Performance measures for public transport accessibility: Learning from international practice

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Abstract: There is a growing recognition by city policymakers that urban public transport systems can be developed in such a way that travelers can be offered an alternative to car-based travel. How to evolve the public transport system for this purpose is a significant challenge and raises questions of accessibility and quality largely absent from current planning evaluation. This paper explores the use of accessibility performance measures, both to assess the extent of current public transport accessibility and as a potential metric for future planning and investment. The Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool is employed for analysis of accessibility. A sample of 21 international cities is assessed, representing a range of transport and land-use policy contexts from best to ordinary practice, including those held up as exemplars in public transport infrastructure, service planning, and delivery in Europe and North America. The findings show that the incidence of successful metropolitan public transport systems, as measured by patronage, can be linked to accessibility performance measures of network and service configurations.

1   Introduction

Many cities in the developed world are experiencing rising road congestion. There has been a growing recognition that public transport systems must be developed in order to offer a real alternative for travel. There is a significant challenge for both public transport planners and the public transport system itself to evolve from a dual orientation, focused on central city job commuting, and the provision of a social safety net, toward a service that is capable of catering to all urban passenger transport needs across metropolitan areas (Mees and Groenhart 2013).

This international trend is mirrored in our own country. Australia has seen strong growth rates in public transport usage since the turn of the century, reversing a previous downward trend (Figure 1).

Each Australian capital city has adopted a metropolitan planning strategy, proposing the integration of public transport with land use, through transit-oriented development, to reshape cities as a means to offer transport choice.
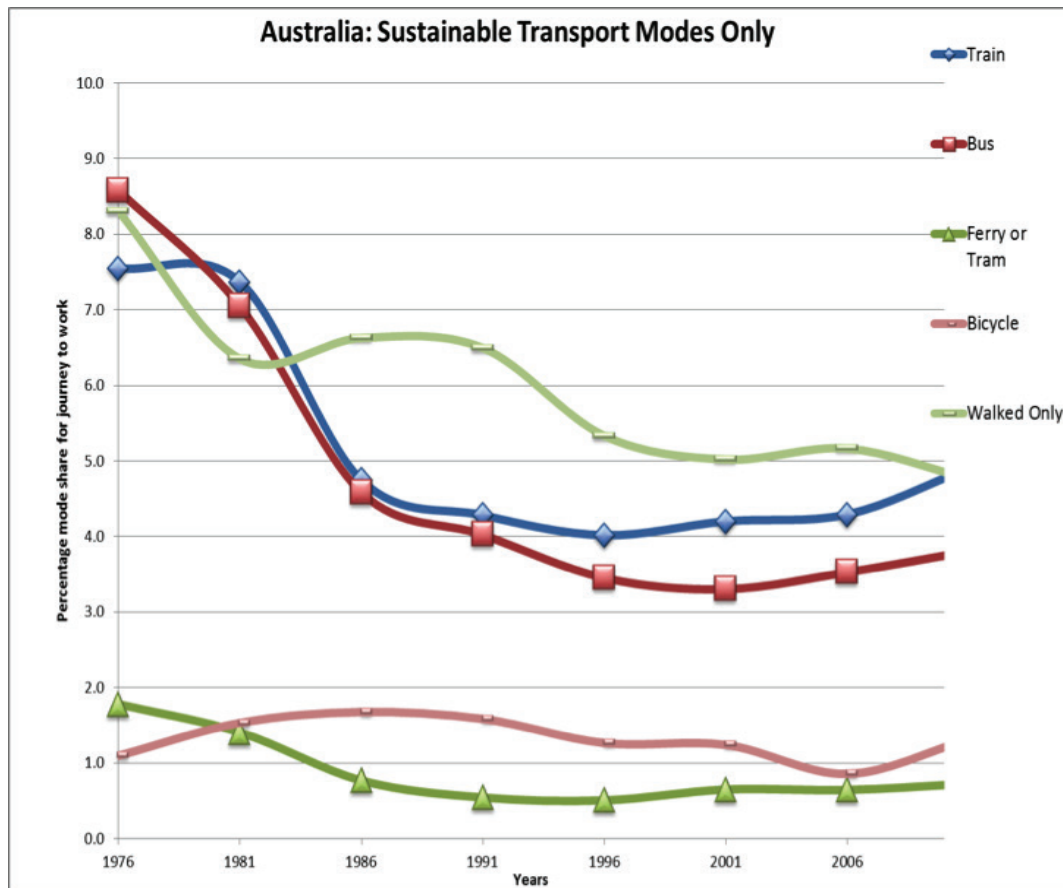

Figure 1: Australia: travel mode share for non-car trips for journey to work 1976–2011
Source: Australian Bureau for Statistics

If public transport is to offer a real alternative transport mode choice to the car, there is a need for a new approach to planning and evaluating public transport accessibility, which takes into account the transport network and also assesses the integration of this network with land use and the consequent activity opportunities. It is evident that there has been an absence of such an approach designed to usefully inform key policy objectives about the future of public transport network in relation to accessibility improvements (Curtis, Scheurer, and Burke 2010). Instead strategic planning for public transport has often been unambitious, with most proposals offering incremental improvements to the existing radial, mono-centric network based on demand forecasting rather than future planning in the context of meeting new policy objectives (ibid.).

Given the multi-billion dollar scope of infrastructure proposals, the substantial costs to the economy and the environment implied in making suboptimal or poorly informed decisions for infrastructure investment (where it fails to deliver alternative accessibility to the car and therefore fails to reduce car-based transport emissions), this quest for greater rigor of assessment is vital to allow for the most efficient allocation of government resources and the greatest benefit to the public. Bearing these issues in mind has brought to the foreground the need to establish an evidence base for public transport investment.

This raises the question as to what should be the appropriate benchmarks for public transport accessibility for metropolitan areas.

There are different ways of considering the notion of benchmarking. At its most basic, benchmarking can be defined as "a standard or point of reference against which things may be compared" (Oxford Dictionary). At this level of definition, the question would be: How do the public transport systems of international cities compare? In the context of the policy imperative "future public transport planning," however, the definition "a standard of excellence, achievement etc., against which similar things must be measured or judged" (Online Reference Dictionary) adds the dimension of excellence or best practice. In the context of this research, it suggests the need to establish a benchmark, or metric, for an excellent public transport system.

In this paper, benchmarking is conceived in two dimensions: current and future. In the first, our interest is in how current public transport systems in international cities compare. Exploring this dimension enables an assessment of accessibility using a set of standardized indicators. These indicators measure different aspects of accessibility and thus respond to different policy questions. Thus it is not our intent to select only one indicator as "best." We apply these indicators to cities that have different contexts (urban form, transport networks, geography). In this way we can consider whether it is possible to offer a universal benchmark. In the second dimension, our interest is in what the standard of excellence for a public transport system in Australian cities should be. This is our reference point. Our overarching metric is derived from policy objectives present in Australian cities and our interest in sustainable accessibility, in this case, a public transport system that provides an alternative mode choice to the car for the city's metropolitan residents.

While our benchmark is based on public transport accessibility for all, others have chosen different metrics. For example, it is common for governments to use "public transport patronage" as a measure that reflects the concern that investment in the public transport network "paid off," or that demand forecasts were met. Others focus on the cost of operating the public transport network, or the costs of construction. We assert that the choice of metric is dependent on what policy objective is being considered. All too often the choice has been based on the cost of public transport framed around the storyline of "public transport subsidy" (Curtis and Low 2012) rather than being based on the need to implement policy imperatives.

