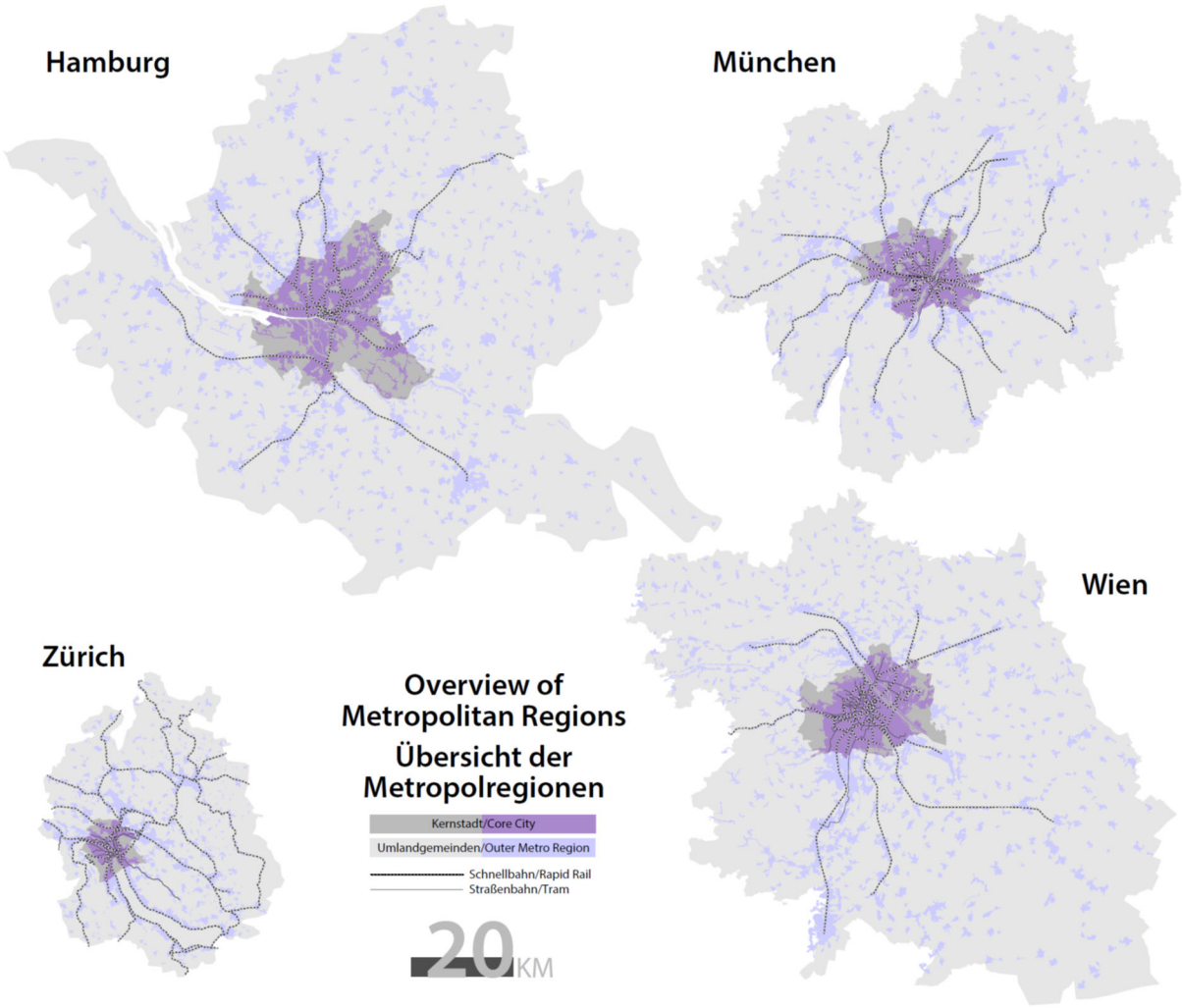
Trends in public transport accessibility and network performance in four German-speaking cities during the 2010s

by Jan Scheurer and Carey Curtis, November 2024

The Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool has been applied to the four German-speaking cities of Hamburg, Munich, Vienna and Zurich in 2010-11 and again in 2020-22. This blog article documents the trends in network performance and land use-transport integration experienced in the four cities during this period, and discusses them in the context of the broader policy environment for land use and transport planning in Germany, Austria, Switzerland and beyond.

All data presented here has been updated to the latest methodological adjustments of the SNAMUTS tool. Hence, some indicator results differ from those included in earlier SNAMUTS publications, including our 2016 book Planning for Public Transport Accessibility.

Population size and growth trends 2011-2021

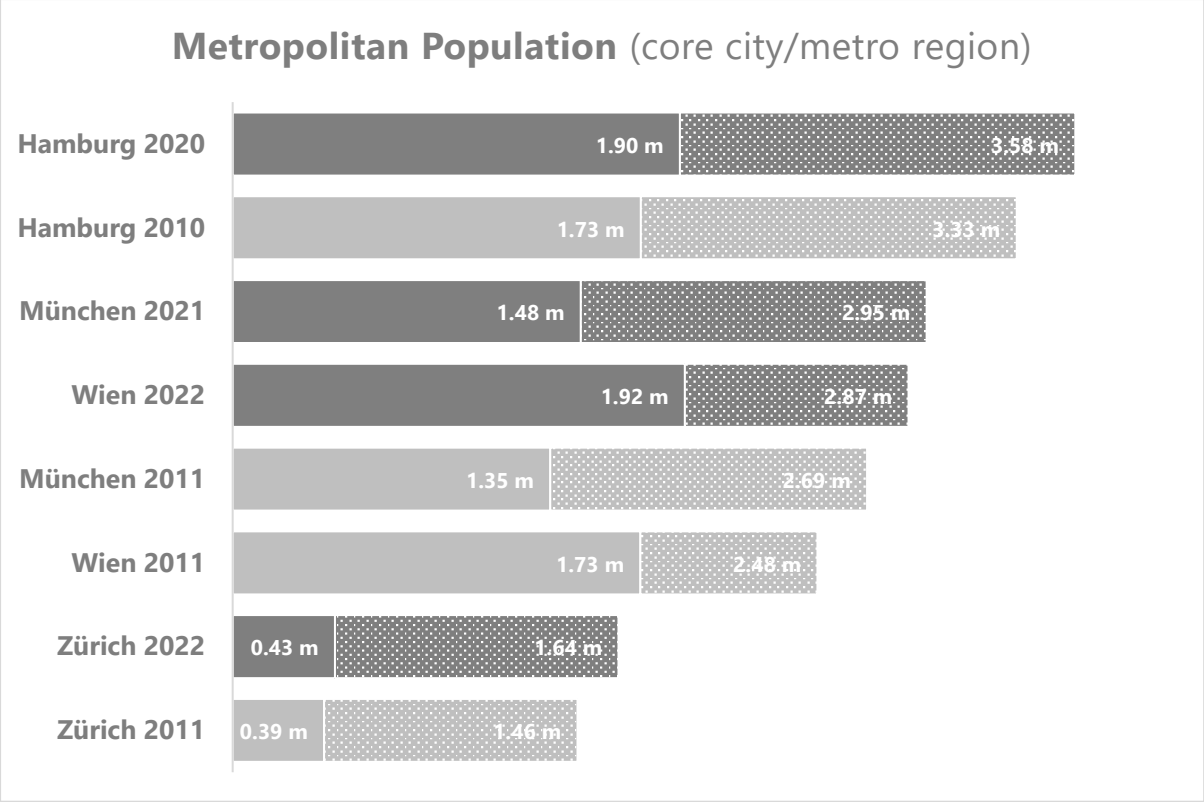


The metropolitan areas of the four cities have been defined as the jurisdictions of their respective integrated transport agencies, namely Hamburger Verkehrsverbund (HVV), Münchner Verkehrsverbund (MVV), Verkehrsverbund Ost-Region (VOR, Wien) and Züricher Verkehrsverbund (ZVV). In each city, these metropolitan regions consist of the core city and some surrounding areas.

The core cities of Hamburg and Vienna form separate city states within the federal systems of Germany and Austria; their outer metropolitan regions thus stretch over parts of their neighbouring states of Schleswig-Holstein and Lower Saxony, and Lower Austria and Burgenland, respectively. In Zürich, the metropolitan area definition is nearly identical to the Swiss administrative region (canton) of the same name, though it is acknowledged that significant cross-commuting exists particularly with parts of the neighbouring canton of Aargau. The SNAMUTS methodology takes this effect into account.

It is notable that while in Hamburg and Munich, there is relative parity between the population of the core city and the surrounding metropolitan region, this is not the case in their Austrian and Swiss counterparts. In Vienna, the core city contains about two thirds of the region's population while in Zurich, whose metropolitan region is significantly smaller than that of the other three cities, the core municipality only makes up just over a quarter of the canton's inhabitants. In Hamburg, Munich and Zurich, population growth during the 2010s occurred at roughly similar rates in the core cities and the surrounding regions; in Vienna, which records the highest growth figure of the four cities, the outer metropolitan region attracted slightly more additional inhabitants (+200,000) than the (larger) core city (+190,000).

Population and employment data for the two German cities were derived from rasterised data (at hectare level) for the two census years of 2011 and 2022. Within the city-state of Hamburg, these figures were aggregated for small statistical areas *(statistische Gebiete*) while in the surrounding region and in the entire metropolitan area of Munich, they were aggregated for actual walkable catchments around public transport nodes and corridors (800 metres for rail/metro stations and ferry terminals, 400 metres around bus and tram routes). German job figures for 2022, which are not (yet) publicly available, were extrapolated from 2011 data obtained during an earlier collaboration. In Switzerland, rasterised residential and employment data at hectare level is made available annually and publicly through the country's statistical agency and was aggregated to actual walkable public transport catchments (as in Munich). In Austria, data for small statistical areas (Zählsprengel) in the census years of 2011 and 2021 informs the population count; as in Germany, job figures for 2021 were extrapolated from 2011 data obtained at an earlier project stage. Note that the variations in data availability and methodology between the four cities may have minor impacts on the comparability of SNAMUTS results between cities; this will be highlighted as relevant during the indicator discussions in the following.



