

How to benchmark public transport accessibility in European cities

Dr Jan Scheurer

*RMIT University – School of Global, Urban and Social Studies, GPO Box 2476,
Melbourne VIC 3001, Australia*

Curtin University – School of Built Environment

jan.scheurer@rmit.edu.au

Prof Carey Curtis

Curtin University – School of Built Environment

c.curtis@curtin.edu.au

Abstract

The development and communication of land use-transport integration measures has become increasingly critical for successful stakeholder engagement in sustainable transport planning in recent years. Similarly, the dissemination of best-practice examples in public transport infrastructure and service planning and delivery has been an important contributor to improvements on the ground that led to a growing share of public transport in the mobility mix in many European cities.

In this paper, we will provide an overview of different strategies to implementing best practice in public transport and land use integration at the scale of entire urban networks, in their real-world context of urban settlement patterns. We draw on the first comparative results from an application of the Spatial Network Analysis for Multimodal Urban Transport Systems (SNAMUTS) tool to a sample of six European cities between 2009 and 2011 (Amsterdam, Copenhagen, Edinburgh, Hamburg, Oporto and Zuid Holland).

Highlighting some of the challenges that accompany the collection of public transport supply and land use data that is robustly compatible between different cities, we will outline a categorisation of the nine cities with regard to the policy environment determining land use planning and public transport provision, as well as accessibility outcomes that can help test the efficacy of such policies. This context will also illustrate and critically review elements of best practice in land use-transport integration from the nine cities, and conclude with some reflections on the relevance of international benchmarking exercises in this field.

Keywords: Accessibility, Public Transport, Land Use-Transport Integration, Benchmarking

Introduction

Successful European cities, like their overseas counterparts, are experiencing deteriorating road congestion as well as increasing public transport usage as a result of growth in population, greater spatial clustering of economic and discretionary activity, as well as intensifying regional and international inter-dependencies between cities. These trends translate into mounting pressure on cities to expand the capacity and improve the service quality of their transport networks. In this context, allocating a greater proportion of limited investment funds for public transport projects offers a critical alternative to continued reliance on a dominant role for the

car in urban mobility. It is recognised that there are significant opportunities for public transport to gain further market share from the car, thus reducing road congestion as well as addressing the social and environmental impacts associated with excessive car dependence.

In many European cities, growth in public transport usage has outpaced population growth over the past decade. This trend is an expression of a fundamental transformation, following the growing recognition of public transport by all tiers of government as a critical and desirable contribution to people's mobility within cities, and its evolution from a dual orientation, focussed on central city job commuting and the provision of a social safety net, towards a service that is capable of catering for all urban passenger transport needs across metropolitan areas (Mees, 2010).

Several cities have set specific, numeric targets of increased mode share for public transport in the urban mobility mix. These are set within a new understanding of the need for transport planning to deliver accessibility rather than simply mobility. Policy aspirations for city planning framed around accessibility rather than mobility have long been promoted by the academic community (Cervero, 1998; Vigar, 2002) and are now being embraced in planning practice. Mobility planning assumes that city dwellers will gain access to services required to support their daily needs through a transport system based on high levels of mobility by car, regardless of the relative location of land uses. In contrast, by planning for accessibility the approach considers proximity of land use as well as the transport network itself.

City planning framed around public transport accessibility raises the question of what quality of public transport system can deliver this objective. Public transport for urban mobility in developed cities varies greatly, from just over 2% of all trips in Atlanta and Los Angeles to between 26-31% of all trips in Barcelona, Vienna and Singapore (Kenworthy and Laube, 2001). The European cities discussed in this sample have public transport mode shares in the 10-20% range and thus does not (yet) contain the 'top performers' mentioned above. The variation in public transport mode share is influenced by historic and current policy priorities for infrastructure and service development as well as settlement form, and the competitiveness of different transport modes (Newman and Kenworthy, 1999; Mees, 2000; Mees, 2010).

