Denne artikel er publiceret i det elektroniske tidsskrift
Artikler fra Trafikdage på Aalborg Universitet
(Proceedings from the Annual Transport Conference
at Aalborg University)
ISSN 1603-9696
www.trafikdage.dk/artikelarkiv

Measuring Copenhagen's public transport accessibility and network performance in a European context

Dr Jan Scheurer, jan.scheurer@rmit.edu.au
RMIT University/Curtin University, Melbourne/Perth, Australia

Abstract

Spatial accessibility measures have gained prominence in recent years as a supportive tool for decision making as well as stakeholder engagement in integrated land use and transport planning. They have also advanced our ability to conduct comparative and benchmarking studies between the land use-transport systems in different cities, or in a particular city over a longitudinal time line.

This paper is based on a public transport accessibility assessment done for metropolitan Copenhagen in 2012 as part of the roll-out of the Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool over a sample of eleven European cities. SNAMUTS utilises a set of seven distinct accessibility indicators to highlight the performance of the public transport network in its urban context from different angles. The application of the tool to Copenhagen showed that the Danish capital is among the top European performers on the majority of these accessibility measures, yet when it comes to actual usage of public transport (expressed by city-wide mode share or number of annual trips per capita), it only occupies a mid-field position in a European context.

A more specific comparison of public transport accessibility in Copenhagen with neighbouring Hamburg, using the results of particular SNAMUTS indicators, will serve to highlight some of the key strengths and weaknesses in Copenhagen's interplay of public transport and urban structure, and inspire some concluding reflections on how the city might use its existing and potential accessibility strengths to attract a higher rate of public transport ridership in the future.

Introduction

Copenhagen is a well-known international showcase in sustainable transport policy. The Danish capital has been a pioneer in central city pedestrianisation, has consistently kept car ownership and use below the levels of comparable cities through a combination of spatial and fiscal policies, and jostles with Amsterdam for the title of the most bicycle-friendly (and most bicycle-using) major city in the world (Gehl and Gemzøe, 1996; Gehl et al, 2006; Grescoe, 2012). Less well known and documented, at least for international audiences, are the standard and the performance of Copenhagen's public transport system as a critical component of the city's sustainable mobility credentials.

As part of a global comparative study in 25 cities, focussing on the ability of public transport systems to provide their cities with spatial accessibility and to facilitate integrated outcomes in land use and transport planning, Copenhagen was shown to be one of the best performers among a sample of eleven European cities on several accessibility indicators (Scheurer and Curtis, 2012). Yet when looking at the actual uptake of public transport usage among the travelling public, Copenhagen only occupies the middle ground within this cohort, with similar numbers of public transport journeys per capita per year to Hamburg, Amsterdam and Barcelona but quite a lot fewer than Zurich, Vienna and Munich (Table 1).

In this paper, we will highlight Copenhagen's profile in terms of public transport accessibility and network performance in more detail and arrive at some suggestions as to why there appears to be gap between above-average supply and average demand.

Table 1: Public transport boarding and mode share data from eleven European cities between 2009 and 2012. Sources: GVB (2012); RET (2012); HTM (2012); GVU (2012); NS (2012); ATM (2012); TMB (2012); Lothian Buses (2012); HVV (2012); DSB (2012); Trafikselskabet Movia (2012); Metroselskabet (2012); MVV (2012); MVG (2012); STCP (2012); VOR (2012); Wiener Linien (2012); VBZ (2012); ZVV (2012).

2009-2012	Annual PT boardings	Metropolitan Population	Annual PT boardings per capita
Zürich	590.0m	1.44m	401
Wien	978.6m	2.48m	394
München	886.0m	2.69m	328
København	397.6m	1.85m	215
Amsterdam	449.0m	2.16m	208
Hamburg	676.3m	3.37m	201
Barcelona	935.5m	4.85m	193
Porto	182.6m	1.23m	148
Zuid Holland	490.0m	3.46m	142
Utrecht	154.0m	1.20m	128
Edinburgh	149.0m	1.27m	117

Note:'Boardings' are generally defined as public transport journeys per mode per operator (transfers between vehicles of the same mode and operator count as a single trip, transfers between different modes and/or operators count as multiple trips). Note that reporting standards vary between agencies and that aggregate figures per city might omit some minor operators for whom no boarding data was available. Some inaccuracy is likely to remain, and the usage figures should be taken as a guide only.

Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS): Outline of an accessibility tool

The Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool, which informs the findings in this paper, is an award-winning strategic planning and decision making instrument that has been applied in 25 global cities, and utilised for policy formulation and stakeholder engagement in the Australian cities of Perth, Melbourne and Adelaide. SNAMUTS work in Copenhagen started in 2009 and informed a comparative analysis with similar-sized Perth (Scheurer, 2010). The construct of SNAMUTS is described in great detail in Curtis and Scheurer (2010) and is based on a set of seven core indicators designed to highlight different aspects of public transport accessibility and network performance. Its analytic structure was originally adapted from the Multiple Centrality Assessment technique developed by Porta et al (2006a, 2006b). The purpose of employing such a tool in strategic planning is less to try and replace traditional transport models, but rather to introduce a discursive layer for stakeholders of a variety of disciplines to better understand the interplay of land use and transport policy measures and outcomes. As such, SNAMUTS does not attempt to quantify present or future levels of patronage or capacity. Rather, it starts with the question: What is the role public transport can play in facilitating accessibility in the land usetransport system, how can this role contribute to sustainability and carbon reduction goals, and how can it evolve in the future as infrastructure, service levels and urban form are subject to change?

The SNAMUTS tool is based on the definition of a set of activity nodes, ie. points on the public transport network that coincide with places where one or several of residential uses, employment, retail or recreational facilities, major education or health institutions, or tourist attractions form a spatial cluster. This group of activity nodes generally corresponds to the hierarchy of neighbourhood or suburban centres identified in strategic planning documents, and for SNAMUTS purposes also includes all major multimodal transport stations (such as rail stations with bus interchanges). In total, 140 activity nodes were identified in the Copenhagen metropolitan region.

SNAMUTS further defines a minimum service standard, below which a public transport route will not be included in the analysis. This is done to limit the work to those components of the public transport network that users can reasonably assume to have a regular presence and thus the ability to facilitate a variety of journeys at a variety of times with a minimum of reliability, features that correspond to the 'go anywhere, anytime' standard identified by Mees (2010) and the 'elements of a useful service' identified by Walker (2012). In SNAMUTS international comparisons, we have set this standard to a minimum service frequency of 20 minutes during the weekday inter-peak period and 30 minutes during the day on weekends for surface routes (buses and trams). For modes with dedicated station or terminal infrastructure and their own right of way (heavy rail and ferries), a more lenient minimum service standard of 30 minutes during the weekday inter-peak period in combination with the operation of the same route 7 days a week applies; this is because these modes define their presence (and more often than not, encourage urban intensification) through their fixed infrastructure as well as through vehicles providing the service. As SNAMUTS has used different minimum service standards in different projects, the standard used here is referred to as SNAMUTS *23*.

In this paper, I will compare and discuss Copenhagen's public transport accessibility in terms of seven SNAMUTS indicators, namely service intensity, closeness centrality, degree centrality, network coverage and contour catchments, betweenness centrality, network stress and nodal connectivity. Some of these indicators contain several measures, of which those most relevant to the Copenhagen profile have been selected and will be presented here.

Analysing Copenhagen

Copenhagen is a medium-sized European capital: in 2009, 1.85 million inhabitants occupied a metropolitan area of 2,780 sq km (DST, 2010). The metropolitan area was subject to substantial spatial expansion in the years after 1945, and while much of this growth followed the modernist paradigm of the day, it did so along a pattern of growth corridors along radial rail lines, and green wedges in between (Svensson, 1981). This template is known as the Finger Plan, directing urban growth in the shape of a stretched handprint, with the palm of the hand depicting the denser, pre-war parts of the city centred on the municipalities of Copenhagen and Frederiksberg, and the thumb following the coastline towards the south-west. As will be of subsequent interest, this template also incurs that the city's coastal location on the island of Sjælland only allows for concentric growth across a limited portion of a full circle. Metropolitan planning since the 1970s converted the radial Finger Plan into a more lattice-shaped pattern, aided by the construction of an orbital motorway system alongside the radial rail network. Today, Copenhagen is among the lowest-density metropolitan areas in Europe at 25.2 residents and 9.5 jobs per urbanised hectare (DST, 2010). Fixed bridge and tunnel connections to the Danish mainland and to Malmö in Sweden, opened in the late 1990s and early 2000s, reduced the city's relative geographical isolation and increased functional interdependence particularly with the Swedish province of Skåne, which is now within convenient commuting distance to and from Copenhagen. This analysis, however, has been limited to the Danish side of this wider metropolitan region, even though rail services at the SNAMUTS *23* standard (albeit attracting quite high fares in comparison to their local counterparts) connect the centres of Copenhagen and Malmö.