2   Research approach

To assess the accessibility of different cities, we employ the Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) accessibility tool. This tool is designed to reflect a vision of world best practice in public transport derived from the contributions of scholars and practitioners over the years and most comprehensively documented in the European Union HiTrans project (Nielsen et al. 2005). In geographical and operational terms, the success factors most frequently discussed in the literature are:

- A configuration of the system in terms of network coverage and service frequencies that offers a viable alternative to the car for most, if not all, travel purposes across the urban area (Laube 1998; Nielsen et al. 2005; Mees and Dodson 2011)
- A legible network structure that is efficient to operate, easy to navigate and offers a choice of routes wherever possible (Mees 2000; Mees 2010; Mees and Dodson 2011; Vuchic 2005)
- A speed advantage of urban rail over road traffic along a city's main corridors (Newman 2009; Newman, Beatley and Boyer 2009)

- The integration of public transport facilities with supportive urban development, in particular high-density, mixed-use, walkable nodes around rail stations and major interchanges (Bernick and Cervero 1997; Cervero 1998; Dittmar and Ohland 2004; Curtis, Renne, and Bertolini 2009)
- An institutional framework that allows for integrated, publicly accountable capital investment and service planning (Mees 2005; Mees 2010; Nielsen et al. 2005)

SNAMUTS is a GIS-based tool designed to assess centrality and connectivity (primarily) of urban public transport networks in their land-use context, and in their market position among multimodal travel options. In particular, SNAMUTS endeavors to identify and visualize a land-use public transport system's strengths and weaknesses of geographical coverage, the ability and efficiency to connect places of activity, the strategic significance of routes and network nodes, the resilience of the network in the face of future patronage growth, and the flexibility of trip makers to use the network for both planned and spontaneous journeys across the metropolitan area. These factors are developed into a set of indicators. The indicators are described, together with the analysis pertaining to them, in the next section.

To examine these geographical and configurative success factors more closely, a range of measures and indicators are employed based on the perspectives of centrality and connectivity. A high level of centrality is understood as spatial proximity to a high number and range of urban activities. In a transport network sense, it can be measured in several different ways, according to the configuration of a movement system around nodes and edges and their distribution over, and their relationship to the activities within, the urban space. Following this approach, SNAMUTS breaks down the land-use transport system into a set of activity nodes and route segments derived from the hierarchy of activity centers identified in strategic-planning documents, and the location and service standard of public transport routes, derived from timetables and other travel information in the public domain. In particular, SNAMUTS makes the following definitions:

- Minimum service standard: SNAMUTS defines a minimum standard for inclusion of a public transport route into the analyzed network, requiring a service frequency of 20 minutes (or better) during the weekday inter-peak period (about 10 a.m. to 5 p.m.) and 30 minutes (or better) during the day on Saturdays and Sundays on surface routes (buses and trams) and 30 minutes (or better) during the weekday inter-peak period in combination with seven-day operation on segregated rail and ferry routes. This level has been chosen as it reflects the minimum for public transport to be perceived as having a full-time presence and attracting usage for a variety of both planned and spontaneous journey purposes. The more lenient treatment of fixed-infrastructure public transport modes in this standard reflects these infrastructures' relative permanence and greater ability to influence land uses in their catchments.
- Activity nodes: These refer to a list of higher-order activity centers across a metropolitan area that appear in strategic planning documents or have been identified by on-site observation, with some adaptations to the configuration of the public transport network to also capture major transfer points and some linear corridors along high-frequency surface lines. Each activity node is assigned an exclusive catchment of residents and jobs located within walking distance from the associated rail station(s) (800 meters) or tram/bus corridors (400 meters).[1] Wherever two or more of these catchments overlap geographically, the residents and jobs are distributed in equal parts among the associated activity nodes. In effect, every resident and job within walking distance from a minimum-standard public transport service has been assigned to one, and only one, activity node catchment.
- Travel impediment: SNAMUTS measures spatial separation, or spatial resistance (a proxy value for distance) by relying on the units that are closest to the user experience, namely travel time and service frequency. Each route segment is labeled with an impediment value consisting of the average travel time divided by the square root of the number of services per hour, separately

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[1] Figures for the geographical distribution of residents and jobs in case study cities that inform the calculation of activity node catchment areas are generally derived from public domain material such as census databases.

for each direction, and multiplied by a factor of four to arrive at more readable numbers. The travel impediment (proxy distance) between any two activity nodes on the network is thus made up of the sum of the impediment values on each route segment traversed along the path.

- Weekday inter-peak: SNAMUTS' network performance measures refer to the service levels offered during the weekday inter-peak period (roughly between 10 a.m. and 5 p.m. on Mondays through Fridays). This is considered to be the time when the greatest diversity of travel purposes over a daily and weekly cycle coincide, and when the potential of public transport to offer a viable alternative (or not) to the "go anywhere, anytime" convenience of the car is most critically determined.

An overview of the formulas used to calculate SNAMUTS indicators can be found in the appendix of this paper. Those interested in further detail on the methodological and contextual explanation of each indicator may refer to Curtis and Scheurer (2010) and Curtis and Scheurer (forthcoming) since this is beyond the scope of this paper.

A sample of 21 international cities is assessed, representing a range of transport and land-use policy contexts from best to ordinary practice, including those held up as exemplars in public transport infrastructure, service planning, and delivery in Europe and North America. These regions include the six largest Australasian cities (Sydney, Melbourne, Brisbane, Perth, Auckland, and Adelaide), 11 European agglomerations (Amsterdam, Barcelona, Edinburgh, Hamburg, Copenhagen, Munich, Oporto, Utrecht, Wien, Zurich, and Zuid Holland), and four North American cities (Montreal, Portland, Seattle, and Vancouver).

3   Findings: Accessibility by public transport

3.1   The context: Public transport usage and mode share patterns

An overview for each city is provided in the following figures in order to set the accessibility metrics in their context. Cities are ranked according to their position for that particular metric. Population size of the defined metropolitan region is shown in Figure 2, where the region generally corresponds to the metropolitan statistic division and/or the jurisdiction of the regional public transport agency (ie., the geographical reach of integrated ticketing). The average urban density in each metropolitan region in residents and jobs per hectare of urbanized land is shown in Figure 3. The average number of public transport journeys per capita per annum in each metropolitan area is noted in Figure 4. These figures are generally derived from publications of statistical offices and public transport agencies; however, definitions for employment, urbanized land, and public transport journeys can and do differ in various jurisdictions. Hence, the numbers in Figures 3 and 4 are not beyond contestation and should be taken as a guide only.

The 21 cities in the sample differ in several respects. The largest conurbations in terms of population are Barcelona, Sydney, Melbourne, Montreal, Zuid Holland, and Hamburg. However, they differ markedly in settlement form. Zuid Holland is a polycentric region with two separate primary urban centers (Rotterdam and Den Haag) and a number of secondary ones (Leiden, Delft, Zoetermeer, Gouda, Dordrecht), whereas in Hamburg, Montreal, Melbourne, and Barcelona, the hierarchy of centers is far more traditionally structured with the primary center at the geographical and functional heart of the metropolitan area and the secondary ones acting as satellites. Sydney can be seen as a hybrid case consisting of a central business district (CBD) away from the region's geographical midpoint and complemented by a number of further significant centers farther inland.

Figures 2, 3, and 4: Metropolitan population (left), urban activity density, or residents and jobs per urbanized hectare (center), and public transport patronage data, or linked trips per capita per year (right) in case study cities.

Sources: ABS (2013), Auckland City Council (2013), Statistics Canada (2013), US Census Bureau (2012), TransPerth (2012), Adelaide Metro (2012), PTV (2012), NSW Bureau of Transport Statistics (2012), TransLink (QLD, 2012), TransLink (BC, 2013), AMT (2013), APTA (2013), Tri-Met (2013), 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).

Urban densities across the sample show a remarkable similarity between the Swiss, Scottish, Dutch, Portuguese, South German, and Canadian cities. Only in the two Nordic cities (Hamburg and Copenhagen) are average densities significantly lower and at a level comparable to the higher density cities in Australasia (Sydney and Auckland). Urban density for Vienna and Barcelona, in contrast, is significantly above the European average. Barcelona's topographical constraints restrict urban expansion with most urban settlement perched along a relatively narrow strip between a coastline and a mountain range. Encroaching water bodies and/or mountains also prominently constrain urban spread in Vancouver, Sydney, and Auckland, lifting these cities to the top of the density table in the Pacific Northwest and Australasia, respectively. The lowest density cities in the sample can be found in the United States and the remainder of Australasia.

