Spatial network analysis for multimodal urban transport systems (SNAMUTS): A planning support tool

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Spatial Network Analysis in European Cities

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A The European case study cities

This second monograph volume will expand the range of public transport accessibility case studies to a group of eleven European cities and conurbations, and review the results of the fieldwork exercises, undertaken between 2009 and 2012, in the context of the earlier work from Australasian cities and the methodological elaborations about the Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool documented in the first volume (Scheurer et al, 2012). Part A will provide an overview of comparative SNAMUTS results for the European case study cities of Amsterdam, Barcelona, Edinburgh, Hamburg, København, München, Porto, Utrecht, Wien, Zuid Holland and Zürich, and introduce the methodological approaches taken in these places. Part B will then discuss SNAMUTS outcomes and the relevant policy context in more detail for each case study city in turn. Part C will conclude by attempting to determine the role the SNAMUTS work plays within the larger body of accessibility research and practical applications that have been undertaken across Europe in recent years.

1. SNAMUTS in European cities: A Synopsis

This section will provide a an overview of the contextual conditions for public transport across the eleven European case study cities, and present the key findings from the SNAMUTS analysis in a comparative format. More in-depth material on each of the case study cities will be presented in Part B.

Urban structure, public transport usage and mode choice patterns

Table A1 presents an extract of key data from the 2001 Millennium Cities database (relating to the survey years 1995/96), a collaboration between UITP and Murdoch University on transport and land use data in some 100 cities world-wide. Out of the eleven European cities from the SNAMUTS sample, this database contains only seven cities (leaving out Edinburgh, Porto, Utrecht and Zuid Holland).

Table A1: Urban density, public transport boarding and mode share data from seven European cities in 1995. Source: Kenworthy and Laube (2001)

Millennium Cities Database (1995)	Amsterdam	Barcelona	Hamburg	København	München	Wien	Zürich
Residential density per urbanised hectare	57.0	197.1	38.4	28.5	55.7	69.4	44.3
Employment density per urbanised hectare	29.0	69.3	22.3	15.0	32.3	37.1	30.6
Annual PT boardings per capita	326	231	240	212	466	472	505
Annual PT passenger km per capita	1,136	1,764	1,446	1,704	2,622	1,642	2,503
Private motorised transport mode share by trips	31.3%	48.3%	61.6%	54.3%	40.4%	41.5%	46.0%
Public transport mode share by trips	17.2%	26.3%	13.7%	15.6%	27.3%	30.3%	19.7%
Non-motorised transport mode share by trips	51.4%	25.5%	24.7%	30.1%	32.3%	28.3%	34.2%

While this small overview of 17-year-old contextual data may in parts have been superseded by land use and transport trends emerging during the intervening period, the table contains a few interesting pointers to the differences between European cities, pointers that have contributed to informing our choice of these (and other) cities as SNAMUTS case studies. Firstly, there is an enormous bandwidth of average urban densities that is indicative of a range of city building traditions across the continent, relating to cultural history and geographical/climatic conditions as well as contemporary policy priorities. The lowest average density is found in the two Nordic cities of Hamburg and Copenhagen, where a low rate of winter insolation and a temperate summer climate informed a long-standing urban design tradition of generous setbacks between buildings. The highest average density is found in Mediterranean Barcelona, a region where the combination of tall buildings and narrow streets has traditionally been used to shade public spaces and shelter them from the summer heat. Also of interest is the ratio between population and employment apparent from the average density figures. In five of the seven cities the number of jobs amounts to between 50 and 60% the number of residents. In Zurich, however, this ratio climbs to nearly 70%, suggesting that the city might act as an ‘employment sponge’ for commuters from beyond the metropolitan region. In contrast, in Barcelona, the ratio is as low as 35%, suggesting that the Catalan capital, which in 1995 had the lowest gross regional product of the seven cities (Kenworthy and Laube, 2001), might have a significantly lower rate of labour market participation than its peer cities further north.

In terms of public transport use, the sample divides into two distinct groups of cities with a relatively high public transport mode share (Barcelona, Munich and Vienna) and those with a relatively low one (Amsterdam, Hamburg and Copenhagen – though mode share here is still higher than in any Australian city), with Zurich occupying something of an intermediate position. In Hamburg and Copenhagen, the subdued role for public transport lifts the modal share for cars above the 50% mark, whereas in Amsterdam, non-motorised transport seems to fill the gap. In Munich, Vienna and Zurich, the high public transport mode share is also matched by high rates of boardings per capita (note that a ‘trip’ in Kenworthy and Laube’s definition may consist of several ‘boardings’ whenever transfers are made). In Barcelona, this is not the case, and the rate of public transport boardings per capita is similar to that found in the lower mode share cities of Hamburg and Copenhagen. This observation may be indicative of the significance afforded to integrated planning and ticketing, and to a network design that aims to encourage and facilitate transfers, in the northern and central European cities with a long-standing tradition of regional transport associations *(Verkehrsverbünde)*. Barcelona only arrived at full integrated ticketing after the reference year of 1995, and as we will explore in Part B, continues with a network design that does not capitalise much on the potential for widespread and easy intermodal transfers.

Lastly, it is instructive to highlight the ratio between annual boardings per capita and annual passenger km per capita, since these figures follow different patterns across the sample of seven cities. The highest ratio – equivalent to average journey leg length per boarding – can be found in Barcelona and Copenhagen (7.6 and 8.0 km, respectively), suggesting that public transport’s role in both cities is dominated by journeys beyond the typical range of walking and cycling trips. In fact, it doesn’t appear unreasonable to hypothesise that the easy walkability of high-density Barcelona, and the easy cyclability of low-density Copenhagen may act to supress the uptake of short public transport journeys. In contrast, average passenger km per boarding are as low as 3.5 km in Amsterdam and Vienna, well within easy cycling range, and suggest that public transport appears to be in a competitive position for short journeys in these cities. Perhaps this is related to the presence of expansive and dense surface tram networks in both Amsterdam and Vienna, a mode that was absent from Barcelona in 1995 and remains absent from Copenhagen to this day.

To capture the trends in population and job density as well as public transport usage since 1995 in our case study cities, we have attempted to update these figures from current information as close to the year of our fieldwork in the respective city as possible. The results are summarised in Table A2.

Table A2: Metropolitan population and jobs, urban density and public transport boarding and mode share data from eleven European cities between 2009 and 2011. Sources: CBS (2012); ATM (2009); TMB (2012); Lothian Buses (2012); Statistikamt Nord (2012); LSKN (2012); HVV (2012); DSB (2012); Trafikselskabet Movia (2012); Metroselskabet (2012); MVV (2012); MVG (2012), BLSD (2012); STCP (2012); VOR (2012); Wiener Linien (2012); Statistik Wien (2012); VBZ (2012); ZVV (2012); BFS (2012)

Contextual Data	Amsterdam (2010)	Barcelona (2011)	Edinburgh (2011)	Hamburg (2010)	København (2009)	München (2011)	Porto (2009)	Utrecht (2010)	Wien (2011)	Zuid Holland (2010)	Zürich (2011)
Metropolitan population	2.16m	4.85m	1.27m	3.37m	1.85m	2.69m	1.23m	1.20m	2.48m	3.46m	1.44m
Metropolitan employment	0.96m	2.12m	0.58m	1.66m	0.70m	1.55m	0.52m	0.54m	1.18m	1.30m	0.86m
Urbanised land in sq km	952[1]	743	342	1,492	734	888	360	355	520	919	378[2]
Residential density per urbanised hectare	32.0[1]	65.3	37.1	22.6	25.2	30.3	34.2	33.8	47.7	37.6	35.6[2]
Employment density per urbanised hectare	14.2[1]	28.5	17.0	11.2	9.5	17.5	14.4	15.2	22.7	13.1	21.2[2]
Annual PT boardings	449.0m	935.5m	149.0m	676.3m	397.6m	886.0m	182.6m	154.0m	978.6m	490.0m	590.0m
Annual PT boardings per capita	208	193	117	201	215	328	148	128	394	142	401

[1] Urbanised area figure relates to the entire provinces of Noord Holland and Flevoland, which stretch beyond the Amsterdam metropolitan area definition (combined residential population in 2010: 3.04 million).
[2] Urbanised area figure is for 2009 and relates to Kanton Zürich only (residential population in 2009: 1.34 million).

The eleven cities in the sample differ in size, roughly breaking into three groups. The largest conurbations in terms of population are Barcelona, Zuid Holland and Hamburg, though they differ quite dramatically in settlement form: Zuid Holland is a polycentric region with two separate primary urban centres (Rotterdam and Den Haag) and a number of secondary ones (Leiden, Delft, Zoetermeer, Gouda, Dordrecht). In Hamburg and Barcelona, the hierarchy of centres, while not free from polycentric elements, is far more traditionally structured with the primary centre at the geographical and functional heart of the metropolitan area and the secondary ones acting as satellites. Barcelona, however, accommodates a larger population than Hamburg on half the area of urbanised land, a testimony to the two cities' aforementioned contrasting city building traditions as well as Barcelona's formidable topographical constraints for expansion, with most urban settlement perched along a relatively narrow strip between a coastline and a mountain range. Amsterdam and Utrecht also share some multi-nuclear settlement characteristics with neighbouring Zuid Holland, together forming a regional urban agglomeration of some 7.7 million inhabitants known as the Dutch Randstad. Conversely Copenhagen, located on an island, only developed a significant functional interdependency with neighbouring Malmö during the last decade, following the opening of a fixed crossing across the Øresund. Vienna and Munich are inland centres without major geographical constraints to their expansion (other than protected nature reserves) within normal commuting distance. Zurich, not unlike centres in the Dutch Randstad, has a pronounced regional interdependency with urban centres across most of the German-speaking part of Switzerland, including Basel and Bern which are approximately an hour-long train ride away. Here, the core city holds only about a quarter of the metropolitan population, lending weight to a multitude of dispersed smaller centres separated from the core city and from each other by mountain ranges, greenbelts and lakes. Edinburgh and Porto are the primary centres of metropolitan regions of roughly similar size, though Edinburgh shares commuting catchments with neighbouring Glasgow in ways that have no equivalent in stand-alone Porto.

In the SNAMUTS project, the sometimes difficult task of arriving at a suitable definition for the extent of the metropolitan area was, in most cases (Barcelona, Hamburg, Copenhagen, Munich, Porto, Vienna and Zurich), informed by the geographical coverage of integrated ticketing under the auspices of the regional public transport association. In Edinburgh, where there is no integrated ticketing, and in the Netherlands, where integrated ticketing (for modes other than national rail) covers the entire country, metropolitan area definitions were derived from spatial planning documents, though it should be noted that in both cases (as well as in other cities in the sample) there is no conclusive consensus concerning the most suitable definition of a functional metropolitan region.

Urban densities across the sample show a remarkable similarity between the Scottish, Dutch, Swiss, South German and Portuguese cities. Only in the two Nordic cities (Hamburg and Copenhagen) are average densities significantly lower, commensurate with the findings from Kenworthy and Laube cited earlier. Vienna's and particularly Barcelona's urban density, in contrast, are significantly above the European average. In the case of Barcelona, this circumstance was one of the prime drivers for including the city in the sample; however when measured at the scale of the metropolitan region, the figure remains dramatically below that in the Millennium Cities database.

Some of the data presented in Table A2 is not beyond contestation in terms of compatibility between cities. During our fieldwork, we found (or suspected) that there are differing definitions on what constitutes a job (full-time, part-time, self-employed, marginal employment) and on what is counted as urbanised land and what is not. Both dilemmas have a bearing on how metropolitan activity densities are calculated. The figures presented should hence be taken with some caution. Denmark, Germany, the Netherlands and Switzerland provide detailed countrywide land use statistics that show the amount of urbanised land at a county/provincial/canton or even municipal level (urbanised land is defined as all land not covered by agricultural or forestry uses, water, mining operations, nature reserves or idle). In Austria, this was only the case for the city-state of Vienna but not the surrounding states within the metropolitan region. Here as well as in Barcelona, Edinburgh and Porto, we employed a technique previously used in the Australian cities which counted a statistical unit (census block or similar) as urbanised if it had a density of at least five residents or five jobs per hectare. Obviously, this procedure might lead to irregularities where such statistical units are of varying average sizes or configurations between cities.

The collection of public transport boarding data also presents some problems, as boardings are not always reported according to the same definition between public transport agencies. Generally, the intention of SNAMUTS is to count boardings separately by transport mode while discounting for transfers between routes of the same mode. This appears pragmatic, for example, when accounting for passenger movement into the paid areas of metro systems where passengers usually only pass the fare gates once per journey, regardless of the number of transfers they might make within the system. In Europe however, many public transport operators traditionally cover more than one mode: in Amsterdam, Den Haag, Rotterdam, Hamburg, Munich, Vienna, Zurich and Barcelona, a dominant operator, often a city subsidiary, has responsibility for both buses, trams and/or metro services and often reports passenger trips as linked trips between (but not beyond) different modes of the same operator. In some cases, unlinked boarding figures are also reported, allowing for a reconstruction of the numbers in the desired format. In the Netherlands in particular, location-specific boarding data from some regional operators is entirely unavailable; the figures reported here, while calculated generously, refer only to boarding data from the national railway (NS) and the city public transport operators in Amsterdam (GVB), Den Haag (HTM), Rotterdam (RET) and Utrecht (GVU and Sneltram), with some understatement likely to remain. Thus the compatibility of the figures shown in Table A2 remains far from perfection and should be taken as a guide only.

