a generalized travel cost function for the respective link. Let $l_{e_{ij}}$ and $t_{e_{ij}}$ denote respectively the length (distance) and travel time associated with link e_{ij} which connects stations i and j $(i, j \in S)$.

In the following, the network indicators used for investigating network states and evolution are defined. Global network indicators are used to characterise network structure whereas local network indicators quantify the centrality of network elements. For a comprehensive review of spatial network indicators, the reader is referred to Barthélemy (2010).

3.1 Global network structure indicators

The number of stations and links is denoted by the cardinality of the node and link sets, $|S|$ and $|E|$, respectively. The *total network length* of all rail segments is

$$l = \sum_{e \in E} l_e \quad (1)$$

In addition, network size can be assessed by measuring its *diameter*:

$$d = \max_{i,j \in S} d_{ij} \quad (2)$$

Where $d_{i,j}$ is the distance shortest path between nodes i and j. The diameter measures the extent of the graph in terms of the maximum topological length (i.e. rail segment-km) between any pair of nodes (i.e. stations). The shortest path in terms of the number of sections (all link labels equal one), network distance or travel time can be found for each pair of nodes using for example the Dijkstra algorithm.

Several network indicators can be used to describe network density and connectivity. A simple and commonly-used measure of *network connectivity*, the gamma index, is defined as the ratio between the number of links and the maximum number of links in a complete planar graph:

$$\gamma = \frac{|E|}{3(|S|-2)} \quad (3)$$

The gamma index equals 1 in the case of a complete graph. In the context of rail networks it can be interpreted as the likelihood that a pair of stations has a direct rail segment connecting them. A more connected network offers a greater number of alternative routes between any pairs of stations. Similarly, the alpha index is an indicator of *network meshedness* and ranges between 0 for a tree and 1 for a complete graph. It is defined as the ratio between the number of elementary cyclic and the maximum number of cycles in a graph:

$$\alpha = \frac{|E|-|S|+1}{2|S|-5} \quad (4)$$

The alpha corresponds to the probability that it is possible to travel from any station back to the same station without traversing the same (bi-directional) rail segment twice. This is an indicator of network robustness as it provides information on network redundancy in case of a link closure.

As a planar spatial network, an important feature of a public transport network is its directness. The directness of each connection is defined as the average discrepancy ratio between network distance (measured in rail segment-km) and the geographical distance, or in other words the percentage-wise detour that the network structure induces. Overall *network directness* is measured as the average ratio calculated over all origin-destination (station) pairs

$$q = \frac{\sum_{i \in S} \sum_{i \neq j \in S} l_{ij}}{|S|(|S|-1) \sum_{i \in S} \sum_{i \neq j \in S} \hat{l}_{ij}} \quad (5)$$

Where $\hat{l}_{ij}$ is the geodesic distance between nodes i and j. The higher node directness is, the greater the travel impedance compared with the hypothetical shortest path.

3.2 Local centrality indicators

In addition to measures that are computed at the network level, indicators defined at the node level allow investigating the spatial variation of topological properties among stations. Moreover, local indicators can facilitate the investigation of global network characteristics by comparing statistics of their distributions across networks.

Three measures of stations centrality are considered in this study to capture the extent of direct connections to other stations, accessibility to all other stations and its role in connecting pairs of stations across the network. The simplest node centrality indicator is *node degree* which is simply the number of stations directly connected to each station

$$k_i = \sum_{j \in S} A_{ij} \quad \forall i \in S \tag{6}$$

The node degree corresponds thus to the number of incoming/outgoing rail segments per station.

While node degree measures the number of direct neighbours, it does not provide information on how close or far the station is from all other stations in the network. *Node closeness* centrality is defined based on the shortest paths from a certain node to all other nodes in the network

$$c_i = \sum_{i \neq j \in S} \frac{1}{d_{i,j}} \quad \forall i \in S \tag{7}$$

This definition implies that station closeness centrality increases for lower travel impedances to other stations in the network and hence reflects the accessibility of each station from all other stations. The average node closeness is commonly used to quantify *network efficiency* since it reflects the average number of stations that are passed when travelling between any pair of stations.

The importance of a station could also be considered in terms of its role in connecting other stations. For example, a peripheral station that is poorly connected locally (i.e. low node degree and closeness) may constitute a bridge between two sub-networks. The latter is especially important in the context of multi-modal metropolitan rail networks where a station may serve as a terminal hub connecting services with distinguished operations and hierarchy (e.g. commuter train and trams). This is measured by *node betweenness* centrality which is defined as the share of shortest paths that traverse through a certain station

$$b_i = \sum_{j \neq k \in S} \frac{n_{j,k}(i)}{n_{j,k}} \quad \forall i \in S \tag{8}$$

Where $n_{j,k}(i)$ is the number of shortest paths between stations j and k that traverse through station i and $n_{j,k}$ is the total number of shortest paths found between these pair of stations. This definition of node betweenness centrality is inherently dependent on the number of nodes. To facilitate the analysis of changes in station relative importance, a standardized indicator is defined by dividing Eq. 8 by the sum of node centrality for all stations:

$$\widetilde{b_i} = \frac{b_i}{\sum_{i \in S} b_i} \quad \forall i \in S \tag{9}$$

The standardized betweenness centrality corresponds thus to the percentage of network shortest paths that traverse through a certain station. The standardized centrality indicator allow comparing the betweenness centrality distribution for different networks.

4. The Case of Stockholm metropolitan rail network

4.1 Study area

The evolution of the metropolitan rail transport network (MRTN) was investigated for the case of Stockholm, Sweden. Only rail-bound services were considered in this analysis because they require substantial long-term investments and therefore become an integral part of the metropolitan infrastructure over long periods of network lifetime. Furthermore, our interest lies in mass public transport services and road-bound services only seldom constitute part of the high-capacity public transport. In the following, important milestones in the development of Stockholm MRTN, as well as future developments, are described to set the analysis in the next section in context.

In the late 19th century and early 20th century, Stockholm gradually grew beyond the old town islands to encompass neighbouring islands. This process was facilitated by a steadily growth of the tram network that connected city districts and nearby suburbs. In 1950, when the first metro line was inaugurated, Stockholm had a large network of 21 tram line serving 212 stations, covering the area now known as the inner-city. A set of detached train lines connected Stockholm and neighbouring towns, and the metro system was gradually expanded to nearby suburbs. The 60's marked an important shift in Stockholm's urban and transport planning. Similarly to many European cities, the tram network was subject to a degradation in the post war decades and was gradually replaced by buses and metro. In 1967, all the remaining inner-city tram lines were closed down as Sweden changed from left-hand to right-hand traffic. The *Miljonprogrammet*, a national program for public housing which was realized between 1965 and 1974, transformed Stockholm into a metropolitan area with the metro system as its backbone. Cervero (1995) describes the importance of the metro in Stockholm's transition from being a monocentric city into being a multi-centred metropolis in the late 20th century. The transition was aided by building an extensive rail network with different branches connecting new satellite towns to Stockholm city centre. However, a recent spatial analysis based on passenger flows suggests that a polycentric or even multi-centric urban structure has not yet emerged in Stockholm (Cats et al. 2015).