Urban intensification around public transport

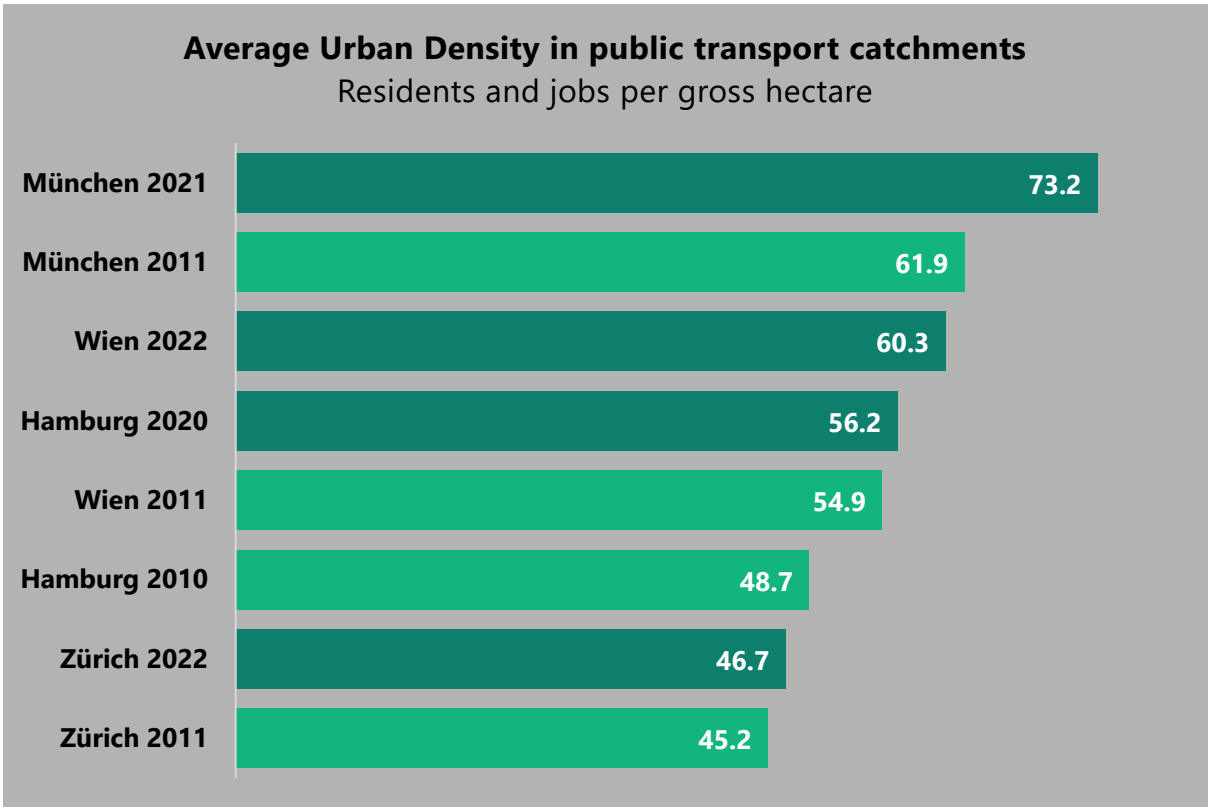
In all four German-speaking cities, average residential and job densities within walking distance from public transport increased during the 2010s. On average across the metropolitan area, this effect appears most pronounced in Munich, and least so in Zurich. However, the metropolitan average figures conceal some significant typological differences between the four cities, and are also influenced by the variation in methodology in extracting this data mentioned above. In short, the use of statistical area units in Hamburg (core city only) and Vienna (entire metropolitan area) tends to understate residential and/or job densities particularly in peripheral locations where these units often extend beyond the walkable catchments of public transport, or otherwise contain a greater share of non-urbanised land than the immediate 400-metre or 800-metre catchments used in Munich and Zurich, and the outer metropolitan region of Hamburg. This shortfall is less consequential in inner urban areas, where urbanised land and walkable public transport access tend to be relatively contiguous in all four cities.

With this caveat in mind, it is notable that urban densities around public transport grew at a comparable average rate (plus 20 residents and jobs per hectare) in the core cities of the four metropoles during the 2010s, though from different levels: in Hamburg, their average density increased from 118 to 138 residents and jobs per hectare, in Munich from 125 to 145, in Zurich from 149 to 167 and in Vienna from 176 to 196. Conversely, public transport catchments in the outer metropolitan regions (beyond the core city) picked up a much smaller increment in density, and from much lower bases: In outer Vienna, average catchment densities went up from 24 to 27 residents and jobs per hectare, in Munich from 39 to 43, in Hamburg from 42 to 47 and in Zurich from 46 to 49 (Vienna's low average on this index is almost certainly influenced by the statistical unit effect described previously).

It is further notable that in Hamburg and Vienna, 86% of residents and jobs in metropolitan public transport catchments could be found in the core city in both 2010/11 and 2020/22. In Munich, the

core city share of activities within walking distance of public transport at the SNAMUTS minimum standard declined slightly from 75% to 73% between 2011 and 2021 while in Zurich, it remained stable at a comparatively low 43%. These figures partly reflect the varying degree of core city dominance in the sample (as elaborated above), with Vienna and Zurich occupying opposite ends of the spectrum. But they also point to the presence of a more developed public transport network outside the core city in Munich and particularly Zurich in comparison with Hamburg and Vienna.

Another worthwhile query on urban density figures concerns the share of residents and jobs in each metropolitan area located in public transport catchments above a certain density threshold – for example, 100 activities per hectare which could be considered a rough minimum for an urban precinct that generates a critical mass of both public transport usage and all-day pedestrian activity at the local scale. In all four cities, the share of such areas grew in percentage terms during the 2010s: in Hamburg and Zurich from 22% to 24% and in Munich from 24% to 29%. In Vienna, it grew from 46% to 48%, suggesting that the associated urban experience is far more widespread in the Austrian capital than in its three peer cities and, given the gradual nature of urban intensification, likely has been for some time.



[Note that these comparisons, both at metropolitan and local catchment level, are based on shifting network configurations and statistical boundaries and thus do not necessarily contrast identical land areas for the different base years.]

Download SNAMUTS network diagrams: Urban Density			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

How public transport service provision evolved during the 2010s

The service intensity indicator measures the extent of operational input into the public transport system at the SNAMUTS minimum standard (every 20 minutes during the day on weekdays, every 30 minutes on both Saturdays and Sundays for buses and trams, every 30 minutes on weekdays with 7-day service for rail and ferries), and hence the disposition of transport agencies and decision makers to supply it with resources. However, high service intensity figures can also represent inefficiencies in operation, such as the deployment of many smaller vehicles at slow speeds (such as buses in congested traffic) rather than that of fewer larger vehicles at faster speeds (such as trains or metros on segregated rights-or-way).

Overall, service provision relative to population went up tangibly in Hamburg and Munich, though it still sits at a level substantially below that of Vienna and Zurich where this indicator remained relatively stable during the 2010s. In all four cities, network expansion and service improvements accompanied population growth; however, the increase in bus movements in all four cities (and in Vienna, also tram movements) may in parts be indicative of declining average speeds as general traffic volumes (motorised and/or non-motorised) increased with urban intensification and impacted the operation of on-street public transport modes.

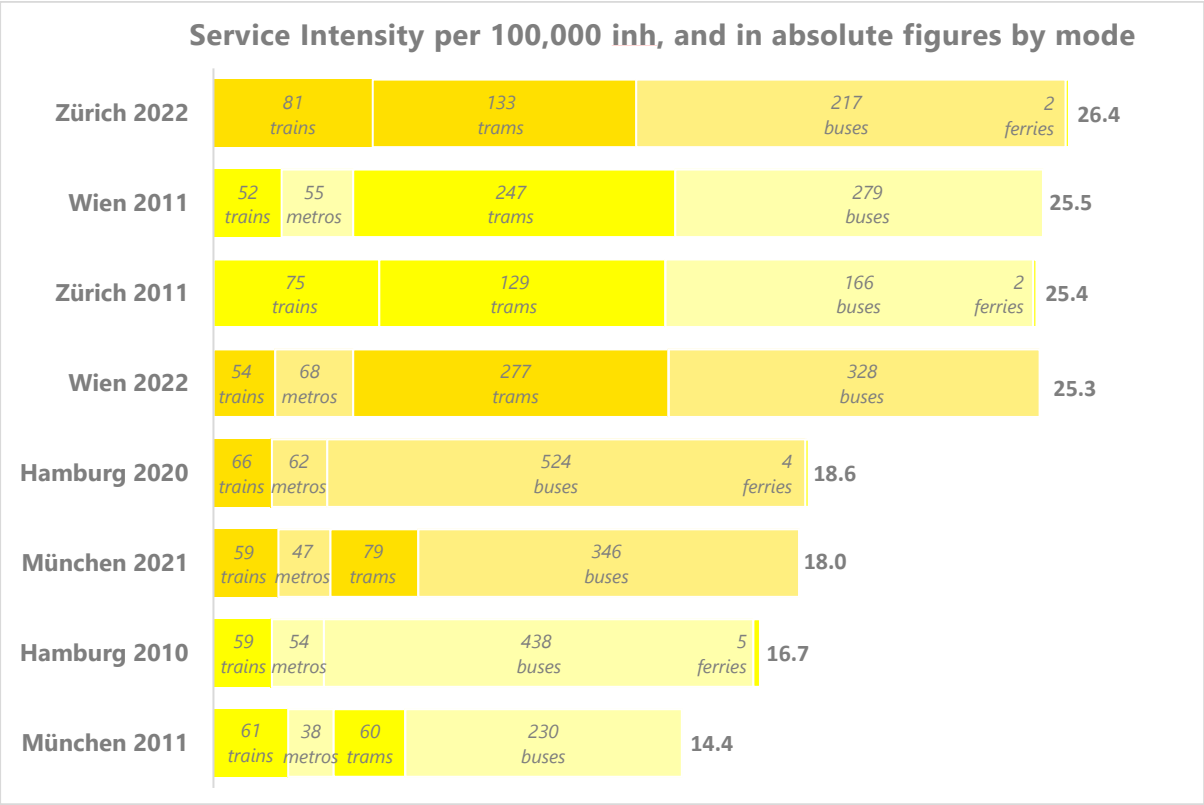
Hamburg opened a new metro branch line (U4) to access the HafenCity redevelopment area in several stages during the 2010s, including a new transfer point along the existing S3 rail corridor at its current terminus (Elbbrücken). Several other existing metro lines saw an outward expansion of higher daytime frequencies (5 minutes), and regional rail services were improved particularly on the northwestern (Elmshorn) corridor. On the bus network, frequency improvements and the addition of new lines to better access and connect neighbourhoods away from the (still unevenly distributed) metro and rail system represent a gradual departure from the 'frugal' approach to network planning we discussed in earlier publications.