That having said, the numbers suggest that there are three distinct categories of trip-making intensity in the sample. Edinburgh, Porto, Zuid Holland and Utrecht have below 150 trips per capita per year and are thus comparable to Melbourne or Sydney. Barcelona, Hamburg, Amsterdam and Copenhagen hover around the 200 trips per capita mark, while Munich, Vienna and Zurich each achieve more than 300 trips per capita per year. While the absolute figures are far from identical to those found by Kenworthy and Laube (2001), with the main reason for the discrepancy likely to be differing counting methods, it is notable that the two latter categories of trip-making intensity are also discernable and apply to the same cities in this earlier work.

Institutional structures of public transport

There is a prevailing pattern in most of the European case study cities of a long-standing coexistence of a national rail operator providing suburban and regional services, a dominant multi-modal city subsidiary operator whose responsibility is usually largely limited to the relevant jurisdiction, and a range of smaller bus (and sometimes rail) operators, in some cases privately owned, servicing the metropolitan region outside the core city limits. A statutory authority with representation from both the core city and regional governments acts as a strategic and tactical planning agency as well as a collector and distributor of integrated public transport fares.

Hamburg, Munich, Porto, Vienna and Zurich are close representatives of this theme, as is Barcelona with the variation of an additional rail operator owned by the regional (Catalan) government, and the presence of a private operator for the (recently reintroduced) tram system. In the Netherlands, city subsidiary operators are responsible for public transport services (bus, tram and metro) in Amsterdam, Rotterdam and Den Haag. In regional areas in the Randstad beyond the limits of these three core cities, there is a system of area-wide contracting of private operators for particular corridors or sub-regions. The country's rail system is operated by a national agency, though some branch lines are contracted out to the private sector. An electronic ticketing system (OV-chipkaart) applies to all urban and regional public transport across the country (bus, tram, metro) and charges fares according to distance travelled (passengers must tag on and off as they enter and leave each vehicle or metro station). While the OV-chipkaart can also be used to pay fares on the national rail system by simply tagging on and off, there are no discounts to travellers who transfer between rail and urban public transport modes. Hence, it is not quite accurate to speak of integrated fares between the two systems – on national rail, the OV-chipkaart acts more as a payment option than as a genuine ticket choice.

In Copenhagen, a regional transport authority collaborates with the national rail operator (responsible for the suburban rail system) and the public-private metro operator while contracting most bus services to private operators. In Edinburgh, there is no regional transport authority in the continental sense, and while a single private bus operator (Lothian Buses) clearly dominates service delivery, competition between operators even along the same routes is encouraged by the governance system and does in fact occur in some cases.

Ticketing systems

Most European case study cities offer full integrated ticketing, and the price levels of different ticket options in the majority of cities is such as to reward the purchase of periodical tickets over single or daily ones. Several cities also offer discounted annual bulk tickets targeted at employers to salary-package for their staff. As a result, the share of public transport users on weekly, monthly or annual tickets is substantial: in Hamburg, for instance, it amounted to 73% of all passengers in 2010 (HVV, 2012).

Electronic ticketing systems have been introduced across the Netherlands, where paper tickets remain available but attract a hefty surcharge, and in Porto. In the Netherlands, the shift to an electronic ticketing system (OV-chipkaart) also coincided with the abolition of fare zones for single tickets – the fare is now by distance and is automatically calculated as users tag on and off their OV-chipkaart. In most other cities, a zonal fare system remains in place. The exception is the bus system in Edinburgh, where each operator charges their own flat fares, with an emphasis on single and daily tickets.

Table A4: Overview of ticketing systems in case study cities

	Randstad Holland	Barcelona	Edinburgh	Hamburg	København	München	Porto	Wien	Zürich
Single Tickets	Paper (pricey) and electronic Integrated, but separate ticketing for national rail and other public transport	Integrated fares (zonal) and some parallel single-mode fares (FGC, RENFE)	Single-mode and single-operator, flat fares on buses	Integrated, zonal	Integrated, zonal (paper and electronic)	Integrated, zonal	Integrated, zonal (paper and electronic) Some minor operators outside the system	Integrated, zonal	Integrated, zonal
Transfers on single tickets	Fares are by distance (regardless of transfer frequency)	Unlimited within validity period	Not permitted	Unlimited within validity period (excludes journeys back to origin)	Unlimited within validity period	Unlimited within validity period	Unlimited within validity period (electronic tickets only)	Unlimited within validity period	Unlimited within validity period
Day Passes	Available for urban public transport operators only	Integrated	Single-mode and single-operator	Integrated (discount for off-peak)	Integrated (core city and all zones only)	Integrated (discount for off-peak)	Integrated (24 hours)	Integrated (24, 48 or 72 hours)	Integrated (24 hours)
Periodical Tickets	Integrated tickets for national rail (route-based) and urban public transport (area-based) available	Integrated	Single-mode (Lothian Buses) Some integrated rail-bus options available	Integrated (discounts for off-peak)	Integrated. zonal	Integrated (discounts for off-peak)	Integrated	Integrated	Integrated

Service intensity

The SNAMUTS timetable database, compiled for each case study city at the SNAMUTS *20* minimum service standard during the weekday inter-peak period, provides us with the numbers of public transport vehicles that are required to be in simultaneous revenue service in order to deliver the extent of the public transport network that is operated at this standard. Note that the figures for the actual numbers of vehicles required by the operators are somewhat higher than that, as the SNAMUTS calculation does not make provision for service breaks at the termini, contingencies for delays or disruptions, non-revenue journeys, and for vehicles undergoing scheduled or unscheduled maintenance. Nor do these figures reflect the usually greater numbers of vehicles required to operate peak hour services.

Table A5: Service intensity in the European case study cities

SNAMUTS *20*	Amsterdam (2010)	Barcelona (2011)	Edinburgh (2011)	Hamburg (2010)	København (2012)	München (2011)	Porto (2009)	Utrecht (2010)	Wien (2011)	Zuid Holland (2010)	Zürich (2011)
Number of trains/ S-Tog/ S-Bahn/ rodalies	56	36 (FGC)[1] 38 (RENFE)	13	47	64 (S-Tog) 24 (R-Tog and Lokalbaner)	52	4	30	49	43	65
Number of metros/ U-Bahn/ LRT	23	114[2]	-	54	16	38	30	8	55	49	-
Number of trams	136	26	-	-	-	60	1[3]	-	247[4]	167	130[5]
Number of buses	401	861	458	439	341	230	271	152	280	309	169
Number of ferries	1	-	-	5	2	-	-	-	-	3	2
Number of services (total)	617	1,074	472	545	444	279	305	190	628	570	3659
Metropolitan population	2.16m	4.85m	1.27m	3.37m	1.85m	2.69m	1.23m	1.20m	2.48m	3.46m	1.44m
Services per 100,000 inh	28.5	22.1	37.2	16.2	24.0	14.1	24.8	15.8	25.4	16.5	25.3

[1] Includes Vallvidrera cable car
[2] Includes Montjuïc cable car
[3] Cable car
[4] Includes WLB light rail
[5] Includes Forchbahn and BDWM light rail, Polybahn, RIgiblick and Dolderbahn cable cars

The SNAMUTS *20* standard imposes a restriction on what proportion of each city's public transport network actually enters the analysis. For instance, in each European case study city, there are regional rail lines that are operated at frequencies of 30 minutes or 60 minutes and thus do not meet the minimum service standard. The same is usually true for a sizeable proportion of the bus network, especially outside the contiguously urbanised areas. Conversely, metro, light rail and tram routes almost consistently meet the SNAMUTS *20* standard, with only a few minor exceptions in Porto.

On the one hand, the exclusion of lower-frequency routes from the SNAMUTS analysis helps to more clearly define a metropolitan area expansion since in most cases, services at the SNAMUTS *20* standard do not cross metropolitan area boundaries. On the other hand, and as discussed at length in Volume 1 of this monograph, it is arguable that half-hourly rail services are still perceived by most users and stakeholders as structuring components of the land use-transport system, which SNAMUTS is attempting to assess. For this reason, an alternative minimum service standard that allows for the inclusion of rail and ferry services (but not bus services) at a 30-minute frequency has been devised (SNAMUTS *23*), applied to all European case study cities and will be presented alongside the results for the SNAMUTS *20* standard throughout this monograph.

Relative service intensity (ie. 'services per 100,000 population') reveals some variation across the sample. The lowest service intensity figures are on record for the Dutch cities (except Amsterdam) and the German cities, especially Munich where a network design with a highly efficient allocation of transport tasks to the most suitable mode has been progressively implemented over the last 50 years, and acts in concert with a frugal approach to service frequencies in comparison to most of its peer cities. Of the continental European cities, Amsterdam has the highest number of public transport vehicles in simultaneous revenue service per capita, while the highest level in the sample, by quite a significant margin, is on record for Edinburgh.

The service intensity indicator is influenced by the propensity of public transport agencies and operators to provide resources to run the system as well as by its efficiency: a dominant role for fast high-capacity modes, particularly heavy rail, will depress relative service intensity figures, while a large number of high-frequency, slow-moving surface routes tends to inflate them. The intensity figure also increases where settlement areas are dispersed or separated by geographical barriers, thus lengthening journey distances and times between places of activity. High service intensity scores are therefore not necessarily indicative of better service, but they may well be indicative of the level of resources stakeholders within a city-region are politically and economically prepared to mobilise and allocate to public transport operation.

In this context, it is unsurprising that Edinburgh, home to the most bus-dominated public transport network in the sample, comes out with the highest service intensity figure and Zuid Holland, the most rail and tram-dominated region, comes out with one of the lowest. Part, though not nearly the full extent of Edinburgh's steep figures on this index are related to the deregulation regime governing public transport delivery across the UK, leading to the provision of competing services by several bus operators along some of the same corridors. The difference between Copenhagen and Hamburg, however, both of which have comparable roles for rail and bus-based modes, is mostly due to Copenhagen operating a far denser and more multi-directional bus network than Hamburg, an observation that will occupy us further in subsequent steps of the analysis.

Closeness and Degree centrality

These two indicators are designed to capture the structural properties of the public transport networks; they do not incorporate a land use dimension beyond defining the number and location of activity centres. Closeness centrality considers accessibility in a way most closely described as 'ease of movement'. An average score for travel impediment (travel time divided by service frequency) is calculated between any two activity nodes on the network. The final figure for each activity node represents the average impediment score for all journey possibilities between this node and all others on the SNAMUTS *20* public transport network. Degree centrality considers accessibility by public transport from the perspective of number of transfers required to make a journey between any two centres. The figure given for each node thus describes the average transfer intensity for journeys to or from all other nodes on the network (Table A6).

Table A6: Closeness and Degree centrality in the European case study cities

SNAMUTS *20*	Amsterdam (2010)	Barcelona (2011)	Edinburgh (2011)	Hamburg (2010)	København (2012)	München (2011)	Porto (2009)	Utrecht (2010)	Wien (2011)	Zuid Holland (2010)	Zürich (2011)
Number of activity nodes	132	225	97	176	132	166	94	69	181	205	127
Average Closeness Centrality	36.4	28.1	47.0	35.3	30.8	35.7	35.8	42.5	27.2	45.1	31.5
Closeness (lowest value)	20.6	15.1	24.8	19.6	16.9	19.1	19.6	23.6	15.2	26.5	17.0
Closeness (highest value)	89.9	112.3	125.7	92.9	159.6	94.4	122.0	87.6	117.9	146.6	73.4
Average Degree Centrality	1.14	1.13	0.99	1.07	0.87	0.90	0.91	1.21	1.21	1.60	1.29

For both indicators, lower figures indicate greater metropolitan public transport accessibility in principle. Comparisons, however, need to be seen in a broader context to allow for valid conclusions across the sample. Firstly, on both closeness and degree centrality we should expect average results to increase with city size (measured here by the size of the public transport network and its number of activity nodes within the area covered by services at 20-minute frequencies or better) and the resulting complexity of the public transport network. On this basis, all other things being equal, smaller networks will invariably return better average, lowest and highest closeness values than larger networks, as well as lower counts of degree centrality (ie. transfer intensity). From this perspective, it should come as no surprise that Edinburgh and Porto, two of the smallest cities in the sample, return relatively low average degree centrality values. Similarly, smaller network size explains part of Copenhagen's superior performance on the closeness index compared to Hamburg, Munich and Zuid Holland. But even within this sample of eleven cities, there are a lot of deviations from this pattern.

Other factors influence the closeness centrality score and can provide a useful insight into where improvements to accessibility can be made. Closeness centrality is measured by travel impediment, which in turn is composed of travel time and service frequency. Cities where activity centres are spaced further apart (in terms of public transport travel time, not necessarily metric distance) or in other words, cities with more dispersed settlement patterns and more convoluted links between places of activity are at a disadvantage for public transport accessibility compared to more compact ones or ones with faster public transport systems. Compactness, in this context, is not necessarily equivalent to density: Part the reason for Copenhagen's low (good) average, lowest and highest closeness scores can be found in the city's location on an island, whose coastline effectively contains the settlement area and ensures that outward growth can only occur within an approximate 135-degree segment of a circle. Topographical constraints also work to improve closeness performance in Barcelona and to a lesser extent Vienna, where a large protected area of hilly, forested open space to the west of the city acts as a growth boundary of similar effectiveness as the coastlines in the Danish and Catalan capitals.

Conversely, the relatively high (poor) average, highest and lowest closeness centrality scores in Zuid Holland are linked to this conurbation's multi-nuclear form without a single overarching centre. Since the closeness matrix treats every origin-destination pair on the network as equally weighted, the spatial separation between dispersed centres, even where these might have compact and contained settlement areas in their own right, is making itself felt here. This is also manifest in the high average transfer intensity of Zuid Holland's network, where several individual cities (Leiden, Den Haag, Rotterdam and Dordrecht) operate self-contained urban networks which are only connected by a limited number of rail and metro lines between them at a regional scale. The spatial pattern of Zurich's agglomeration partially mirrors the situation in Zuid Holland; however, better closeness and degree centrality results (and particularly the relatively small range between lowest and highest closeness score) suggest that there is a more cohesive approach to favour the interaction of land use and public transport in the Swiss city-region.