Functional interdependencies with other metropolitan areas in commuting distance play a part in
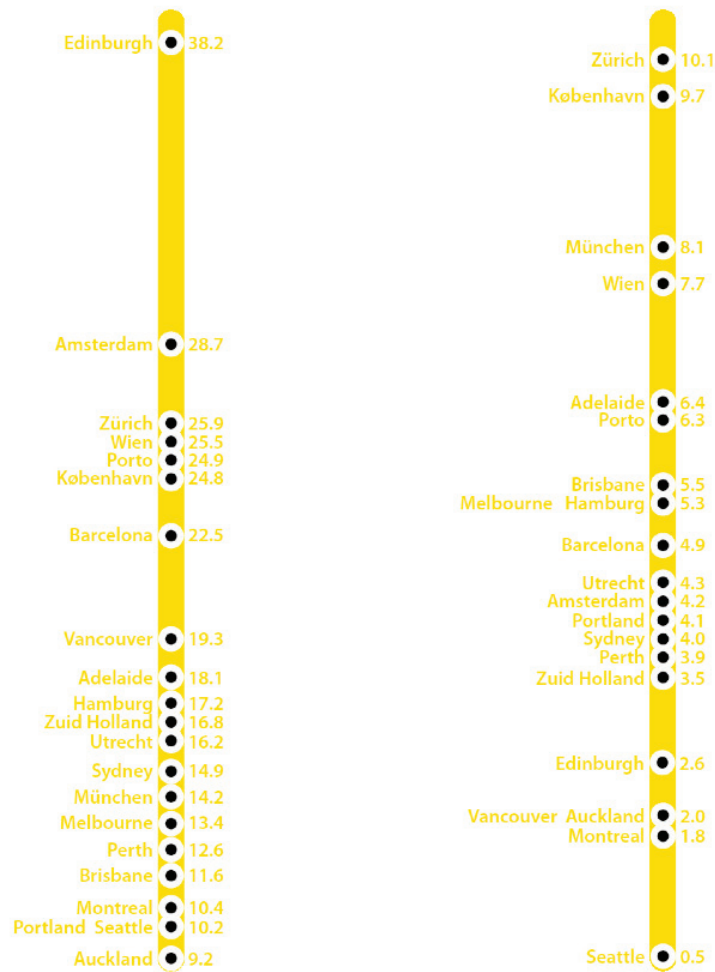
public transport accessibility. This is evident in the multi-nuclear structure of the Zuid Holland region, and also plays a role in neighboring Amsterdam and Utrecht, together forming a regional urban agglomeration of some 7.7 million inhabitants known as the Randstad. Zurich also has a pronounced regional interdependency with multiple, dispersed urban centers across most of the German-speaking part of Switzerland, including Basel and Bern, which are approximately an hour-long train ride away. In the New World, the Canada-US border to the south provides a settlement boundary for both Vancouver and Montreal, while Seattle and Portland are characterized by some continuity of urban agglomeration beyond the metropolitan area definitions used here (which exclude the Tacoma area south of Seattle, and the Vancouver, Washington, area north of Portland, Oregon). Vienna and Munich are inland centers without major geographical constraints to their expansion (other than protected nature reserves) within normal commuting distance. Edinburgh and Oporto are the primary centers of metropolitan regions of roughly similar size, though Edinburgh shares commuting catchments with neighboring Glasgow in ways that have no equivalent in stand-alone Oporto. Copenhagen, located on an island, only developed a significant functional interdependency with neighboring Malmö during the last decade following the opening of the Øresund bridge. Australasian metropolitan regions generally have a pronounced stand-alone character; however, Brisbane shares commuter catchments with the Gold Coast and Sydney shares commuter catchments with Wollongong and Newcastle.

Public transport patronage suggests five distinct categories of trip-making intensity in the sample. Zurich and Vienna each achieve a significant number of trips per capita per year, 401 and 394, respectively. Munich, Copenhagen, Hamburg, Amsterdam and Barcelona are around the 200-trips-per-capita mark, just over half of that for the first category of cities. The third category of cities has between 100 and 160 trips per capita per year. The US cities, Brisbane, and Perth occupy the fourth category of cities with between 50 and 100 trips. At the bottom end of the scale, Adelaide and Auckland attract less than 50 trips per capita per year.

4   Service intensity

The number of public transport vehicles in simultaneous revenue service required to deliver the public transport network relative to metropolitan population for each city is shown in Figure 5. Figure 6 shows the number of heavy rail and segregated light rail stations relative to population to provide an indication of the presence of dedicated public transport infrastructure in each city and the ability of this infrastructure to service the urban population.

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[2] Operated at the standard, the SNAMUTS minimum service standard during the weekday inter-peak period. Note that actual numbers of vehicles required by the operators are higher since no provision is made for service breaks at the termini, contingencies for delays or disruptions, non-revenue journeys, and for vehicles undergoing scheduled or unscheduled maintenance. Figures do not reflect the greater numbers of vehicles required to operate peak-hour services.

Edinburgh ● 38.2

Zürich ● 10.1
København ● 9.7

München ● 8.1
Wien ● 7.7

Amsterdam ● 28.7

Adelaide ● 6.4
Porto ● 6.3

Zürich ● 25.9
Wien ● 25.5
Porto ● 24.9
København ● 24.8

Brisbane ● 5.5
Melbourne Hamburg ● 5.3

Barcelona ● 22.5

Barcelona ● 4.9

Utrecht ● 4.3
Amsterdam ● 4.2
Portland ● 4.1
Sydney ● 4.0
Perth ● 3.9
Zuid Holland ● 3.5

Vancouver ● 19.3

Adelaide ● 18.1
Hamburg ● 17.2
Zuid Holland ● 16.8
Utrecht ● 16.2

Edinburgh ● 2.6

Sydney ● 14.9
München ● 14.2
Melbourne ● 13.4
Perth ● 12.6
Brisbane ● 11.6

Vancouver Auckland ● 2.0
Montreal ● 1.8

Montreal ● 10.4
Portland Seattle ● 10.2
Auckland ● 9.2

Seattle ● 0.5

Figures 5 and 6: Service intensity, or vehicles in simultaneous revenue services per 100,000 population during the weekday inter-peak period (left) and segregated rail stations per 100,000 population (right) in case study cities

There is some variation in relative service intensity across the sample. Of the continental European cities, Amsterdam has the highest service intensity per capita, while the highest level in the sample, by a significant margin, is for Edinburgh. The lowest service intensity figures in Europe are for the Dutch cities (except Amsterdam) and the German cities. In Munich there is a highly efficient network design where allocation of transport tasks to the most suitable mode has been progressively implemented over the last 50 years. This acts in concert with a frugal approach to service frequencies in comparison to most of Munich's peer cities. Among the New World cities, Vancouver and Adelaide have the highest service intensity figures, eclipsing some European cities, followed by the remaining Australian cities. The lowest service intensity figures are in Montreal (where the CBD relies almost exclusively on metro access rather than bus services) and the US and New Zealand cities.