The inseparable urban and transport planning in Stockholm is a prime example of a radial public transport system which is primarily oriented towards regional accessibility rather than providing local coverage. In addition, the commuter train services provide faster connection to the outer-suburbs and in recent years also cities in nearby counties, facilitating the further integration of the Mälaren lake region. However, the current regional planning guidelines promote a more polycentric structure (Stockholm City 2011). Future developments of the MRTN which were approved in 2013 are designed to support a stronger network of strategic nodes. The investment plan includes the extension of the cross-radial light rail train (Cats and Jenelius 2015), several extensions of the metro system and a cross-town tram line. In 2017 Stockholm City Line project will become operational, increasing the capacity of the commuter and regional train system.

4.2 Implementation

Stockholm MRTN was analysed for each year between 1950 and 2025. The starting year marks the opening of the metro system while the end year is set to mark the completion of the current mass transit expansion plan. The network consists of tram, light rail train, metro, express high-speed connections and local, commuter and regional trains. Only lines that operated with at least 23 departures per day per direction (which typically implies 3 departures per direction in the peak hour) were included in the analysis for each of the years. Network data, including all operating stations and lines, track lengths and service timetables were acquired from professional literature, technical reports and databases, development programs, rail history books, museums and archives including the Royal Library, Stockholm City Museum, Stockholm Transport Museum and Stockholm Railway Association, among others (for more details see Appendix). Data collection involved compiling network configurations including the exact location of stations, service lines, distances and scheduled travel times between stations and service frequencies. Year on year changes in either network or operations were carefully noted.

For each year, the list of MRTN lines that satisfy the frequency criterion, stations and scheduled travel time between consecutive stations were recorded and mapped. Remarkably, network topology has changed in 52 out of the 75 years considered. Undirected L-space graphs were coded in Gephi, a free network visualization and analysis tool. Network indicators that involve the calculation of link labels (i.e. diameter, betweenness and closeness centrality, directness) were computed in MATLAB and then imported and visualized in Gephi. Coordinates of existing and future stations were available from Stockholm County Traffic Administration (SLL), whereas coordinates of stations that closed down were approximated based on their locations in the respective maps.

5. Results and Discussion

Based on the analysis of network indicators, phases in the development of the case study network are identified (Section 5.1). Network structure and its evolution in terms of its global coverage, connectivity, efficiency and directness are then analysed (5.2). Trends in local centrality indicators and their underlying causes are then discussed (5.3). Finally, the co-evolution of several key indicators is investigated (5.4).

5.1 Three periods in the evolution of the network

Based on the evolution of three indicators of Stockholm MRTN size (Figure 1), three distinctive periods with pronounced transition points can be identified:

(a) *Contraction*, 1950-1967: The number of stations and links contracted gradually between 1950-1966 where each year saw on average the closure of one tram line and then fell dramatically in 1967 when the remaining tram lines were dismantled. The latter happened in conjunction with the shift into right-side driving which marked the end of the compact street-level rail network in the inner-city. Notwithstanding, the simultaneous construction of metro lines counteracted these closures resulting with a slight increase in total network length.

(b) *Stagnation*, 1968-1998: Three decades of relative stagnation with incremental extensions of existing lines. This period starts after the completion of the large-scale urban and transport development of suburbs built around stations along radial metro corridors. Already in 1978 the metro lines have almost reached their current form, extending well-beyond the inner-city. Total network length increased by less than 2.5% between 1978-1998.

(c) *Growth*, 1999-2025: A period of substantial and consistent growth. This period is characterized by a shift in urban and transport policy with a focus on: (1) regional integration, and (2) increased capacity and connections in the core of the network. While these two trends may seem contradictory at first, the analysis below demonstrates that they are pursued simultaneously. The development of long commuter and regional services culminated in 1999-2003 resulting in an rapid increase in network length. The opening of new light rail line in the 2000's and future metro extension plans lead to a growing number of stations and rail links in the core of the network contributing to a modest increase in network length.

It is thus evident that Stockholm MRTN manifests a complex non-monotonous growth pattern, demonstrating some abrupt changes as well as periods of incremental growth. The average number of new links per year increased steadily from 1.22 in the period 1967-1985 to 1.53 in 1986-1998, 2.2 in 1999-2009 and set to increase to 2.6 in the period of 2010-2025. Moreover, while the number of nodes and links follows an overall similar trend of contraction, stagnation and growth, the total network length follows a generally increasing trend with long periods of incremental increases and a short period of a rapid growth. Remarkably, the number of nodes and links in 2025 will still fall short by 12% and 8% of the respective values in 1950, while network length and the population of Stockholm metropolitan area increase to 213% and 267%, respectively, of their 1950 values. This reflects the shift from a dense inner-city tram network to a metropolitan mass transit system with larger station spacing. It is thus important to analyse the trends in the context of the underlying transition from low-capacity rail services characterized by short distances between stations and lower speeds (i.e. city trams operating in mixed traffic) to high-capacity rail-bound services that operate with longer distances between stations with higher speeds (i.e. underground and commuter trains).

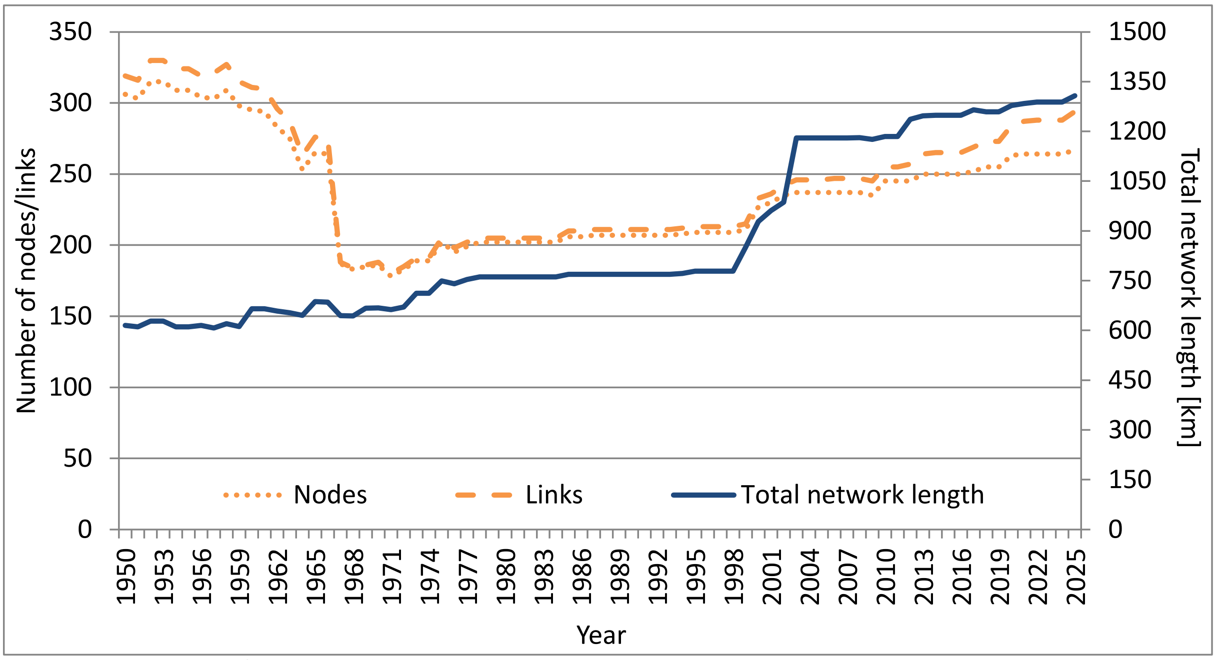


Figure 1: Numbers of nodes and links and total network length per year

5.2 Network structure

Table 1 provides a summary of network indicators for six selected years that mark important milestones in Stockholm MRTN development. Alongside the population in the case study area and in addition to the number of nodes, links and network length, columns 6-10 present the network-level indicators: diameter, average path length, connectivity, meshedness, and directness.