On the other hand, it is precisely the presence of fast rail connections that works to bring the closeness average down in each case study city where they exist, and thus compensate for the effect of settlement dispersal to some extent. Barcelona, Copenhagen, Hamburg and Vienna stand out on this aspect as their rail and metro systems are not only speed-competitive with road travel, but also operate at very high frequencies during business hours (5 minutes or even better throughout the inner areas). In the Dutch Randstad and in Munich, such frequencies are only achieved on metro trunk lines (in Amsterdam and Rotterdam) whereas the regional rail system, similar to Zurich, operates a mix of overlapping all-stop and intercity trains, which each stopping pattern typically operating every 15 or 30 minutes and thus usually adding up to frequencies of between four and eight trains per hour on each route (less for minor intermediate stops, some of which consequently do not meet the SNAMUTS *20* standard). In Edinburgh and Porto, the maximum rail frequency tends to be four trains per hour, and there are several suburban lines that operate only half-hourly and thus do not enter our analysis at this standard. The low frequencies on the rail system, as well as on bus routes to outer suburban and regional centres, also explain the breakout highest closeness values in the two smaller cities, which overall appear to be less successful than Copenhagen, Amsterdam, Zurich and (to a lesser extent) Hamburg and Munich in offering a uniform standard of public transport accessibility throughout their urban region. Instead, they seem to be allowing some outlying areas to contend with long travel times and/or low-frequency services, a situation that helps to push up average closeness centrality values for the entire network.

Porto's advantage over Edinburgh on the closeness index appears to be almost entirely related to the presence of a light rail network in the Portuguese city. Two mostly underground inner-city trunk lines provide travel speeds through Porto's urban core that have no match in the congested streets in the centre of the Scottish capital, some of which need to cope with more than 200 bus movements per hour even outside the peak period. Also incorporated in this index, though with only minor effects in this context, is the circumstance that Porto offers fully integrated fares with free transfers between light rail and buses, while in Edinburgh most fares are operator-specific, ie. a transfer between bus routes of different operators incurs an additional cost to the user.

Network coverage and contour catchments

The network coverage indicator is designed to query the land use patterns of the metropolitan area in question, and in particular identify those parts of it that are serviced by public transport at the minimum service standard. It measures the percentage of residents and jobs that are located within walking distance (800 metres around rail or metro stations and ferry terminals, 400 metres along tram and bus corridors) of at least one public transport service that meets this standard, and expresses them as a percentage of the total metropolitan number of residents and jobs.

The contour catchment index uses the same approach to measuring land uses, but identifies the average percentage of residents and jobs that can be accessed from each node by way of a public transport journey of 30 minutes or less. This time window can include up to one transfer as long as both legs of the transfer journey are operated at least every 15 minutes, and with a penalty deducted that is equivalent to the average transfer time across the network from arrival of the first vehicle to departure of the second vehicle. The index adds a further dimension to the network coverage assessment, in that average 30-minute contour catchments are also influenced by the density and concentration of urban settlement, the speed of public transport and the spacing of activity nodes within the metropolitan area, which can be read as a proxy measure to its degree of compactness or dispersal (Table A7).

Table A7: Network coverage and average 30-minute contour catchment in the European case study cities

SNAMUTS *20*	Amsterdam (2010)	Barcelona (2011)	Edinburgh (2011)	Hamburg (2010)	København (2012)	Porto (2009)	Utrecht (2010)	Wien (2011)	Zuid Holland (2010)	Zürich (2011)
Network Coverage	2,446,000 (78.3%)	5,064,000 (72.7%)	1,037,000 (55.9%)	2,749,000 (54.6%)	1,811,000 (71.2%)	1,086,000 (62.0%)	931,000 (53.6%)	2,821,000 (77.0%)	2,965,000 (62.3%)	1,469,000 (63.9%)
Average 30-min contour catchment	599,000 (19.2%)	1,752,000 (25.1%)	259,000 (14.0%)	880,000 (17.5%)	793,000 (31.2%)	346,000 (19.7%)	274,000 (15.8%)	1,168,000 (31.9%)	521,000 (11.0%)	527,000 (22.9%)

Across the sample, network coverage ranges from a low of between 54% and 56% in Utrecht, Hamburg and Edinburgh to a high of between 72% and 78% in Copenhagen, Barcelona, Vienna and Amsterdam. Some of this variation is explicable when considering the figures in conjunction with the service intensity index discussed above: cities that put more resources into public transport operation should be able to provide a larger network (relative to city size) that services a greater percentage of its urbanised area. This pattern is clearly present in the comparison between Copenhagen, Amsterdam or Vienna with Hamburg. But it does not yet explain why Hamburg falls even behind Zuid Holland despite having a comparable level of service intensity. A possible reason, also observed in Vienna and Munich, is that historically, public transport provision in Hamburg has been a local government responsibility, meaning in this case the city-state of Hamburg which in 2010 comprised only just over half of the metropolitan area population. Hamburg may have been a global pioneer in the conception of the first integrated public transport agency as far as back as 1965; however, only during the last decade did this governance model grow significantly beyond the city-state borders to encompass the seven neighbouring counties in Schleswig-Holstein and Lower Saxony in their entirety. And while some metro and regional rail services have since been improved and extended to regional centres, on the whole the outer metropolitan area remains characterised by a legacy of urbanisation that was either focussed on regional rail services with frequencies too low to meet the SNAMUTS *20* standard, or without much public transport orientation at all. Zuid Holland is by no means free of comparable settlement and public transport service patterns, but its multi-nuclear nature ensures that there is a lower number of regional centres than in Hamburg without services that meet the SNAMUTS *20* standard, and that these tend to be smaller than their northern German counterparts.

In Edinburgh, the second lowest network coverage figure paradoxically coincides with the highest service intensity figure, for reasons that resemble those discussed in the context of Hamburg: a high level of penetration of the core city with bus services at reasonable (and in some cases, extremely high) frequencies is countered by a very patchy network in the wider metropolitan region, including only a minority of regional rail lines that meet the SNAMUTS *20* standard.

On the average 30-minute contour catchment size, Copenhagen and Vienna deliver another breakout performance within the sample that reflects several observations already made earlier, namely the high speed and frequency of both cities' suburban rail and metro networks and the dense grid of tram (Vienna) and bus routes in the inner area. The combination of these two factors maximises both the number of destinations that can be reached within the time window, and the number of trips for which no transfer is necessary. The next best performer is Barcelona, where a larger size of the metropolitan area (nominally reducing average contour catchments in percentage terms) is partially compensated by the extraordinarily high settlement density, which leads to a greater average number of residents and jobs in each activity node catchment than in any other city in the sample. At considerable distance, the figures for Porto, Amsterdam and Hamburg are relatively similar, considering that this index, like closeness centrality, can be expected to decline with growing city size and geographical complexity (and the ensuing difficulty to provide short travel times across a large settlement area). The reasons why Edinburgh and Zuid Holland trail the sample on this index are also quite straightforward: in Edinburgh, the slow average speeds on a bus-dominated network and the patchy configuration of public transport services outside the core city conspire to depress the average contour size, while in Zuid Holland, the dispersed nature of settlement across a multitude of spatially separated urban centres is the key driver for the low figure.

Betweenness centrality

The last SNAMUTS index discussed in this introductory chapter tries to measure the geographical distribution of travel opportunities across the networks' nodes and route segments as generated by the land use system and the configuration and service levels of the public transport network. Betweenness is a dynamic index, acknowledging that fast and frequent services between a pair of centres will be more attractive for urban movement than slow and infrequent services between another pair of centres of similar size. The index is designed to highlight which centres and public transport routes are 'at the crossroads' of movement across the metropolitan area, and how well different modes fare in terms of attracting such movement opportunities, not least with a view to their varying passenger capacity. The global betweenness index represents an attempt to benchmark the attractiveness of the public transport system as a whole to facilitate movement and accessibility across a case study city, and may allow for an insightful comparison within our eleven-city sample (Table A8).

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Table A8: Betweenness centrality in the European case study cities

SNAMUTS *20*	Amsterdam (2010)	Barcelona (2011)	Edinburgh (2011)	Hamburg (2010)	København (2012)	Porto (2009)	Utrecht (2010)	Wien (2011)	Zuid Holland (2010)	Zürich (2011)
Global betweenness index	1,726	5,494	677	1,612	1,879	736	864	2,364	844	938
Average nodal betweenness	55.2	170.5	33.3	51.6	67.8	34.5	45.1	72.3	24.1	27.4
Average catchment (residents and jobs) of typical path length	78,000	157,000	51,000	88,000	65,000	51,000	49,000	91,000	85,000	43,000
Segmental betweenness Rail/S-tog/S-Bahn/rodalies	24.5%	10.1% (FGC)[1] 10.4% (RENFE)	8.7%	27.8%	43.1% (S-Tog) 9.5% (R-Tog and Lokalbaner)	1.9%	21.4%	12.7%	32.4%	44.5%
Segmental betweenness Metro/U-Bahn/LRT	14.1%	49.5%[2]	-	33.5%	10.8%	27.3%	14.5%	42.7%	17.6%	-
Segmental betweenness Tram	21.9%	1.1%	-	-	-	0.0%[4]	-	33.1%[3]	30.7%	34.1%[5]
Segmental betweenness Bus	39.4%	29.0%	91.3%	38.3%	36.5%	70.7%	64.1%	11.5%	19.4%	21.4%
Segmental betweenness Ferry	0.0%	-	-	0.3%	-	-	-	-	-	0.0%
Segmental betweenness CBD area	29.1%	21.8%	44.0%	24.6%	28.5%	46.9%	45.2%	24.9%	21.3% (Rotterdam) 18.9% (Den Haag)	35.2%

[1] Includes Vallvidrera cable car
[2] Includes Montjuïc cable car
[3] Includes WLB light rail
[4] Cable car
[5] Includes Forchbahn and BDWM light rail, Polybahn, RIgiblick and Dolderbahn cable cars

The global betweenness index appears to divide the sample firmly into two groups. It suggests that Barcelona, Vienna, Copenhagen, Amsterdam and Hamburg (in this order) are characterised by a much higher presence of public transport travel opportunities throughout their metropolitan areas than Zurich, Utrecht, Zuid Holland, Oporto and Edinburgh (again in this order). In the case of Zuid Holland and also Zurich, this is not surprising, since this index strongly rewards compact, dense and contiguously urbanised settlement areas and penalises spatial discontinuities, regardless of whether they are generated by topographical constraints or result from policy decisions or historical trends. On the other hand, the poor results for Zuid Holland as well as Zurich as a whole could also be read as an indication that both regions are characterised by two dominant and only partially compatible public transport accessibility trends: on the one hand, they continue to provide quite favourable conditions for intra-urban public transport movement within each of their centres, especially Den Haag and Zurich, and (to a lesser extent) Rotterdam and Winterthur. On the other hand, the proximity of these centres to one another generates a high volume of inter-urban travel flows. This observation invariably raises the question, already posed in previous work (Scheurer and Straatemeier, 2011), which scale of public transport accessibility is in fact the most relevant for the Dutch Randstad, or the Swiss urban network, in representing a 'daily urban system': the core city, the sub-region (the metropolitan area definitions used in this sample) or the Randstad region/northern Switzerland in their entirety?

Yet, the difference in the figures between Zuid Holland and Amsterdam, where polycentrality is less pronounced than in Zuid Holland but still a critical feature of the settlement pattern, remains striking. With a view to Copenhagen's, Barcelona's and Vienna's outstanding performance on this index, it is likely that the cities with high global and nodal betweenness results benefit strongly from a relatively intact interplay of a dense surface public transport network (dominated by trams in Amsterdam and Vienna, and buses in Barcelona and Copenhagen) and a functional pre-war, originally transit-oriented, mixed-use settlement pattern in their inner areas. In contrast, Rotterdam and Hamburg, both extensively damaged during World War II, significantly departed from this pattern during post-war reconstruction in favour of a more functionally segregated urban form with reduced urban density compared to the pre-war stock.

The influencing factors of land use density and network compactness/dispersal can both amplify and neutralise each other on this index, for which reason it is useful to devise a measure that is capable of separating the two. This is being attempted by the 'catchment of typical path length' index, which multiplies the average nodal catchment across the network by the number of activity nodes an average weighted node-to-node path passes through (a number that varies between cities according to the spacing of activity nodes, the travel impediment between them and the ability of the network to provide a choice of routes). This measure thus compensates for the compact/dispersed properties of the network in question and focuses more exclusively on land use concentrations and network coherence. As a result, Hamburg and Zuid Holland have a narrow lead over Amsterdam and Copenhagen (both pairs in this order) precisely because their networks (in the case of Zuid Holland, particularly the Rotterdam component) are configured to facilitate longer journeys on faster modes rather than the short-range opportunities that central Amsterdam's and Copenhagen's extensive surface networks excel in. Edinburgh and Porto, where slower modes dominate to an even greater extent, follow the larger cities at a quite considerable distance on this index. Conversely, in Barcelona and Vienna greater settlement density is the primary influence that leads to a top performance, whereas in Zurich, the opposite is the case.