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. Therefore, where fast high-capacity modes play a dominant role (particularly heavy rail) relative to service intensity, figures are lower, conversely a large number of high-frequency, slow-moving surface routes results in a higher figure. 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 mobilize and allocate to public transport operation. In this context, it is unsurprising that among European cities, Edinburgh (home to the most bus-dominated public transport network in the sample) achieves the highest service-intensity figure and that Munich (the most rail and tram-dominated region) achieves the lowest. In part Edinburgh's result is 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. Copenhagen and Hamburg have comparable roles for rail and bus-based modes; the difference in service intensity is mostly due to Copenhagen operating a far denser and more multi-directional bus network than Hamburg, an observation re-visited later in the analysis.
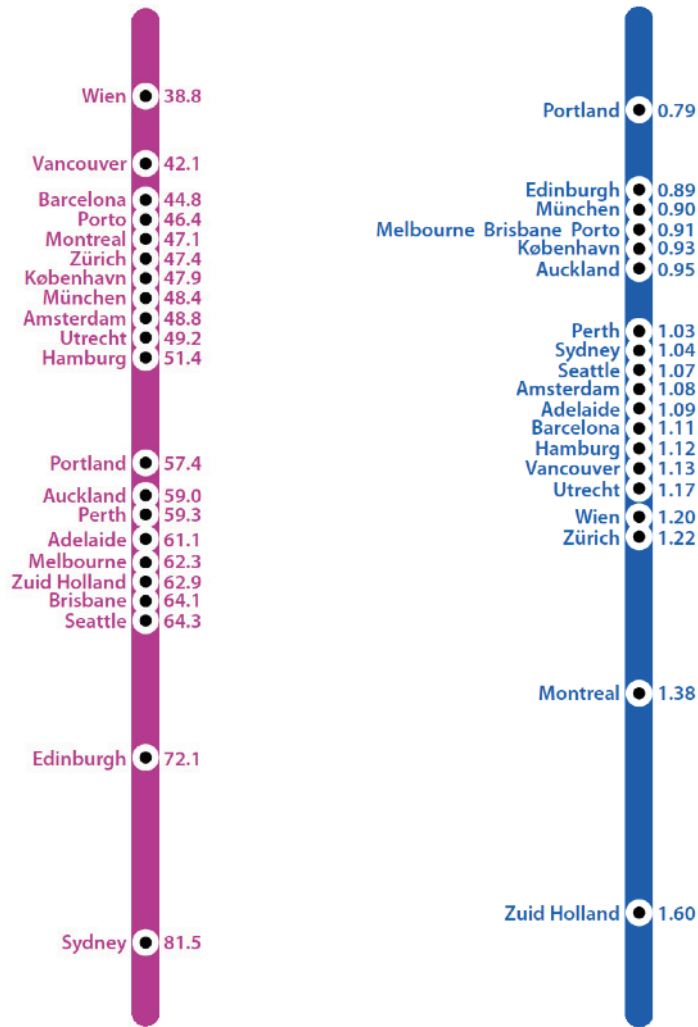
In New World cities, the varying dominance of buses over rail in the modal mix is seen in the service intensity result for Adelaide compared to its Australasian peers, and Vancouver compared to Montreal. Across this group, however, there is also a strong correlation to the degree to which the network is capable of reaching urban activities in the first place (shown in the network coverage indicator below). In this respect Auckland, Seattle, Brisbane, Perth, and Portland have both low service intensity and low network coverage results.

In relation to rail infrastructure, the European cities of Zurich, Vienna, Copenhagen, and Munich deliver the highest density of rail stations, reflecting a strong tradition of metro and/or suburban rail orientation in their urban evolution. Zurich and Copenhagen retained regional light rail or branch lines to primarily service recreational areas along coastlines and mountains, a type of infrastructure that typically did not survive the post-war era of rapid motorization in other cities. Australia, Adelaide, Brisbane, and Melbourne have a rail station density that is comparable to that of most other European cities. This is indicative of the presence of networks of purpose-built suburban lines dating back to the late 19th and early 20th century when they were designed to service long corridors of walkable station catchments. In Sydney and Perth, there is a greater prevalence of faster rail lines with limited numbers of stations. In Auckland and the North American cities, the low rail station density indicates the very limited extent of rail infrastructure operated at SNAMUTS standards—the commuter rail services in all four North American case study cities fall well short of the 30-minute frequency threshold required for inclusion in the analysis. Portland stands out as an exception due to the maturing expansion of the city's light rail network over the last 25 years.

5 The public transport network

5.1 Closeness and degree centrality

These indicators focus on the structural properties of the public transport network. Closeness centrality considers accessibility 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 public transport network (Figure 7). Degree centrality considers accessibility as the number of transfers required to make a journey between any two centers. Each node thus describes the average transfer intensity for journeys to or from all other nodes on the network (Figure 8).

| Wien | 38.8 |

| Vancouver | 42.1 |

Barcelona	44.8
Porto	46.4
Montreal	47.1
Zürich	47.4
København	47.9
München	48.4
Amsterdam	48.8
Utrecht	49.2
Hamburg	51.4

| Portland | 57.4 |

Auckland	59.0
Perth	59.3
Adelaide	61.1
Melbourne	62.3
Zuid Holland	62.9
Brisbane	64.1
Seattle	64.3

| Edinburgh | 72.1 |

| Sydney | 81.5 |

| Portland | 0.79 |

Edinburgh	0.89
München	0.90
Melbourne Brisbane Porto	0.91
København	0.93
Auckland	0.95

Perth	1.03
Sydney	1.04
Seattle	1.07
Amsterdam	1.08
Adelaide	1.09
Barcelona	1.11
Hamburg	1.12
Vancouver	1.13
Utrecht	1.17
Wien	1.20
Zürich	1.22

| Montreal | 1.38 |

| Zuid Holland | 1.60 |

Figures 7 and 8: Average closeness and degree centrality in case study cities

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.

For closeness centrality, cities where activity centers are spaced farther apart[3] (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 cities or those with faster public transport systems. Compactness, in this context, is not necessarily equivalent to density. Vancouver, Barcelona, and Copenhagen have the better closeness centrality scores in part because they are in geographically constrained locations on peninsulas, between coastlines and mountains, or on an island, respectively. In Vienna, a large protected area of hilly, forested open space to the west of the city acts as a growth boundary of similar effectiveness. Conversely, the relatively poor average closeness centrality scores in Zuid Holland, the Australian and US cities are linked to the relatively wide spacing of places of activity. In Zuid Holland this relates to the conurbation's multi-nuclear form without a single overarching center. In Australia and the United States, places of activity tend to be separated by expanses of low-density suburban fabric, usually lacking in high-speed public transport infrastructure that could make up for

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[3] In terms of public transport travel time, not necessarily metric distance

the spatial discontinuity. Perth is the Australian exception where the principal public transport spine (the fastest suburban rail service in the sample cities) is optimized for the specific conditions of a low-density city with relatively weak sub-centers.

Since the closeness matrix treats every origin-destination pair on the network as equally weighted, the spatial separation between dispersed centers is affecting the overall result, even where these cities might have pockets of compact and contained settlement areas. 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 suggest that there is a more cohesive approach to favor 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, Vienna, and the Canadian cities are examples—their rail and metro systems are both speed-competitive with road travel and operate at very high frequencies during business hours (six minutes or better throughout the inner areas). In the Randstad and Munich, such frequencies are only achieved on metro trunk lines (in Amsterdam and Rotterdam). The Dutch regional rail system operates a mix of overlapping all-stop and intercity trains with each stopping pattern typically operating every 15 or 30 minutes, resulting in frequencies between four and eight trains per hour on each route. In Edinburgh, Oporto, and Australasian cities (with few exceptions), the maximum rail frequency averages four trains per hour.

Oporto's advantage over Edinburgh on the closeness indicator appears to be related to the presence of a light rail network in the Portuguese city, which provides unmatched travel speeds through the urban core compared to the congested streets of Edinburgh (coping with up to 200 bus movements per hour). Also incorporated in this indicator, though with only minor effects in this context, is the circumstance that Oporto 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. Such lack of integrated ticketing is also present in Sydney and is partially responsible for the poor average closeness result in Australia's largest city.

6   Land use patterns integrated with public transport networks

6.1   Network coverage and contour catchments

The network coverage indicator (Figure 9) is designed to query the land-use patterns and, in particular, identify those places serviced by public transport at the minimum service standard. It measures the percentage of residents and jobs located within walking distance (800 meters around rail or metro stations and ferry terminals, and 400 meters along tram and bus corridors) of at least one public transport service that meets this standard, and expresses this as a percentage of the total metropolitan number of residents and jobs.

The contour catchment indicator (Figure 10) also measures 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 [4]. The indicator adds a further dimension to the network coverage indicator 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 for its degree of compactness or dispersal.