To meet such an objective where public transport can offer a real alternative transport mode choice to the car requires a new approach for planning and evaluating public transport accessibility. It requires a method that can also serve stakeholders and decision makers as they deliberate on the best public transport network configuration, service levels and capacity upgrades. In many cities, however, there has been a relative absence of such an approach designed to usefully inform key policy objectives about the future public transport network in relation to accessibility improvements (Curtis et al, 2010). Instead strategic planning for public transport has often been unambitious, with most proposals offering incremental improvements to existing networks based on demand forecasting rather than future planning in the context of meeting policy objectives (Curtis et al, 2010).

There are parallels here to the situation in Australia, where the development and establishment in practice of methodologically robust and user-friendly accessibility tools for integrated land use-transport planning in Australasian cities and regions has become an urgent endeavour in the context of recent changes to policy priorities at Federal and State level (SSCRRAT, 2009). Only during the last five years, the Commonwealth Government has identified the significance of public transport

investment in cities and stated its intention to greatly increase its contributions for funding these pivotal items of infrastructure, while clearly tying such contributions to a satisfactory integration of strategic planning in land use and infrastructure at state level (IA, 2009). This contrasts with the situation in Europe where national and EU-level contributions to public transport infrastructure development in cities have been commonplace for many decades. However, such European funding schemes face a similar challenge to their Australian counterparts in incorporating the more recent principles of land use-transport integration and accessibility performance within their parameters. Given the multi-billion dollar/euro scope of infrastructure proposals, the substantial costs to regional economies and the environment implied in making sub-optimal 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 and other externalities), this quest for greater rigour of assessment is vital to allow for the most efficient allocation of government resources and the greatest benefit to the public. Our ongoing work in the development of a new accessibility tool provides one way of evaluating the extent to which cities offer the potential for residents and employees to have accessibility by public transport (Curtis and Scheurer, 2010). The application of our tool in planning practice in Perth and Melbourne has demonstrated its useful role in forging constructive collaborations between transport and land use planning agendas. Considering this work within the context of the above national and super-national policy agendas for evidence-based public transport investment has brought to the foreground the need to establish appropriate benchmarks for public transport accessibility for cities world-wide.

As we explore the notion of benchmarking we expose many different ways of considering it. To go back to basics, benchmarking can be defined as, “a standard or point of reference against which things may be compared” (Oxford Dictionary). At this level of definition we might be asking simply – how do the public transport systems of European cities compare? To take the idea a step further, in the context of the policy imperative ‘future public transport planning’, 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. So in the context of this paper this suggests the need to establish a benchmark, or metric, for an excellent public transport system.

The idea of benchmarking in this paper is conceived in two dimensions: current and future. In the first, our interest is in how current public transport systems in European cities compare. Exploring this dimension enables us to assess the merits of the SNAMUTS indicators in different contexts and with differing data availability. In this way we can consider whether it is even possible to apply a universal benchmark. In the second dimension, our interest is in what the benchmark, or standard of excellence, for a public transport system in European cities should be. Our overarching metric is derived from regional, national and European policy objectives 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 might 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, forthcoming) rather than being based on the need to implement policy imperatives.

The context: Public transport usage and mode share patterns

An important consideration in understanding any application of a benchmark must be to consider the SNAMUTS outputs for different cities in their broader context (Table 1). Before presenting our SNAMUTS outputs, therefore, we compare population, employment, the geographic size of the city, the intensity of residential and employment uses. All of these factors have an impact on the public transport task and are important considerations in the context of our later accessibility findings. In addition we report mode share and public transport use; both factors may well be the product of the extent to which public transport accessibility is achieved.

Table 1: Metropolitan population and jobs, urban density and public transport boarding and mode share data from seven Australasian cities in 2006 and 2010.

Contextual Data	København (2009)	Hamburg (2010)	Amsterdam (2010)	Zuid Holland (2010)	Edinburgh (2011)	Oporto (2009)
Metropolitan population	1.85m	3.37m	2.16m	3.46m	1.27m	1.23m
Metropolitan employment	0.99m	1.66m	0.96m	1.30m	0.58m	0.52m
Urbanised land in sq km	734	1,492	952*	919	342	360
Residential density per urbanised hectare	25.2	22.6	32.0*	37.6	37.1	34.2
Employment density per urbanised hectare	13.5	11.2	14.2*	13.1	17.0	14.4
Annual PT boardings	397.6m	676.3m	NA	NA	149.0m	NA
Annual PT boardings per capita	215	201	NA	NA	117	NA

* Urbanised area figure relates to the entire provinces of Noord Holland and Flevoland, which stretches beyond the Amsterdam metropolitan area definition (combined residential population in 2010: 3.04 million).