Service intensity

The first SNAMUTS index (Table 2) calculates the amount of rolling stock (vehicles or train sets in simultaneous revenue operation) required to operate Copenhagen's network at the SNAMUTS *23* standard.

The figure includes practically the entire rail network of the Danish capital region, a circumstance that is also reflected in the related figure for the number of heavy rail stations in relation to population in Table 3 (also at the SNAMUTS *23* standard).

Tables 2, 3: Service intensity in number of vehicles/train sets in simultaneous revenue service during the weekday inter-peak period, and number of rail stations at the SNAMUTS *23* in eleven European cities, highlighting Copenhagen

2009-2012	Number of services	Services per 100,000 inh
Edinburgh	485	38.2
Amsterdam	619	28.7
Zürich	373	25.9
Wien	634	25.5
Porto	306	24.9
København	459	**24.8**
Barcelona	1,090	22.5
Zuid Holland	580	16.8
Hamburg	557	16.5
Utrecht	194	16.2
München	389	14.2

2009-2012	Rail stations (excl. tram)	Rail stations per 100,000 inh
Zürich	146	10.1
København	180	**9.7**
München	222	8.1
Wien	190	7.7
Porto	78	6.3
Hamburg	176	5.2
Barcelona	236	4.9
Utrecht	52	4.3
Amsterdam	91	4.2
Zuid Holland	121	3.5
Edinburgh	33	2.6

The measure of service intensity can be understood as a proxy for the determination of the relevant authorities to make operational resources available for the benefit of a useful public transport system. Conversely, a high service intensity figure can also be the result of operational inefficiencies: a high reliance on small units at slow speeds (such as buses in congested conditions) will inflate these numbers without a concomitant return in service quality. This latter circumstance certainly explains most of (highly busdominated) Edinburgh's pole position in Table 2. Among the remaining cities, there appear to be two distinct groups of relatively generous providers of operational resources (of which Copenhagen forms part alongside Amsterdam, Vienna, Zurich, Porto and Barcelona) and of relatively frugal providers, comprised of the remaining Dutch and German cities. Thus relative to population, Copenhagen's service intensity is roughly 50% higher than, for instance, that of neighbouring Hamburg.

The Danish capital region further has the second highest numbers of heavy rail stations relative to population after Zurich. Some, but not all, of this position can be explained by the presence of an expansive network of non-electrified regional rail lines in the outskirts of Copenhagen's metropolitan region *(lokalbaner)*. But even if these are discounted, Copenhagen once again out-supplies its southern neighbor of Hamburg by more than 50%.

Closeness centrality

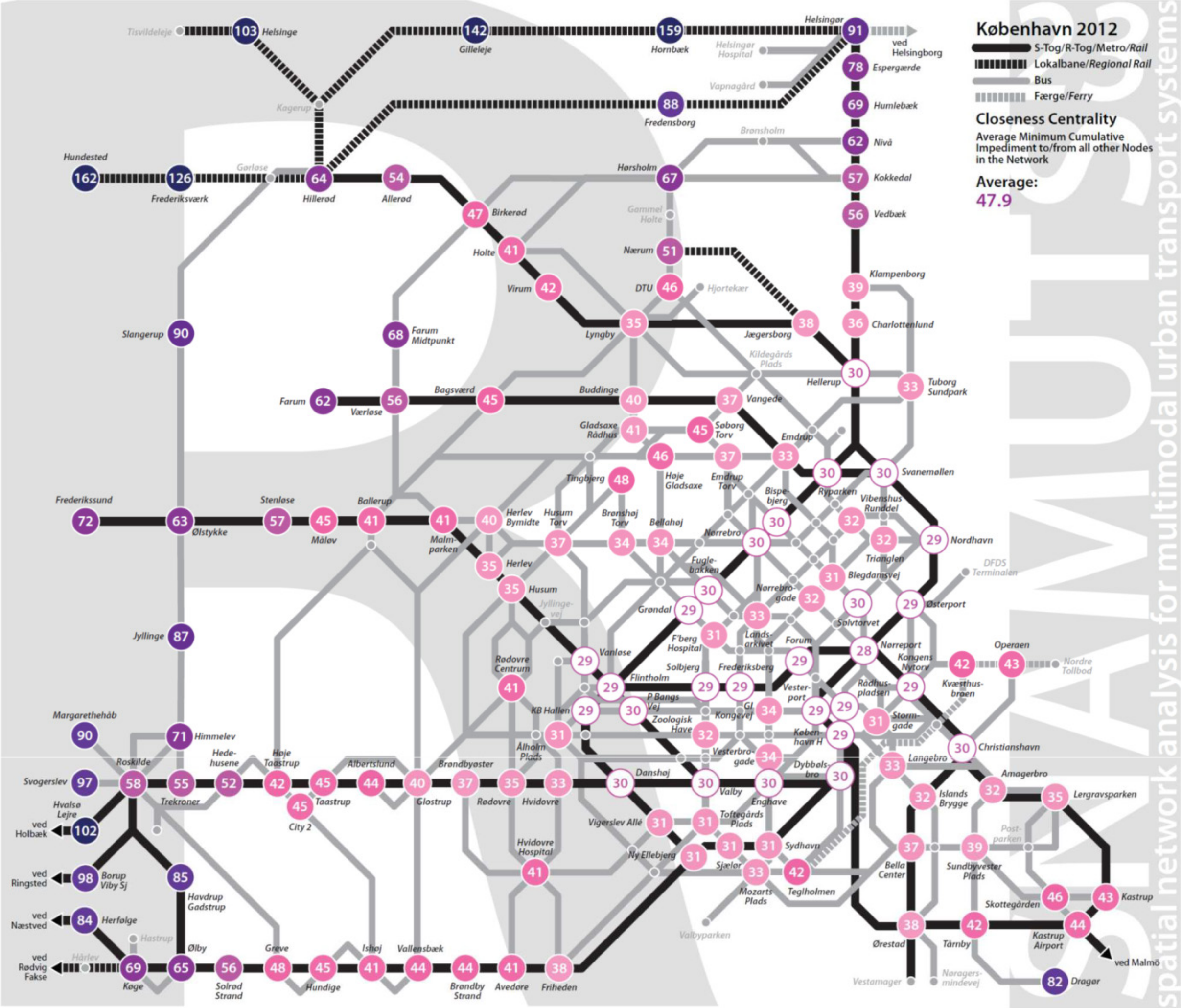
The closeness centrality index can be understood as a proxy for the ease of movement provided by the public transport network. It is based on a GIS way-finding script and determines the journey path between any pair of SNAMUTS activity nodes that has the lowest value of spatial separation or travel impediment. Travel impediment is defined as a combination of travel time and service frequency (four times travel time in minutes divided by the square root of service frequency in departures per hour), as these are the variables of most practical interest to public transport users, and is counted separately for each route segment (link between adjacent nodes). For each activity node as well as for the network as a whole, an average is calculated using the matrix of (in Copenhagen) 140 defined activity nodes. Table 4 shows these averages as well as lowest and highest closeness centrality values. Lower values indicate better accessibility.