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[4] 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 the departure of the second vehicle.
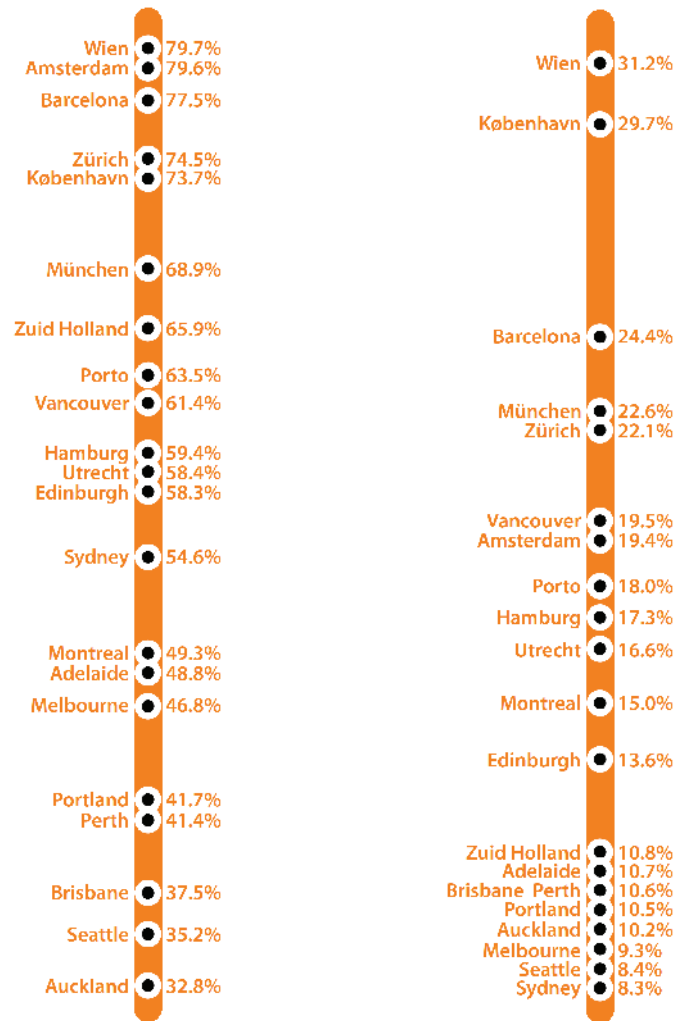
Figures 9 and 10: Network coverage (left) and average 30-minute contour catchments (right) in percentage of all metropolitan residents and jobs in case study cities

Across the sample, network coverage ranges from a low of between 33 percent in Auckland to a high of 80 percent in Vienna. Some of this variation is explained in relation to the service intensity indicator 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 urbanized area. This pattern is clearly present in the comparison between Copenhagen, Amsterdam, and Vienna with Hamburg or any of the New World cities. It does not explain, however, why Hamburg falls behind Zuid Holland despite having a comparable level of service intensity. A possible reason, also observed in Vienna, Munich, and the Canadian cities, is that historically, public transport provision in Hamburg has been a local government responsibility (in Hamburg the city-state, which comprised just over half of the metropolitan area population in 2010) and despite the existence of a regional transport agency, still tends to focus on the associated jurisdiction. In Edinburgh, the (equal) lowest European 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.

Among the New World cities, Vancouver has the highest network coverage, a city that is arguably characterized by the most consolidated framework for regional transport and land-use planning (Filion and Kramer 2012; Stone 2014). Otherwise, among the Australasian and North American sample, only Sydney has more than half of all residents and jobs within walking distance of public transport at the SNAMUTS standard. This reflects Sydney's longstanding policy of urban intensification around rail stations, higher settlement density, and greater constraints to outer suburban expansion compared to its regional peers.

On the average 30-minute contour catchment size, Copenhagen and Vienna show strong performance, reflecting earlier observations—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 maximizes both the number of destinations that can be reached within the half-hour time window, and the number of trips for which no transfer is necessary (particularly prevalent in Copenhagen). In Vienna the high concentration of the settlement area within the core city together with the high overall urban density plays a role. The same is true for Barcelona, where a larger size of the metropolitan area (nominally reducing average contour catchments in percentage terms) is partially compensated by very high settlement density, leading to a greater average number of residents and jobs in each activity node catchment than in any other city in the sample. At a much lower level of performance, Vancouver as the best-performing New World city has a similar result as the European cities of Oporto, Amsterdam, and Hamburg.

Average 30-minute contour catchments, 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, Zuid Holland, and all US and Australasian cities trail the sample on this indicator 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 and the New World, the dispersed nature of settlement across a multitude of spatially separated urban centers is the key driver for the low figure.

6.2   Betweenness centrality

This cohort of indicators measures 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 indicator, assuming that fast and frequent services between a pair of centers will be more attractive for urban movement than slow and infrequent services between another pair of centers of similar size. The indicator is designed to highlight which centers 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.
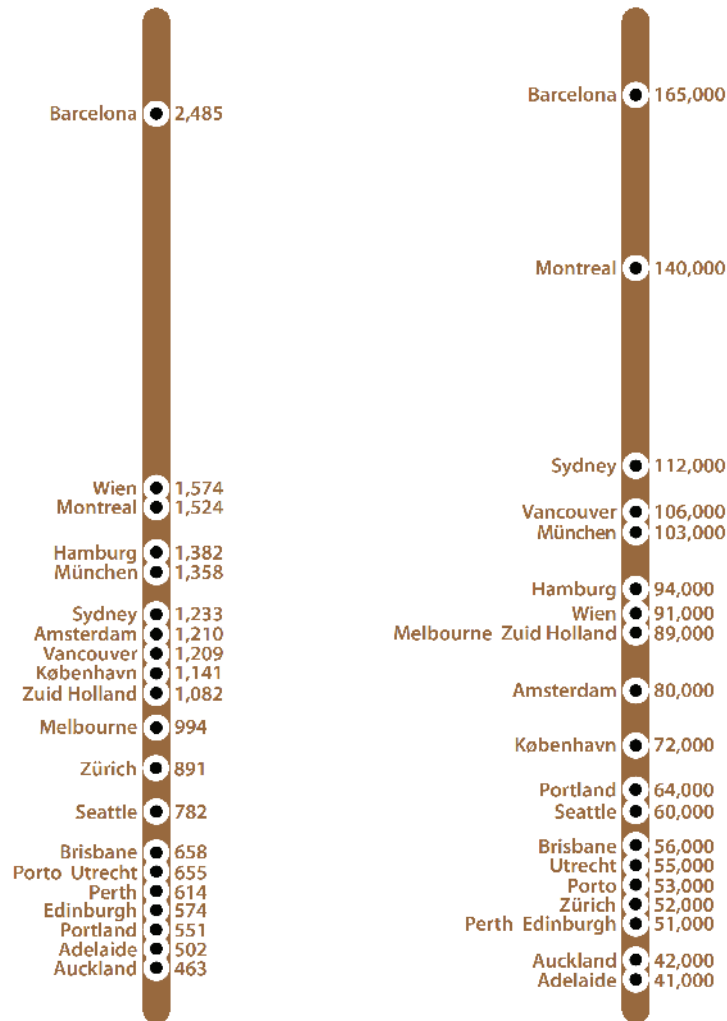
Figures 11 and 12: Global betweenness indicator (left) and catchment size of typical journey path (in residents and jobs) in case study cities

The global betweenness indicator (Figure 11) benchmarks the attractiveness of the public transport system as a whole to facilitate movement and accessibility across a case study city, allowing for comparison between cities. It is affected by the urban compactness and contiguity bias seen in the network coverage indicator. The catchment size of a typical journey path measure, designed to compensate for this bias, determines the number of residents and jobs traveled past on a public transport journey of average length in the respective metropolitan area. This figure is influenced by the concentration of activities in each nodal catchment area as well as the propensity of the network to attract passengers (or not) along geographical detours that may lengthen the journey but offer shorter travel times and better service frequencies (Figure 12).

The global betweenness indicator splits the sample into three groups. In group one, Barcelona, Vienna, Hamburg, Munich, Sydney, Amsterdam, Copenhagen, and the Canadian cities are characterized by a much higher presence of public transport travel opportunities throughout their metropolitan areas than Utrecht, Oporto, Edinburgh, and the US and smaller Australasian cities. Zuid Holland, Melbourne, and Zurich occupy an intermediate position. For Zuid Holland and Melbourne as relatively large cities, this could be read as a lower-than -expected performance; however unsurprisingly, since this

indicator strongly rewards compact, dense, and contiguously urbanized settlement areas and penalizes spatial discontinuities, regardless of whether they are generated by topographical constraints or result from policy decisions or historical trends. On the other hand, the results for Zuid Holland as well as Zurich as a whole could also be understood as an indication that both regions are characterized by two dominant and only partially compatible public transport accessibility trends. On the one hand, they continue to provide quite favorable conditions for intra-urban public transport movement within each of their centers, especially Den Haag and Zurich, and (to a lesser extent) Rotterdam and Winterthur. On the other hand, the proximity of these centers to one another generates a high volume of inter-urban travel flows. This observation invariably raises the question as to which scale of public transport accessibility is the most relevant for the Randstad and 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.