Some of the data presented in Table 1 is not beyond contestation in terms of compatibility between cities. It is likely that there are differing definitions on what constitutes a job (full-time, part-time, self-employed, marginal employment) and on what is counted as urbanised land and what is not, the detailed exploration of which is beyond the scope of this paper. However, the figures can be taken as a general guide to highlight the differences between cities or, to be more precise, metropolitan regions. The two northernmost cities, Copenhagen and Hamburg, are characterised by the lowest settlement density in the sample, while average densities in the Dutch cities, Edinburgh and Oporto are remarkably similar. The largest conurbations in terms of population are Zuid Holland and Hamburg, though they differ quite dramatically in settlement form: Zuid Holland is a polycentric region with two

separate primary urban centres (Rotterdam and Den Haag) and a number of secondary ones (Leiden, Delft, Zoetermeer, Gouda, Dordrecht). In Hamburg, the hierarchy of centres, while not free from polycentric elements, is far more traditionally structured with the primary centre at the geographical and functional heart of the metropolitan area and the secondary ones acting as satellites. Amsterdam, too, shares some multi-nuclear settlement characteristics with its immediate neighbour, while similar-sized Copenhagen, located on an island, only developed a significant functional interdependency with neighbouring Malmö during the last decade, following the opening of a fixed crossing across the Øresund. Edinburgh and Oporto are the primary centres of metropolitan regions of roughly similar size, though Edinburgh shares commuting catchments with neighbouring Glasgow in ways that have no equivalent in stand-alone Oporto.

Robustly comparable public transport usage data remains patchy at this stage, but it is obvious that Copenhagen and Hamburg can boast of a much higher rate of public transport journeys per capita than Edinburgh. However, at a level of just over 200 per year the two Northern cities (as well as Amsterdam and Zuid Holland, which we expect to have roughly similar usage rates to their Danish and German counterparts) are still likely to be 'mid-fielders' in a European comparison, where figures of 300 or more journeys per capita per year are not unheard of in places such as Vienna (Kenworthy and Laube, 2001).

SNAMUTS: An overview of the accessibility tool

This section is intended to provide the reader with a broad overview of the tool prior to the discussion on 'current benchmarks'. A full explanation of the tool can be found in Curtis and Scheurer (2010). The Spatial Network Analysis for Multimodal Urban Transport Systems (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 endeavours to identify and visualise 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; and the speed competitiveness between public transport and car travel in a coherent mapping exercise. The tool is intended to aid discussion and to lend weight to decision making within the fields of land use planning and transport planning, particularly where outcomes leading to more sustainable transport options are needed.

The tool is designed to reflect a vision of world best practice in public transport that has consolidated from the contributions of numerous scholars and practitioners over the years and is most comprehensively documented in the European Union HiTrans project (Nielsen et al, 2005). In geographical and operational terms, the most critical success factors relate to the integration of public transport services as a coherent, legible network, offering travel speeds competitive to the road system and service frequencies on a significant number of routes that make timetable consultation unnecessary (see also Mees and Dodson, 2011).

SNAMUTS breaks down the land use-transport system into a set of activity nodes and route segments derived from the hierarchy of activity centres identified in strategic planning documents, and the location and service standard of public transport routes. In particular, SNAMUTS makes the following definitions:

Minimum service standard

SNAMUTS defines a minimum standard for inclusion of a public transport route into the analysed network, normally requiring a service frequency of 20 minutes (or better) during the weekday interpeak period (about 10.00 to 15.00) and 30 minutes (or better) during the day on Saturdays and Sundays. This level is referred to as SNAMUTS 20 and has been used in all international SNAMUTS comparisons to date. It was chosen to reflect a reasonable 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.