Stockholm MRTN growth stems from a combination of increased network coverage, i.e. extending its reach, and increased network density, by connecting already existing stations. Growing geographical coverage was the main driver of network growth until the 2000's. Even though the diameter is determined by the extreme value of the path length distribution, its development is in line with that of other indicators of network size until 2010. The diameter of the Stockholm MRTN decreased slightly between 1950 and 1967 as the tramways that extended to nearby suburbs were closed down while the metro had covered a smaller area until the 1990's. Since the mid-1990's, network diameter was determined by commuter and regional trains which increased the reach of the MRTN from approximately 100km to 150km, extending beyond the boundaries of Stockholm county into neighbouring counties to the north, north west and south west of Stockholm. However, the diameter slightly decreased in 2025 due to the closure of one of the regional train terminals and with investments focused on central parts of the network.

Network growth in 2010-2025 stems from a rapid construction of new links (Figure 1) that densify the network rather than extend it. The densification of the core is driven by a combination of planning policies: (1) intensifying sub-centres and strengthening their inter-connections (Cats et al. 2015); (2) increasing the capacity and relieving congestion of main axes by adding parallel corridors and bypass alternatives (Cats et al. 2016, Jenelius and Cats 2015); (3) improving network robustness by adding redundancy and thus rerouting possibilities (Cats 2016). The average path length which had consistently increased until 2010, decreases as a result of the current expansion plan. In other words, network efficiency improves as new travel alternatives offer shorter connections. The sharp increase in average path length in 1967 stems from the closure of many tram stations which exercised shorter stop spacing compared with other rail-bound modes. This reflects thus a change in the composition of the multi-modal mix of Stockholm MRTN, shifting towards longer spacing modes such as metro and commuter train.

Network connectivity has followed a U-shaped development in the period between 1950-2025 as indicated by both gamma (Eq. 3) and alpha (Eq. 4) indicators. The compact dense network of the 1950s fragmented to the minimum values of 0.339 and 0.0054 in 1967 for the gamma and alpha indicators, respectively, indicating that the network included about one third of all possible links and half a percent of all possible cycles. Network connectivity and meshedness increased gradually between the years 1968-2000 and then increased substantially in the following decade and finally reached the 1950 level in 2010. An accelerated growth in network connectivity is projected in the years leading to 2025, reflecting a densification of the network and the construction of cross-radial (suburb to suburb) connections. In 2025 Stockholm MRTN will offer the same connectivity as in 1950 but for a much greater service area. Network meshedness will be in 2025 more than twice as high as in 2010 and ten times higher than in 1967, suggesting a significant improvement in network robustness thanks to increased redundancy in case of disruptions (Jenelius and Cats 2015).

Table 1: Summary of network indicators for selected years

Year	Pop. [millions]	No. nodes $\|S\|$	No. Links $\|E\|$	Network length [km] l	Diameter [km] d	Average path length [km]	Connect-ivity γ	Meshed-ness α	Directness q
1950	0.952	306	319	614.9	97.35	1.928	0.350	0.0231	1.311
1967	1.427	187	188	644.6	93.81	3.429	0.339	0.0054	1.426
1985	1.578	206	210	769.6	93.95	3.665	0.343	0.0123	1.402
2000	1.823	227	233	928.0	119.98	3.983	0.345	0.0156	1.373
2010	2.054	245	255	1184.2	156.72	4.644	0.350	0.0227	1.338
2025	2.368	267	294	1307.3	153.92	4.447	0.370	0.0529	1.312

The average network directness (Eq. 5) follows an inverted U-shape development with the detour rate yielding the maximal value in 1967 with the average path length being 42.6% longer than the geodesic distance (Table 1). This large path discrepancy is attributed to the dominance of local train services in Stockholm archipelago landscape in 1967 and their reliance on few bridges that often require detours. Directness improved gradually between 1967-1999 and then more rapidly in 2000-2025, yielding after 75 years approximately the same level of directness that was offered in 1950. This pattern is evident in Figure 2 where the cumulative density functions of the directness indicators for each year from 1950 to 2025 is plotted. The median path detour ratio increased from 1.35 in 1950 to 1.47 in 1968, decreased gradually due to relatively direct commuter and regional train services and will get back to 1.35 by 2025 thanks to the availability of cross-radial connections that enable travellers to bypass the city centre which was almost inevitable in the radial MRTN structure.

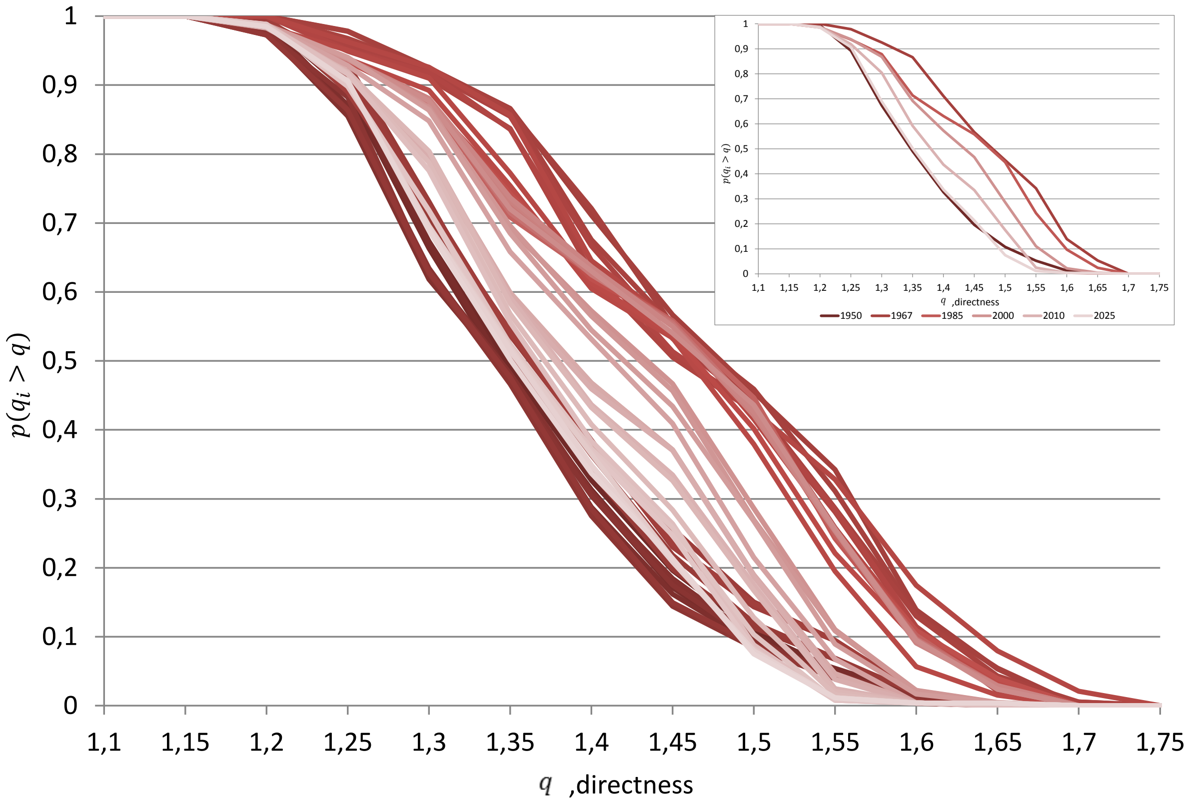


Figure 2: The evolution of the distribution of directness –each curve corresponds to the cumulative distribution of one year, progressing from the darkest curve (1950) to the lightest curve (2025) (for selected years in the inset)