A similar trend is discernible in *Munich*, whose metro network remained static during the 2010s but where significant daytime frequency improvements occurred, among others, along the length of route U2 (Feldmoching to Messestadt Ost) as well as on parts of the tram and bus network in the core city. Two tram extensions to St Emmeram and Berg am Laim, and a short link to consolidate the multimodal transfer hub at Pasing, opened between 2011 and 2021. The eastern suburbs beyond the core city limits saw a program of bus service improvements that lifted several critical lines above the SNAMUTS minimum standard (if mostly only just so) for the first time.

Vienna opened two suburban metro extensions to Oberlaa (U1) and Seestadt (U2) during the 2010s but simultaneously closed the inner section of route U2 for major reconstruction. Instead, the corridor was flooded with tram replacement services which are partly responsible for the increase in tram service intensity on this index, though there have also been three tram network extensions in the north of the city, near Vienna's newly consolidated central rail station and in the inner urban redevelopment area of Nordbahnviertel. Some regional rail services saw frequency improvements, expanding the network at the SNAMUTS minimum standard.

In *Zurich*, the rail system was reorganised following the opening of an additional inner city rail tunnel between Hauptbahnhof and Oerlikon, while other infrastructure measures enabled frequency improvements on existing regional lines such as Oberglatt to Bülach and Baden, and Bauma/Turbenthal to Rüti. Three tram extensions to Schlieren, Altstetten and across the important rail transfer point at Hardbrücke make up the small increment in service intensity for the tram network, which is otherwise quite saturated. Numerous bus improvements occurred particularly in

suburban areas outside the core city, accessing previously underserved areas and creating new connections.



Ease of movement: are travel times and frequencies improving?

The closeness centrality index measures the ease of movement on a public transport network, taking in travel time and service frequencies as factors of spatial separation. Lower figures indicate greater centrality. The geographical spread of the network influences the results on this index, with a greater share of far-flung, peripheral nodes tending to inflate average figures, and with smaller metropolitan areas tending to deliver better averages than larger ones.

All four German-speaking cities record an average improvement on this index during the 2010s; however, Vienna (-3.2 points) and Zurich (-3.8 points) clearly outperform Munich (-1.1 points) and Hamburg (-0.3 points) while also topping the ranks in absolute terms.

In Vienna, Munich and Hamburg, improving closeness performance can be traced to frequency upgrades on parts of the cities' rail systems. In Vienna, average weekday interpeak frequencies on the metro (U-Bahn) system increased from an already high 11.9 per hour in 2011 to 13.9 in 2022. In Munich, average metro frequencies increased from 7.1 to 9.1 during the 2010s, and in Hamburg from 9.1 to 10.0. Suburban rail (S-Bahn) frequencies, in contrast, more or less stagnated between 4.1 and 4.3 per hour in Munich and Vienna (where singular inner-city trunk lines operate near the limit of their practical capacity), and at 7.0 per hour in Hamburg (which has two parallel inner-city trunk lines and thus some room for further growth). Hamburg's higher figure can also be attributed to the fact that the metro-like S-Bahn system in the Hanseatic city is largely technically and operationally segregated from the regional rail system; a common figure for both systems which would be more comparable to the conditions in Munich and Vienna puts Hamburg's average frequency at 5.0 per hour in 2010, and at 5.4 in 2020. In Vienna, average weekday interpeak tram frequencies increased

from 10.3 to 11.3 during the 2010s; in Munich, they increased from 8.0 to 9.3. Hamburg remains Europe's largest city without a tram or light rail system.

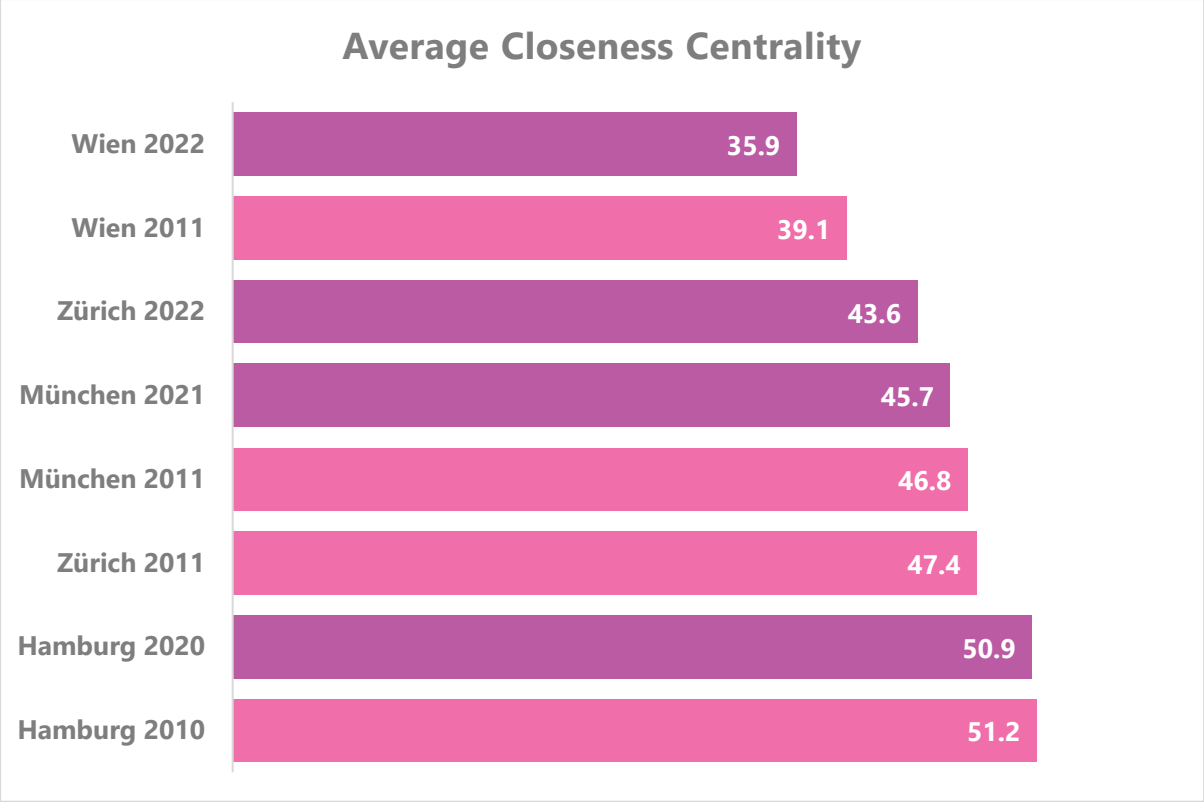
In Munich, the effect of rail and tram frequency improvements on average closeness results is mitigated by the addition of seven peripheral, bus-based activity nodes outside the core city between 2011 and 2021 (Aschheim, Brunnthal, Kirchheim, Martinsried, Neuried, Putzbrunn and Unterföhring Rathaus) with inherently higher (poorer) closeness values. Services to and from these nodes now meet the SNAMUTS minimum standard, following frequency improvements on regional bus routes, though in most cases these improvements concerned weekend rather than weekday services.

In Hamburg and Vienna, only one regional activity node each (Bargteheide and Ebreichsdorf, respectively) was added to the SNAMUTS network outside the core city during the 2010s, in both cases following the introduction of half-hourly rail services now meeting the (more lenient) SNAMUTS minimum standard for rail.

In Zurich, no tangible average frequency improvements between 2011 and 2022 are on record for either the heavy rail system (average of 3.8 per hour) or the tram/light rail system (average of 11.5 per hour). Yet the Swiss city displays the largest positive shift in average closeness results in the sample. How was this achieved?

It helps in this context to focus less on average service frequencies across the network, but on improvements in both frequencies and travel times on specific, critical segments. In Zurich, we find that the new underground rail link between Hauptbahnhof and Oerlikon (Weinbergtunnel, opened 2014/15) with 12 trains per hour per direction reduced the travel impediment between these two critical nodes, as well as on other main routes converging at Hauptbahnhof where the new tunnel eliminated the need for some trains to change direction (and thus gain valuable minutes of travel time). In other words, a well-targeted capacity and operational upgrade at the very heart of the regional rail system had the reverberating effect of speeding up movement across the entire metropolitan network.

Other factors for Zurich's improved closeness result are expansions of half-hourly or better rail services at the northern and eastern fringes of the metropolitan area (Winterthur-Rüti, Winterthur-Stein am Rhein, Oerlikon-Bülach and Oerlikon-Baden). These measures may not have moved the metropolitan average much but resulted in significantly greater ease of movement for the peripheral towns and villages affected, thus improving their closeness scores (especially Bülach, Seuzach and Turbenthal/Wald). Lastly, a number of new or frequency-boosted tram and bus links in both the core city and the region (for example, tram route 4 between Altstetten and Escher-Wyss-Platz or bus route 485 between Frankental and Adlikon-Buchs) created time-saving additional travel opportunities closer to geographical desire lines.