Table 4: Closeness centrality in eleven European cities, highlighting Copenhagen

2009-2012	**Closeness centrality (average)**	Closeness centrality (lowest value)	Closeness centrality (highest value)
Wien	**38.8**	22.6	125.6
Barcelona	**44.8**	25.0	156.5
Porto	**46.4**	26.1	115.3
Zürich	**47.4**	26.8	143.3
København	**47.9**	28.0	161.8
München	**48.4**	26.9	121.7
Amsterdam	**48.8**	28.7	105.2
Utrecht	**49.2**	27.2	101.8
Hamburg	**51.9**	29.5	135.6
Zuid Holland	**62.9**	38.3	155.4
Edinburgh	**72.1**	38.7	157.9

Copenhagen's average closeness centrality value lies within a relatively small band shared with most other European case study cities, except the 'outliers' of Vienna, Zuid Holland and Edinburgh. Map 1 shows the distribution of closeness centrality scores across the Copenhagen network. In the inner area of the Danish capital, the structure of the network, particularly within the area circumscribed by the inner orbital rail line (S-tog line F) is akin to a tightly-knit grid, offering a multitude of route choices for any node-to-node journey and a similar abundance of potential transfer points. Passengers in Copenhagen thus have the option to travel along geographical desire lines, including for chain journeys involving multiple destinations. For this reason, closeness results within most of the inner area (Cities of Copenhagen and Frederiksberg and in some cases beyond) are consistently within a narrow spectrum at the bottom end of the scale, though it is notable that rail nodes perform slightly better than bus-only nodes in their vicinity. In the outskirts of the metropolis, the network becomes much sparser and as a result, closeness values there rise at a much faster rate with growing distance from the central area. This is especially true for activity nodes along the relatively slow and low-frequency local rail lines along the urban fringe in Copenhagen such as Fredensborg, Gilleleje, Herfølge or Hundested (which has the highest closeness centrality value in the entire European sample).

Map 1: Closeness centrality on Copenhagen's public transport network in 2012



Degree centrality

The degree centrality index is also based on a GIS way-finding script, only in this case preference is given to the journey path between any pair of nodes that incurs the lowest number of transfers. Average degree centrality is thus a proxy measure for the transfer intensity of the network. A derived measure, network density, determines what percentage of the 140 x 139 potential journey paths in Copenhagen's network can be made without a transfer. Since some pairs of nodes are connected by more than one transfer-free journey path (for example, it is possible to travel by S-tog between Ny Ellebjerg and Hellerup either via central Copenhagen or via Flintholm), these alternative paths are also considered in the total score since they add practical choices for passengers (one of the alternative routes might be faster, less crowded or more reliable than the other, or it might travel past particular intermediate points where a traveller needs to break their journey for further activities). Thus in theory, the network density figure could rise above 100% (but in practice that is highly unlikely).

Table 5: Degree centrality and network density in eleven European cities, highlighting Copenhagen

2009-2012	Degree centrality (average)	Number of activity nodes	**Network density**
Edinburgh	0.89	102	**33.4%**
København	0.93	140	**22.4%**
Porto	0.91	96	**22.0%**
München	0.90	179	**18.3%**
Hamburg	1.12	186	**17.8%**
Barcelona	1.11	235	**17.1%**
Amsterdam	1.08	134	**16.5%**
Utrecht	1.17	75	**16.2%**
Zürich	1.22	137	**14.2%**
Wien	1.20	187	**12.6%**
Zuid Holland	1.60	217	**8.8%**

On the degree centrality index, European cities split into two distinct groups: those with an average below one transfer, and those with an average above one transfer. This distinction is only partially related to different approaches of organising networks in terms of modal hierarchy and reliance on transfers (Mees, 2012; Walker, 2012). Moreover, there seems to be a link to the network density measure which also divides the same two groups of cities at the 18% mark, and thus to the concept of route choice versus prescriptiveness in a complex public transport network.

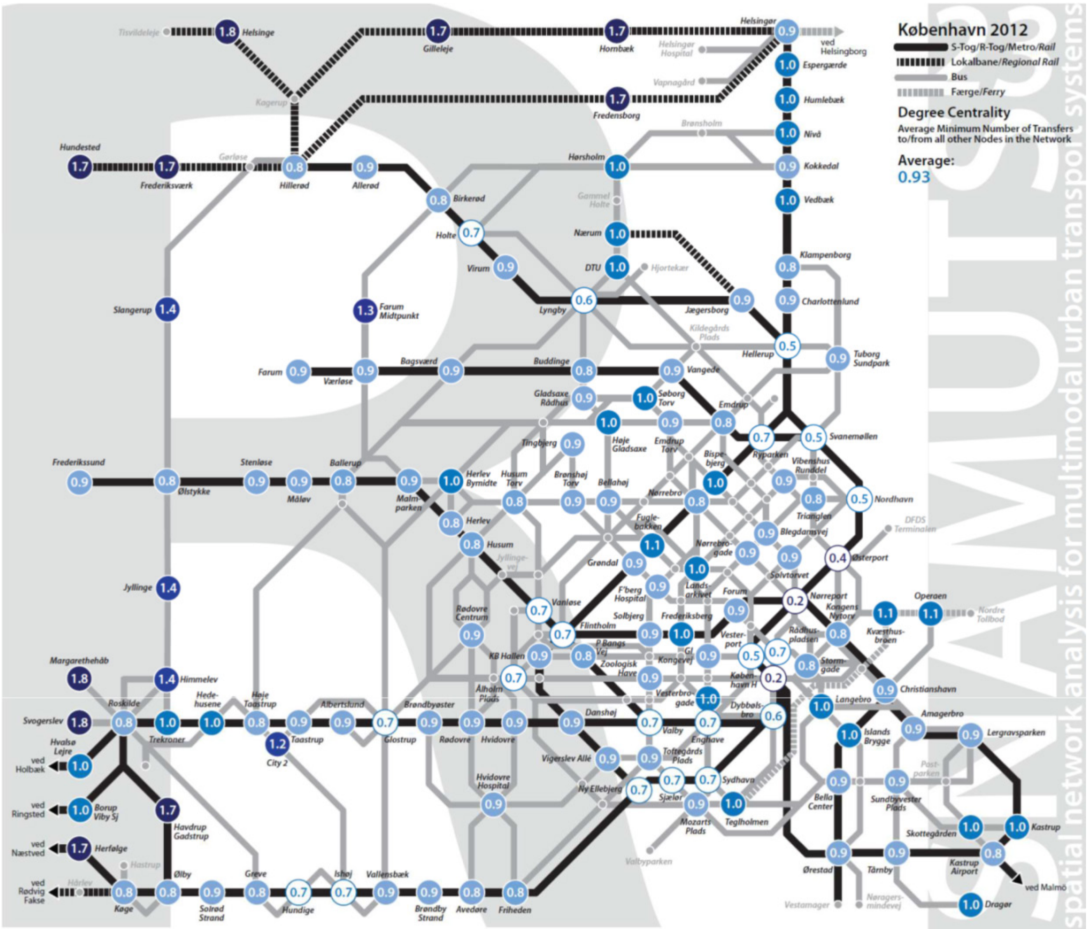
Copenhagen achieves the second highest network density figure after Edinburgh (whose bus system, unlike Copenhagen's, is configured around a predominance of transfer-free links without a strong modal or product hierarchy). In the Danish capital, a substantial number of radial, orbital and diagonal routes traversing the entire city from settlement edge to settlement edge (or settlement edge to coastline) offer transfer-free links between nodes that in other cities would require one or more transfers. As a consequence, the bus network at minimum service standards provides a geographically congruent movement system in its own right, dedicated to frequent service along second-order urban corridors linking a multitude of transfer points with rail and with each other.

A comparison of network structures between Copenhagen and its southern neighbour, Hamburg, which has a mid-field average degree centrality performance within the European cohort, illustrates this context. Hamburg's greater transfer intensity compared to Copenhagen can primarily be traced back to the much lower density of the surface network in the inner areas, as well as the less developed nature of orbital bus links in the outer areas than in Copenhagen. This observation is also supported by the lower service intensity figure for Hamburg discussed previously. Both Nordic cities converted their once-extensive tram systems to bus operation in the 1960s and 1970s, but while Copenhagen retained practically each and every former tram route as a bus link (and then added some further ones), Hamburg abandoned a significant number of tram routes without full bus replacement, 'thinning out' its inner urban network in the process and making public transport movement much more dependent on transfers between surface and sub-surface modes, even for some relatively short journeys, than its Danish neighbour. Or in other words, Copenhagen's bus network alone provides a 'random-access grid' (Nielsen et al, 2005; Mees, 2010) across the inner area and supplements this function with fast, high-capacity rail and metro links servicing some of the same corridors, while in Hamburg, only the interplay of rail and bus modes on different corridors achieves a comparable network configuration (Maps 2, 3).