As the influencing factors of land-use density and network compactness/dispersal can both amplify and neutralize each other on this indicator, the "catchment of typical path length" indicator is designed to separate the two. This measure 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). Thus it focuses more exclusively on land-use concentrations and network coherence. Barcelona's top performance for this indicator may be related to its significant land-use intensity.

In Montreal, Sydney and Vancouver (the next highest performers), the large performance gap between heavy rail and buses is notable, resulting in attractive journey paths being drawn away from bus routes and onto rail even where buses offer more geographically direct (but slower, and in Vancouver and Montreal, less frequent) journeys. In such cases, the network configuration tends to encourage longer-than-necessary trips (in terms of geographical distance and by extension, number of other activity centers passed along the way). At the lower end of the scale, Melbourne's and Zuid Holland's similar results may be attributed to the incidence of "missing links" between neighboring activity centers. Vienna and to a lesser extent Munich, in contrast, have a well-developed and graded modal hierarchy and a dense, multidirectional network, and they likely also owe their position on this indicator to a high land-use intensity in the core city. Adelaide and Auckland's low typical path catchment is related to the networks' limited ability to provide a significant number of attractive journey paths. These are dependent on relatively slow and/or infrequent radial routes with underdeveloped multi-directionality. In contrast, the relatively low figure for Zurich is influenced by the Swiss city's network's ability to provide fairly direct and fast connections between many dispersed activity centers on its regional network.
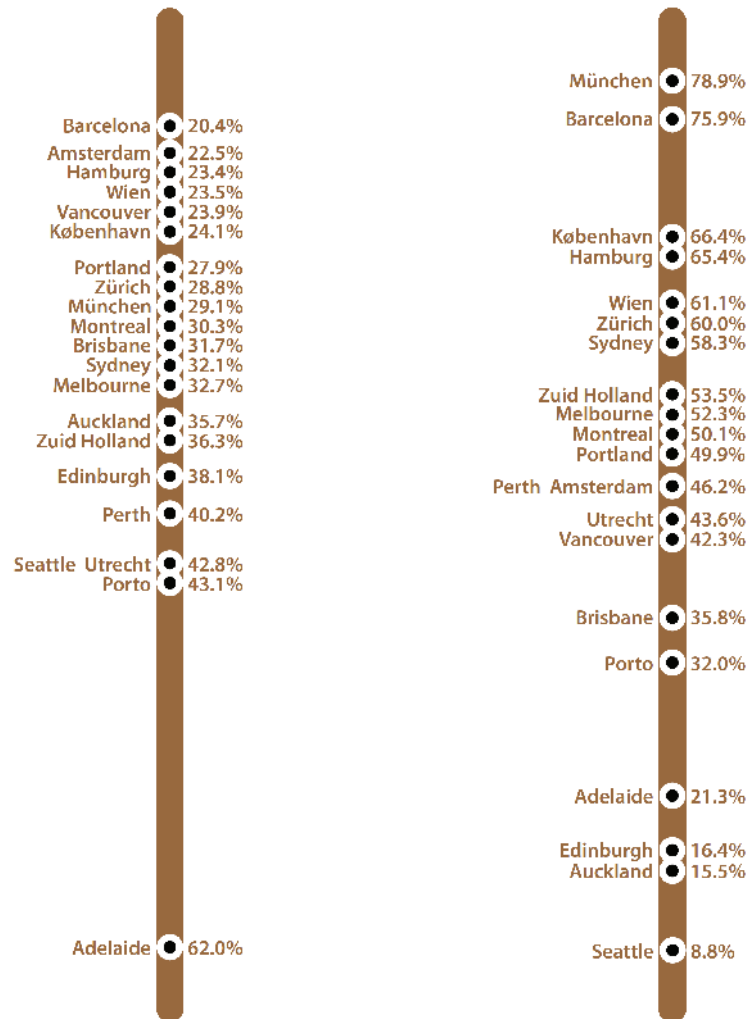
Figures 13 and 14: Percentage of total segmental betweenness on CBD segments (left) and on segregated rail segments (right) in case study cities

Figure 13 expands the betweenness results by interrogating what percentage of total travel opportunities can be found in each city's CBD area (the part of the network where congestion is most likely to occur), while Figure 14 illustrates the same measure in relation to travel opportunities captured by heavy rail and segregated light rail as the highest-performing modes.

For the CBD area, the percentage of travel opportunities to, from, or passing through the central city can be expected to drop with growing city size, polycentrality, and where a network configuration offers attractive alternative travel paths for cross-suburban journeys. High-capacity orbital transport links are most developed in Amsterdam, Vienna, and Copenhagen and to a slightly lesser extent Hamburg and Barcelona (in the latter two, strong performance is further influenced by their larger size). Conversely, in Munich the rapid transit network remains heavily CBD-centered. The low performance for Vancouver and Portland CBDs may be related to the relative peripheral position of the city center in geographical terms. In both cases, important network hubs exist in non-CBD areas that perform more of a central spine function for the network—Broadway in Vancouver, and the light rail corridor between Rose Quarter and Gateway in Portland. Adelaide has by far the highest concentration of travel oppor-

tunities through the CBD. This relates to the absence of orbital or cross-suburban public transport links that meet the SNAMUTS minimum standard. As a consequence, passengers need to enter the CBD for almost any journey that involves a transfer.

Copenhagen and Hamburg have a near-identical distribution of travel opportunities between rail and bus modes, underscoring the significance and superior service standards of the suburban and metro systems in both cities. In contrast, in the Randstad, surface modes play a much greater role, which may be related to a comparatively small heavy rail network length (in relation to population) in Amsterdam as well as in neighboring Zuid Holland and the presence of mature, first-generation tram networks in Amsterdam, Rotterdam, and Den Haag. Vienna and Zurich, where trams also provide for a large share of the surface travel task, occupy an intermediate position on this indicator.

Seattle, Auckland, Edinburgh, Adelaide, and to a lesser extent Oporto and Brisbane remain strongly dependent on buses to service mobility needs arising from the land-use system. In Oporto and especially Seattle, the metro/light rail networks, both second generation systems developed during the last decade, remain incomplete but are subject to ambitious expansion plans. In Edinburgh, Auckland, and Adelaide, the role of the cities' relatively extensive heavy-rail infrastructure for frequent suburban services remains underdeveloped, although in each case, plans are underway to improve this. In Adelaide, Auckland, and particularly Brisbane, past decisions to supply selected radial corridors with busways rather than rail lines also play a role in depressing segmental betweenness figures for rail.