It is remarkable that Copenhagen and Hamburg have a near-identical distribution of travel opportunities between rail and bus modes, underscoring the aforementioned significance and superior service standards of the suburban and metro systems in both cities. In contrast, in Amsterdam surface modes play a much greater role, which may be partly related to a comparatively small heavy rail network length (in relation to population) in Amsterdam as well as in neighbouring Zuid Holland. Zuid Holland, in contrast, appears to have relegated buses into an auxiliary role while Den Haag's and Rotterdam's extensive tram systems clearly dominate travel opportunities among surface modes. The same is true for Vienna, as well as Zurich, though here the significance of the regional rail system, as well as its network density, is far superior to that in Zuid Holland.

Edinburgh, Utrecht and to a lesser extent Porto remain strongly dependent on buses for the bulk of their public transport system's ability to service mobility needs arising from the land use system. In Porto and Utrecht, the metro/light rail networks, both second generation systems developed only since 1983 and 2002 respectively, arguably remain incomplete and are in fact subject to ambitious expansion plans. Barcelona also has a recently (2004) reintroduced tram system servicing middle suburban and redevelopment areas, but not yet penetrating the heart of the city. In Edinburgh, the role of its relatively extensive heavy rail infrastructure for frequent suburban services remains underdeveloped, though here too, plans are underway to address this (as well as introduce a light rail system).

The segmental betweenness scores for the CBD area – percentage of travel opportunities to, from or passing through the central city - can be expected to drop with growing city size and polycentrality, as well as a network configuration that offers attractive alternative travel paths for cross-suburban journeys. Within our sample, high-capacity orbital transport links are arguably best developed in Amsterdam and Vienna, yet it is Hamburg that comes out with a lower segmental betweenness figure for the CBD than both (very narrowly so in the case of Vienna), perhaps primarily due to its larger size and a flatter hierarchy in network significance (nodal betweenness) between the dominant CBD node and other rail hubs in its vicinity in Hamburg and Vienna than in Amsterdam.

2. Methodology

Revision of SNAMUTS indicator formulas

Volume 1 of this monograph contained a discussion on modifications to the SNAMUTS methodology that was designed to eliminate some anomalies that were experienced during the expansion of the tool to the full Australasian sample, and to better capture certain aspects of public transport accessibility that were deemed to be insufficiently or confusingly handled in earlier versions of the tool. In particular, the monograph recommended to consider:

- the inclusion of rail and ferry routes at a more lenient minimum service standard than bus routes (30 minutes during the weekday interpeak period in combination with 7-days-a-week service), to acknowledge the structuring effect fixed-infrastructure public transport routes have on the land use-transport system even at this level of service, and thus to arrive at a more complete network analysis;
- the modification of the travel impediment formula in order to de-emphasise, to the extent that it was considered excessive, the contribution of service frequencies and to afford greater emphasis to the contribution of travel times and network configuration to the measure as used in the analysis;
- the modification of the global betweenness index in order to align it better with increases or decreases in travel opportunities that result from adding or reducing network elements and land uses;
- the inclusion of a network stress index designed to pinpoint network elements whose significance as derived from the land use-transport system appears mismatched to the level of service (transport mode, frequency, travel time) provided, and to establish a further comparable standard for timeline and inter-city analysis;
- the modification of the nodal connectivity index in order to treat nodes along linear corridors with no cross-connections differently from dead-end (cul-de-sac) nodes;
- the modification of several conversion formulas from component indicators to the SNAMUTS composite index.

In the following, we will thus present the SNAMUTS results for European cities, as well as any comparisons to Australian cities, in two formats. We will utilise the original SNAMUTS *20* standard and methodology without any of the changes outlined above as well as the SNAMUTS *23* standard including the modifications. This latter standard will be referred to as SNAMUTS *23R* (R for 'revised') and labelled clearly as such in all tables and maps. Note that the revisions do not affect all SNAMUTS indicators: the service intensity, degree centrality, network coverage and contour catchment indexes will return the same results at the SNAMUTS *23* and the SNAMUTS *23R* standard.

Network stress index

This monograph will also include a new indicator, developed in the context of research consultancy projects for several local governments in metropolitan Melbourne in 2011 and 2012 (Scheurer, 2011; McIntosh et al, 2012). The **network stress** or **segmental congestion index** takes in the segmental betweenness index and draws a ratio with the actual quantitative ability

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of the public transport service to move passengers along each segment, determined by the service frequency and the size of the vehicles used. This index is designed to highlight where in the network the concentration of travel opportunities generated by the land use-transport system appears to outstrip, match or remain below the carrying capacity offered by the transport mode(s) and service levels on the route segment in question (Scheurer and Woodcock, 2011).

The starting point for building this index, namely the measure of betweenness centrality that has been a component of SNAMUTS since its inception, is already a composite index in its own right. It takes in findings from the closeness centrality index (ease of movement) as well as land use parameters, travel times and transfer intensity. For this reason, it behaves in non-linear ways: small changes in network configuration and service levels can sometimes have disproportionate effects, and the best outcomes for accessibility and network performance are not always achieved by simply maximising betweenness scores wherever possible. Rather, it is advisable that there is a good fit of betweenness values with modal performance and capacity, in that rail or metro segments should typically be characterised by higher betweenness values than tram or ferry segments, and tram or ferry segments in turn by higher betweenness values than bus segments. And while it is inevitable in a metropolitan area that betweenness centrality scores will be higher near the geographical centre of the network than at its periphery, it is further advisable that the decay curve of this discrepancy is as gradual as possible and avoids excessive spikes in betweenness values in areas or on route segments where congestion is likely to occur.

The segmental congestion/network stress index thus attempts to capture the ratio of the betweenness index score and the actual passenger capacity offered on each route segment (depending on the mode or combination of modes servicing the segment, and their service frequency). This procedure follows the logic that a bus-operated route segment will hit a congestion ceiling at a much lower number of passengers than a rail-operated route segment, given that a train is usually capable of moving more than ten times as many people as a bus.

High levels of network stress as captured in this index, however, do not necessarily correlate with an actual experience of overcrowding, and conversely, low stress levels need not always indicate ample spare capacity on the route segments in question. Beyond land use concentration and ease of movement on the public transport system (the variables that make up the betweenness index), actual usage of public transport is further influenced by factors such as the competitiveness of other transport modes (in terms of speed, availability, comfort, safety and/or user cost) and the legibility of the network (and thus the ability of passengers to easily pick the most effective journey path as suggested by the SNAMUTS analysis). To avoid a potentially congested public transport service, passengers may also employ strategies such as deciding to travel to less convenient destinations, travel via less convenient routes or forego travel altogether as long as they can absorb the subsequent reduction in amenity.

Another critical characteristic of the stress index is its dynamic reference to public transport levels of service, in that travel impediment (travel times and service frequency) in itself influences the number of travel opportunities offered along a particular route or route segment. For this reason, route segments are not necessarily relieved from high stress on this index by simply increasing the service frequency, since the additional services also increase the travel opportunities in this area. Nor do routes segments with low stress necessarily develop a more balanced ratio between travel opportunities and service level if the latter is reduced. Instead, the segmental congestion index puts far greater emphasis on the way the network hangs together as a system, and how the role and interplay of different modes with different carrying capacities can be optimised to mutual benefit.

Testing the network stress index over the full sample of European and Australian case study cities revealed that the formula originally used in just one city (Scheurer and Woodcock, 2011) led to a bias depending on the size of the network and the concentration of travel opportunities it offers, meaning that cities that score highly on these factors automatically delivered higher network stress figures than those that did not. As these parameters of network size and intensity of travel opportunities are quite neatly captured in the global betweenness index, it was decided to use this measure as a compensating component in the denominator of the formula, leading to the following calculation:

$$SC_k = \frac{\Sigma(p_{ij}(k) * (act_i * act_j)/L_{ij})}{\sqrt{(\Sigma((act_i * act_j)/L_{ij})/(1000 * N))} * f_k * c_k} \quad [1]$$

where:
SC_k = Segmental congestion index of segment k
$p_{ij}(k)$ = Paths between nodes i and j that pass through route segment k, for all i, $j \in N$ and $i \neq j$
act_i = Number of residents and jobs in catchment area of node i
act_j = Number of residents and jobs in catchment area of node j
L_{ij} = Minimum impediment value between nodes i and j
f_k = Service frequency along route segment k
c_k = Modal coefficient for route segment k
N = All activity nodes in the network

The network stress index is impacted by the package of revisions to the SNAMUTS indicators outlined above through several elements, namely the impediment value and the global betweenness index. For this reason, it will deliver different results at different SNAMUTS standards. Since the revised global betweenness measure in particular was found in Volume 1 of this monograph to behave along a more accurate and intuitive scale in this respect, we have decided to only conduct the network stress assessment at the revised (SNAMUTS *23R*) standard in this volume.

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7. Zurich, Switzerland

Switzerland's largest city is located in the German-speaking, north-eastern part of the country. It is also the population, economic and administrative centre of the Kanton (confederate state) of the same name, a geographical unit that stretches over an area of 1,752 sq km and in 2009, was home to a population of 1.34 million. Of these, only 390,000 (2011) reside in the core city of Zurich while the remainder disperses across the Kanton, whose mountainous topography interspersed by lakes generates a multitude of natural separators between pods of urban settlement. This circumstance echoes a historic pattern of strong local autonomy (there are over 170 separate local government areas within the Kanton of Zurich) and a planning system that continues to strongly enforce the protection of agricultural land at the municipal level, as well as requiring the presence of a public transport meeting a certain standard within walking distance from any urban development. *(look for sources for this)*

Thus it is fair to say that the urbanisation pattern of the Zurich region is considerably less contiguous and centralised than that of any of the other European SNAMUTS case study cities, with the partial exception of the Dutch Randstad. Nor does this pattern stop at the Kanton borders: effectively, the region forms part of a much larger urban network covering the entire north of Switzerland, a geographical triangle between the three largest German-speaking cities of Basel, Bern and Zurich, which are located within an approximate 60-minute rail journey from each other. It can be expected that this proximity generates a substantial amount of cross-commuting and other daily functional interdependencies, a notion that seems to be supported by the finding from the metropolitan-level compliation of employment data already presented in the introductory chapter and which seems to suggest that Zurich acts as an 'employment sponge' for a catchment area far exceeding its region as defined by the Kanton. This circumstance replicates a challenge already identified in our analysis of the Dutch Randstad: what is the appropriate spatial range of investigation to capture the public transport accessibility conditions relevant for the choices of users to fulfil their daily travel needs?

On the other hand, the practicalities of data collection suggest that the geographical range of our analysis be confined to pragmatic limits. Like its German, Austrian and Danish counterparts, Zurich has a regional public transport planning agency with full fare integration across all modes (Züricher Verkehrsverbund or ZVV), which covers the entire Kanton of Zurich as well as some municipalities immediately outside its borders particularly at the south-eastern edge (Pfäffikon, Rapperswil). It is the service area of this entity that came to inform our metropolitan area definition, stretching to some 1.44 million inhabitants in 2009 (the latest year for which coherent land use data was available), while acknowledging that some significant travel flows, particularly to and from the west of Zurich where the ZVV boundary is located only 12 km from the city centre, may not be sufficiently reflected in the analysis.

Our primary interest in including Zurich in the SNAMUTS sample relates to its high rate of public transport usage, as determined by passenger boardings: Kenworthy and Laube (2001) put this number down at 505 per person per year in 1995; our own (more stringently defined) updated calculation (for 2011) arrives at 401 boardings. In both cases, these figures are higher than in any other European SNAMUTS city. Clearly, Zurich's public transport system must exert a superior level of attractiveness to the travelling public – but how does this attractiveness spell out in spatial accessibility terms?

Public transport infrastructure in the Zurich region consists of an expansive heavy rail system with a mixed operation of intercity, regional and suburban (S-Bahn) services. Most of these lines run under the auspices of national rail operator SBB, except for routes S4 and S10 which are operated by a rail company mostly in joint federal, regional and local ownership (SZU). Unlike in Germany, ZVV tickets are valid on each type of train with the effect that intercity trains connecting central Zurich, the international airport and the Kanton's second largest city (Winterthur) have a not insignificant role for intra-metropolitan travel. The S-Bahn system is organised by numbered and colour-coded lines with fixed stopping patterns, the majority of which are operated every 30 minutes, seven days a week, with overlapping lines on major routes generating 15-minute or better intervals. However, the coexistence of all-stop and semi-express lines across the system has the result that some intermediate stations even on the busier routes receive only half-hourly services and thus meet the SNAMUTS *23*, but not the SNAMUTS *20* standard.

A plan to build a metro system in Zurich was defeated in a referendum in the 1970s, leading to a shift of investment priorities within the core city towards an improved and expanded tram network, and the conversion of a completed section of metro tunnel (between Milchbuck and Schwamendingerplatz in the inner north) for tram operation. Operated by a city subsidiary (Verkehrsbetriebe Zurich or VBZ) also bearing responsibility for buses, this tram network has become renowned for one of the world's most advanced traffic priority systems and a corresponding restrictive approach to private motor vehicle access in central areas. At typical 7½-minute intervals on each of the 15 lines (better where several lines overlap, like practically anywhere in the inner city), trams have a very tangible presence in Zurich's activity centres and corridors. During the 2000s, the network was extended along faster, segregated routes to cover the Glattal region in Zurich's north, an area characterised by post-war patchwork urbanisation that is home to the international airport and much associated employment. Tram infrastructure is also shared by an older regional light rail line (Forchbahn) on its city section.

Within the city of Zurich, trams in conjunction with buses and trolleybuses form a tightly woven, grid-shaped network facilitating multi-directional movement and constrained only by geography (the Uetliberg and Dolder mountain ranges to the north and south of the core city). Transfer points are clearly identified on ubiquitous, high-quality mapping material and on screens in many vehicles which display real-time departures of connecting services, complete with recommendations to hurry whenever transfer times are tight. Well-timed transfers are also a feature of many hubs in the surrounding region, with a pulse timetable system applied between trains and buses particularly where frequencies on both modes drop to 30 minutes. Within the city of Winterthur, there is a separate urban trolleybus operation; however, in this smaller agglomeration the network structure is of a more radial nature, focussed on the central railway station as the dominant transfer hub.