Maps 2, 3: Bus networks in the inner areas of Hamburg (2010) and København (2009) at the SNAMUTS 23 standard, shown at the same scale

In contrast, the uneven comparison of both cities' outer urban orbital bus networks boils down to geography rather than policy (notwithstanding the fact that there remains scope for some easy-win network extensions in Hamburg). Hamburg's only significant geographical constraint to outer urban expansion is the linear Elbe estuary which connects it to the North Sea nearly 100 km to the west, and which has no fixed transport crossings west of the metropolitan area. This leaves nearly 360 degrees of a circle for orbital travel in outer suburbs, compared to only around 135 degrees in Copenhagen which is perched along the coastline of the island of Sjælland. The provision of a full set of orbital links is thus much easier to achieve in the Danish capital than in its southern neighbour.

Map 4: Degree centrality on Copenhagen's public transport network in 2012



Network coverage and contour catchments

The network coverage and contour catchment indexes add a land use dimension to the SNAMUTS analysis by inquiring about the walkable catchment areas of each activity node, defined as 800-metre radii around train stations and ferry terminals, and 400-metre corridors along bus and tram routes. Network coverage measures the absolute number and percentage of residents and jobs across the metropolitan area that have walkable access to public transport at the defined minimum service standard. The 30-minute contour catchment measure then adds a performance element: it also wants to know how far passengers can travel within a given time budget and how many activities (residents and jobs) are located within this contour, taking in components such as travel speed, network and settlement density.

Tables 6, 7: Average network coverage and 30-minute contour catchments in ten European cities, highlighting Copenhagen

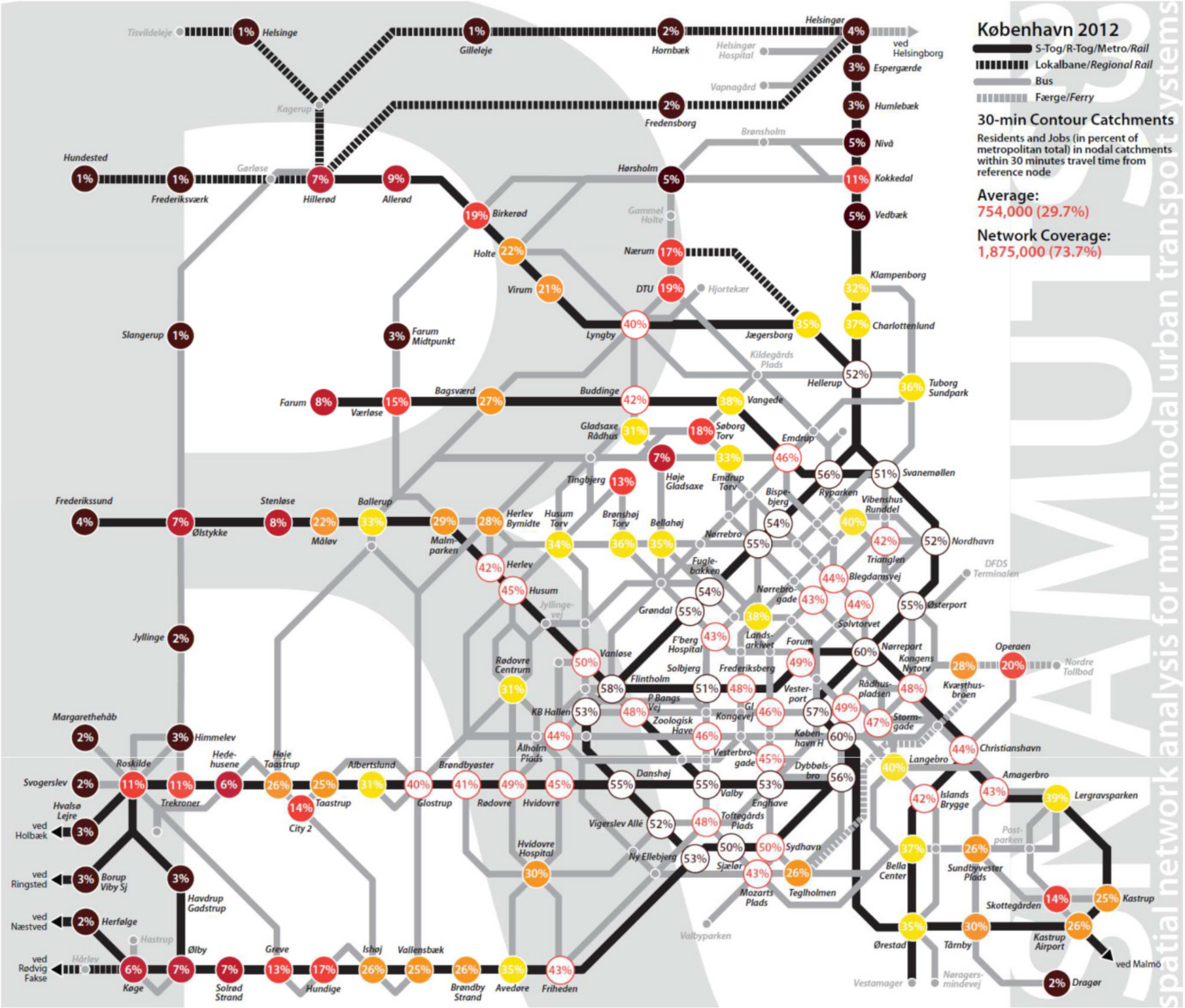
2009-2012	Network coverage (residents and jobs)	Percentage of metropolitan residents and jobs
Wien	2,920m	**79.7%**
Amsterdam	2,486m	**79.6%**
Barcelona	5,396m	**77.5%**
Zürich	1,705m	**74.5%**
København	1,875m	**73.7%**
Zuid Holland	3,135m	**65.9%**
Porto	1,112m	**63.5%**
Utrecht	1,014m	**58.4%**
Edinburgh	1,081m	**58.3%**
Hamburg	2,882m	**57.3%**

2009-2012	Average 30-minute contour catchment (residents and jobs)	Percentage of metropolitan residents and jobs
Wien	1,142,000	**31.2%**
København	754,000	**29.7%**
Barcelona	1,702,000	**24.4%**
Zürich	508,000	**22.1%**
Amsterdam	606,000	**19.4%**
Porto	315,000	**18.0%**
Hamburg	841,000	**16.7%**
Utrecht	287,000	**16.6%**
Edinburgh	252,000	**13.6%**
Zuid Holland	512,000	**10.8%**

On the network coverage index, Copenhagen falls a few percentage points short of Europe's best performers (Vienna and Amsterdam), but is still clearly positioned within the higher-coverage group of European cities. In terms of 30-minute contour catchments measured in percentage terms, Copenhagen comes out second best after Vienna. This outcome is an indication that despite the city's low average settlement density in comparison with most of its European peers, the public transport system seems to offer travel time standards and a level of integration with the land use pattern that result in a superior performance on this index.

From the two most important rail hubs (Nørreport and København H), sixty percent of metropolitan residents and jobs can be reached within half an hour, which alongside Vienna are the equal highest such scores found in any SNAMUTS city. Along both the diametrical S-tog trunk line and the inner orbital between Hellerup and Ny Ellebjerg, contour catchment values are consistently at 50% or higher, while on activity nodes within the area circumscribed by these two lines that are based on bus-only access, the figures drop somewhat, owing to lower travel speeds. Even some of Copenhagen's key middle suburban centres such as Lyngby, Herlev or Glostrup are accessible to a greater proportion of metropolitan residents and jobs by way of a 30-minute public transport journey than the central cities of several of its European peers. A more rapid drop-off in values occurs on the island of Amager in the south-east, and mostly for geographical reasons (as well as for the elimination of destinations on the Swedish side from this analysis, the connection to which traverses Amager). Only beyond the outer termini of the high-frequency S-tog system (Køge, Høge Taastrup, Frederikssund, Farum, Hillerød and Klampenborg) is there a prevalence of activity nodes that arguably do not provide access to a significant proportion of the metropolitan area within this time bracket.