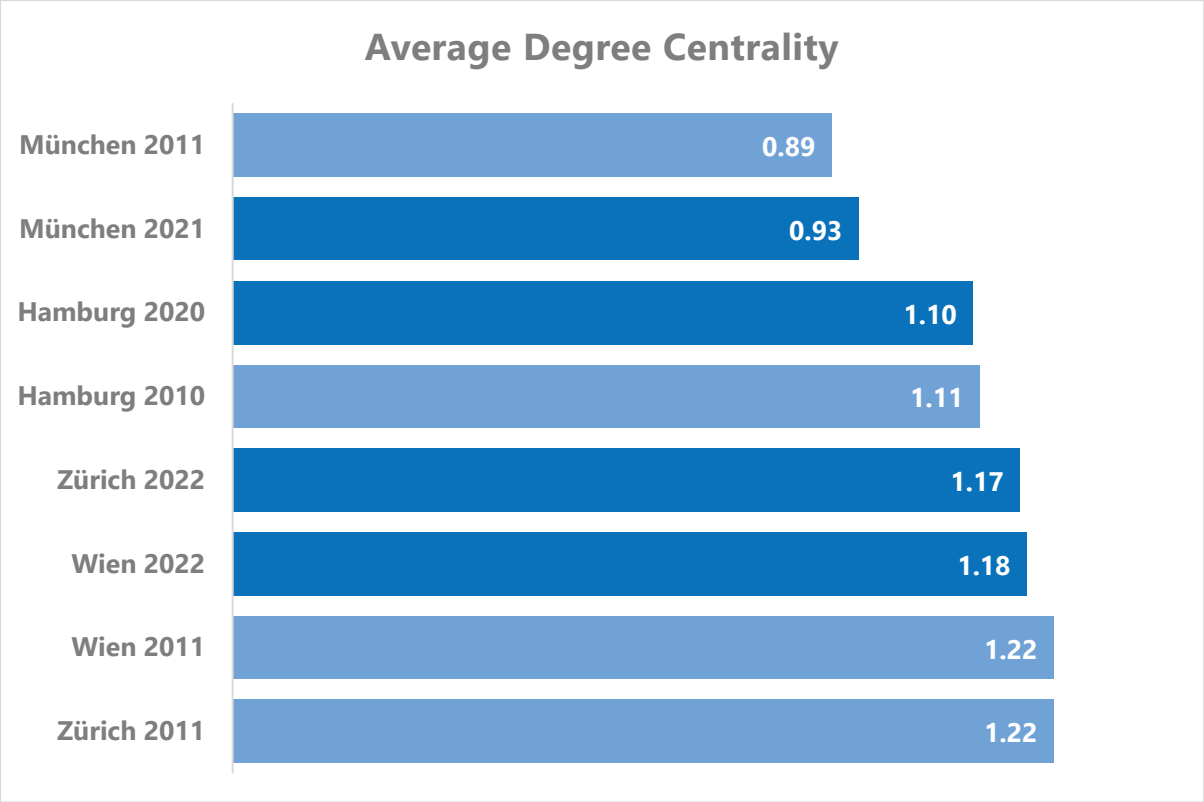
Download SNAMUTS network diagrams: Closeness Centrality			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

Transfer intensity: is the network making us change modes more often or less often?

Degree centrality measures the degrees of separation between origins and destination; in a public transport network, such degrees of separation are experienced as transfers. Lower figures indicate lower transfer intensity and can be read both as a successful quest for minimising the inconvenience of transfers for passengers, and as a sign of inefficiencies such as insufficient integration between modes or the failure to channel as much public transport movement as possible along the fastest and highest-capacity services.

In 2011, Munich had the least transfer-dependent network and Vienna and Zurich the most transfer-dependent ones, with Hamburg occupying an intermediate position that changed little during the 2010s. Over the decade, Munich's average degree centrality deteriorated slightly, which can largely be attributed to the addition of seven regional activity nodes that depend on bus feeder services to rail (previously, all but one node outside the core city were rail stations with direct services to the central city). In Vienna and Zurich, some improvement is on record. In Vienna, this is likely associated with metro extensions to Oberlaa and Seestadt replacing bus and tram feeder routes and supported by improved orbital links. In Zurich, rail network reconfigurations around the new tunnel and regional frequency improvements as well as the creation of more 'diagonal' tram and bus links have eliminated some transfer needs. Hamburg outperforms Vienna on this index largely because its rail system is more interconnected (all U-Bahn and S-Bahn lines intersect with all others, which is not the case in Vienna). Hamburg outperforms Zurich because it has more 'super-connected' multimodal

nodes in the core city (85 rail stations that are also SNAMUTS activity nodes, compared to Zurich's 19). In contrast, Hamburg is outperformed by Munich because its rail system retains more geographical service gaps in both the core city and the region, with a higher share of activity nodes even in inner urban areas depending on bus feeders to rail.



Download SNAMUTS network diagrams: Degree Centrality			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

Network coverage and 30-minute contour catchments: who gets access and can we travel further in less time?

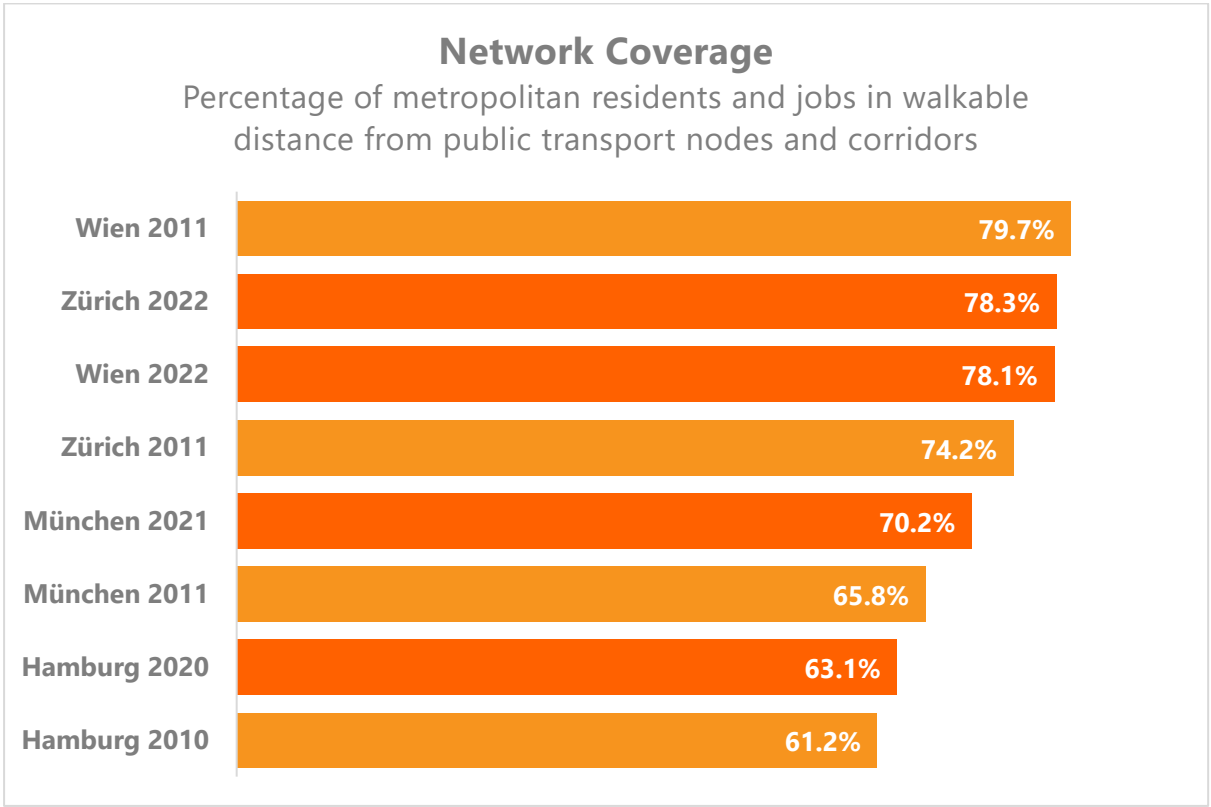
Network coverage is a public transport endowment measure, asking a simple binary question: who in a metropolitan area lives or works within 400 metres (trams, buses) or 800 metres (rail, ferries) of public transport at the SNAMUTS minimum standard and who doesn't? Over time, network coverage can increase either by the geographical expansion of public transport services, or by a higher rate of urban growth/intensification within public transport-accessible areas than outside of them (or a combination of both).

During the 2010s, the percentage of metropolitan residents and jobs within walking distance of useful public transport grew by 4.4 points in Munich, 4.1 points in Zurich and 1.9 points in Hamburg. In Vienna, it fell by 1.6 points, albeit from a high level. In all four cities, the network coverage situation differs quite starkly between the core city and the remainder of the metropolitan region. Core city coverage is nearly universal (between 93% and 100%) across the sample and in both base years. But beyond the core city limits, the figures drop as far as 19% (2010) and 21% (2020) in

Hamburg. In Vienna, an outer region coverage of 37% in 2011 contracted to 34% in 2022, a product of sluggish network expansion in areas where the population and job growth rate exceeds that of the core city. In contrast, Munich's outer region climbed from 35% (2011) to 41% coverage (2021), largely thanks to the introduction of several minimum-service bus routes there to access additional areas. Of the four case study cities, Zurich had the highest outer area network coverage in 2011 (62%) and increased it further to 66% in 2022.

The sizeable performance gap between Hamburg and Munich on this index has its roots in the ubiquity of rail infrastructure serving the outer metropolitan region. In Munich, there are no less than 12 radial S-Bahn corridors converging on the core city while in Hamburg, there are only five (of which one does not even extend beyond the core city limits). Two further corridors are currently being upgraded to S-Bahn standards while another two regional rail routes (just) meet the SNAMUTS minimum standard. In total, Hamburg's outer metropolitan area has 48 U-Bahn, S-Bahn or regional rail stations meeting the SNAMUTS minimum standard (2020) while Munich's has 97 (2021). In outer Vienna, there are 51 such stations (2022) and in outer Zurich, 129 (2022), in each case not counting tram or light rail infrastructure.

Hamburg's outer metropolitan region thus counts on a much lower level of penetration by useful public transport services than those of its peer cities, which more than likely translates into more widespread car dependence across a significant number of regional centres with very rudimentary public transport services (Uetersen, Barmstedt, Ratzeburg, Mölln, Trittau, Schwarzenbek, Lauenburg, Seevetal and Jesteburg come to mind). But Vienna's outer region, especially if current growth trends continue, also has room for improvement in this regard – perhaps by identifying and acting on the 'low-hanging fruit' that enabled Munich to add more useful, 7-day bus services penetrating the outer region with only a modest outlay of extra resources, even though these measures are thus far limited to only one out of eight counties that make up the Bavarian capital's outer metropolitan area.