There are 45 fare zones in the ZVV area, and ZVV tickets are valid for unlimited transfers between all modes of transport including intercity trains. Fares are calculated according to the number of zones traversed, with a maximum of eight (at which level a ticket is automatically valid for the entire ZVV area). Daily (24-hour) tickets are available at the cost of two single tickets, and an approximate 10% discount applies to both single and daily tickets if bought in a six-pack. The price of monthly tickets is equivalent to approximately 14-19 single tickets (depending on the number of zones), and an annual ticket comes at the price of nine monthly tickets. It is thus attractive to purchase an annual pass even for semi-regular public transport users: two weekly return trips will generally suffice to make it worthwhile. For others, a supplement of just over 10% renders daily, monthly and annual tickets transferable; a supplement of 50% provides access to first class seats on trains. Heavily discounted daily, monthly and annual tickets are available for users not travelling before 9.00 on weekdays; however, the choice of zone combinations for these off-peak tickets is limited to the three options of greater Zurich, greater Winterthur (seven zones each) and the full network (45 zones).

Service intensity

Table B37 shows the amount of rolling stock (in simultaneous revenue operation) required to operate Zurich's network at the SNAMUTS *20* and SNAMUTS *23* standards. In this chapter, we will use Copenhagen and Amsterdam for comparative purposes; while both the Dutch and Danish cities are larger than Zurich in terms of population, the complexity and size of the public transport networks as measured by number of SNAMUTS activity nodes is relatively similar.

Table B37: Service intensity on Zurich's public transport network in number of vehicles in simultaneous revenue service during the weekday inter-peak period at the SNAMUTS *20* and SNAMUTS *23* standards, with comparative figures for Copenhagen and Amsterdam

2010/2011/2012	Zürich SNAMUTS *20*	Zürich SNAMUTS *23*	København SNAMUTS *20*	København SNAMUTS *23*	Amsterdam SNAMUTS *20*	Amsterdam SNAMUTS *23*
Number of trains (suburban/regional)	65	74	87	102	56	58
Number of trains (metro)	-	-	16	16	23	23
Number of trams	130[1]	130[1]	-	-	136	136
Number of buses	169	169	341	341	401	401
Number of ferries	2	2	-	3	1	2
Number of services (total)	**365**	**373**	**444**	**459**	**617**	**619**
Metropolitan population	1.44m	1.44m	1.85m	1.85m	2.16m	2.16m
Services per 100,000 inh	**25.3**	**25.9**	**24.0**	**24.8**	**28.5**	**28.7**
Rail stations (suburban/regional/metro)	70	146	128	180	76	91
Rail stations per 100,000 inh	**4.9**	**10.1**	**6.9**	**9.7**	**3.5**	**4.2**

[1] Includes Forchbahn and BDWM light rail, Polybahn, Rigiblick and Dolderbahn cable cars

Relative to population, Zurich as well as the two comparison cities fall into the upper band of the European SNAMUTS sample when it comes to service intensity. There is a slightly higher outlay on operational resources in Zurich than in Copenhagen, but a lower one than in Amsterdam. Remarkably, the absolute number of heavy rail (including metro) as well as tram services in Zurich is only marginally lower than in Amsterdam, despite the Dutch city's agglomeration being about 50% larger in population. Conversely, Zurich bus system (at 20-minute or better weekday frequencies) has a more marginal role than in both Amsterdam and Copenhagen. Copenhagen's heavy rail service intensity per capita is roughly similar to that of Zurich, bearing in mind that the Copenhagen figure also counts some diesel-operated regional light rail routes *(lokalbaner)* whose closest Zurich equivalents, the (electrified) Forchbahn and BDWM light rail routes (S17 and S18), are listed under the tram figure. A similar disclaimer needs to be made with regard to the number of rail stations relative to population (which includes the stations along Copenhagen's *lokalbaner* but not stations with light rail characteristics along Zurich's tram system or on routes S17 and S18). But even discounting for light rail, it becomes obvious that Zurich's rail station density is extraordinarily high, particularly when half-hourly services are counted at the SNAMUTS *23* standard and resulting in the highest score of all European case study cities on this measure. In contrast, heavy rail station density in Amsterdam, even though it does count the stations along light rail route 51, remains far behind the standard found in its Swiss and Danish peer cities.

Closeness and degree centrality

Table B38 shows average, lowest and highest closeness centrality values and average degree centrality values across the Zurich network at both the SNAMUTS *20* and the revised SNAMUTS *23R* standards. Note that due to the different calculations used, closeness results for the original and revised standards are not comparable to each other.

Table B38: Closeness and degree centrality on Zurich's public transport network in 2011 at the SNAMUTS *20* and SNAMUTS *23R* standards, with comparative figures for Copenhagen and Amsterdam

2010/2011/2012	Zürich SNAMUTS *20*	Zürich SNAMUTS *23R*	København SNAMUTS *20*	København SNAMUTS *23R*	Amsterdam SNAMUTS *20*	Amsterdam SNAMUTS *23R*
Number of activity nodes	122	137	132	140	132	134
Closeness centrality (average)	**31.5**	**47.4**	**30.8**	**47.9**	**36.4**	**48.8**
Closeness centrality (lowest value)	17.0	26.8	16.9	28.0	20.6	28.7
Closeness centrality (highest value)	73.4	143.3	159.6	161.8	89.9	105.2
Degree centrality (average)	**1.29**	**1.22**	**0.87**	**0.93**	**1.14**	**1.08**

To define the number and location of SNAMUTS activity nodes in inner Zurich, we made use of the tried and tested method of including every intersection of rail and surface routes, as well as every intersection between surface routes unless these are 'dependent nodes' (meaning there is another, larger SNAMUTS activity node within walking distance serviced by the same combination of lines). Towards the periphery of the core city, activity density tangibly drops as the urbanised area fades into mountain slopes or garden-oriented residential neighbourhoods. For this reason, several termini of tram routes such as Farbhof, Frankenthal, Zoo, or of cable cars such as Rigiblick or Dolder do not feature as SNAMUTS activity nodes. Along heavy rail lines, the primary approach of activity node identification was to include those stations serviced by both semi-express and all-stop S-Bahn trains, and those that provide transfers to bus routes at the SNAMUTS *20* standard. Along half-hourly train routes (SNAMUTS *23* standard), we generally only included larger centres (examples are Regensdorf-Watt along route S6 or Pfäffikon ZH along route S3), or in the absence of a dominant larger centre along a line, selected the terminus as representative for the corridor (such as Bauma along route S26 or Eigg along route S35).

The complex interplay of overlapping half-hourly services with different stopping patterns on Zurich's S-Bahn network also presented new methodological challenges for the calculation of minimum cumulative impediment scores (closeness centrality) between points connected by more than one rail line. For example, there are four separate half-hourly services (and one hourly service) that link Effretikon and Zürich HB via different routes, together adding up to nine relatively evenly spaced services per hour per direction. Like previously in Sydney (see Volume 1 of this monograph), we would count each of these services (two or three trains per hour) separately for the SNAMUTS *23* standard but then also enter a joint segment at the higher frequency (nine trains per hour) and a travel time averaged across these services into the database, assuming that this higher-frequency segment makes no intermediate stops (or more precisely, no intermediate stops common to all nine services) between Effretikon and Zürich HB. Applied across the network, this procedure generates a quite complex database and reflects that many Zurich public transport users have choices between faster and slower services along different journey paths, which have been allocated proportionally to these routes and intermediate stations when calculating the betweenness index (see below).

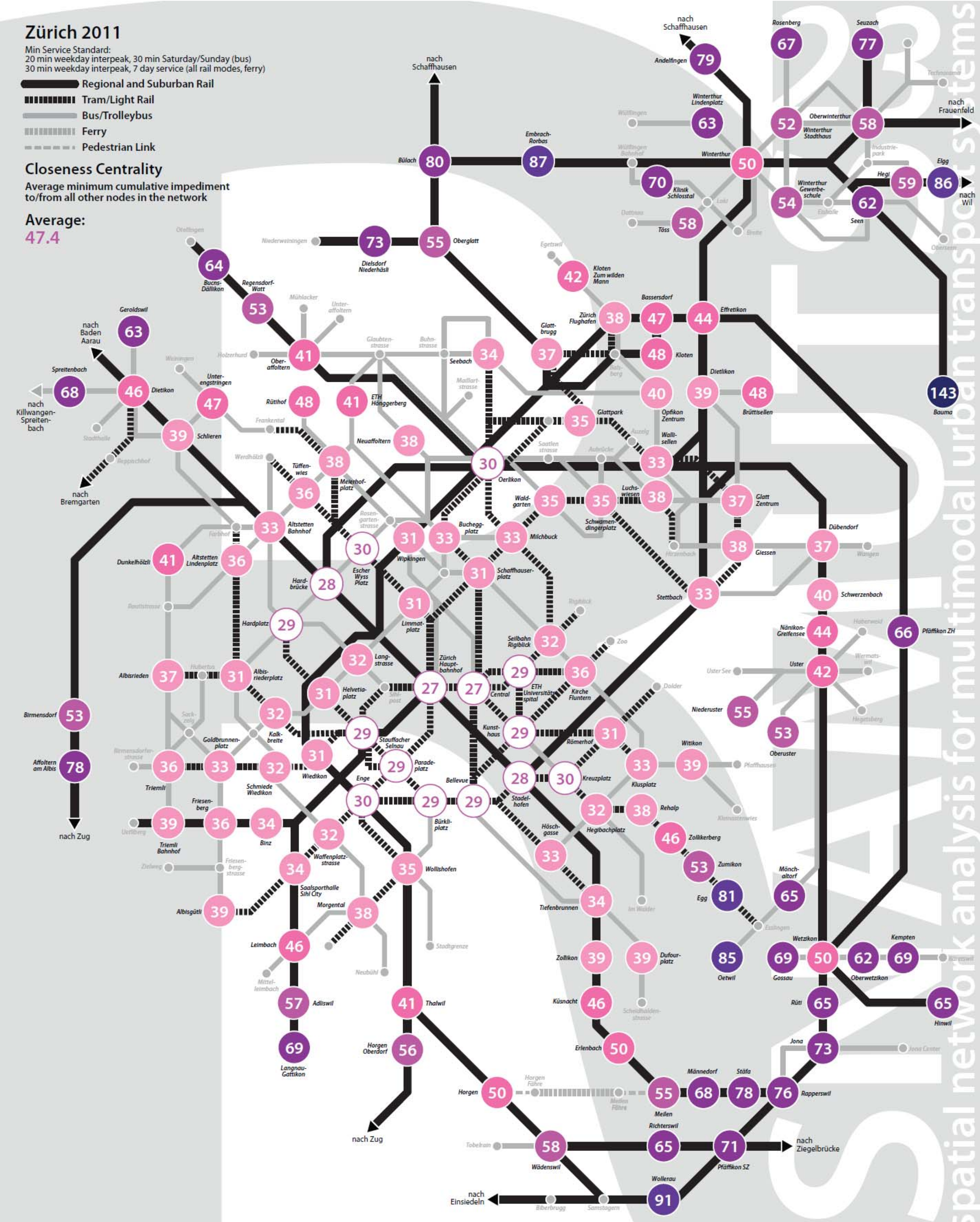
On the average closeness index at the SNAMUTS *23R* standard, Zurich seems to have a minimal edge over Copenhagen and Amsterdam though it remains well within the relatively narrow bandwidth shared by eight out of eleven European SNAMUTS cities. More remarkably, Zurich has a quite narrow spread between lowest (best) and highest (poorest) nodal closeness score at both service standards, if the result of 143 for Bauma at the SNAMUTS *23R* standard is considered an outlier (the next highest result – 91 - is found at Wollerau). This could be seen as indicative of a service approach that attempts to equalise public transport accessibility as much as possible across a settlement area whose uncontiguous character nominally presents formidable challenges for penetration by attractive public transport services. There are 66 nodes with a closeness score of 40 or below in Zurich (covering all but four nodes within the core city of Zurich), compared with 70 in Copenhagen and 58 in Amsterdam. Like in the two peer cities, low closeness values extend further from the central area along the faster, relatively high-frequency rail network than along surface modes and in turn influence the performance of some bus or tram nodes in their vicinity (seen most impressively at Hardplatz and Escher Wyss Platz either side of the CBD fringe rail-bus transfer station of Hardbrücke).

On the degree centrality index, the transfer intensity of Zurich's network is tangibly higher than that in Amsterdam and especially Copenhagen. The key reason for this finding is the existence of a number of localised sub-networks in the Zurich metropolitan region, most prominently in Winterthur but also, at a smaller scale, in centres such as Uster, Wetzikon and Dietikon. Additionally, the configuration of Zurich's S-Bahn network sometimes enforces transfers at least for the purposes of analysis at the SNAMUTS *23* standard. For example, every other train on the half-hourly section between Niederweningen and Oberglatt (S5) terminates at Oberglatt rather than continuing into central Zurich, necessitating a transfer to a connecting train that originated in Bülach. In SNAMUTS terms, this operational pattern reduces the Niederweningen to Oberglatt section to a transfer-dependent shuttle service (as no half-hourly through trains are provided) and inflates the degree centrality score for the activity node at Dielsdorf accordingly.