Map 5: 30-minute contour catchments on Copenhagen's public transport network



Betweenness centrality

The betweenness centrality index attempts to assess the significance of each network element for the functioning of the network as a whole. It does this by tracking preferred journey paths between any pair of activity nodes across the network, allocating a weighted measure to each intermediate node or route segment passed along the way. The aim is to capture the elusive concept of 'movement energy', or travel opportunities, generated by the geographical distribution of land uses in the city and the configuration of the network in spatial and service terms to facilitate such movement.

There are several component measures to the betweenness centrality index. The nodal betweenness index measures the concentration of travel opportunities in each activity node and takes a network-wide average. However, a straightforward comparison of averages can be problematic, as maximising nodal betweenness scores is not always in the interest of a user-friendly and efficient public transport network: high scores may be associated with congestion effects (or potential congestion effects), or a network structure that is prone to attracting passengers onto detours from geographical desire lines. A stark contrast between a group of nodes with high betweenness scores and a group with low betweenness scores, with a steep performance gradient in between, may also be indicative of a 'divided city' where good public transport accessibility in selected areas or corridors coexists with very poor accessibility everywhere else.

A more meaningful comparative measure is the global betweenness index, calculated by converging and moderating the betweenness weighting measures for each pair of nodes, which in turn are determined by nodal catchment size (number of residents and jobs in walking distance) and travel impediment (the basis of the closeness centrality index discussed above). Global betweenness (Table 8) is a proxy for the absolute number of travel opportunities within a given metropolitan area. While this measure behaves roughly proportionally to network coverage as discussed previously (again in absolute figures), it is remarkable that Copenhagen outperforms Zuid Holland (the agglomeration of Rotterdam, Den Haag and adjacent cities in the Dutch province of the same name) despite being only just over half the size. This finding is mostly associated with the heavily polycentric structure of the Dutch agglomeration, which produces greater average spatial segregation between activity nodes than in its more monocentric counterparts such as Copenhagen. Here, the high frequencies and speeds on the S-tog system, the compactness and close spacing of activity nodes in the core city (Copenhagen and Frederiksberg), and the relatively small number of significant suburban activity nodes away from the rail system, owing to six decades of mostly effective finger planning, make itself felt.

The third measure in Table 8, catchment of typical path length, tries to compensate for such effects of urban compactness and contiguity inherent in the global and nodal betweenness measures. Put simply, the catchment of typical path length calculates the length of an average public transport trip in the metropolitan area in question in terms of number of intermediate activity nodes traversed, regardless of their geographical spacing. It then multiplies this figure with the average walkable catchment of each activity node in terms of residents and jobs (or expressed differently, the absolute network coverage figure divided by the number of defined activity nodes). This measure is a proxy for the number of residents and jobs travelled past on an average journey. This number will inflate if there is a strong degree of land use intensification around public transport nodes, but it will also inflate if the network is spatially configured to encourage passengers to take longer or more circuitous journeys than theoretically necessary (for example, where suburb-to-suburb travel can be done faster and with greater frequency by a rail transfer trip through the central city than by a bus that follows a more direct route).

On this measure, Copenhagen is a lean performer in comparison to its cohort of nearest neighbours in the sample, Hamburg and Amsterdam, both of which are larger in overall population. This is likely to be related to the aforementioned high network density of Copenhagen's public transport system and its functional interplay of radial, circumferential and diagonal lines which facilitate multi-directional movement without deviating excessively from geographical desire lines. On the other hand, the key reason why Copenhagen's catchment of typical path length is significantly higher than Zurich's (which is smaller in overall population) can likely be found in the linear character of its finger plan-inspired linear suburban activity corridors, which line up a relatively large number of activity nodes like pearls on a string. Zurich, in contrast, has a more multi-directional rail system with a greater prevalence of point-to-point express services.

Tables 8-10: Betweenness centrality in ten European cities, highlighting Copenhagen

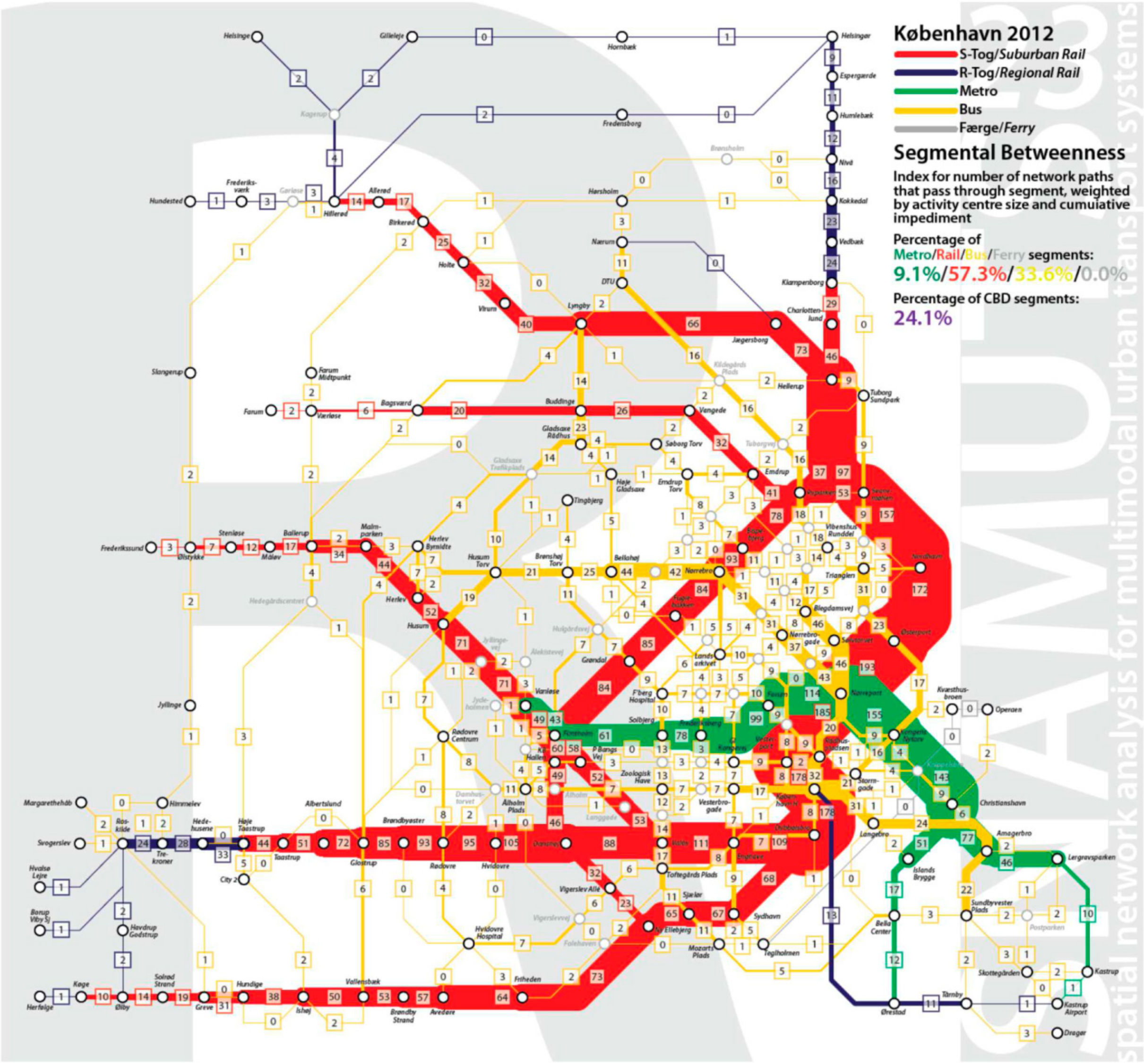
2009-2012	**Global betweenness index**	Average nodal betweenness	Catchment of typical path length
Barcelona	**2,485**	75.9	165,000
Wien	**1,574**	46.6	91,000
Hamburg	**1,320**	41.4	90,000
Amsterdam	**1,210**	38.8	80,000
København	**1,141**	43.7	72,000
Zuid Holland	**1,082**	30.7	89,000
Zürich	**891**	26.7	52,000
Utrecht	**655**	35.8	55,000
Porto	**655**	31.0	53,000
Edinburgh	**574**	27.2	51,000