5.3 Evolution in node centrality measures

The investigation of station centrality measures enables the analysis of station importance and role in the greater network for a given year and how they evolve over the study period. Changes in the statistical properties of the distributions of node centrality indicators are first discussed followed by a discussion of the patterns of their spatial distribution.

The three periods identified in Section 5.1 are also visible in the evolution of node degree. Figure 3 depicts the average and coefficient of variation (CV) of the node degree for 1950-2025. The average value decreases from about 2.1 direct neighbours for each node to almost 2.01 and then increased gradually to 2.05 in 2000 to then rapidly bounce back to an average value of 2.2 in 2025. The vast majority of the nodes having a degree of two (consecutive stations along the same line) and few nodes having many connections (transfer hubs) or only one (terminals). This pattern emerges from a preferential attachment scheme with only 1% of the stations having a degree of six or higher. This finding is in line with previous studies that examined L-space of public transport networks (Lin and Ban 2013). As reflected in the increase of CV from 0.3 to 0.45, the node degree distribution becomes more skewed due to the increase in number and diversity of transfer hubs, with second- and third-tier interchanges emerging in the boundaries of Stockholm inner-city (2000's) and nearby suburbs (2010's). The pronounced radial network dominated by the metro network with a single station that allows transferring between all metro and commuter train lines has evolved into a meshed centre with a ring of hubs beyond which rail lines fork (see Figure 5).

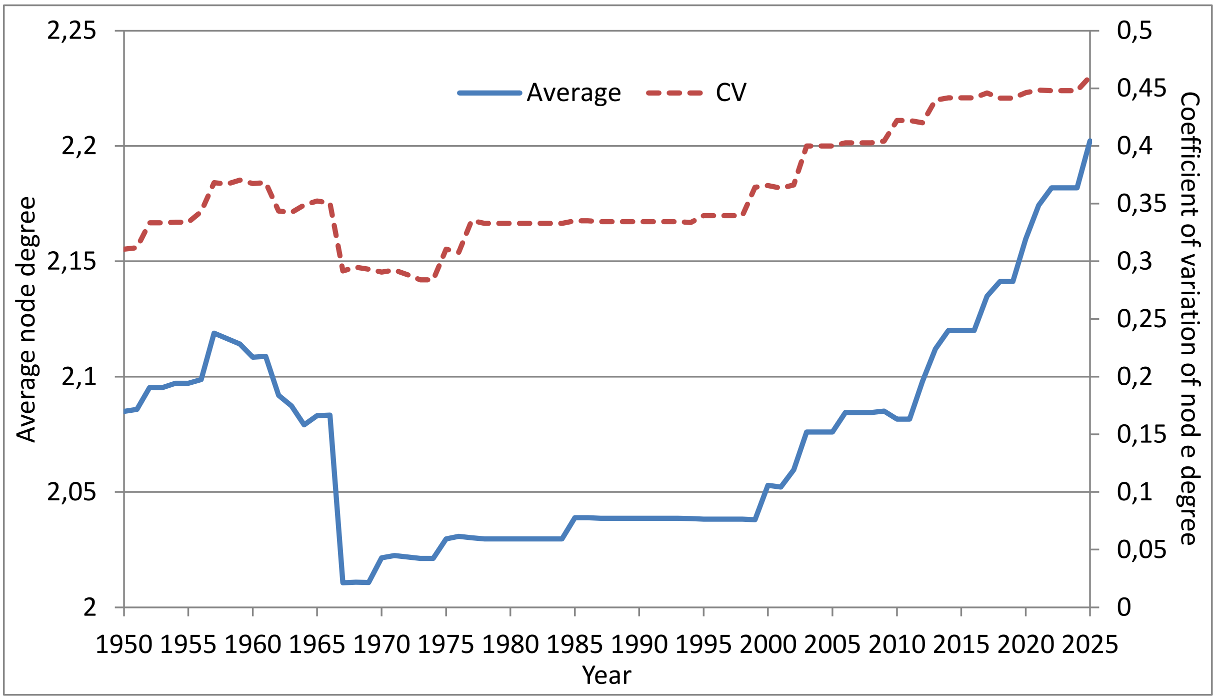


Figure 3: Average and coefficient of variation of node degree per year

The evolution of average node closeness centrality in terms of distance and travel time manifests a distinctively different pattern than node degree. The signature of the three development period is evident in Figure 4 where average closeness centrality is shown for both distance and travel time. While global closeness is often considered an indicator of network transmission efficiency, this analysis highlights the sensitivity of the results to the selected impedance factor. Both closeness centrality indicators yielded the maximum value in the mid-1950s and then fell drastically in 1967. The compact and dense tram network resulted with closely connected nodes in terms of both distance and travel time and its degradation meant longer paths between the remaining stations. The expansion of the metro led to a further decrease (1968-1978) in average distance closeness because new stations were situated further away from the network core, increasing the average path distance. In contrast, travel time closeness increased because the metro offers significantly higher speeds and new travel alternatives leading to a reduction in the average path travel time. This transport planning policy catered for improving regional accessibility in conjunction with the construction of satellite towns.

The distance closeness further decreased in the 2000's due to the integration of regional services into the MRTN and then bounces back from 2010 onwards due to the densification of the network core with new centrally positioned stations and cross-radial connections that cut down travel distances as well as travel times, improving accessibility in the case study area. This trend will result with a travel time closeness centrality in 2025 (0.032) that is approaching the average value in 1950 (0.034). This is remarkable as the distance covered by the network is much greater (see network diameter and a 43% decrease in distance closeness centrality - reflecting that the average distance between a pair of nodes has almost doubled) but the greater travel speeds provided by primarily metro and commuter trains will achieve a similar travel time closeness to the one that existed in the much smaller urban area of 1950 which was served by trams. This demonstrates the improved accessibility and enlarged labour market enabled by the development of the MRTN.