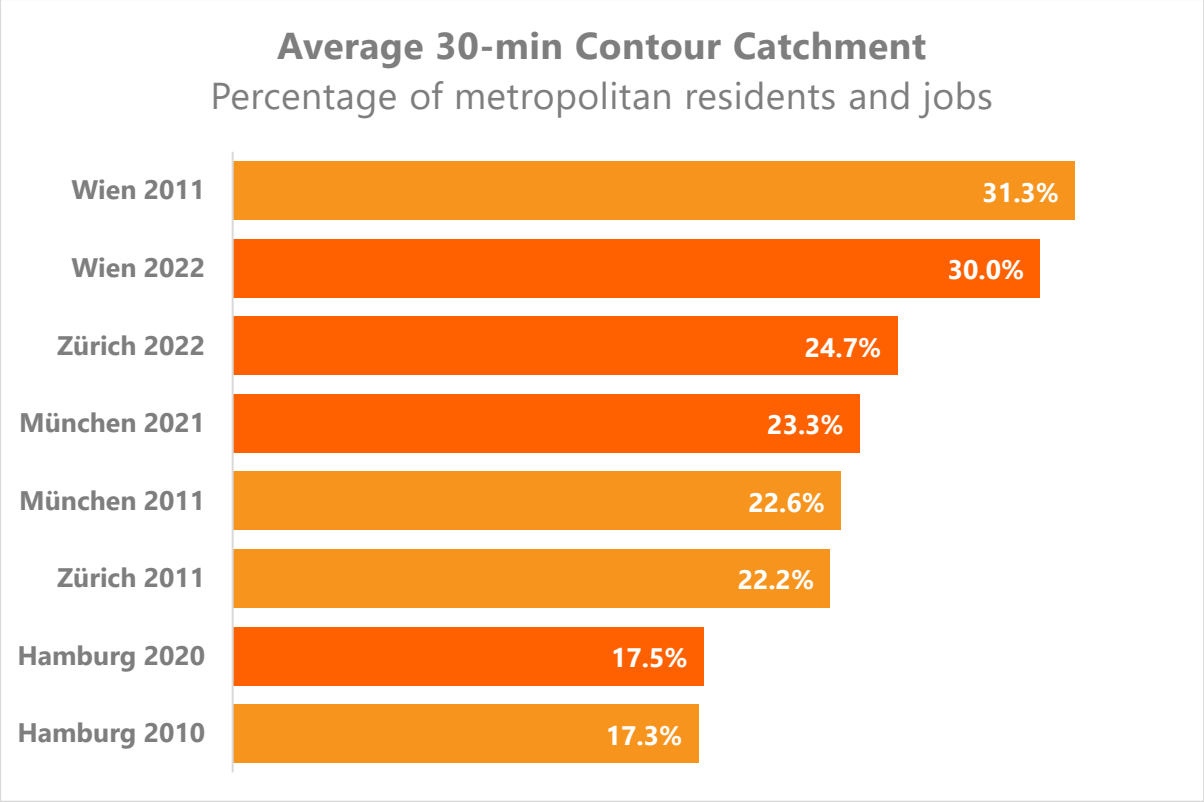


The 30-minute contour catchment measure adds a qualitative dimension to the network coverage index: besides public transport endowment, we are now also examining the extent to which a metropolitan area is penetrated by useful public transport travel opportunities. Useful in the sense of: achievable within a limited time frame (30 minutes) and accessing a high number of potential origins and destinations (catchment density). Travel speed, frequency (waiting and transfer times) and the geographical directness of journey paths (network configuration and geography) play a role here.

On this index, Vienna occupies the top average position in this four-city sample though its performance has dropped slightly from its high level over the 2010s. As in the previous indicator, the relative increase in weight of the outer metropolitan area (from 30% to 32% of all metropolitan residents and jobs) between 2011 and 2022 appears to be the most likely explanation, while Vienna's overall superior rating can be attributed to its spatial compactness and more widespread high settlement densities (as discussed previously).

Hamburg's average performance on this index markedly trails that of its peer cities, and barely moved between 2010 and 2020. The city's geography around a tidal estuary including a large seaport with limited crossing points, and the relative spatial patchiness of its rail network compared to its peer cities, conspire to depress average contour catchment figures. Despite an ongoing bus priority program, there have been few significant improvements in public transport speed that could expand the contours (the city's only metro extension during the 2010s accesses a major redevelopment area and thus far fulfils more of a local than a network function). The average transfer delay across the network, which is applied to all transfer journeys in this index and benefits from frequency upgrades, also remained nearly constant between 2010 and 2020 at 6.5 minutes.

In Munich and especially Zurich, an average increase of contour catchments is on record. In Munich, unlike in Vienna, the core city's share of metropolitan population and employment grew very slightly from 53% to 54% between 2011 and 2021, suggesting a faster pace of urban intensification around public transport than elsewhere. The average transfer delay declined from 6.9 to 6.3 minutes following frequency improvements on metro, tram and bus lines, and (slightly) expanded average contours accordingly. Zurich's improving performance, as in the case of the closeness centrality index discussed above, can primarily be attributed to the additional rail tunnel and associated improvements around the central station (Hauptbahnhof), which led to travel time savings where they matter most, and to the creation of some shortcuts in the form of new tram and bus links.



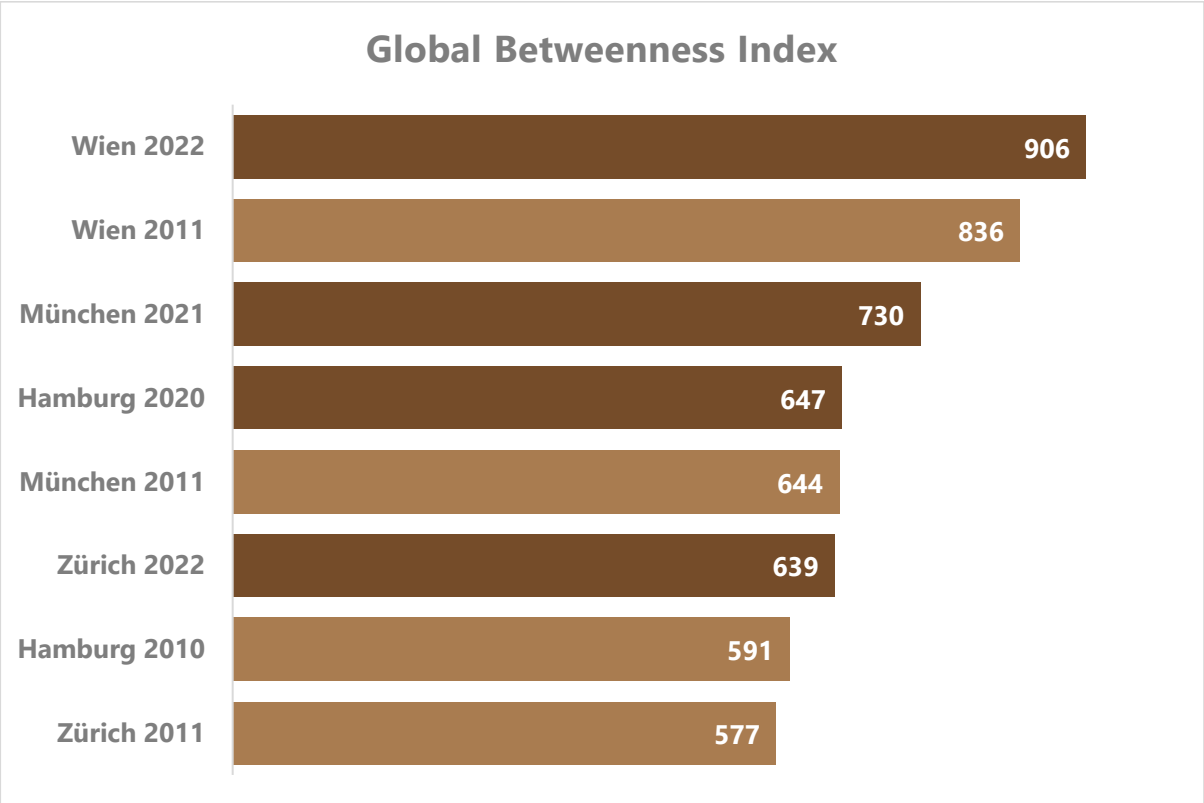
Download SNAMUTS network diagrams: 30-min Contour Catchments			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

Betweenness centrality: how does the network channel our journeys?

This index captures and visualises how travel opportunities flow across the network in geographical detail, and the volume they have, dependent on the ease of movement (closeness centrality, see above) and the spatial distribution of land use activities. A network-wide figure (global betweenness) aggregates all origin-destination values in relation to the number of metropolitan residents and jobs, and thus attempts to quantify the overall presence of public transport movement opportunities within a city. As the metropolitan-wide catchments of public transport networks grow, in relative figures (network coverage index) and even more so in absolute ones (amplified by population growth), we can expect this index to go up – and go up it did in all four German-speaking cities during the 2010s.

Vienna, commensurate with its stellar performance on the closeness index (as discussed above) and its wider proliferation of higher-density urban fabric, occupies the top rank in this comparison. Hamburg and Zurich make up the bottom half of the table but seem to perform at quite similar levels over time on the global betweenness index. This is primarily related to the spatial incontiguity of the land use-transport system. In Zurich, such incontiguity is generated by the dispersed-concentrated settlement structure of the region, separating urban and suburban cores by networks of open space, agricultural land, lakes and mountains, and thus prolonging travel times and distances compared to what they would be if the settlement area was as compact as in, for example, Vienna. In Hamburg, apart from the already mentioned effect of water bodies and the large seaport

on geographically separating urban clusters, the coexistence of activity centres with varying public transport quality at every distance band from the centre plays a dominant role here. Owing to the city's failure to complete its post-war metro expansion program and its historic decision to close down its first-generation tram system regardless, we can now find neighbourhoods served by fast and high-capacity metros and rail quite randomly side-by-side with neighbourhoods depending exclusively on slow and lower-capacity bus access throughout inner, middle and outer areas. In Munich, a similar effect was averted by a more ambitious and better resourced metro infrastructure program between the 1970s and 2000s, and by the retention of medium-capacity trams for secondary corridors in the inner and middle area. These policies resulted in a more contiguous land use-transport system and greater accessibility equity between places in the Bavarian capital over its Hanseatic counterpart.