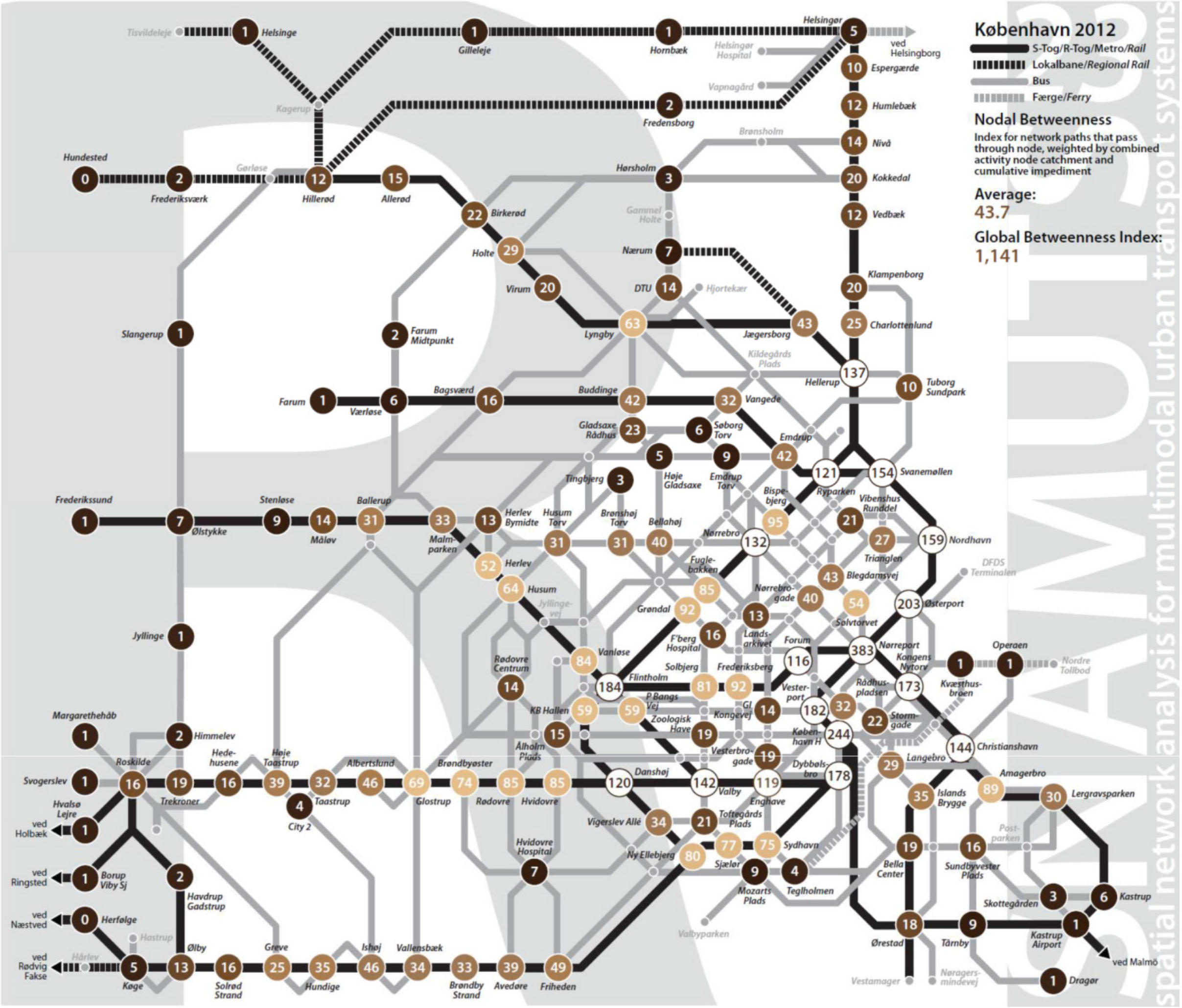
[1] Includes the CBDs of both Rotterdam and Den Haag

Table 9 assesses segmental betweenness results by mode and shows how Copenhagen’s reliance on heavy rail modes to facilitate movement across the city is second only to Barcelona (though it is very close to that of Hamburg, the only other major tram-free city in the sample). The degree of reliance on traversing the CBD for public transport journeys is more or less at par with the other larger European cities such as Amsterdam, Hamburg or Vienna, and much lower than in the smaller cities. This circumstance is most likely owed to the effectiveness of the inner orbital rail link (S-tog route F) in deflecting non-CBD related movement paths away from the central area. Yet, some minor modal imbalances remain and will be discussed in more detail in the next section on network stress.

Maps 6 and 7 show the detailed betweenness results for Copenhagen in two formats: by route segment (segmental betweenness) and by activity node (nodal betweenness). The methodological approach, as well as the scale of the values, remains the same.

Maps 6, 7: Segmental and nodal betweenness centrality index in Copenhagen's public transport network





Network stress

The network stress or segmental congestion index intends to identify critical points on the public transport system where the significance of a route segment for the functioning of the network as a whole, as assessed by the segmental betweenness index in Map 6, appears to produce a mismatch when compared to the actual capacity offered on the same route segment. This is done by drawing a ratio between segmental betweenness and capacity where higher values indicate greater segmental congestion. The capacity of a route segment depends on the transport mode(s) servicing the segment and its service frequency. It aims at using a comfortable load rather than a crush load to determine the capacity per vehicle or train set that serves as input to the calculation. In Copenhagen, assumptions for maximum comfortable passenger capacity on public transport vehicles or train sets are 600 for each suburban or regional train (S-tog/R-tog), 300 for each metro or *lokalbane* train (both systems use relatively short vehicles, which the metro system compensates for by very high frequencies, themselves facilitated by driverless operation), and 50 for each bus (there is only a marginal number of articulated or double-deck buses in Copenhagen whose capacity would be higher).

Note that high levels of network stress as identified by this index do not necessarily have to correlate with an actual experience of frequent overcrowding on the route segments in question. Alternatively, they could indicate a significant amount of latent demand, where alternative forms of travel have greater appeal than public transport, or where public transport services are less legible or familiar to users than the way-finding tool would suggest, or where demographic factors specific to particular origins and destinations depress trip-making rates. Conversely, a low level of network stress on this index is no guarantee that overcrowding will never occur on the segment; for instance, it may derive from travel generators not sufficiently captured by SNAMUTS' limitation on defining the geographical distribution of land uses through residences and workplaces alone.