6.3   Network resilience

The network resilience or stress indicator is based on the segmental betweenness indicator and determines the ratio between the concentration of potential travel opportunities on a route segment and the carrying capacity offered (derived from the service frequency and the size of the vehicles used). This indicator can demonstrate whether a network element can absorb an increase in patronage. It is expressed as a stress measure on an open-ended scale where higher figures correspond to declining segmental resilience, and where a score in excess of 30 is considered to place limits on resilience as understood in this context. Network resilience or stress is not necessarily a proxy measure for the actual occurrence of congestion or overcrowding, since passengers generally have alternative responses to the incidence of a mismatch between a route's network significance and transport supply. They may resort to using motorized or non-motorized private transport at a higher rate than along routes less affected by stress, or they may choose alternative routes or access alternative destinations for their travel purposes. Figure 15 shows the network-wide measures on the resilience indicator, while Figure 16 shows the performance of the CBD area where congestion is generally most likely to become a problem.
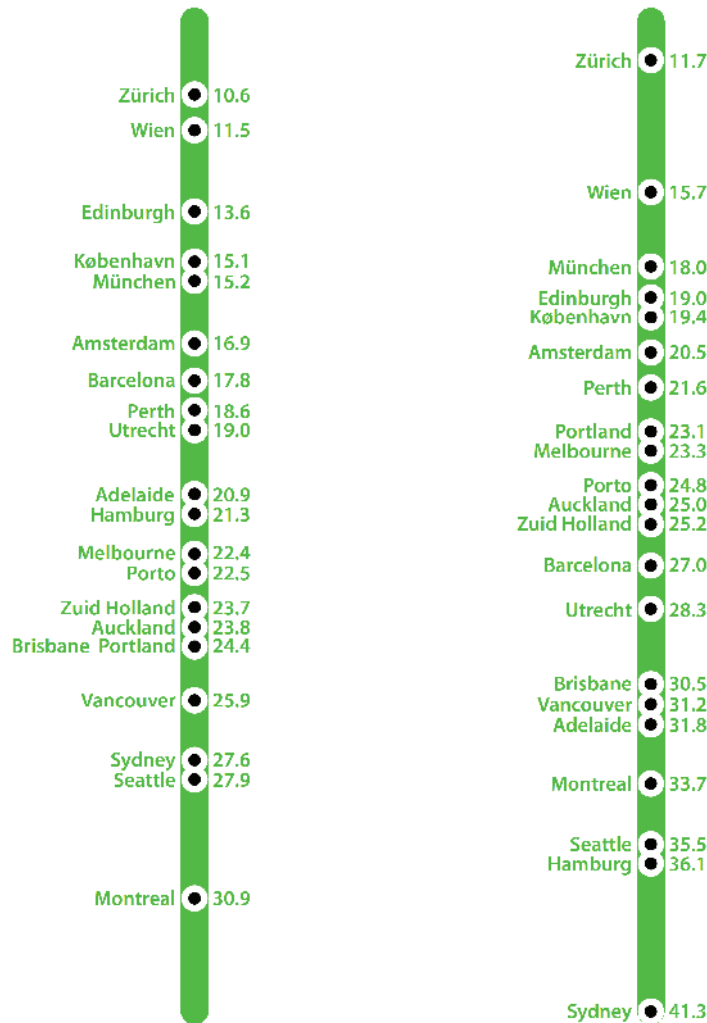
Figures 15 and 16: Resilience indicator for entire networks (left) and for CBD route segments in case study cities

Zurich and Vienna perform best on the metropolitan-wide resilience indicator, they are both known for the highest rates of public transport usage. This may appear counter-intuitive since a greater number of passengers should result in greater stress on the resources. However, both cities also have relatively high service intensity and network coverage (discussed above), and these factors in combination with a highly optimized network configuration and task-sharing between modes of varying performance act as the principal enablers of high patronage numbers. Conversely, Edinburgh's good performance on this indicator is primarily owed to the high volume of high-capacity buses (double-deckers). The more frugally serviced European cities (Hamburg and the Randstad outside Amsterdam) show middling performance as do several Australasian cities. In Perth this is influenced by the network's ability to maximize the attraction of travel opportunities onto the rail system (despite its still limited spatial reach) through a hierarchical model of task sharing between rail and bus. In Australasian cities, where this factor of configurational efficiency is underdeveloped (Brisbane, Auckland, and Sydney), average network resilience performance deteriorates accordingly. The North American cities are the poorest performers, with comparatively low levels of public transport patronage, the key determinant that saves these systems from collapse. Should these cities aspire to patronage levels closer to European cities, fundamental upgrades

to the networks' carrying capacity through modal upgrades and greater route density would be required.

With the exception of Portland, where the CBD is located away from the highest geographical concentration of travel opportunities, stress levels are higher in the central area than network-wide across the entire sample of case study cities, though the variation occurs at different rates. Barcelona, Hamburg, and Sydney in particular have substantially greater resilience shortfalls in their CBDs than metropolitan-wide. These are three relatively large cities with no or only marginal intermediate-capacity modes (tram/light rail), reliant instead on a significant proportion of bus access from inner urban corridors into the CBD. Among the smaller cities, high bus dependence, in combination with a radial network shape that converges the majority of travel paths in the central area, prominently influences the low CBD resilience performance in Utrecht and Adelaide.

6.4 Nodal connectivity

The nodal connectivity indicator is a measure for the ability of nodes to act as hubs for the network. The indicator counts the number of travel opportunities (departures) per hour on different modes in different directions. A mode-specific weighting factor proportional to average load factor (occupancy) is a component to the score. The indicator thus measures the multi-directionality (or not) of network elements as well as the carrying capacity, not just in terms of seats provided but also in terms of the propensity of users to choose particular modes over others (for instance, in many cities rail modes have a higher average seat occupancy ratio than buses). For the user, this indicator can be read as a proxy for origins and destinations that allow for "autonomous mobility"—frequent services in many directions that enable both planned and spontaneous trips across the urban geography (Dowling and Kent 2013). For land-use developers, this indicator indicates the attractiveness of a location for activities that depend on or benefit from the presence of large numbers of public transport passengers. Therefore, high nodal connectivity figures should denote a location's suitability for transit-oriented development. While this indicator is best interpreted in more geographical detail for each city, the averages shown in Figure 17 highlight the overall propensity to provide these benefits.

Barcelona, Vienna, Munich, Hamburg, and Amsterdam perform best on this indicator, where autonomous mobility and attractiveness for transit-oriented development appear to be widespread across the urban fabric. The networks in these cities provide a multitude of nodes where many routes intersect and are also characterized by high patronage figures. In Hamburg and Munich, the score may be driven up by the relatively frugal approach to service provision, which results in higher occupancy rates on trains and buses than elsewhere. In contrast, Copenhagen performs poorly primarily due to a more generous approach to service provision, which depresses average occupancy rates.

Figure 17: Nodal connectivity indicator in case study cities

Average nodal connectivity can be expected to increase with growing network size, as larger cities tend to develop more complex networks with an exponentially increasing number of transfer points. In this context, the figures for Zuid Holland as well as the larger New World cities (Montreal, Melbourne, Sydney) express deficiencies in the penetration of the networks into options for multi-directional movement, likely related to the many gaps and missing links found in these agglomerations based on public transport services at the SNAMUTS minimum standard. In contrast, Zurich's position as the smaller city (below 1.5 million inhabitants) with the highest average nodal connectivity score demonstrates a network where multi-directionality has been successfully expanded, not just around the core city but the entire cantonal region.

At the bottom end of the scale, the US and smaller Australasian cities only have high connectivity scores in their immediate central areas, indicating that a life with autonomous mobility while relying primarily on public transport is infeasible for those not residing in the city center.

7   Discussion and conclusions

The collection of a suite of accessibility indicators across a global sample of cities, representing a range of transport and land-use policy contexts from best to ordinary practice, can help identify a number of

benchmarks that serve as inspiration for the future role of public transport in any city that wishes to improve its performance. Our research makes a significant contribution to public transport policy by providing indicators that could be applied to assess particular policy questions.

This research demonstrates that the incidence of a successful urban public transport system, as measured either in terms of high per capita patronage or of extraordinary recent growth rates in patronage, can be linked to a number of factors. These factors are manifest in network and service configurations as well as in accessibility outcomes and thus the respective cities' performances on the SNAMUTS accessibility indicators.

All successful European cities have mature rapid transit networks that consist of radial as well as non-radial elements and are well integrated—physically, functionally and institutionally—with the network of surface public transport routes. This interplay affords the user easy multidirectional movement by public transport within the core cities, a geographical range whose equivalent in Australasian cities would typically reach to a cordon of middle suburban centers at a distance of 10-15 kilometers from the CBD. The successful European cities, as well as Vancouver, also generally operate both their rapid transit networks and major surface routes at off-peak service frequencies—often seven days a week and into the evening—that make timetable consultation unnecessary (i.e., every 10 minutes or better). These two components—network density/multi-directionality and minimum service frequencies—require a higher input and a more balanced deployment (away from congested CBD streets) of operational resources than what is common in New World cities. The benefits of higher levels of service intensity under these circumstances are evident in greater ease of movement on public transport, expanded activity ranges within fixed travel time windows, a more even distribution of public transport journeys across the city's geography, and much improved opportunities for users to choose public transport for both planned and unplanned journeys that are flexible in time and space.