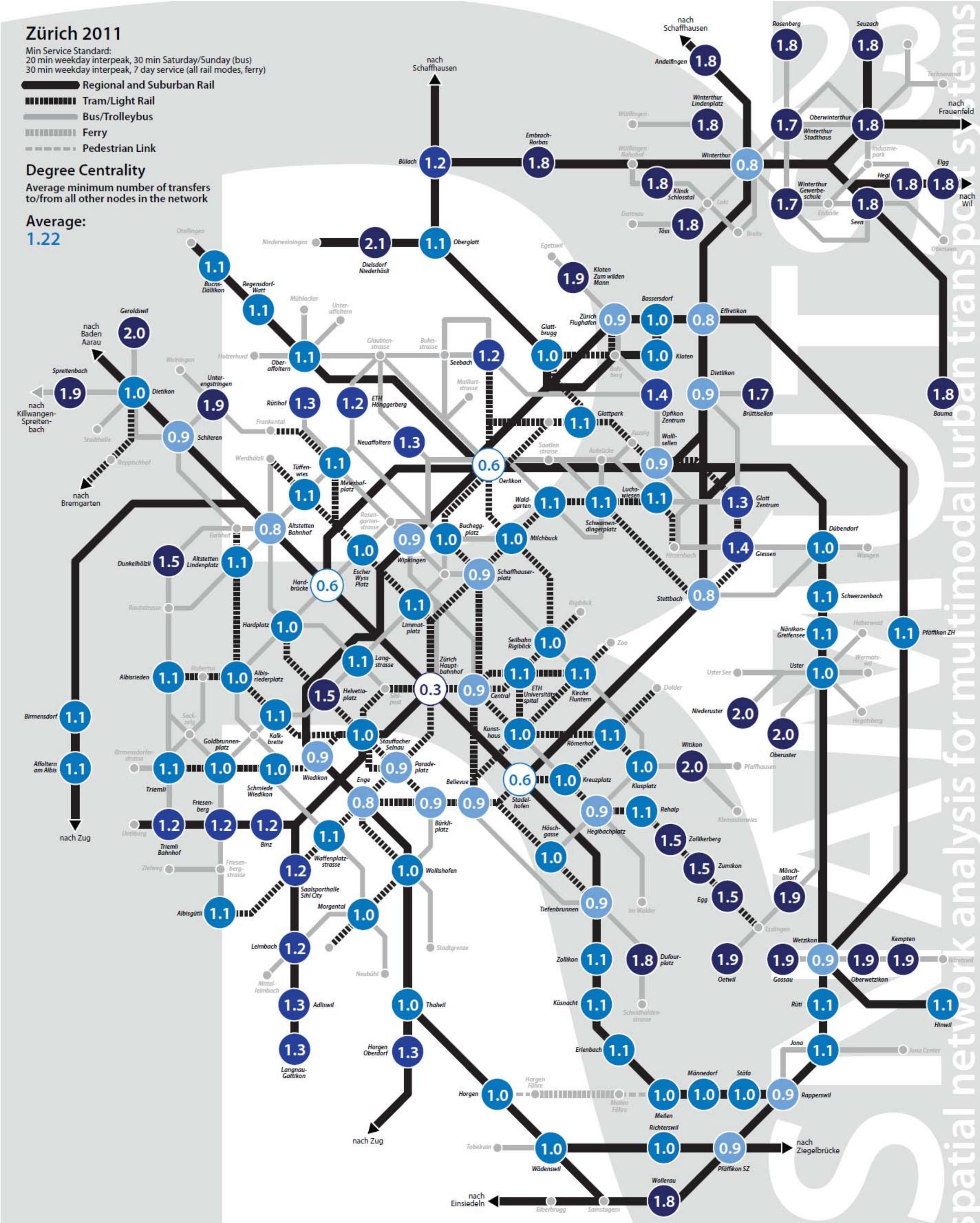
At the other end of the scale, Zürich HB stands out as the node with by far the lowest (best) degree centrality result, followed by its neighbouring rail-surface hubs at Oerlikon, Hardbrücke and Stadelhofen. There is a relatively narrow band of better-than-average transfer intensity scores within most of the tram network, with the exception of route 8 (Helvetiaplatz) which does not connect with any SBB station, orbital route 12 in the Glattal area and the Forchbahn light rail, whose city terminus is at Stadelhofen on the CBD edge rather than penetrating the heart of the city centre. S-Bahn routes S4 (Langnau-Gattikon) and S10 (Uetliberg), separate from the remaining heavy rail network by way of technical incompatibility, suffer from similar constraints on this index, albeit at a smaller magnitude.

Maps B58, B59: Closeness and degree centrality on Zurich's public transport network in 2011 at the SNAMUTS *23R* standard

draft



Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Pedestrian Link
Closeness Centrality
Average minimum cumulative impediment to/from all other nodes in the network
Average:
47.4
spatial network analysis for multimodal urban transport systems


Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Pedestrian Link
Degree Centrality
Average minimum number of transfers to/from all other nodes in the network
Average:
1.22
spatial network analysis for multimodal urban transport systems
nach Schaffhausen
nach Frauenfeld
nach Wil
nach Baden Aarau
nach Killwangen-Spreitenbach
nach Bremgarten
nach Zug
nach Ziegelbrücke
nach Einsiedeln
Bülach
Embrach-Rorbas
Winterthur
Oberglatt
Dielsdorf Niederhasli
Zürich Flughafen
Kloten
Bassersdorf
Effretikon
Dietlikon
Oerlikon
Zürich Hauptbahnhof
Stadelhofen
Hardbrücke
Altstetten Bahnhof
Dietikon
Schlieren
Stettbach
Dübendorf
Schwerzenbach
Nänikon-Greifensee
Uster
Wetzikon
Rüti
Rapperswil
Pfäffikon SZ
Wollerau
Horgen
Wädenswil
Thalwil
Meilen
Männedorf
Stäfa
Küsnacht
Zollikon
Tiefenbrunnen
Birmensdorf
Affoltern am Albis
Adliswil
Langnau-Gattikon
Leimbach
Hinwil
Bauma
Pfäffikon ZH
Seuzach
Rosenberg
Andelfingen
Seen
Elgg

Network coverage and contour catchments

Table B39 shows the network coverage and average 30-minute contour catchments per activity node for the Zurich network, with figures for Copenhagen and Amsterdam as a comparison. Neither index is affected by the package of revisions to the SNAMUTS calculations, so they are shown here at the original SNAMUTS *20* and SNAMUTS *23* standards.

Table B39: Average 30-minute contour catchments and network coverage on Zurich's public transport network in 2011 at the SNAMUTS *20* and SNAMUTS *23* standards, with comparative figures for Copenhagen and Amsterdam

2010/2011/2012	Zürich SNAMUTS *20*	Zürich SNAMUTS *23*	København SNAMUTS *20*	København SNAMUTS *23*	Amsterdam SNAMUTS *20*	Amsterdam SNAMUTS *23*
Average 30-minute contour catchment	22.9%	22.1%	31.2%	29.7%	19.2%	19.4%
Network coverage	63.9%	74.5%	71.2%	73.7%	78.3%	79.6%

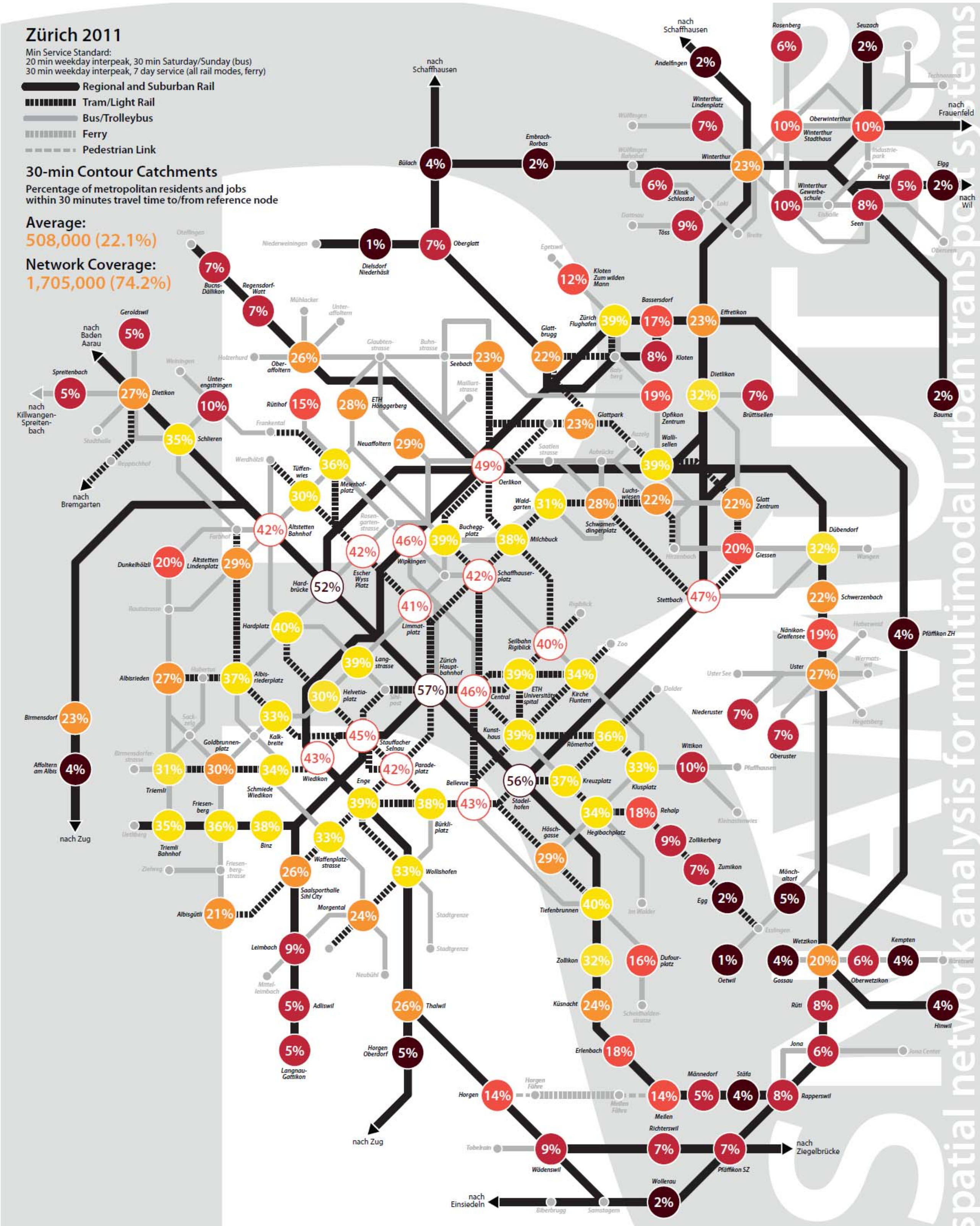
The collection of land use data in Zurich occurred by utilising a public-access database of the Swiss Federal Statistics Office (Bundesamt für Statistik, 2012). This database rasterises residential population and employment data to hectare level, which in comparison with other case study cities provides an extremely detailed representation of the geographical distribution of urban activities. It is, however, not entirely suitable for defining the size of the urbanised area, as some urban land uses whose residential or employment uses do not cover their entire spatial expanse (such as airports or rail maintenance yards) remain blank on the map.

There is a quite substantial jump in the network coverage figure in Zurich as the SNAMUTS *20* standard is relaxed to SNAMUTS *23*. This is indicative of a sizeable proportion of the metropolitan area depending on half-hourly rail services as their principal mode of public transport access. In Amsterdam and Copenhagen, half-hourly rail services play a more marginal role in relation to the network formed by services operating at least every 20 minutes. At the SNAMUTS *23* standard, Zurich's network coverage in percentage of metropolitan residents and jobs edges ahead of Copenhagen's and remains slightly below Amsterdam's. All three cities, however, are situated in the top half of the European SNAMUTS sample on this index, jointly with Vienna and Barcelona.

Average 30-minute contour catchments in Zurich relative to metropolitan population and jobs are larger than in Amsterdam but smaller than in Copenhagen. The Danish capital clearly benefits from its monocentricity and relative urban contiguousness compared to its more multi-centred Dutch and Swiss counterparts on this index. The superior performance of Zurich over Amsterdam may be associated both with metropolitan area size (average percentage contour catchments tend to be smaller in larger agglomerations) and with the greater prevalence of (faster) rail services in Zurich's network, as elaborated earlier.

Zurich's peak-performing nodes on this index are the three CBD or CBD fringe rail stations of Zürich HB, Stadelhofen and Hardbrücke, followed closely by Oerlikon and Stettbach in the north of the core city. Within the City of Zurich, only nine out of 61 activity nodes are accessible to and from less than 25% of all residents and jobs within the ZVV area. Important regional centres such as Dietikon, Thalwil, Effretikon, Uster and Winterthur also hover around the 25% mark on this index, eclipsing their Amsterdam equivalents which are generally located at a further distance from the core city.

Map B60: 30-minute contour catchments on Zurich's public transport network in 2011 at the SNAMUTS *23* standard


Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Pedestrian Link
30-min Contour Catchments
Percentage of metropolitan residents and jobs within 30 minutes travel time to/from reference node
Average:
508,000 (22.1%)
Network Coverage:
1,705,000 (74.2%)
spatial network analysis for multimodal urban transport systems

Betweenness centrality

Table B40 shows a range of indicators derived from this measure: the global betweenness index as a proxy for the general presence of public transport travel opportunities in the land use system, the average nodal betweenness index as an indication for the balance of distribution of such opportunities across the network, the catchment of typical path length as an attempt to compensate this index's bias towards concentrated and contiguous settlement patterns, and the distribution of travel opportunities across different modes and geographical areas. The revised formulas in the SNAMUTS *23R* standard alter the calculation of this index quite significantly and thus do not allow for valid comparisons with outcomes from the original calculation (SNAMUTS *20*).