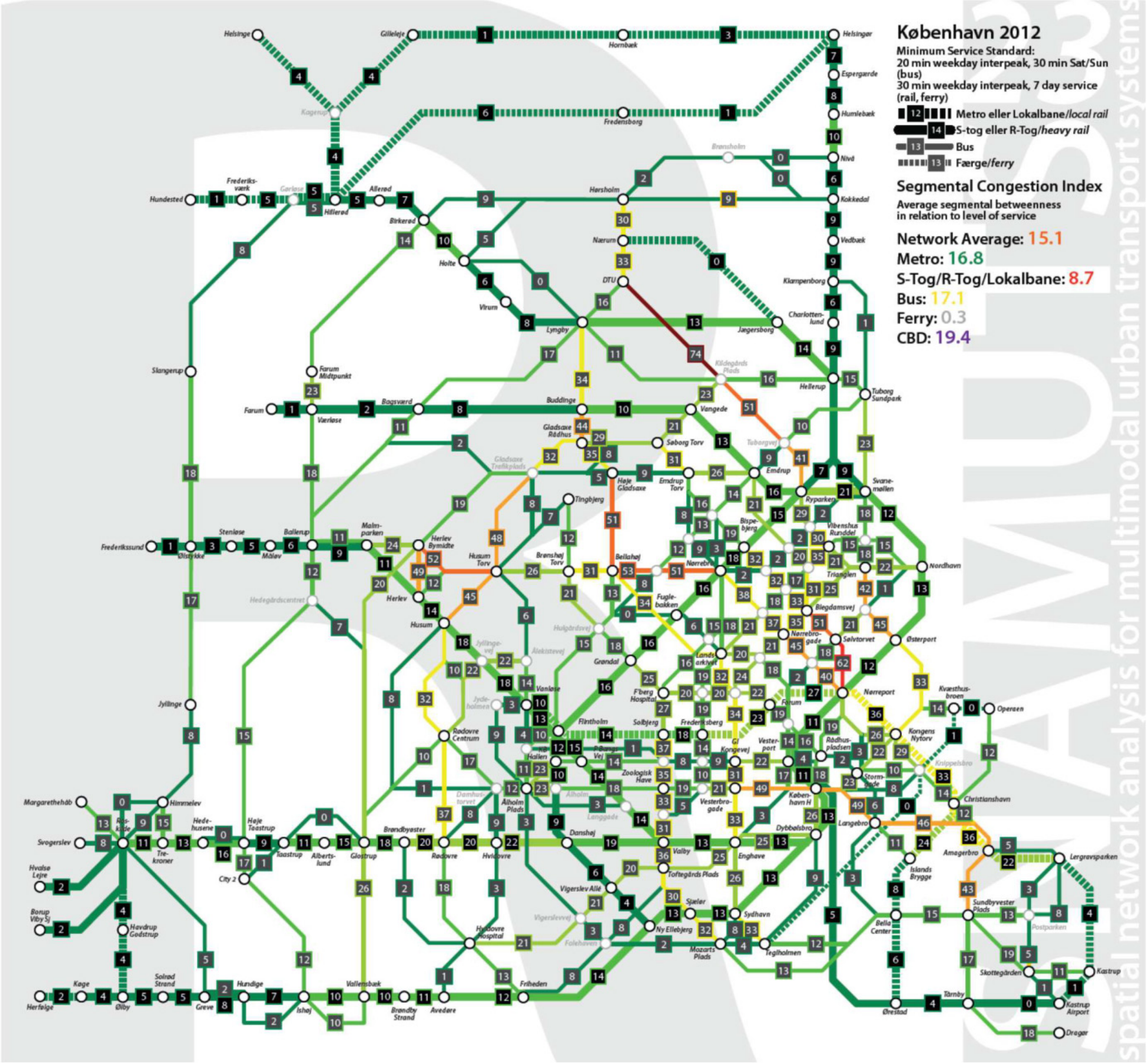
Table 11: Segmental congestion (network stress) index in ten European cities, highlighting Copenhagen

2009-2012	Average network stress
Zürich	10.6
Wien	11.5
Edinburgh	12.2
København	**15.1**
Amsterdam	16.9
Barcelona	17.8
Utrecht	19.0
Hamburg	21.3
Porto	22.5
Zuid Holland	23.7

Average segmental congestion results in Copenhagen remain below those of most of the European peer cities, suggesting that the system should be able to accommodate some future growth in travel opportunities from land use intensification and increased public transport mode share, provided such growth is distributed well over the system. This is a task that Copenhagen's multi-directional network might actually find easier to address than a more prescriptive like in, say, Hamburg (whose position towards the higher network stress end of the table might already be expressing this very observation). In Copenhagen, however, the predominant picture of balanced network performance does conceal a few local weaknesses as well. A radial bus corridor along Lyngbyvejen, connecting the outlying main campus of DTU directly with central Copenhagen, accommodates the highest network stress values on the network and reveals deficiencies in the provision of Copenhagen's usually high standard of multimodal integration in its catchment. Further challenges are apparent around some centres away from the rail network in the dense inner urban neighbourhoods of Nørrebro and Østerbro, where a new circular metro line currently under construction may provide some relief in years to come. No committed modal conversion plans are in place for the two radial bus corridors approaching the betweenness performance (and far exceeding the network stress results) of the outer sections of S-tog lines, namely between Husum and Nørreport in the inner north-west, and between Langebro and Sundbyvester Plads on Amager. Copenhagen's first secondgeneration light rail line, also under construction, is slated to connect Lyngby and Glostrup in the midnorthern and mid-western suburbs (roughly following current express bus route 300S), a link that shows up with some prominence in the segmental betweenness and network stress indexes (probably even more so if an integrated S-tog/light rail/bus interchange can be created at Herlev), though the orbital bus route 200S corridor at a closer distance to central Copenhagen through Husum and Rødovre already appears to attract a higher level of network stress.

Conversely, the network significance as well as the stress levels of the regional rail line between København H and the airport is likely significantly understated, since this route continues on to Malmö on the Swedish side, which was omitted from this network analysis exercise.

Map 8: Segmental congestion (network stress) index for Copenhagen



Nodal connectivity

The last index in the SNAMUTS set determines the number of travel opportunities available at each node, and can serve as a proxy for the ease with which such a node can be accessed particularly as a transfer or stopover point. It is thus related to the incidental interaction of public transport users with the station environment, and by extension, with the land uses that are concentrated there. Or in other words: nodal connectivity expresses the attractiveness of a place for land use development that depends on good access by public transport.

To determine the nodal connectivity score for each node, we count the number of public transport links converging there, then multiply them by the number of departures per hour and by a mode-specific coefficient that is equivalent to the average occupancy or load factor of each public transport vehicle or train set (on a 24 hours, 7 days basis).

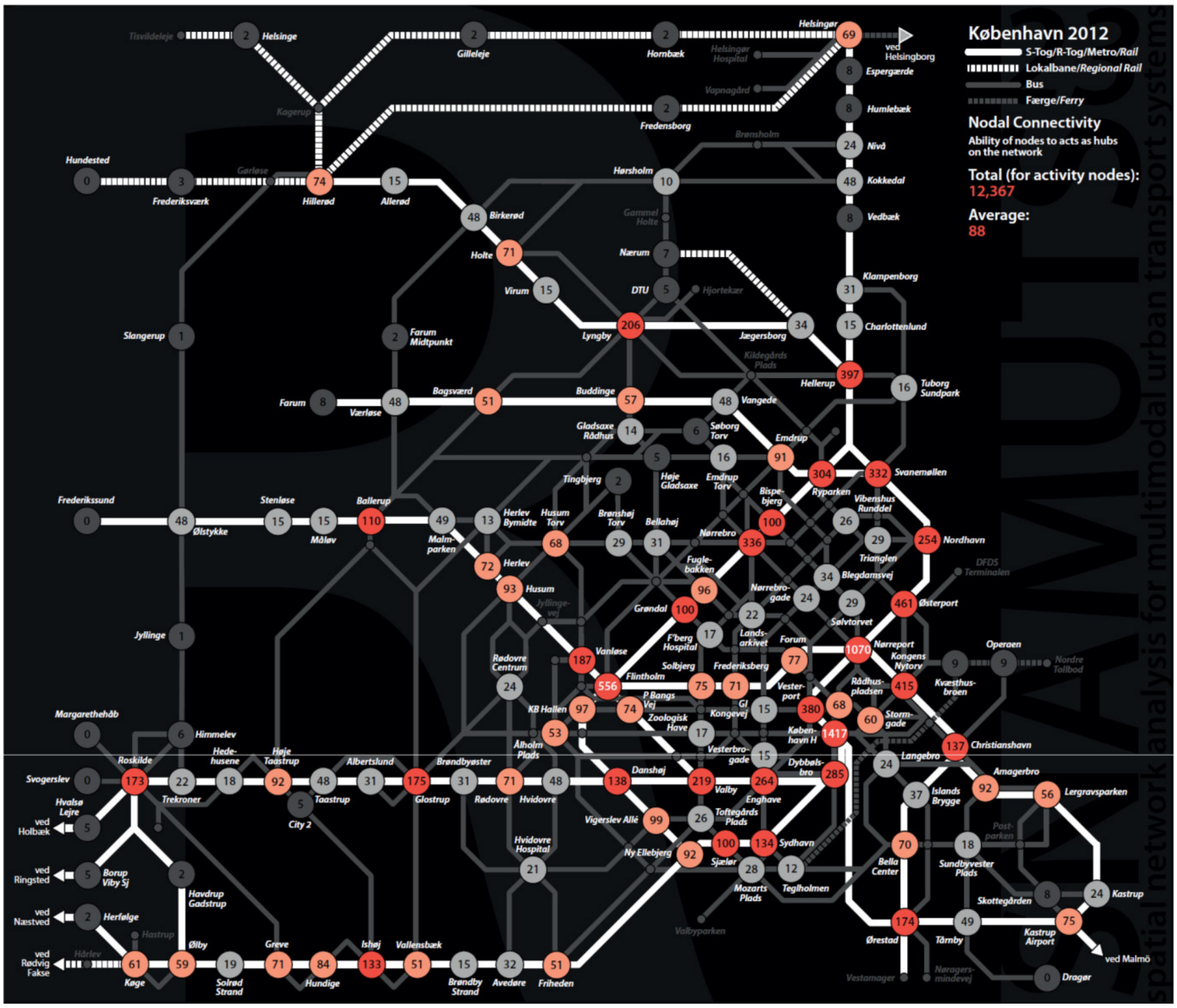
Table 12 summarises the average results for our sample of ten European cities, showing that Copenhagen appears to share a category with Zuid Holland and the smaller cities of Zurich, Utrecht and Porto, while being outperformed by Amsterdam, Hamburg, Munich, Vienna and Barcelona. Metropolitan area size does influence this index to an extent, as travel opportunities and patronage in a constrained area (such as a group of central city nodes) tend to grow exponentially with network size for simple reasons of geometry. But it also appears true that Copenhagen's average occupancy of public transport services, and thus average levels of actual congestion, remain lower than in most of its European peer cities.