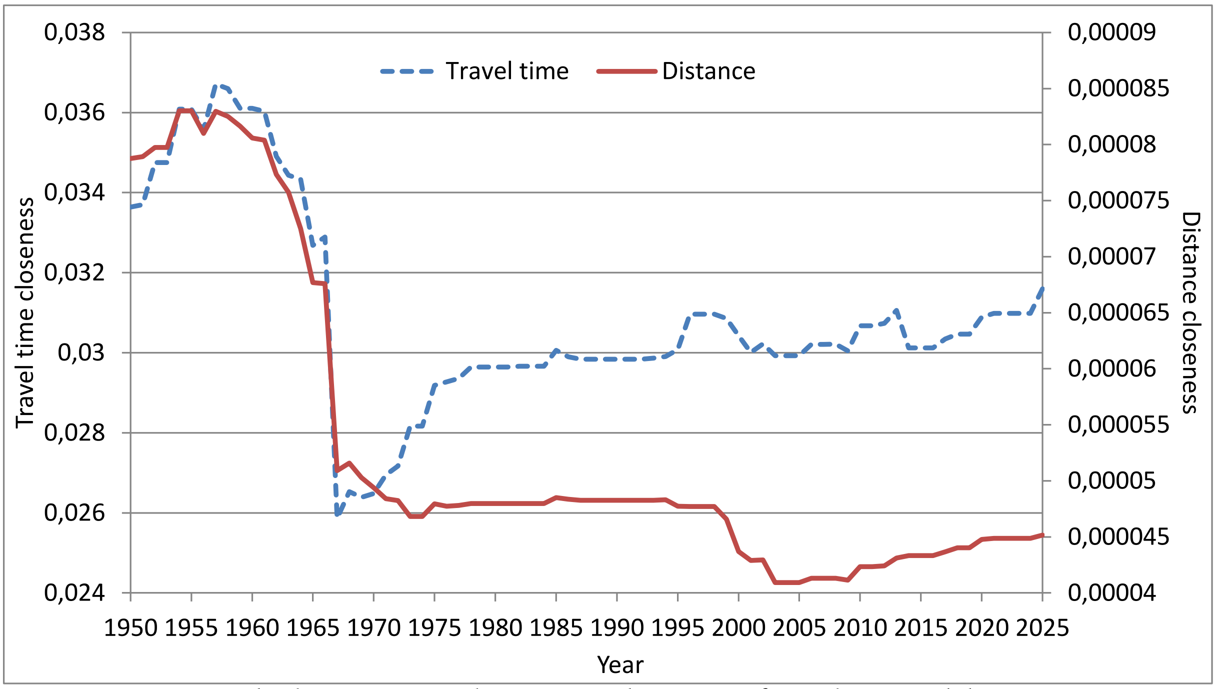
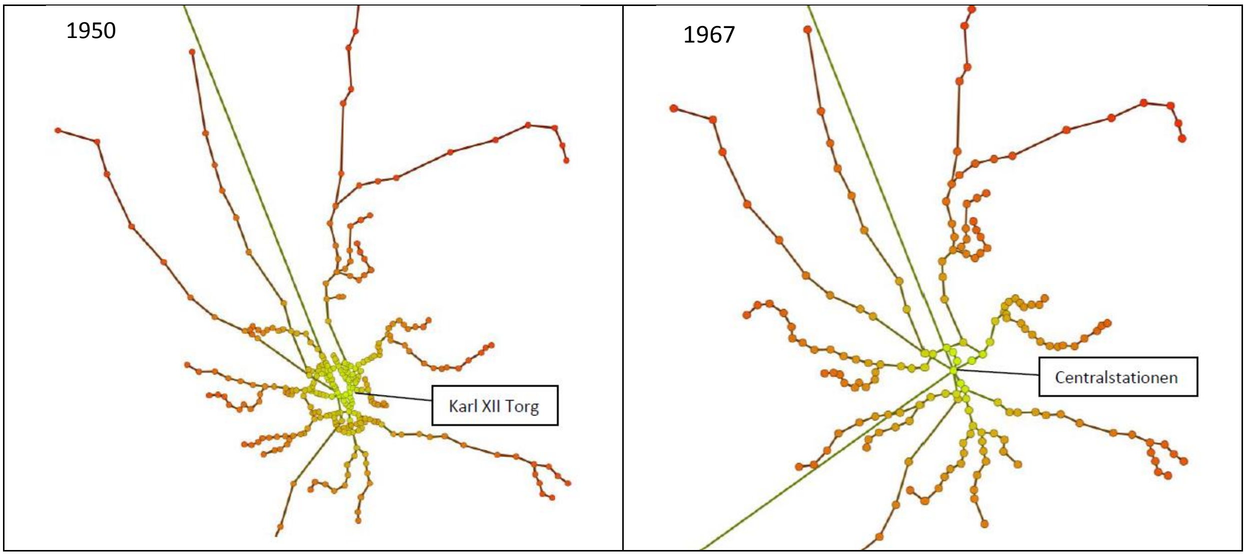


Figure 4: Average node closeness centrality measured in terms of travel time and distance per year

The spatial variation of accessibility, as measured in terms of travel time node closeness centrality, is illustrated for the selected years in Figure 5. There are pronounced and persistent differences between network core and branches. In line with the findings based on the analysis of passenger flows in Stockholm by Cats et al. (2015), the MRTN reflects as well as facilitates a growing and denser network core connecting centres of activities. The on-going networks extensions will result with a significant improvement in accessibility, especially in the southern part of the network core and north-west of the network core, which was also found to contribute to the capability of the case study network to withstand link breakdowns (Cats 2016). These developments constitute strategic and costly investments as they entail constructing tunnels and bridges to connect islands and land on different shores of the sea and lake as well as constructing over- and underground tracks in densely built-up areas.