Activity nodes

These refer to a list of higher-order activity centres 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 in order 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 m) or tram/bus corridors (400 m). 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 labelled with an impediment value consisting of the average travel time divided by the number of services per hour, separately for each direction, and multiplied by a factor of 8 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 interpeak

SNAMUTS' network performance measures refer to the service levels offered during the weekday interpeak period (roughly between 10.00 and 15.00 on Mondays to 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.

Benchmarking: How do current public transport systems compare?

Applying SNAMUTS to European cities incurred the consideration of varying methodologies on how transport operators and public agencies in different cities report (or do not report) public transport and land use data, and the challenge to convert the findings into a format that allows for valid and robust comparisons between cities. These data items include public transport timetables and maps, geographically fine-grained records of the location of residents and jobs, and some

operational parameters such as average load factors on different public transport modes.

Timetables and maps

SNAMUTS timetable databases are compiled from public-domain material. This is a deliberate choice as the intention is to evaluate public transport accessibility from a user perspective. It is therefore important to rely on the passenger information that all users can access. In each European city in the sample, such material is available both as printed timetable brochures as well as an online format. However, only in Hamburg are timetables and maps published in an annual, network-wide compilation across all public transport operators covering the entire metropolitan area. In the Dutch cities, a similar booklet is available for the regional and intercity rail system, while timetable folders for urban public transport are usually only available on a line-by-line basis, and in some cases only in electronic format. Similar standards prevail in Edinburgh, Oporto and Copenhagen (though in the latter case there are also folders covering the entire rail system, or the entire express bus system).

Definition of activity nodes

SNAMUTS indicators are derived from an origin-destination matrix based on activity nodes, ie. places with geographical concentrations of trip origins and destinations (urban activities) that are linked through the public transport system. The number and location of relevant activity nodes requires careful definition and needs to contend with the differing urban structure and public transport network configuration in each case study city.

In the denser inner sections of European cities where mixed land uses prevail and there is thus a more or less spatially contiguous presence of trip origins and destinations, it is usually most straightforward to define every intersection of public transport routes as a separate activity node. In more suburban locations, however, particularly those from the post-war era when segregation of land uses was the norm, it is necessary to be more discriminating. In the Danish, German and Dutch cities, it was found that most post-war suburban housing estates contain shopping and service clusters that usually offer good walking and cycling access within the neighbourhood and are also generally well served by centrally located public transport stops. Such centres were included on the list if they either had a significant spatial concentration of residents – manifest, for instance, by clusters of multi-storey apartment blocks – or a concentration of employment that went beyond that of a service and retail centre with an exclusively local catchment area (for example if there was a hospital, tertiary education facility or business district in the same neighbourhood). In Edinburgh, the spatial co-location of housing and non-residential uses in post-war city extensions appears to be much weaker than in the continental cities: many housing estates appear to lack even basic shopping and service facilities, while on the other hand, there are numerous larger commercial centres outside an easily walkable context from residential areas, but often supplied with dedicated bus terminals. In Edinburgh, activity node allocation outside the older parts of the city thus refers more to such ‘stand-alone’, mono-functional facilities. In Oporto, there is a greater mixed-use building tradition even in suburban areas than in the northern cities as well as the presence of some large-scale retail centres, meaning that the technique from the inner cities of defining public transport interchanges and termini as SNAMUTS activity nodes could generally be extended to the entire network in the Portuguese city.

In some cases, activity centres that are located on the public transport network have multiple, not always functionally connected access points (such as where spatially separate rail stations and tram or bus corridors service the same activity centre within walking distance). In such cases a separate activity node was assigned to each of these access points, resulting in the division of some suburban activity centres into two or three SNAMUTS activity nodes.

Geographical distribution of residents and employment

A SNAMUTS land use database ideally consists of residential and job figures at as fine-grained a geographical level as possible, to allow for a best-fit allocation of their locations to the 400/800-metre catchment areas of public transport access points.

The Danish, German and Dutch cities conduct the continental European tradition of a council registry, ie. a local government office where citizens are obliged to register their residential address and which in turn enables the collation of a frequently updated and quite accurate database of residential population and its geographical distribution. Employment data, in turn, usually relies on business surveys taken at less frequent intervals. In Copenhagen and Hamburg, residential and employment output data is available at a sufficient level of geographical detail, based on travel survey zones. In Hamburg however, whose metropolitan area stretches over three federal states and two state statistical departments, the reporting standards differ from one jurisdiction to the next, and privacy legislation prevented the release of the full list of job figures per statistical unit within the territory of the city-state of Hamburg. In these circumstances, we resorted to estimates based on average job densities in the surroundings of the missing units in Hamburg itself, and to an assessment at the municipal scale for data in the surrounding states of Schleswig-Holstein and Lower Saxony.