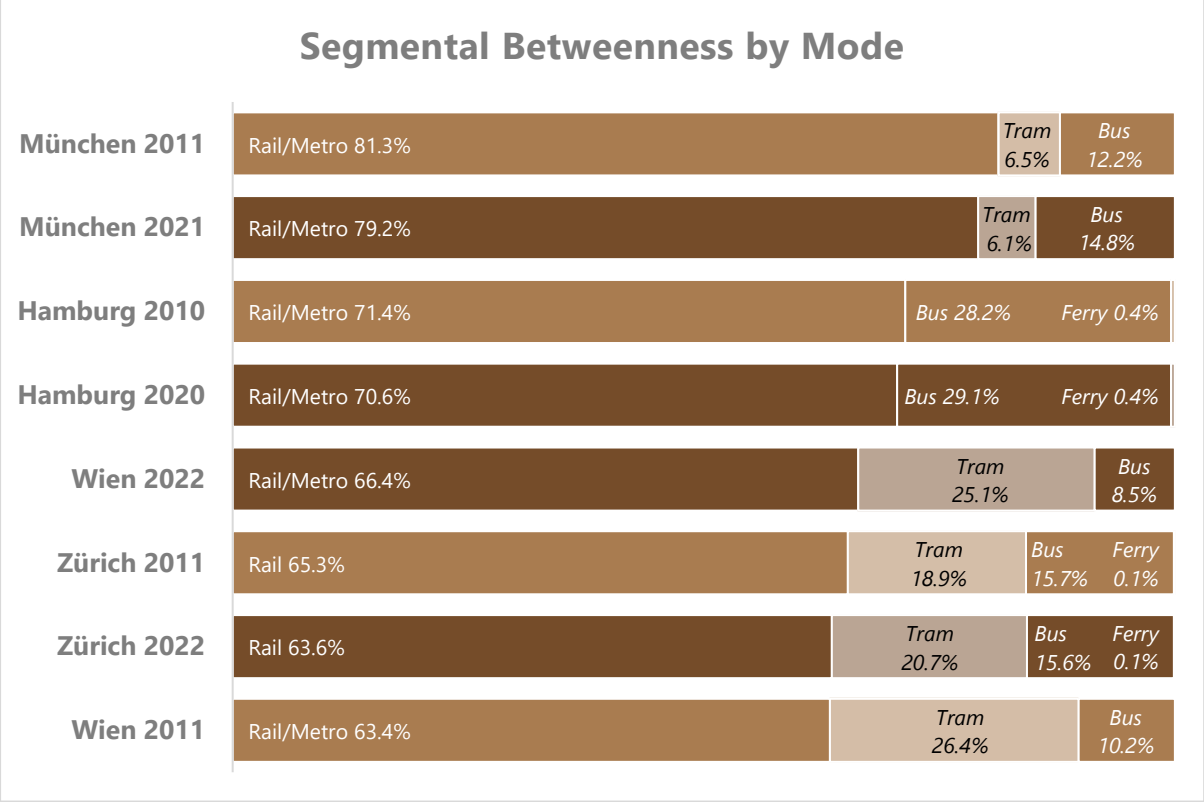


Download SNAMUTS network diagrams: Betweenness Centrality			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

Munich also leads the sample in its reliance on (heavy) rail for facilitating movement across the city-region, while the tram network, much reduced in size over its heyday in the 1970s as metro construction progressed, occupies more of a niche function. Interestingly, during the 2010s the relative role of buses increased at the expense of rail (S-Bahn) and trams, a development chiefly associated with network improvements in the outer metropolitan region where upgraded bus routes created additional orbital links and rail feeder services for towns and suburbs away from the rail stations.

In Hamburg, the relative importance of different public transport modes for facilitating movement shifted only marginally during the 2010s. Heavy rail dominance is greater than in Vienna and Zurich; however, in the absence of a medium-capacity mode Hamburg also sports the greatest (and on recent trends, further increasing) dependence on buses in the four-city sample. Vienna experienced a shift in importance from buses and trams to heavy rail between 2011 and 2022, which is within expectations following two metro extensions replacing former tram and/or bus trunk routes, and frequency improvements across both the U-Bahn and S-Bahn networks.

In Zurich, the importance of heavy rail declined slightly in favour of trams and light rail between 2011 and 2022, despite the newly opened Weinbergtunnel increasing capacity and ease-of-movement across the rail network. We have speculated about this somewhat surprising effect in an earlier blog post and postulated that inner urban intensification likely places disproportionate additional pressure on the tram system, which serves the core city ubiquitously while the rail system, configured more for region-wide than intra-urban travel, has only a limited number of stations within city limits.



Network Resilience: can the public transport service offer cope with the role the land use system assigns to it?

This index can be understood as a troubleshooting tool for public transport networks. By calculating a ratio between segmental betweenness results and the actual passenger capacity offered on each route segment, and to and from each activity node, we can determine whether the service level on a particular network element is well-matched to its significance for metropolitan-wide movement, or whether (and to what extent) it falls short. Positive values, shown in green on the diagrams, indicate a good match. Smaller negative values (between 0 and -12, shown in yellow and orange) indicate a

measure of underperformance. Larger negative values (beyond -12, shown in red and maroon) indicate a more severe capacity constraint.

All four German-speaking cities remain in positive average figures on this index, though all four have also seen some deterioration in their performance during the 2010s (very slightly so in the case of Vienna, and from an exceptionally high base in the case of Zurich).

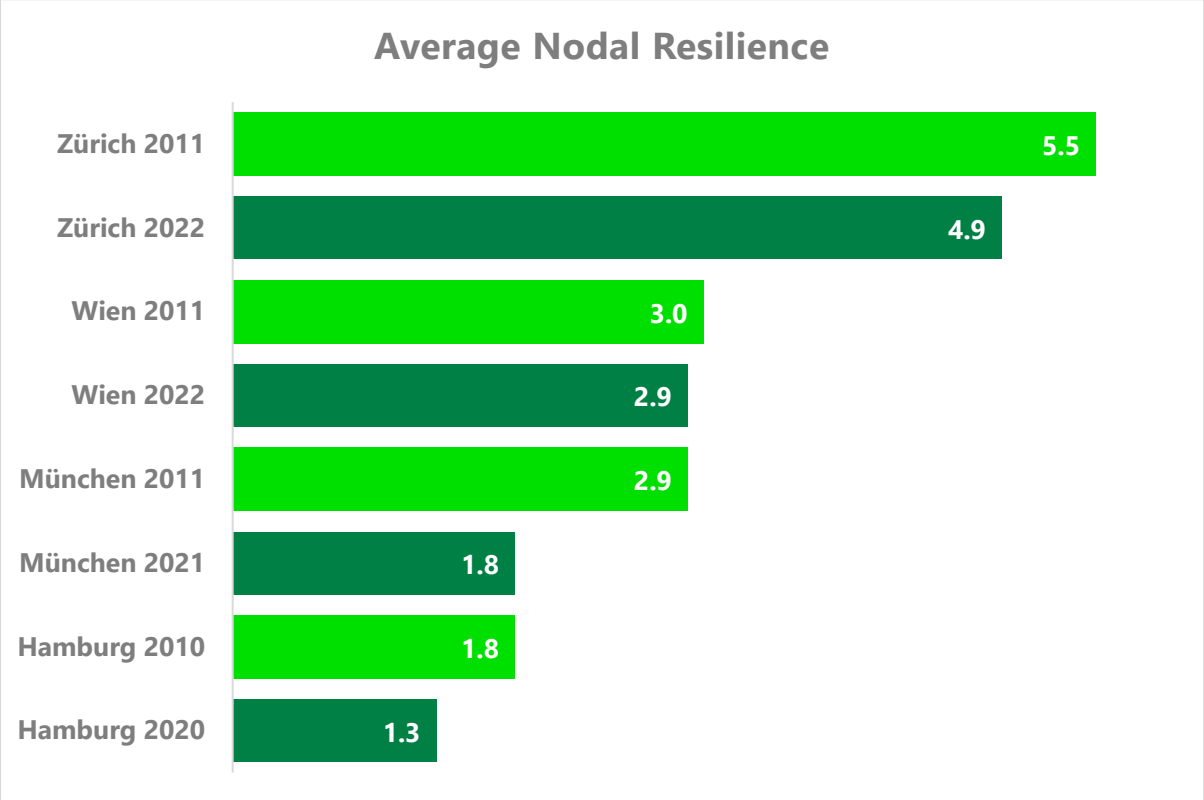
In Hamburg, a slight decline on resilience performance is on record for the suburban rail (S-Bahn) system and the CBD area, while the metro (U-Bahn) and bus system roughly maintained their average level between 2010 and 2020. Looking at greater geographical detail, however, it becomes obvious that these trends are not evenly distributed. Deteriorating resilience on the bus system is particularly apparent on bus route M5 between Schnelsen and Rathausmarkt, following the corridor of Hamburg's last tram route to close in 1978 and now allegedly Europe's busiest bus line. During the 2010s, the route was subject to a bus priority program which cut 4 minutes from the scheduled travel time on the inner section south of Siemersplatz. In SNAMUTS terms, this achievement has the effect of making the line more attractive for trip making even though it does not really have the capacity to absorb more patronage. This is true both intrinsically through inducing more travel opportunities along its immediate corridor as well as pulling more transfer journeys from neighbouring areas towards it, with the result of sharply declining resilience along the line while generating relief along connecting routes (witness the improvement in resilience at the adjacent nodes of Hagenbecks Tierpark, Eppendorf Markt and Kellinghusenstraße, from where a faster bus route M5 may have syphoned off bus-metro transfer journeys). A related effect can be observed for some recent initiatives to introduce more express bus routes providing longer-distance links for middle suburbs away from metro or rail stations, namely Osdorfer Born and Lurup (route X3), and Marienthal and Jenfeld (route X35). While such express bus routes are commendable in the absence of the much longer-term alternative of developing metro extensions to these areas, they simultaneously run the risk of rapidly becoming 'victims of their own success', leaving passengers with the unappealing choice of an overcrowded and possibly unreliable direct bus service and a slower and less convenient bus-metro transfer journey away from their geographical desire line. While Hamburg continues to play 'catch-up' to implement critical additional metro lines that are 50 years overdue, and to drag its feet about reintroducing trams or another medium-capacity mode to its public transport offer, such resilience shortfalls are likely to perpetuate into the future.