There are nuanced variations. Munich, and to a lesser extent Hamburg, achieve this accessibility performance by minimizing the service input required without compromising accessibility. For Munich, this was facilitated by a half-century program of extensive investment in rapid transit adapted to the specific urban form that the city assumed since the era of post-war reconstruction. It was designed to largely eliminate the need for surface public transport operating at shorter than the typical 10-minute frequencies. In Vancouver, public transport's recent success is also closely related to the ongoing retrofit of this previously road-based New World city, with a user-friendly rapid transit system designed to maximize accessibility outcomes. However, its limited extent to date poses some constraints to further growth without further network expansion. The remaining cities adopt a more generous approach to service provision. In Amsterdam, Barcelona, and Copenhagen, this results in a share of metropolitan residents and jobs with walkable access to public transport at or above the SNAMUTS minimum standard, which is up to twice as high as in most Australasian cities. The same is true for Vienna and Zurich, which display a further dimension of excellence: The interplay of public transport modes with different performance and capacity characteristics draws, first, on the broadest possible range of component technologies—bus, trolleybus (Zurich), tram, light rail, metro (Vienna), suburban rail, with some cable cars and ferries also thrown in to address topographical challenges (Zurich)—and second, has been optimized over time to allocate to each mode a role in the multi-modal network based on its inherent strengths. The performance combines the highest per capita public transport patronage in the sample with the highest level of resilience in the face of future changes to the land-use transport system that may push ridership even further.

However, in assessing the role of benchmark for public transport accessibility, it is also necessary to account for context. Some cities have historically grown to a mono-centric template; others have a more polycentric character. Some cities are compact in terms of land coverage, often the cities constrained by

topographic features. Others have been relatively unrestricted in their outward expansion. The density or intensity of residents and jobs also varies between cities and can be independent of the extent of compactness of urban structure. In each case, these variations can influence the type of public transport network provided.

Public transport systems are also affected by the institutional decisions made. Are infrastructure investments made with city-wide network performance in mind, or do they represent mostly isolated insertions, reflecting political expediency? Are service frequencies and service patterns primarily determined by the commercial or logistical requirements of operators or their political clients, or do they have the needs of public transport users at heart? Are public transport systems planned for a variety of journey purposes, or is there a singular focus on job commuting, or on providing a "safety net" for the mobility disadvantaged? Of the sampled cities, it is evident that there is a wide range in the service intensity (vehicles in simultaneous revenue services per 100,000 population during the weekday inter-peak period). This variation reflects the choices decision makers have taken—in Edinburgh, to provide a system dominated by buses, in other cities to provide a rail-based system, and in yet others (such as Auckland) to offer a very low level of service—which to some extent reflects the level of interest in providing public transport as a viable alternative to the car.

The analysis of factors influencing network performance as reported above shows that the results are finely nuanced, interdependent, and that it is neither possible nor appropriate to simply say that one city over all others provides an exemplar that other cities should aspire to. Instead, the choice of benchmark to select will depend on the type of question that needs to be answered, whether the question is: How quickly (on average) can I navigate my city by public transport? How many transfers (on average) do I have to make in order to access my city? Who gets access to public transport? Does public transport provide a viable alternative to the car? What opportunities are there for land-use development? Or where might the public transport system become constrained in future? Thus, rather than hunt for the holy grail by seeking out the best city, inspiration must be drawn from the strengths and weaknesses that are found in the sample cities.

The accessibility analysis and its detailed reflection provide valuable lessons for metropolitan cities in moving forward. As a guide to the future of public transport in Australasian cities, we have shown elsewhere (Curtis and Scheurer 2010; Scheurer 2011) that significant progress can be made on average closeness centrality values as well overall network coverage (though much less so on degree centrality) in scenarios of future improvements to public transport services and infrastructure as well as greater intensification of land-use patterns around public transport facilities. However, in seeking to progress, it is clear that many structural features of both the activity center and movement networks are sufficiently entrenched as to render a full ascension of, for example, New World cities, to a European standard of public accessibility unrealistic within a 25-year time frame even under the most favorable assumptions (Scheurer 2010).

Acknowledgements

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Appendix – Indicator Formulas

Travel impediment

$$d_{ij} = 4 \times \sqrt{t_{ij} / f_{ij}} \quad [1]$$

where:

d_{ij} = Impediment value of route segment between nodes i and j

t_{ij} = Travel time between nodes i and j in minutes

f_{ij} = Service frequency in departures per hour per direction between nodes i and j

Closeness centrality

$$c_i = \Sigma_{j=1, j \neq i}^{N} \frac{L_{min,ij}}{N-1} \quad [2]$$

where:

C_i = Closeness centrality of node i

$L_{min,ij}$ = Minimum cumulative impediment between nodes i and j

N = Number of activity nodes in the network

Degree centrality

$$D_i = \Sigma_{j=1, j \neq i}^{N} \frac{P_{min,ij}}{N-1} \quad [3]$$

where:

C_i = Degree centrality of node i

$p_{min,ij}$ = Minimum number of transfers between nodes i and j

N = Number of activity nodes in the network

Network coverage

$$Q_n = \frac{\Sigma_{j=1}^{N} act_j}{act_m} \quad [4]$$

where:

Q_n = Network coverage index

N = Number of activity nodes in the network

t_{ij} = Minimum travel time between nodes i and j

act_j = Number of residents and jobs in the catchment area of node j

act_m = Number of residents and jobs in the metropolitan area

30-minute contour catchment

$$Q_i(30) = \Sigma_{j=1}^{t_{ij} \leq 30} act_j \quad [5]$$

where:

$Q_i(30)$ = 30-minute contour catchment of node i

t_{ij} = Minimum travel time between nodes i and j

act_j = Number of residents and jobs in the catchment area of node j

act_m = Number of residents and jobs in the metropolitan area

Betweenness centrality

$$B_k = \frac{\Sigma_{i=1, j=1, j \neq i}^{N(N-1)} \frac{P_{ij}(k) * act_i * act_j}{L_{min,ij}}}{1000 * \Sigma_{i=1, j=1, j \neq i}^{N(N-1)} \frac{act_i * act_j}{L_{min,ij}}} * B_g \quad [6]$$

where:

B_k = Betweenness centrality of node/segment k

$P_{ij(k)}$ = Paths between nodes i and j that pass through node/segment k

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

$L_{min,ij}$ = Minimum cumulative impediment between nodes i and j

B_g = Global betweenness index

N = Number of activity nodes in the network

Global betweenness

$$B_g = \sqrt{\frac{\sum_{i=1,j=1,j\neq i}^{N(N-1)} \frac{P_{ij}(k)*act_i*act_j}{L_{min,ij}}}{1000*N}} \quad [7]$$

where:

B_g = Global betweenness index

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

$L_{min,ij}$ = Minimum cumulative impediment between nodes i and j

N = Number of activity nodes in the network

Segmental resilience

$$R_k = \frac{\sum_{i=1,j=1,j\neq i}^{N(N-1)} \frac{P_{ij}(k)*act_i*act_j}{L_{min,ij}}}{f_k*c_k*B_g} [8]$$

where:

R_k = Segmental resilience index of segment k

$P_{ij}(k)$ = Paths between nodes i and j that pass through route segment k

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

$L_{min,ij}$ = Minimum cumulative impediment between nodes i and j

f_k = Service frequency along route segment k

c_k = Modal coefficient for route segment k

B_g = Global betweenness index

N = Number of activity nodes in the network

Nodal connectivity

$$Vi = (\sum_{j=1,j\neq i}^{N(i)} a_{ij} - 1) * (\frac{3*o_r*f_r(i)}{200} + \frac{3*o_t*f_t(i)}{200} + \frac{3*o_b*f_b(i)}{200} + \frac{3*o_f*f_f(i)}{200}) \quad [9]$$

where:

V_i = Connectivity index for node i

a_{ij} = links converging in node i, with $j \in N(i)$ and $i \neq j$

$N(i)$ = network nodes adjacent (nearest neighbors) to node i

$f_r(i)$ = number of rail departures per hour per direction from node i

$f_t(i)$ = number of tram/LRT departures per hour per direction from node i

$f_b(i)$ = number of bus departures per hour per direction from node i

$f_f(i)$ = number of ferry departures per hour per direction from node i

o_r = average network-wide load factor rail (passenger-km divided by revenue train-km)

o_t = average network-wide load factor tram/LRT (passenger-km divided by revenue train/vehicle-km)

o_b = average network-wide load factor bus (passenger-km divided by revenue vehicle-km)

o_f = average network-wide load factor ferry (passenger-km divided by revenue vehicle-km)