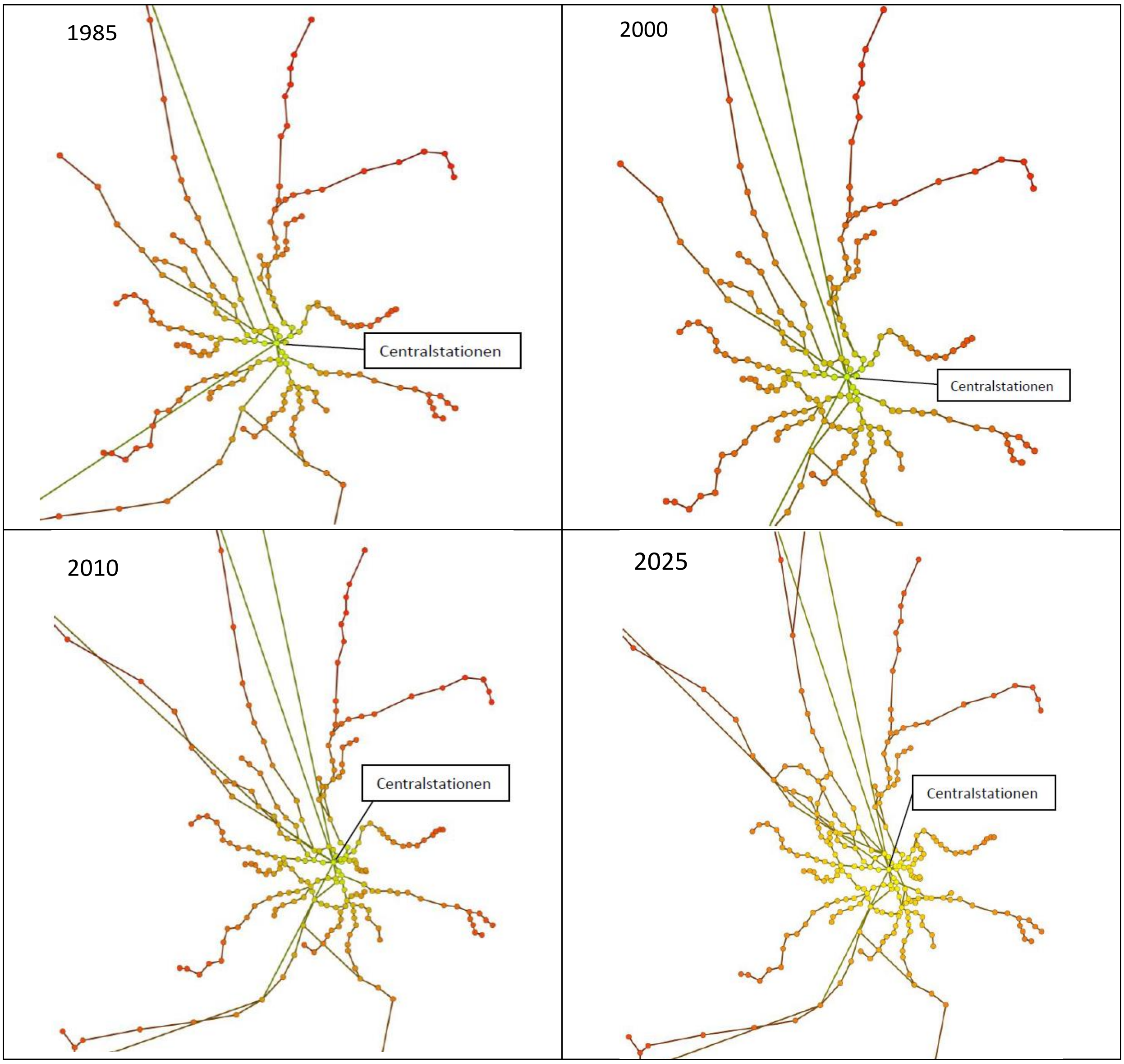


Figure 5: Travel time closeness centrality maps for selected years, main part of the network, 1cm = 8km (lighter colours indicating higher closeness centrality values, the station with the highest closeness centrality is highlighted)

The Stockholm MRTN is becoming increasingly dependent on few stations. Figure 6 presents the distribution of the standardized betweenness node centrality (Eq. 9) for 1950-2025 in its cumulative form. It shows the distribution of relative station importance in connecting origin-destination pairs across the network when searching for the paths that yield the shortest travel time. While the overall shape of the distribution remains stable over the analysis period, the distribution becomes in the first several decades more egalitarian and thereafter reverses into a more oligarchic form, even if having few more oligarchs. This implies that passenger flow distribution can be expected to be extremely uneven. This finding is in disagreement with Derrible (2012) who concluded from the topological analysis of 28 worldwide metro networks that betweenness centrality is more evenly distributed for larger networks while neglecting travel times (i.e shortest path was calculated in terms of number of intermediate hubs) in his analysis. For example, the share of nodes that are situated on the shortest paths connecting more than 1% of all origin-destination pairs each in the case study network increased from 7.5% in 1950 to 21% in 1971 and then decreases to 11% in 2025. These shifts suggest that the network was heavily dependent on a small number of nodes in the 1950s for transmitting travel flows, followed by a more distributed structure that was then gradually almost reversed back to earlier centralization levels, albeit for a larger network. Due to the relation between betweenness centrality and flow distribution, this can have ramifications for hub saturation levels and passenger and pedestrian congestion.

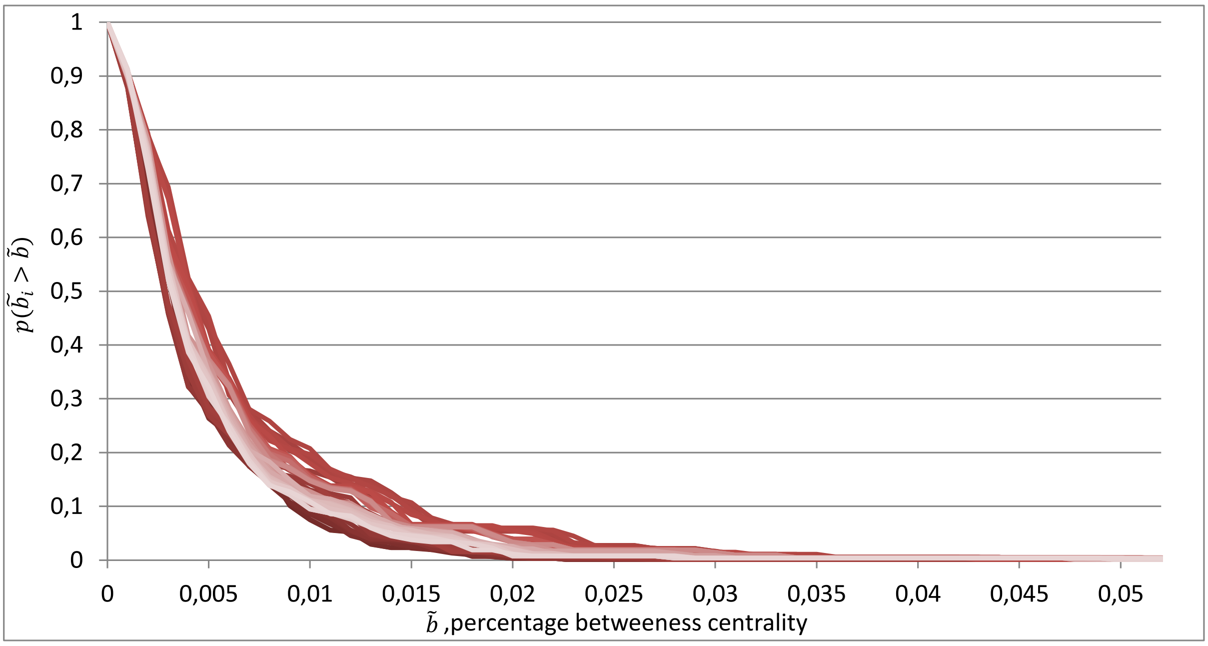


Figure 6: The evolution of the distribution of standardized betweenness centrality – each curve corresponds to the cumulative distribution of one year, progressing from the darkest curve (1950) to the lightest curve (2025)

The most central stations as measured by node centrality indicators change considerably during the analysis period. The most central stations as measured in terms of their node degree change considerably over the years because of the local nature of this indicator which can change more rapidly in response to limited interventions. For example, only one of the top five stations in 1950, (i.e. *Centralstationen*) retains its position in the top five in 2025. In contrast, betweenness and closeness centrality see dramatic changes between 1950 and 1967 due to the overhaul change in network topology while more incremental changes have taken place ever since.

There is a consensus among the three centrality indicators that *Centralstationen* is the most central station as it name implies from 1967 onwards. This is however far from universal as the centrality of many stations varies considerably depending on the centrality indicator considered. For example, some of the most central stations when measured in terms of its travel time-wise closeness are neither transfer hubs nor heavily traversed station for connecting origin-destination pairs (i.e. *Kungsträdgården*). In contrast, stations that serve as gateway transfer hubs between network trunks and branches (e.g. *Östra Station*, *Älvsjö*) are characterized by high betweenness centrality due to their bridging function even if they are not central in terms of closeness travel time.

Until the late 1970's, all central stations are in the core of the inner-city.. The construction of the metro system resulted with new hubs in the edges of the inner-city. The urban and transport development since the 1990's aimed at expending the boundaries of the inner-city and provide greater accessibility to such strategic nodes.