Table 12: Nodal connectivity index in ten European cities, highlighting Copenhagen

2009-2012	Nodal connectivity (average)
Barcelona	305
Wien	193
München	175
Hamburg	143
Amsterdam	123
København	88
Zuid Holland	86
Zürich	83
Utrecht	60
Porto	47

The highest nodal connectivity results can be found along the S-tog trunk line between Danshøj/Sjælør and Hellerup, and the northern section of the inner orbital line between Flintholm and Hellerup. Some suburban centres such as Ishøj, Glostrup, Ballerup, Lyngby and Roskilde also score well on this index. With the exception of the two 'super nodes' at København H and Nørreport, the performance gradient is quite smooth from centre to periphery, leaving only a relatively small number of 'connectivity deserts' in the urban fabric of inner and middle suburban Copenhagen. The performance of bus-only nodes in Nørrebro and Østerbro remains sluggish in this context; however, the circular metro line currently under construction should lift these values when opened.

Map 9: Nodal connectivity on Copenhagen's public transport network



Conclusions

In summary, the spatial analysis of Copenhagen's public transport and land use system has shown:

- Copenhagen has an average public transport mode share, as expressed by journeys per capita per year, for a European city – similar to Amsterdam, Barcelona or Hamburg, but significantly below that of Zurich, Vienna or Munich.
- Copenhagen has a relatively generous approach to providing operational resources for public transport – similar to Amsterdam, Vienna, Zurich and Barcelona and significantly greater than the more 'frugal' cities of Hamburg, Munich and the Dutch Randstad outside Amsterdam.
- Ease of movement on Copenhagen's public transport is of a comparable level to most of its European peer cities, but Copenhagen's network density is significantly greater than that of most other cities and as a result, the transfer intensity of the city's network is also at the low end of the European spectrum.
- Copenhagen provides walking-distance access to regular public transport to nearly three out of four residents and jobs in the metropolitan area, a high level comparable to that achieved in Amsterdam, Vienna, Barcelona and Zurich, and significantly greater than in Hamburg, Porto, Edinburgh and the Dutch Randstad outside Amsterdam.
- Copenhagen's public transport and land use system is configured in a way that maximises the reach of a 30-minute journey to a level otherwise only achieved in Vienna, and comfortably outperforming all other European cities examined.
- The overall presence of public transport travel opportunities in Copenhagen is slightly higher than the European trend for a city its size, and these travel opportunities seem to be spatially distributed in ways that largely minimise imbalances and congestion effects.

- Copenhagen relies on heavy rail modes to facilitate movement across its metropolitan area to a greater extent than any other European city examined, except Barcelona, while successfully deflecting a significant number of travel opportunities away from the CBD by way of a well-placed and well-serviced inner orbital rail line.
- Copenhagen offers a good geographical spread of public transport nodes with opportunities for land use intensification or greater public transport orientation, but the magnitude of associated passenger flow appears to be below that of comparable European cities.

Thus the question remains: in the light of what, all component indicators considered, amounts to an above-average supply profile for public transport in the Danish capital, why does Copenhagen's public transport usage rate not also approach the level found in cities such as Zurich, Vienna or Munich? And moreover, how is this possible in a core city which retains a comparatively low rate of car ownership and usage compared to its European peers, and where public transport's main competitor thus arguably has a weaker position than in many other cities?

There are likely to be answers to this question in the realm of cultural or historic nuances, community attitudes to public transport and other modes of transport, the incentive structure of the fare system or even the pronounced seasonality of the Nordic climate, all of which are beyond the scope of this paper. But a small data item from Kenworthy and Laube's (2001) multi-city data collection on average trip lengths might provide a tentative clue. On these figures from the mid-1990s, the authors found an average public transport journey in Copenhagen to amount to 8.0 km in length, one of the highest such figures among their European sample. In Zurich, Munich and Vienna, the equivalent figures were between 3.5 and 5.6 km. Clearly, there is a much greater role in the Alpine cities for shorter journeys on public transport than in Copenhagen, where there appears to be a greater prevalence of longer journeys. And this notion, in turn, may well be associated with the greater role of the bicycle in Copenhagen compared to its three central European cousins. Aided by a corridor-based (rather than area-wide) heavy rail system with relatively high average speeds, Copenhagen's public transport in inner areas may simply be outcompeted by the bicycle when it comes to shorter journeys that would mostly be captured by surface modes. This situation then depresses overall trip-making rates on public transport. From a sustainability perspective, substituting bicycle trips for potential bus trips is scarcely an undesirable outcome. But it also appears as though Copenhagen's post-2000 cycle of public transport infrastructure investment, with its centre piece being the establishment and expansion of a driverless metro system in the inner area with short station spacings, was almost designed to allow public transport to make further inroads precisely into this currently bicycle- dominated market.

References

Curtis C, Scheurer J (2010) Planning for Sustainable Accessibility. Developing Tools to Aid Discussion and Decision Making. Progress in Planning, Vol 74, pp53-106

Danmarks Statistik (DST, 2010) Statistisk Årbog 2009, available online at www.dst.dk

Gehl J, Gemzøe L (1996) Public Spaces Public Life, Copenhagen. Arkitektens Forlag, København, Danmark

Gehl J, Gemzøe L, Kirknæs S, Søndergaard B S (2006) New City Life. Arkitektens Forlag, København, Danmark

Gremscoe T (2012) Straphanger. Saving Our Cities and Ourselves From the Automobile. Times Books, New York (NY), USA

Kenworthy J, Laube F (2001) The Millennium Cities Database for Sustainable Cities. Union Internationale des Transports Publics (UITP), Bruxelles, Belgium and Institute for Sustainability and Technology Policy (ISTP), Murdoch University, Perth (WA), Australia

Mees P (2010) Transport for Suburbia. Beyond the Automobile Age. Earthscan, London, UK

Nielsen G, Nelson J D, Mulley C, Tegnér G, Lind G, Lange T (2005) Public Transport – Planning the Networks. HiTrans Best Practice Guide 2, Civitas Consultants, Oslo, Norway

Porta S, Crucitti P, Latora V (2006a) The Network Analysis of Urban Streets: A Dual Approach. Physica A: Statistical Mechanics and its Applications, Vol 369, No 2

Porta S, Crucitti P, Latora V (2006b) The Network Analysis of Urban Streets: A Primal Approach. Environment and Planning B: Planning and Design, Vol 33, pp 705-725

Scheurer J (2010) Benchmarking Accessibility and Public Transport Network Performance in Copenhagen and Perth. 33rd Australasian Transport Research Forum (ATRF), Canberra (ACT), Australia, September 2010

Scheurer J, Curtis C (2012) How to Benchmark Public Transport Accessibility in European Cities. 25th AESOP Congress, Ankara, Turkey, July 2012

Svensson O (1981) Dansk Byplan Guide. Miljøministeriet, Planstyrelsen, Dansk Byplanlaboratorium, Copenhagen, Denmark

Walker J (2012) Human Transit. How Clearer Thinking Can Enrich Our Communities and Our Lives. Island Press, Washington (DC), USA