In the Dutch cities, residential data is available at an exceptionally detailed geographical scale based on six-digit postcode areas, each of which sometimes only extends to a single city block and occasionally only a single building. Employment data, however, is only available for free for statistical units based on the first four digits of the postcode.

In Edinburgh and Oporto, we relied on census data for both residential and employment counts. While both cities delivered this data in sufficient geographical detail for SNAMUTS purposes, the level of spatial precision was much higher in Oporto than in Edinburgh.

Current Benchmarks – Comparing European Cities

This section presents the results for six SNAMUTS indicators: service intensity, closeness centrality, degree centrality, network coverage, contour catchments and nodal betweenness. In so doing we highlight important differences and similarities between the eight case study cities, allowing for a new understanding of public transport accessibility and for the identification of specific trends and patterns in land use and transport integration.

Service intensity

The SNAMUTS timetable database, compiled for each case study city at the SNAMUTS 20 minimum service standard during the weekday inter-peak period, provides us with an estimate of the numbers of public transport vehicles that are

required to be in simultaneous revenue service in order to deliver the public transport network that is operated at this standard (Table 2). Note that the figures for the actual numbers of vehicles required by the operators are somewhat higher than that, as the SNAMUTS calculation does not make provision for service breaks at the termini, contingencies for delays or disruptions, non-revenue journeys, and for vehicles undergoing scheduled or unscheduled maintenance. Nor do these figures reflect the usually greater numbers of vehicles required to operate peak hour services.

Table 2: Service intensity in the European case study cities

SNAMUTS 20	København (2009)	Hamburg (2010)	Amsterdam (2010)	Zuid Holland (2010)	Edinburgh (2011)	Oporto (2009)
Number of trains/ S-Tog/S-Bahn	81	47	50	36	13	4
Number of metros/ U-Bahn/LRT	16	54	23	36	-	30
Number of trams	-	-	136	182	-	1*
Number of buses	329	439	398	308	158	271
Number of ferries	2	5	1	-	-	-
Number of services (total)	426	545	607	562	472	305
Metropolitan population	1.85m	3.37m	2.16m	3.46m	1.27m	1.23m
Services per 100,000 inh	23.1	16.2	28.1	16.3	37.2	24.8

*Cable car

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

Relative service intensity (ie. 'services per 100,000 population') reveals some variation across the sample. The most frugal cities on this index appear to be Hamburg and Zuid Holland, while Copenhagen and Oporto occupy an intermediate position. Of the continental European cities, Amsterdam has the highest number of public transport vehicles in simultaneous revenue service per capita, while the highest level in the sample, by quite a significant margin, is on record for Edinburgh.

The service intensity indicator is influenced by the propensity of public transport agencies and operators to provide resources to run the system as well as by its efficiency: a dominant role for fast high-capacity modes, particularly heavy rail, will depress relative service intensity figures, while a large number of high-frequency, slow-moving surface routes tends to inflate them. The intensity figure also increases where settlement areas are dispersed or separated by geographical barriers, thus

lengthening journey distances and times between places of activity. High service intensity scores are therefore not necessarily indicative of better service. It is, however, reasonable to suggest this indicator as a benchmark, hereby using it as a focus to examine the public transport effort in cities with low service intensity scores. The examination could be conducted by cross-reference to other SNAMUTS indicators (see later) to ascertain whether accessibility benefits in relation to operational inputs into the public transport system could be lifted to a level commensurate with peer cities.