5.4 Relations between network indicators

The evolution of Stockholm MRTN was assessed in the previous sections by studying the evolution of various network indicators. The inter-relation between selected network indicators was examined by investigating their co-evolution to provide further insights into the underlying changes in network structure. Figure 7 presents a scatter plot of the number of nodes and the gamma index (Eq. 3) of network connectivity for the 52 unique network topologies in 1950-2025. The three development periods described in Section 5.1 are again clearly visible: (a) with the removal of nodes, connectivity decreases linearly (1950-1966) and then falls abruptly to the lowest number of stations in 1967; (b) the addition of nodes gradually improves connectivity (1967-1999), and; (c) this trend accelerates in the last period (2000-2025) as the number of connections increases faster than the number of stations. The latter signifies an investment policy focused on increased connectivity rather than coverage.

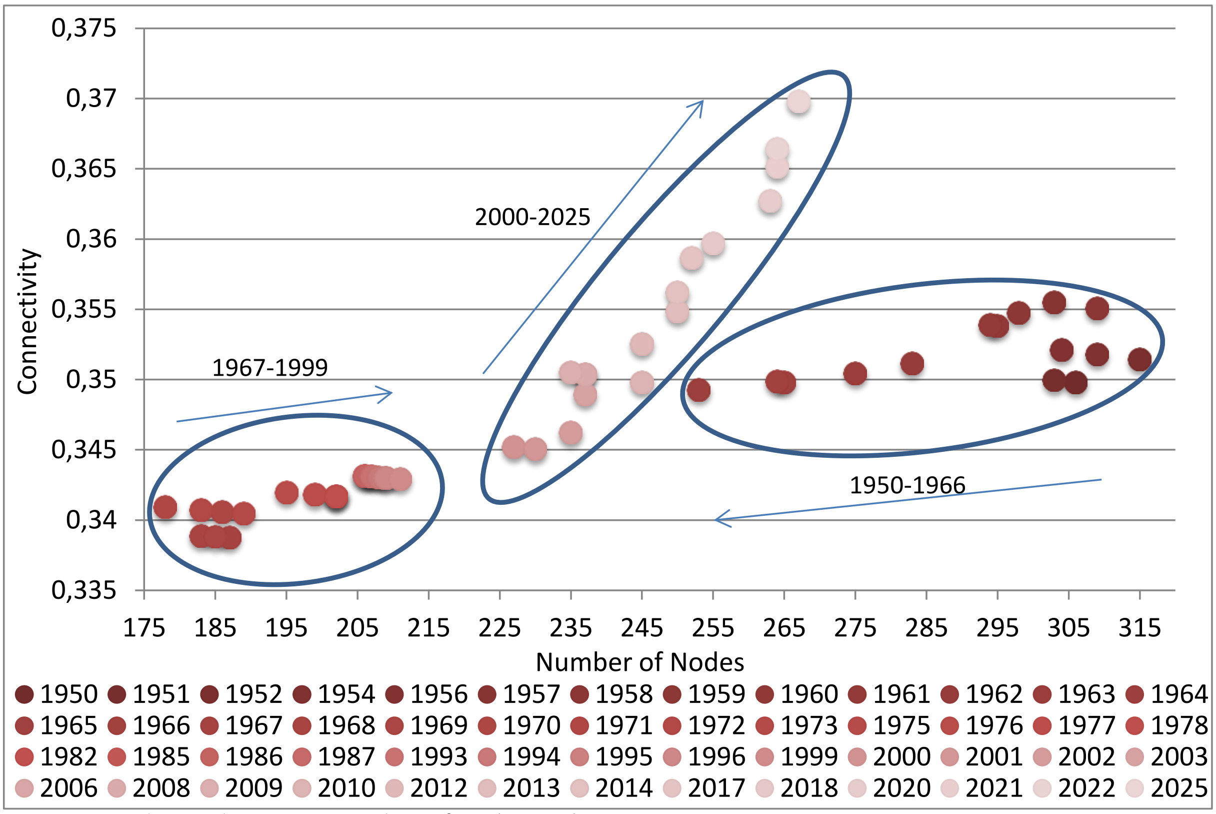


Figure 7: Relation between number of nodes and connectivity 1950-2025

When investigating the relation between the number of nodes and the average node degree, a very similar trend to the one observed in Figure 7 is revealed. While Zhang et al. (2013) found only a slight increasing trend in average node degree for networks with a higher number of nodes, there is a clear positive linear relation between these two network indicators in the case of Stockholm ($R^2 = 0.56$ and $R^2 = 0.95$ when calculated only for 2000-2025). This is expected since the development of the Stockholm network was first directed towards low-density coverage followed by increased connectivity leading to an increase in node degree at more mature network stages.

The co-evolution of average node closeness centrality in terms of distance and travel time is presented in Figure 8. As can be expected, there is a strong positive correlation between the average values of the two closeness indicators, albeit only 68% of the variation in closeness centrality in terms of travel time is explained by closeness centrality in terms of distance. A perfect correlation would have been yielded if travel times were to remain the same across the networks throughout the analysis period. This is evidently not the case given the aforementioned shift towards relying on faster rail services.

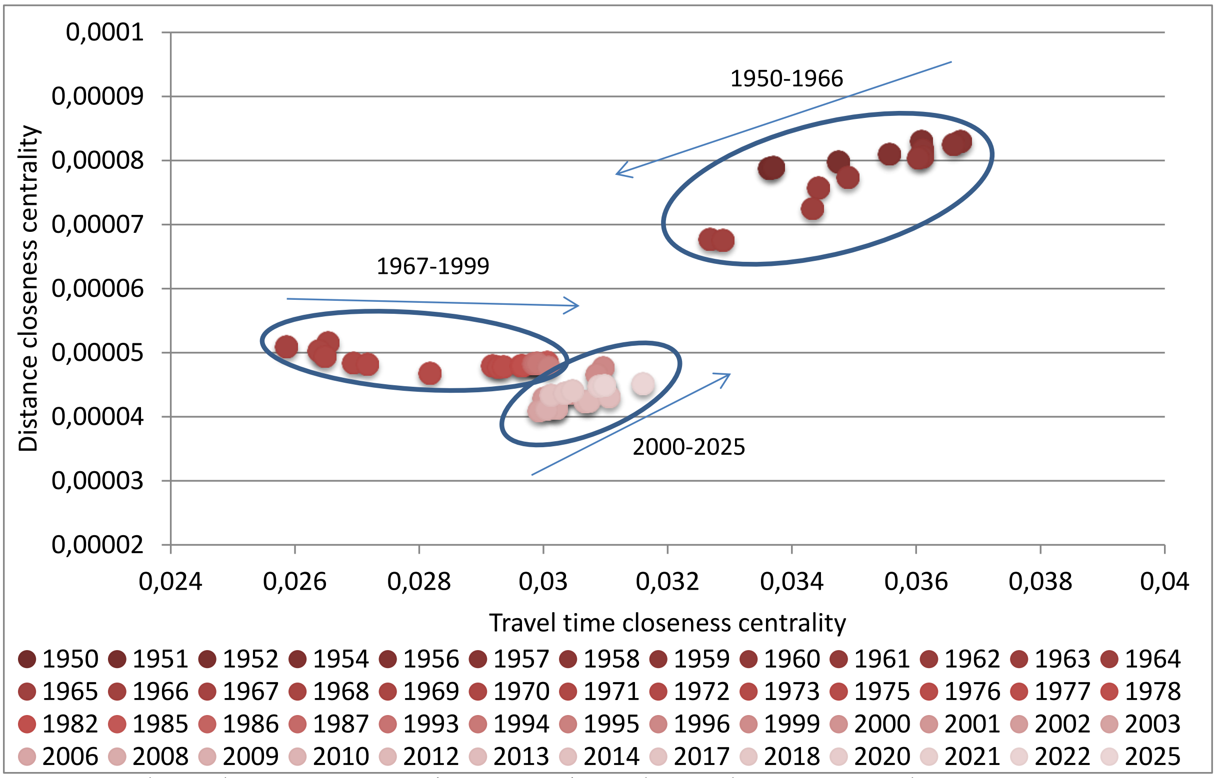


Figure 8: Relation between average distance and travel time closeness centrality 1950-2025