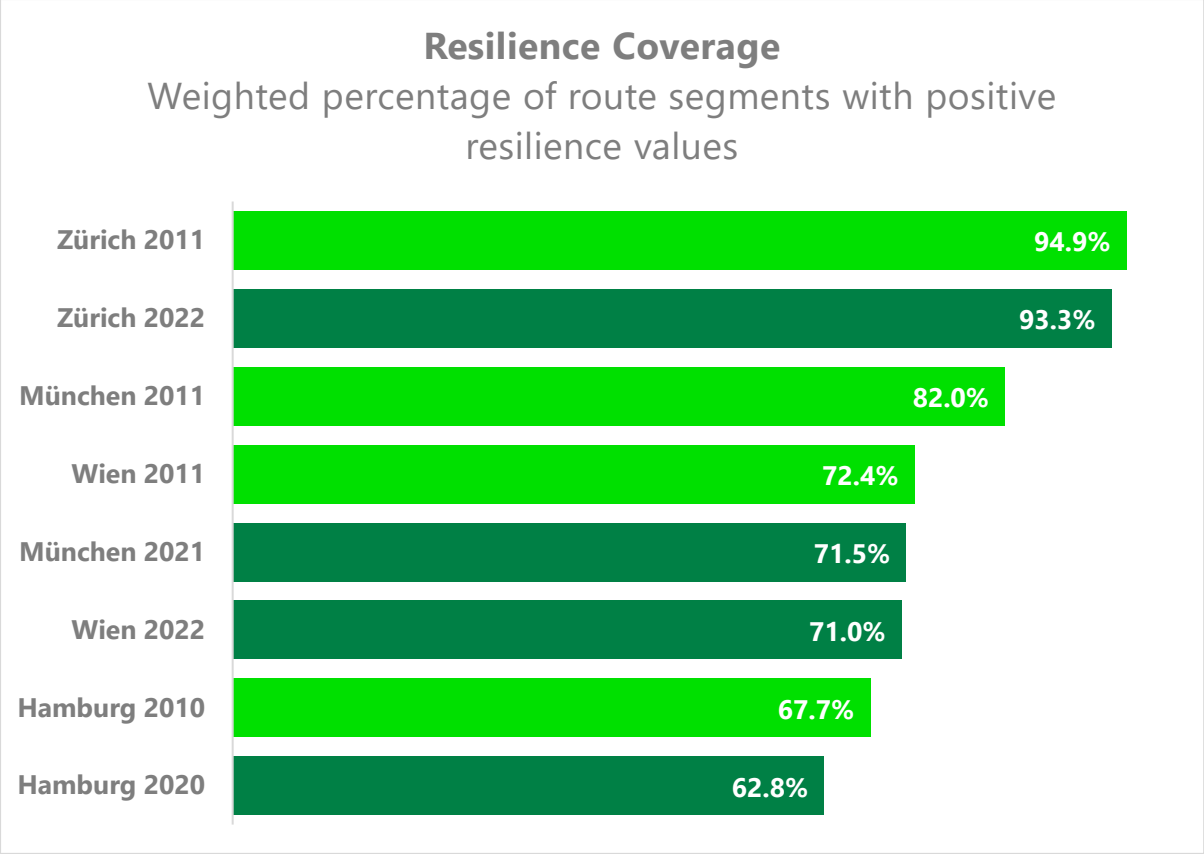
Munich saw the largest drop in resilience performance among our four-city sample, affecting all public transport modes on an average basis. It is notable that the effective doubling of daytime frequencies along metro route U2 (Feldmoching-Messestadt Ost) barely improved the line's resilience performance: rather, it strengthened its position in the network by pulling more travel opportunities from alternative journey paths towards it. The Fürstenrieder Straße corridor in the city's mid-west (route M51) was the poorest resilience performer on the bus system in 2021, deteriorating since 2011 despite or perhaps because of a generous frequency upgrade, but now sensibly in progress for conversion to tram operation by 2028. The upgraded regional bus routes in the outer west (Martinsried, Neuried) and east of the city-region seem to have had a mixed effect on network resilience: The northeastern routes around Ismaning, Aschheim, Kirchheim and Feldkirchen seem to not have added drastically to stress on the connecting rail lines, perhaps because orbital route 230 (Garching-Haar) distributes the additional travel opportunities quite effectively. However, the opposite is the case in the south-east around Putzbrunn, Ottobrunn, Brunnthal and Taufkirchen, where additional feeder bus routes put downward pressure on the resilience of radial S-Bahn routes S3 (Holzkirchen) and S7 (Aying), as well as metro route U5 through the interchange at Neuperlach Süd. Frequency upgrades on these rail lines to absorb the effect better would be desirable; however,

in the case of the S-Bahn lines these are constrained by the limited capacity of the central underground trunk between Hauptbahnhof and Ostbahnhof, whose duplication is under way but unlikely to open before 2035.

Vienna and Zurich's overall resilience performance looks more unburdened than that of Hamburg and Munich, with a couple of exceptions: In Vienna, pressure seems to have mounted on the central section (Praterstern-Hauptbahnhof) of diametrical metro route U1 between 2011 and 2022; this is likely at least partially related to the temporary closure of the central city section (Schottenring-Karlsplatz) of route U2. The absence of this metro link, expected to reopen in 2026 after conversion to driverless operation as part of new route U5, also affects the tram services in the area. Below-average resilience performance is also on record for critical parts of metro route U3 (Westbahnhof to Stephansplatz) and U6 (Währinger Straße-Volksoper to Meidling); here, the inner west extension of route U2 between Schottentor and Matzleinsdorfer Platz, scheduled to open by 2030, should provide some relief.

Zurich's resilience shortfalls are few and far between, and perhaps less consequential than those in its peer cities. The city approach of the Uetliberg and Sihltal railways (routes S4 and S10) catches the eye here, an inner urban link with short train and platform lengths and technically and operationally separate from the remainder of the regional rail system, but it has plentiful travel alternatives on parallel and connecting tram and bus lines. Throughout the core city of Zurich, some bus segments record problematic and deteriorating resilience results, underscoring the importance of an ongoing program to convert some of the busiest routes to tram operation.





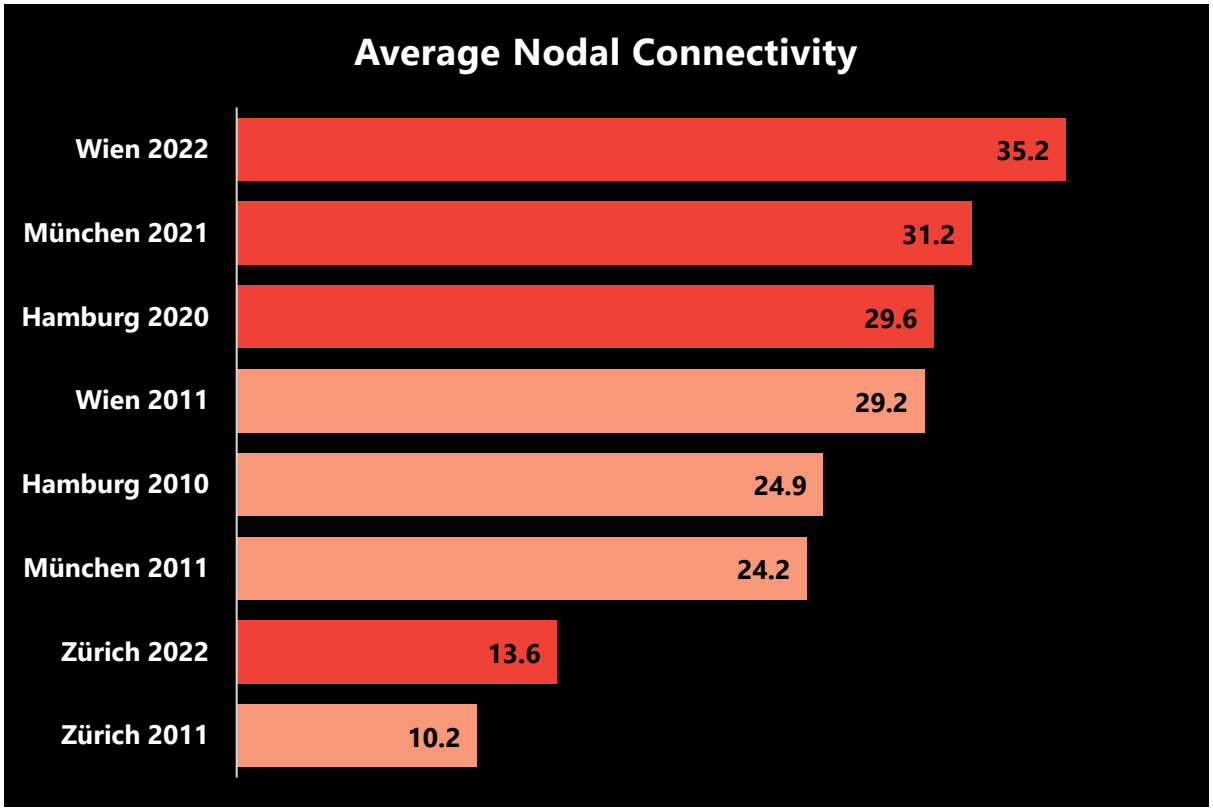
Download SNAMUTS network diagrams: Network Resilience			
Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