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

Closeness and Degree Centrality

These two indicators are designed to capture the structural properties of the public transport networks; they do not incorporate a land use dimension beyond defining the number and location of activity centres. Closeness centrality considers accessibility in a way most closely described as 'ease of movement'. An average score for travel impediment (travel time divided by service frequency), or ease of movement, is calculated between any two activity nodes on the network. The final figure for each activity node represents the average impediment score for all journey possibilities between this node and all others on the SNAMUTS 20 public transport network. Degree centrality considers accessibility by public transport from the perspective of number of transfers required to make a journey between any two centres. The figure given for each node thus describes the average transfer intensity for journeys to or from all other nodes on the network (Table 3).

Table 3: Closeness and degree centrality in the European case study cities

SNAMUTS 20	København (2009)	Hamburg (2010)	Amsterdam (2010)	Zuid Holland (2010)	Edinburgh (2011)	Oporto (2009)
Number of activity nodes	128	176	132	205	97	94
Average Closeness Centrality	25.6	35.3	36.4	45.1	47.0	35.8
Closeness (lowest value)	14.3	19.6	20.6	26.5	24.8	19.6
Closeness (highest value)	78.9	92.9	89.9	146.6	125.7	122.0
Average Degree Centrality	0.80	1.07	1.14	1.60	0.99	0.91

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

Other factors influence the closeness centrality score and can provide a useful insight into where improvements to accessibility can be made. Closeness centrality is measured by travel impediment, which in turn is composed of travel time and service frequency. Cities where activity centres are spaced further apart (in terms of public transport travel time, not necessarily metric distance) or in other words, cities with more dispersed settlement patterns and more convoluted links between places of activity are at a disadvantage for public transport accessibility compared to more compact ones or ones with faster public transport systems. Compactness, in this context, is not necessarily equivalent to density: Part the reason for Copenhagen's low (good) average, lowest and highest closeness scores can be found in the city's location on an island, whose coastline effectively contains the settlement area and ensures that outward growth can only occur within an approximate 135-degree segment of a circle. While all the other case study cities also have coastal access, nowhere else does this circumstance provide such a compelling constraint to urban expansion as in Copenhagen.

Conversely, the relatively high (poor) average, highest and lowest closeness centrality scores in Zuid Holland are linked to this conurbation's multi-nuclear form without a single overarching centre. Since the closeness matrix treats every origin-destination pair on the network as equally weighted, the spatial separation between dispersed centres, even where these might have compact and contained settlement areas in their own right, is making itself felt here. This is also manifest in the high average transfer intensity of Zuid Holland's network, where several individual cities (Leiden, Den Haag, Rotterdam and Dordrecht) operate self-contained urban networks which are only connected by a limited number of rail and metro lines between them at a regional scale.

On the other hand, it is such fast rail connections that work 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. Copenhagen and Hamburg stand out on this aspect as their rail and metro systems are not only speed-competitive with road travel, but also operate at very high frequencies during business hours (5 minutes or even better throughout the inner areas). In the Dutch Randstad, such frequencies are only achieved on metro trunk lines (in Amsterdam and Rotterdam) whereas the regional rail system operates a mix of overlapping all-stop and intercity trains, which each stopping pattern typically operating every 15 or 30 minutes and

thus usually adding up to frequencies of between four and eight trains per hour on each route (less for minor intermediate stops, some of which consequently do not meet the SNAMUTS 20 standard). In Edinburgh and Oporto, the maximum rail frequency tends to be four trains per hour, and there are several suburban lines that operate only half-hourly and thus do not enter our analysis. The low frequencies on the rail system, as well as on bus routes to outer suburban and regional centres, also explain the breakout highest closeness values in the two smaller cities, which overall appear to be less successful than Copenhagen, Amsterdam and (to a lesser extent) Hamburg in offering a uniform standard of public transport accessibility throughout their urban region. Instead, they seem to be allowing some outlying areas to contend with long travel times and/or low-frequency services, a situation that helps to push up average closeness centrality values for the entire network.

Oporto's advantage over Edinburgh appears to be almost entirely related to the presence of a light rail network in the Portuguese city, with two mostly underground inner-city trunk lines providing travel speeds through the urban core that have no match in the congested streets in the centre of the Scottish capital, some of which need to cope with more than 200 bus movements per hour even outside the peak period. Also incorporated in this index, though with only minor effects in this case, 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. even a transfer between bus routes of different operators incurs an additional cost to the user.