6. Conclusions

The case of Stockholm demonstrates that network evolution patterns carry the signature of planning policies, metropolitan developments and changes in system operations. The results of the analysis of the development of network structure along with a discussion of the underlying policies and technological changes are relevant for both transport planners and network scientists. The analysis reveals that network evolution can be characterised by abrupt changes as well as incremental growth and by investments as well as disinvestments. Network development does not follow thus in reality a simple growth pattern but is rather subject to multiple simultaneous trends that manifest themselves over a long period of time due to the lag between planning policies, investment decisions, construction of large-scale infrastructure projects and launching new passenger services. Notwithstanding, network evolution is clearly path-dependent and even though changes in planning policies can result in a change in course (e.g. dismantling the tramways or shifting towards densification and polycentric planning), network states and the range of possible futures highly depends, although not fully determined, by previous stages.

The evolution of the Stockholm rail network is characterized by three distinctive development phases of contraction, stagnation and growth. Network developments exhibit first a period of exploration (1967-2000) followed by a period of densification (2000-2025). This represents a shift from peripheral attachment – adding stations at the edges of existing lines, extending branches - to preferential attachment – new stations are connected to nodes which are already well-connected. The current development trends can be expected to continue in the foreseen future also beyond 2025 based on Stockholm's unusually long-term vision plan for the development of its public transport network up to 2070 (Stockholm2070, 2017). If this trend will indeed persist in the future, then the network may become scale-free (Barabasi and Albert 1999), resembling the evolutionary process identified by Strano et al (2012) for a region-wide street network which went through a similar transition from exploration to densification.

Technological changes that result with increased commercial speed play an important role alongside the construction of previously non-existing links. It is remarkable that in 2025 the Stockholm network will offer the same level of directness, connectivity and accessibility that were offered in 1950 for a much smaller area. This is driven by the dramatic shift in the modal composition of Stockholm rail-bound network during the analysis period. This shift is characterized by the construction of modes with higher speed, longer distances between stations, higher capacity and higher costs per kilometre. The three development periods correspond to (a) short distances-short travel times, dominated by trams in the inner-city and inner-suburbs, with both falling with the dismantle of tram services; (b) long distances- longer travel times, metro extended to outer suburbs, gradually attaining shorter travel times with almost unchanged distances due to improved technology, and; (c) intermediate distances and speeds, multi-modal network, densification of the network core and cross-radial connections contribute to improvements in accessibility in terms of both distances and travel times. Hence, the longitudinal analysis performed in this study reveals that the technological changes that took place during this time span have contributed to the evolution of network topological structure, in conjunction with transformations in urban and transport planning.

The network science indicators used in this study allow for a systematic analysis and comparison of the networks constructed for the entire study period based on the well-established principles of complex system theory. Global topological indicators provide information on coverage, connectivity, efficiency and directness. Local indicators are instrumental in analysing the spatial distribution of accessibility (closeness centrality) and flows (betweenness centrality) which are often used by transport planners and geographers in their analysis of transport networks. The consequences of alternative planning strategies can be investigated using these indicators to examine how it relates to past trends. While the analysis performed in this study goes beyond a strictly topological analysis by including travel time, it is limited to the analysis of the infrastructure. Future studies may analyse the evolution of the service layer superimposed on this network and passenger flows. This will potentially allow gaining insights into how service types and congestion evolve in transport networks.

While the exploration phase extends the network coverage and regional accessibility, the densification phase increases network efficiency and contributes to network robustness. Overall, network shape is developing towards the form seen by Roth et al (2012) for metro networks with a dense core from which branches fork at secondary hubs. Increasing the number of circuits and moving away from Stockholm's MRTN dependency on few central and saturated hubs will contribute to relieving congestion under normal conditions as well as strengthen network robustness in case of disruptions by offering alternative routes. This yields a considerable strengthening of network robustness compared to the findings of Wang et al. (2017) who compared 33 metro worldwide networks and found Stockholm to be among the least robust networks with the lowest meshedness coefficient and robustness indicator values (i.e. both being zero).

The findings of this study can support the development and increase the realism of models designed to mimic transport network evolution. The topological analysis performed in this study can be further enhanced by considering alternative graph representations that account for the service layer (i.e. lines and frequencies) and its impacts on passenger travel times. Future studies of the development patterns exhibited by other public transport networks will allow investigating whether there are common drivers and rules that underlie network evolution and formation. In particular, this will allow determining the extent to which path dependency and exploration-densification phases dominate network development. Alternatively, various transport network planning strategies undertaken by various actors can be specified and tested for example in an agent-based modelling environment and the network structure results thereof be compared with those observed for real transport networks. For example, different patterns might be observed for systems which have been developed over a long period of time of about a century by a large number of actors in a traditionally monocentric metropolitan area such as Moscow, London and Paris, as opposed to systems centrally developed and rapidly expanded within a short time span of less than two decades such as in the case of Guangzhou, Shanghai and Madrid.

Acknowledgments

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Appendix: Sources used in compiling and reconstructing case study networks data

Data was gathered from searching through the archives of the Stockholm Transport Museum, Stockholm City Museum, Swedish Railway Association and Royal Library. The former was especially instrumental for retrieving the topological development of the metro network while service timetables were mostly found in the latter.

The following books were used as primary sources for reconstructing the topological information for the Stockholm tram network:

Aspenberg N. (1998). The tramways in Stockholm: The history of the tramways, interurbans, trolleybuses and underground. Oslo: Banerforlaget

Eriksson G. (1991). All of Stockholm's tramways – a 90 years tram journey in Stockholm [in Swedish]. Stockholm: Jan Jangö AB.

Lange T. (1998). Stockholm on track. From horse trams to fast trams [in Swedish]. Stockholm: Svenska Spårvägssällskapet.

The following books were used as the primary source for reconstructing the topological information for the Stockholm commuter train network and light rail lines:

Hällqvist A. (2008). Commuter train in Stockholm's region [in Swedish]. Stockholm: Trafiknostalgiska Förlaget.

Landgren K. (1993). Saltsjöbanan [in Swedish]. Stockholm: Svenska Järnvägsklubben.

SLJ (1985). Roslagsbanan 100 years [in Swedish]. Malmö: Frank Stenvalls Förlag.

Information concerning future developments of the network were obtained from Stockholm County Transport Administration reports and press releases.