Table B40: Betweenness centrality in Zurich's public transport network in 2011 at the SNAMUTS *20* and SNAMUTS *23R* standards, with comparative figures for Copenhagen and Amsterdam

2010/2011/2012	Zürich SNAMUTS *20*	Zürich SNAMUTS *23R*	København SNAMUTS *20*	København SNAMUTS *23R*	Amsterdam SNAMUTS *20*	Amsterdam SNAMUTS *23R*
Global betweenness index	**938**	**891**	**1,879**	**1,141**	**1,726**	**1,210**
Average nodal betweenness	**27.4**	**26.7**	**67.8**	**43.7**	**55.2**	**38.8**
Number of activity nodes	122	137	132	140	132	134
Catchment of typical path length	43,000	52,000	65,000	72,000	78,000	80,000
Segmental betweenness Rail (suburban/regional)	44.5%	60.0%	52.7%	57.3%	24.5%	32.7%
Segmental betweenness Rail (metro)	-	-	10.8%	9.1%	14.1%	13.5%
Segmental betweenness Tram	34.1%[1]	21.7%[1]	-	-	21.9%	16.6%
Segmental betweenness Bus	21.4%	18.1%	36.5%	33.6%	39.4%	37.2%
Segmental betweenness Ferry	0.0%	0.1%	-	0.0%	0.0%	0.0%
Segmental betweenness CBD	35.2%	28.8%	28.5%	24.1%	29.1%	22.5%

[1] Includes Forchbahn and BDWM light rail, Polybahn, Rigiblick and Dolderbahn cable cars

A methodological adjustment made to this index was inspired by the rail network and service patterns in the Zurich agglomeration, and the concern that the previous approach to allocating journey paths to nodes and segments in the betweenness index produced some distortions. Essentially, whenever a preferred journey path makes use of an express rail segment on the network, we are now allocating a proportion of the betweenness score for this path to the intermediate stations where express trains do not stop. In earlier calculations we would ignore the intermediate stations. The reason for this modification is linked to an inherent bias that makes itself felt in networks where there is a significant proportion of station-skipping in the train schedules (or those of other modes). The SNAMUTS procedure for determining preferred journey paths tends to select these express segments over all stop-segments, not only because their travel time is usually shorter but also because their frequency includes the trains making all stops along the same route. For the user, however, this increased level of service frequency, and hence a much reduced travel impediment, is only available if the slower, all-stop trains are also deemed worthy of consideration as a travel option. Hence, in an example where there are two express trains and two all-stop trains per hour per direction on a section of line, it would appear accurate to allocate half the betweeness score accrued on the express segment to the intermediate stations, given that about half the passengers making use of the 15-minute service that informs the travel impediment of the segment are likely to be travelling on trains that stop at these stations.

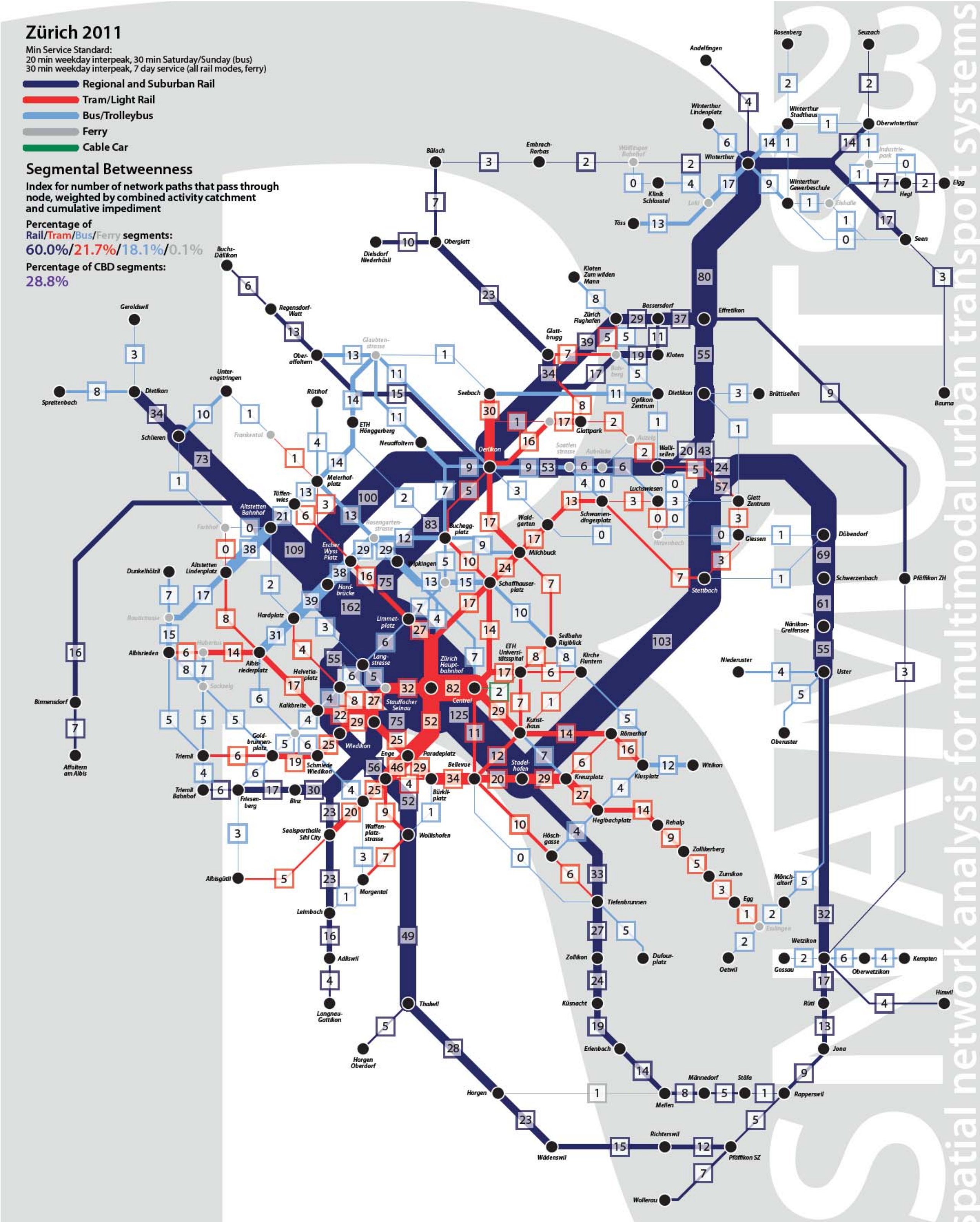
In theory, this procedure should lift the global and average nodal betweenness scores for a network with a large variety of stoppng patterns such as Zurich’s. In practice however, Zurich still trails behind its Dutch and Danish counterparts on both counts. The key reason for this discrepancy can likely be found in the third measure in Table B40: the catchment of a typical journey path. In Copenhagen and Amsterdam, this figure, designed to compensate for the effects of compactness or dispersal of the settlement area, is around 40-50% higher than in Zurich. Such an effect could perhaps be expected if the networks of Copenhagen and Amsterdam offered a greater ease of movement, particularly over longer distances, than Zurich’s. But the outcomes of the closeness centrality and contour catchment indicators discussed above suggest a relatively even performance between the three cities. More likely, Zurich’s sluggish betweenness figures are predominantly related to the ratio of settlement density and network density – in other words, the Swiss city provides, in relative terms, a larger network with a greater proportion of high-performance modes for a sparser urban settlement than Copenhagen and (even more so) Amsterdam. Perhaps this largesse can be traced to the higher level of public transport usage in Zurich, which has nearly twice the number of annual boardings per capita of the Danish and Dutch capitals and thus appears to squeeze greater levels of patronage out of a smaller pool of potential users.

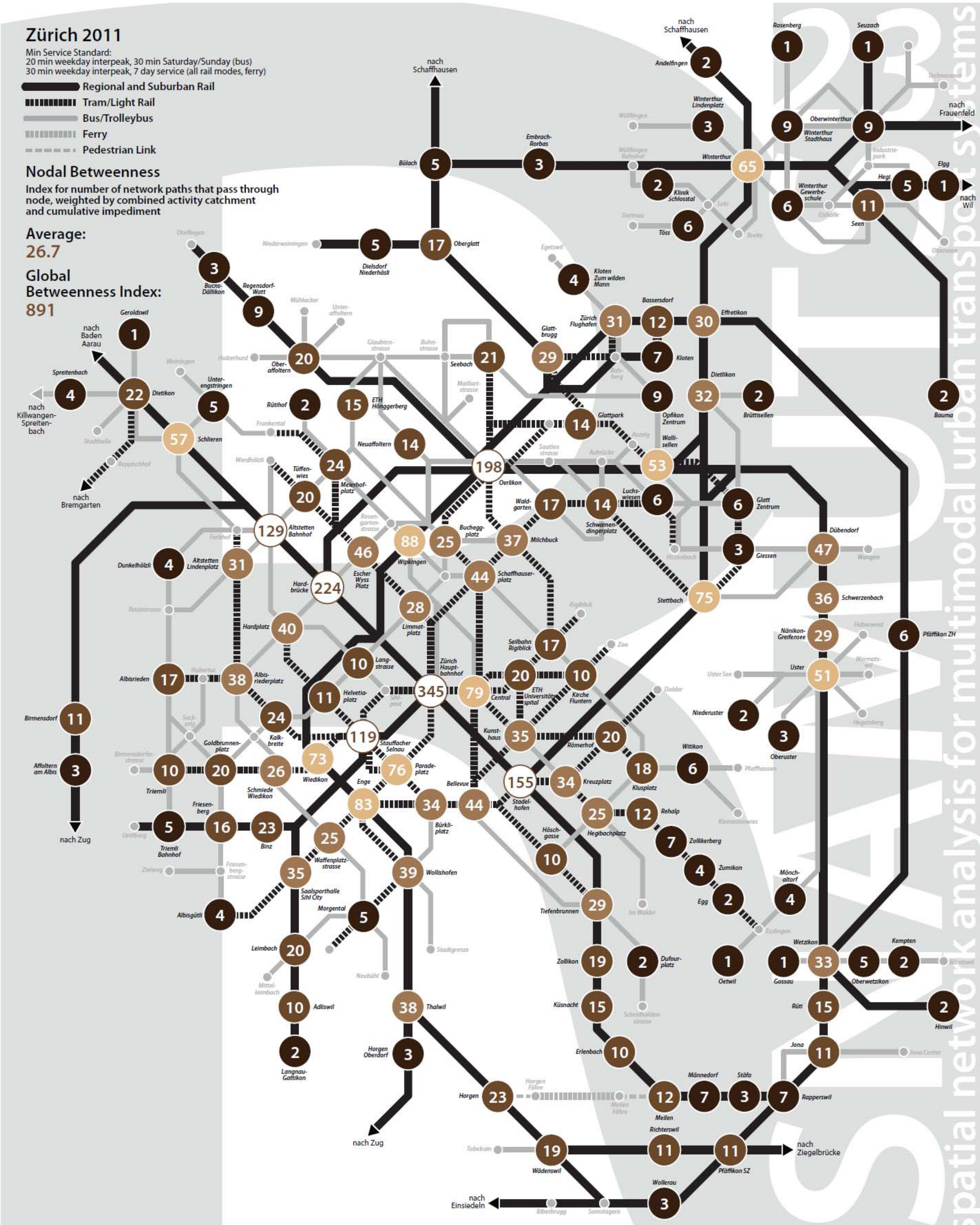
According to the segmental betweenness index, Zurich’s reliance on heavy rail for facilitating movement across its public transport network is of similar magnitude to Copenhagen’s, once allowance is made for the varying categorisations of regional light rail in the table as discussed earlier in this section. It is, however, significantly greater than in Amsterdam, which seems to support the notion that Zurich has historically placed greater emphasis on penetrating its metropolitan region with high-performance modes than Amsterdam. There is a greater relative importance of the CBD in Zurich than in its Dutch and Danish counterparts, though this index tends to decline in inverse proportion to metropolitan population and may thus be largely related to the varying sizes of the three cities.

Maps B61 and B62 confirm the existence of a dominant ‘super node’ at Zürich HB where a particularly high number of metropolitan travel opportunities converge. The absolute betweenness score of this node (345) is virtually identical to that of Amsterdam Centraal (347) and slightly lower than Copenhagen’s Nørreport (383). The centripetal rate of decay of betweenness figures in Zurich generally seems to be well balanced, following the dense grid structure of the surface network and its good integration with heavy rail in the core city. On the north-western approach route however (the Altstetten-Dietikon corridor), betweenness results appear to be higher than on comparable corridors elsewhere – and likely still understated, as this link is also the principal connection to the western commuter belt around Baden and Aarau that is located outside the ZVV area and thus does not enter the SNAMUTS analysis. The high concentration of travel opportunities here has a flow-on effect on connecting orbital bus routes at Altstetten and Hardbrücke, producing the highest segmental betweenness scores on the bus network across the metropolitan area and the highest scores on any surface route outside the immediate CBD area.