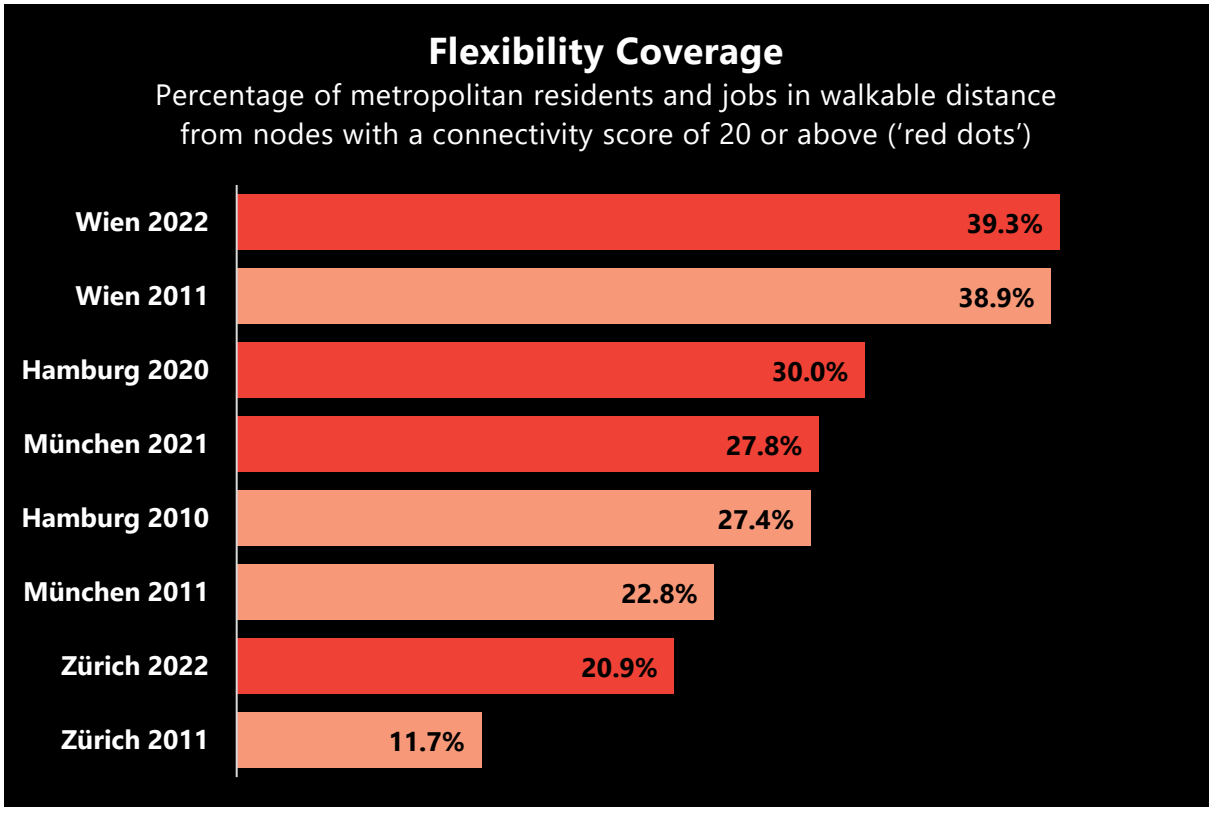
Nodal Connectivity: how freely can we navigate the public transport-land use system?

The nodal connectivity index conveys a sense of how flexibly users can move to and from a particular node on the network, by counting the number of directions one can travel in, the number of departures per hour, and the capacity (average occupancy) of the different modes that converge in each location. This has a bearing on the perception of a location to support public transport-oriented lifestyles and business models, and in turn influences its attractiveness for transit-oriented development. 'Red dots' with a nodal connectivity score of 20 or above can be considered the hotspots of a network for these qualities. The prevalence of such hotspots is naturally greater in larger, more complex networks – however, the average occupancy of each mode also enters this index as a proxy for the number of people boarding, alighting or transferring at a node and is subject to change over time in relation to betweenness and resilience performance.

In all four cities, average results on this index as well as the proportion of people living or working in the walkable catchments of nodes with 'red dot' status grew over the 2010s. Zurich's bottom-ranked performance in this sample can be attributed to the city-region's smaller size and the relatively small number of rail stations within the core city, where they are hyper-connected to all modes of transport. Simultaneously, the number of 'red-dot' nodes in Zurich grew from 12 to 21 between 2012 and 2021, and the share of metropolitan residents and jobs in their walkable catchments

nearly doubled. In contrast, Vienna has a clear edge over similar-sized Hamburg and Munich on both counts of the index, but the number and aggregate catchment size of ‘red-dot’ nodes barely changed there during the 2010s.





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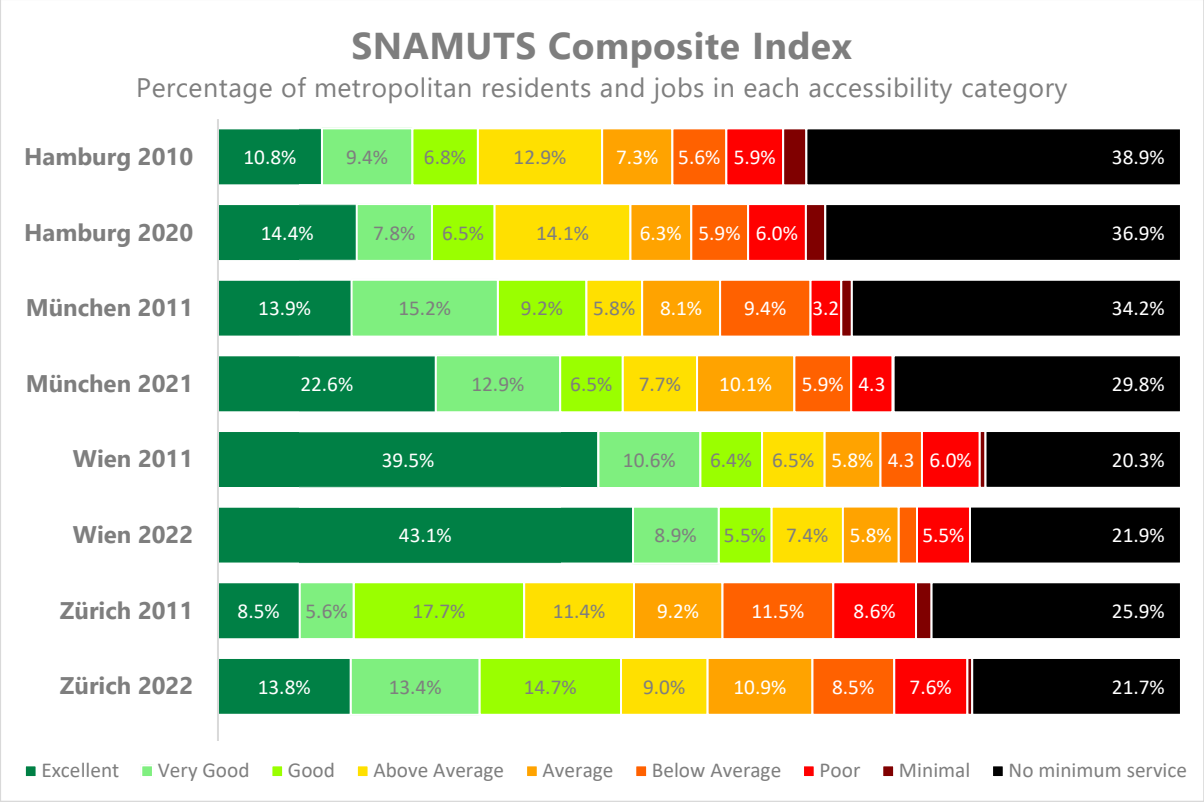
Hamburg 2020	München 2021	Wien 2022	Zürich 2022

SNAMUTS Benchmark Composite Index

The SNAMUTS composite index takes in results from the component indicators of closeness centrality, degree centrality, contour catchments, betweenness centrality, nodal connectivity and nodal resilience and calibrates them on a scale from 0-60 (maximum 12 points for each component indicator except resilience, where negative values lead to deductions). It is primarily conceptualised as a visualisation tool to quickly identify areas of good, average and poor public transport accessibility on a metropolitan scale map, and to follow their evolution over time.

On a numerical scale, Vienna leads the four-city sample on the composite index, followed by Munich in second place, while Zurich narrowly leapfrogged Hamburg for third place between 2010/11 and 2020/22. All four cities improved their average performance over the course of the 2010s, enabled by network expansion, frequency improvements and population and employment growth while, with few exceptions, keeping resilience shortfalls in check. Meanwhile, the composite maps illustrate the spatial patchwork character of better and poorer accessibility categories particularly across the inner and middle areas of Hamburg, while Munich and Vienna display a more concentric pattern of accessibility decay from centre to periphery. Munich and Vienna's maps also clearly show the accessibility lift achieved by the frequency improvements on metro route U2 in Munich, and by the U1 and U2 extensions in Vienna. In Zurich, network improvements visualise the catchments of key rail stations in the core city (Altstetten, Hardbrücke, Hauptbahnhof, Stadelhofen, Enge, Oerlikon, Stettbach), all reaching the highest accessibility category by 2022. While the Swiss city still lags Hamburg in the percentage of residents and jobs within this category, it shows a stronger increase in the next two (lighter green) categories, in 2021/22 offering this quality of accessibility to a share of the residential and working population comparable to Munich despite its far more dispersed settlement form. In Vienna, the sheer number of activities within the highest accessibility bracket probably makes it advisable to introduce further, even better categories for a more differentiated visualisation; this has been avoided here to maintain easier comparability within the sample.

By the next European census year in 2031, when we hope to repeat the SNAMUTS analysis for these four cities, we should expect further infrastructure measures particularly in Vienna, where the initial stage of the U2/U5 metro project will have reached completion, and several shorter tram extensions will have opened. Munich and Hamburg have two shorter metro extensions each on the books for likely completion by that time; in Hamburg we will also see the conversion of two currently underperforming regional rail corridors (to Kaltenkirchen and Bad Oldesloe) to S-Bahn operation and in Munich, the completion of several tram extensions including the critical western orbital route. However, the more ambitious, transformational projects such as Munich's second inner-city S-Bahn tunnel, releasing enormous capacity reserves across the existing network, and Hamburg's automated new metro route U5 to provide a high-capacity, rapid transit option for its most congested current bus corridors, will not fully open until well into the 2030s. In Zurich, a new regional light rail route along the Limmat valley to the west of the city opened in 2023; another tram extension to Affoltern in the core city may be completed by 2029. Meanwhile, all four cities expect population and employment growth to continue unabated.



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Hamburg 2010	München 2011	Wien 2011	Zürich 2011
Hamburg 2020	München 2021	Wien 2022	Zürich 2022