Maps B61, B62: Segmental and nodal betweenness centrality index in Zurich’s public transport network in 2011 at the SNAMUTS *23R* standard

draft


Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Cable Car
Segmental Betweenness
Index for number of network paths that pass through node, weighted by combined activity catchment and cumulative impediment
Percentage of Rail/Tram/Bus/Ferry segments:
60.0%/21.7%/18.1%/0.1%
Percentage of CBD segments:
28.8%
SNAMUTS 23
spatial network analysis for urban transport systems



Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Pedestrian Link
Nodal Betweenness
Index for number of network paths that pass through node, weighted by combined activity catchment and cumulative impediment
Average:
26.7
Global Betweenness Index:
891
spatial network analysis for multimodal urban transport systems
nach Schaffhausen
nach Frauenfeld
nach Wil
nach Baden Aarau
nach Killwangen-Spreitenbach
nach Bremgarten
nach Zug
nach Ziegelbrücke
nach Einsiedeln

Network stress

Table B41 shows the average results from the segmental congestion (network stress) index for Zurich, Copenhagen and Amsterdam as a whole, specifically for each mode and for the CBD area. Assumptions for maximum comfortable passenger capacity on public transport vehicles or train sets in Zurich are 600 for each SBB train (though acknowledging that S-Bahn and intercity trains come in a variety of vehicle types and lengths), 300 for each SZU train (routes S4 and S10, where trains and platforms are significantly shorter than on the SBB lines), 150 for each tram (including Forchbahn and BDWM light rail routes S17 and S18) and ferry, and 65 for each bus (which reflects the VBZ fleet mix of standard, single-articulated and double-articulated buses and trolley buses).

Table B41: Segmental congestion index in Zurich's public transport network in 2011 at the SNAMUTS *23R* standard, with comparative figures for Copenhagen and Amsterdam

SNAMUTS *23R* 1010/2011/2012	Zürich (2011)	København (2012)	Amsterdam (2011)
Average segmental congestion index	**10.6**	**15.1**	**16.9**
Segmental congestion - suburban and regional rail	11.9	8.7	15.0
Segmental congestion - metro	-	16.8	15.9
Segmental congestion - tram	8.3[1]	-	11.9
Segmental congestion - bus	12.0	17.1	19.5
Segmental congestion - ferry	1.8	0.3	-
Segmental congestion - CBD area	11.7	19.4	20.5

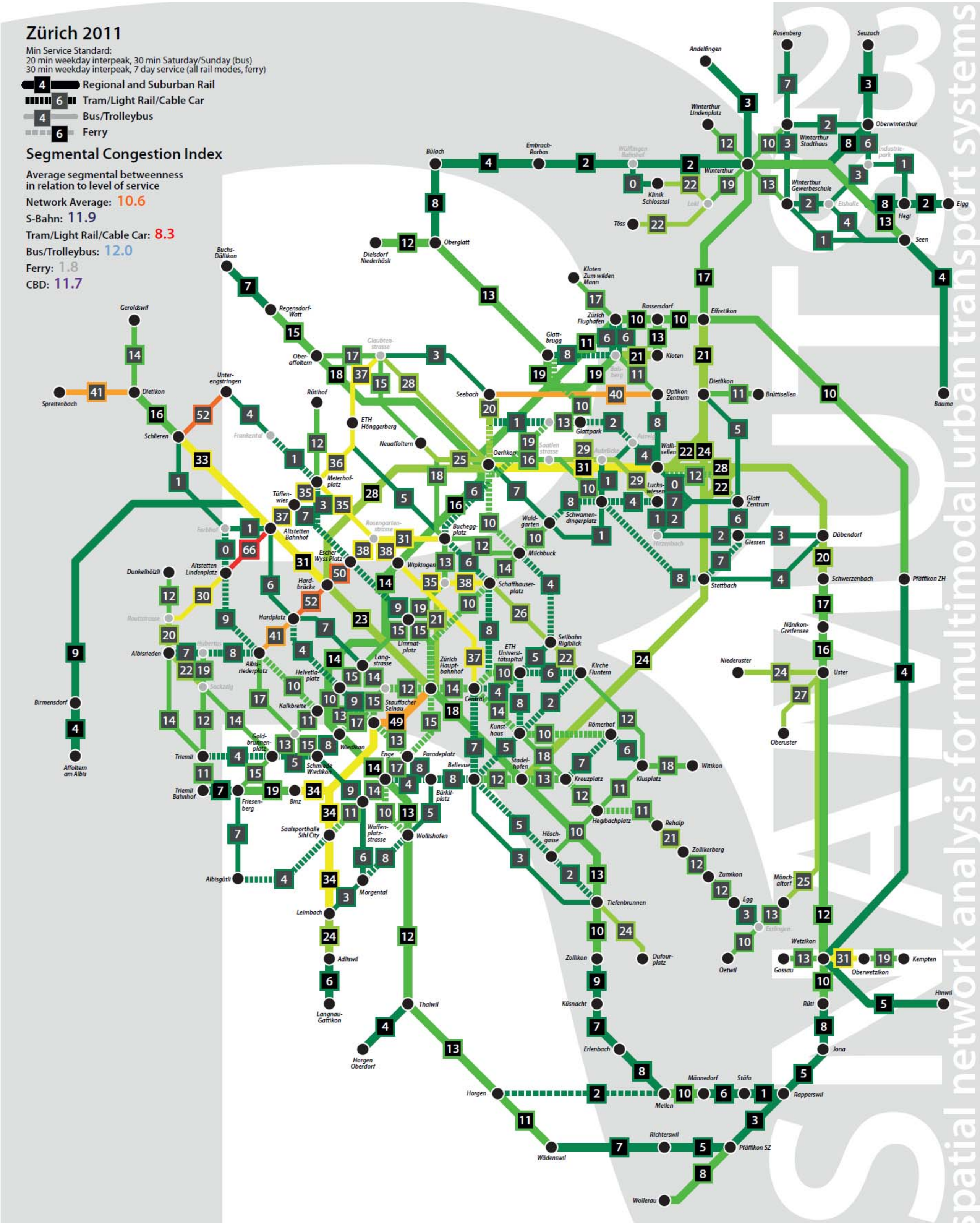
[1] Includes Forchbahn and BDWM light rail, Polybahn, Rigiblick and Dolderbahn cable cars

Zurich's average levels of segmental congestion (network stress) are significantly lower than those in Copenhagen and Amsterdam, and in fact lower than in any other SNAMUTS city across Europe or Australia thus far. In the comparison with Amsterdam, the same is true across all modes the two cities share. Copenhagen records a lower level of network stress on its S-Tog and R-Tog system than on Zurich's S-Bahn and regional rail network; however this is more than compensated for by higher levels of stress on the surface network.

This finding from an index that compares segmental betweenness and passenger capacity neatly supports the assumption made previously that Zurich's provision of public transport services in relation to its land use pattern is relatively generous – not merely in the sense of number of vehicles or train sets as discussed in the service intensity index earlier in this section, but also in terms of carrying capacity due to the greater weight of higher-performance modes. This circumstance has a dual effect on the network stress index: it subdues segmental betweenness scores (the numerator of the index) by enabling much of the transport task to be done at the relatively low frequencies of the rail system, while lifting the average passenger capacity of each service (the denominator of the index) through greater reliance on high-capacity rail.

This is not to say that there was no variation in network stress across Zurich's network. The trunk line of the SZU lines (S4 and S10) in the city centre shows up as the most stressed segment on the rail system, while most bus segments with potential congestion intersect with the Altstetten-Dietikon rail corridor, itself characterised by the highest segmental stress results on the SBB rail network. Conversely, there is a notable absence of network stress across the entire tram and light rail system, perhaps indicating that its mature network extension, high service frequencies and mid-range speeds appear to be a near-ideal fit for the accessibility needs of the core city.

Map B63: Segmental congestion (network stress) index for Zurich's public transport network in 2011 at the SNAMUTS *23R* standard



Nodal connectivity

Table B42 shows the assumptions for average occupancy per mode, metropolitan-wide and average nodal connectivity results for Zurich. The occupancy (load factor) figures for rail modes have been obtained from ZVV and represent averages across the familiar groupings of modes. Different calculations are used for this index at the original and revised SNAMUTS standards, hence the SNAMUTS *20* and SNAMUTS *23R* results should not be compared directly.

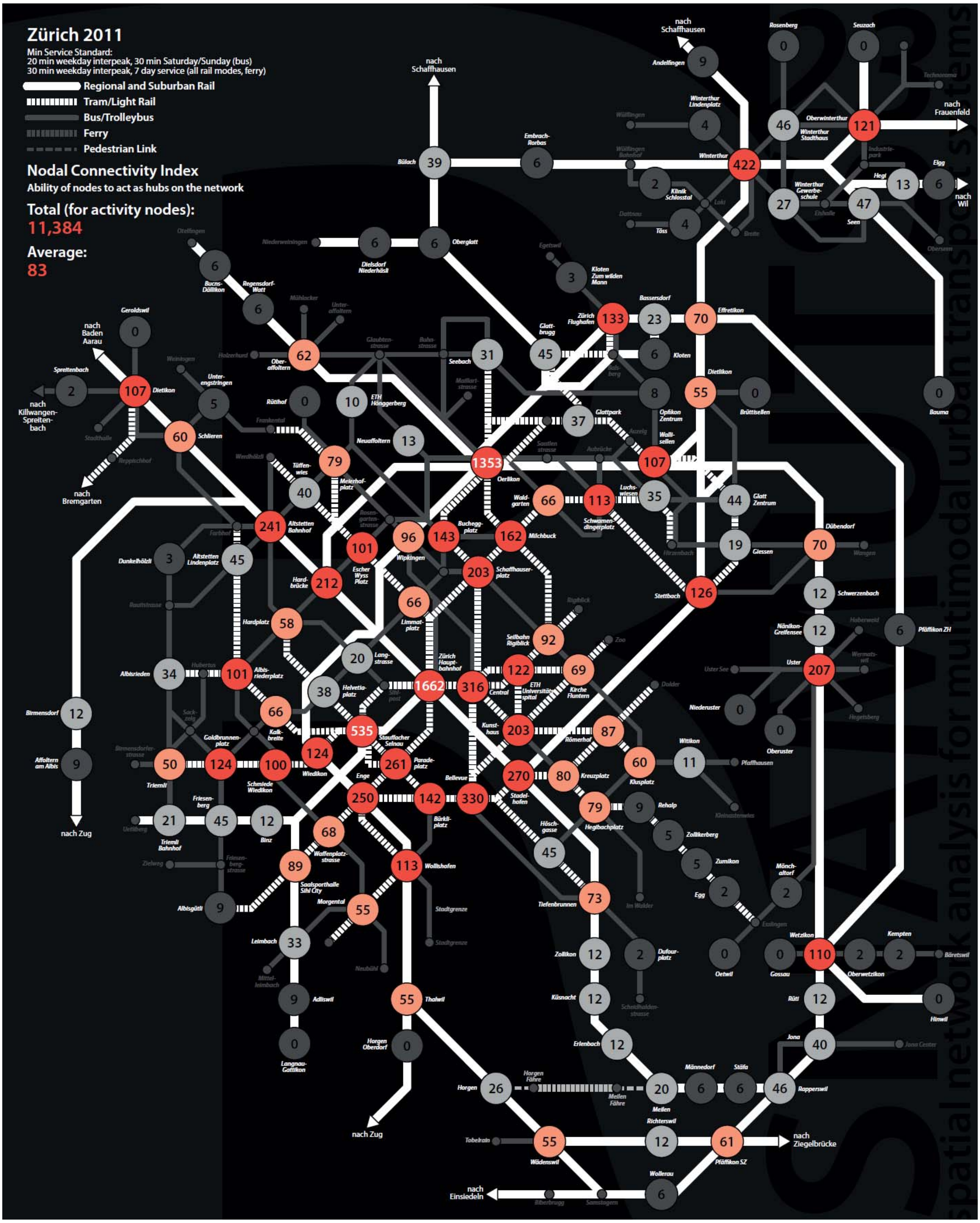
Table B42: Nodal connectivity index on Zurich's public transport network in 2011 at the SNAMUTS *20* and SNAMUTS *23R* standards, with comparative figures for Copenhagen and Amsterdam

2011/2012	Zürich SNAMUTS *20*	Zürich SNAMUTS *23R*	København SNAMUTS *20*	København SNAMUTS *23R*	Amsterdam SNAMUTS *20*	Amsterdam SNAMUTS *23R*
Average occupancy rate (suburban/regional rail)	97		85		138	
Average occupancy rate (metro/local rail)	-		37		140	
Average occupancy rate (tram/light rail)	39		-		29.5	
Average occupancy rate (bus)	14		9		13.5	
Nodal connectivity (all activity nodes)	**11,241**	**11,384**	**12,468**	**12,367**	**15,807**	**16,434**
Nodal connectivity (average)	**93**	**83**	**94**	**88**	**120**	**123**

There is a lower rate average occupancy on the heavy rail network in Zurich than in Amsterdam; however, it is higher than in Copenhagen. Zurich trams and light rail vehicles seem to carry more passengers on average than Amsterdam's. Buses in both the Swiss and Dutch agglomerations seem to be loaded to similar levels, which are a good 50% higher than in Copenhagen.

All up, Zurich's and Copenhagen's average nodal connectivity results are remarkably similar, and Amsterdam's edge on its Swiss and Danish counterparts appears to be primarily owed to larger crowds on its (less expansive) heavy rail system. While Zürich HB and Oerlikon, expectedly, show as the nodes with by far the highest nodal connectivity scores, the dense tram network in inner Zurich clearly has the effect of distributing the benefits associated with this index across the central city and in some cases beyond.

Map B64: Nodal connectivity on Zurich's public transport network at the SNAMUTS *23R* standard in 2011


Zürich 2011
Min Service Standard:
20 min weekday interpeak, 30 min Saturday/Sunday (bus)
30 min weekday interpeak, 7 day service (all rail modes, ferry)
Regional and Suburban Rail
Tram/Light Rail
Bus/Trolleybus
Ferry
Pedestrian Link
Nodal Connectivity Index
Ability of nodes to act as hubs on the network
Total (for activity nodes):
11,384
Average:
83
spatial network analysis for multimodal urban transport systems