Lastly, Copenhagen's top performance on the degree centrality index merits an explanation, given that the public transport network in the Danish capital, not unlike Hamburg's, is organised around a hierarchy of modes where rail picks up the primary corridors and buses the secondary ones, as well as feeder and distributor functions to the rail system. But why does Copenhagen outperform Hamburg (as well as Amsterdam) so dramatically on this index? In Amsterdam, the core explanation can likely be found in a circumstance similar to what was said about Zuid-Holland earlier: the metropolitan region is multi-nuclear, and the neighbouring secondary centres of Haarlem and Almere operate their own, relatively self-contained urban bus networks that are connected to Amsterdam only through rail links and some express buses, resulting in the near-inevitability of two or more transfers between places located in different cities away from the rail network. But in Hamburg, the greater transfer intensity can primarily be traced back to the much lower density of the surface network in the inner areas, as well as the less developed nature of orbital bus links in the outer areas than in Copenhagen. This observation is also supported by the lower service intensity figure for Hamburg. Both Nordic cities converted their once-extensive tram systems to bus operation in the 1960s and 1970s, but while Copenhagen retained practically each and every former tram route as a bus link (and then added some further ones), Hamburg abandoned a significant number of tram routes without full bus replacement, 'thinning out' its inner urban network in the process and making public transport movement much more dependent on transfers between modes, even for some relatively short journeys, than its Danish neighbour. Or in other words, Copenhagen's bus network alone provides a 'random-access grid' (Nielsen et al, 2005; Mees, 2010) across the inner area and supplements this function with fast, high-capacity rail and metro links servicing some of the same corridors, while in Hamburg, only the interplay of rail and bus modes on different corridors achieves a comparable network configuration.

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

Network coverage and contour catchments

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

The contour catchment index uses the same approach to measuring land uses, but identifies the average percentage of residents and jobs that can be accessed from each node by way of a public transport journey of 30 minutes or less. This time window can include up to one transfer as long as both legs of the transfer journey are operated at least every 15 minutes, and with a penalty deducted that is equivalent to the average transfer time across the network from arrival of the first vehicle to departure of the second vehicle. The index adds a further dimension to the network coverage assessment, in that average 30-minute contour catchments are also influenced by the density and concentration of urban settlement, the speed of public transport and the spacing of activity nodes within the metropolitan area, which can be read as a proxy measure to its degree of compactness or dispersal (Table 4).

Table 4: Network coverage and average 30-minute contour catchment in the European case study cities

SNAMUTS 20	København (2009)	Hamburg (2010)	Amsterdam (2010)	Zuid Holland (2010)	Edinburgh (2011)	Oporto (2009)
Network Coverage	1,927,000 (71.9%)	2,749,000 (54.6%)	2,446,000 (78.3%)	2,965,000 (62.3%)	1,037,000 (55.9%)	1,086,000 (62.0%)
Average 30-min contour catchment	879,000 (32.8%)	880,000 (17.5%)	599,000 (19.2%)	521,000 (11.0%)	259,000 (14.0%)	346,000 (19.7%)

Across the sample, network coverage ranges from a low of 55% and 56% in Hamburg and Edinburgh, respectively, to a high of 72% in Copenhagen and 78% in Amsterdam. Some of this variation is explicable when considering the figures in conjunction with the service intensity index discussed above: cities that put more resources into public transport operation should be able to provide a larger network (relative to city size) that services a greater percentage of its urbanised area. This pattern is clearly present in the comparison between Copenhagen and Amsterdam with Hamburg. But it does not yet explain why Hamburg falls even behind Zuid Holland despite having a comparable level of service intensity. A possible reason,

also observed in future SNAMUTS case study cities such as Vienna and Munich, is that historically, public transport provision in Hamburg has been a local government responsibility, meaning in this case the city-state of Hamburg which in 2010 comprised only just over half of the metropolitan area population. Hamburg may have been a pioneer in the conception of the first integrated public transport agency as far as back as 1965; however, only during the last decade did this governance model grow significantly beyond the city-state borders to encompass the seven neighbouring counties in Schleswig-Holstein and Lower Saxony in their entirety. And while some metro and regional rail services have since been improved and extended to regional centres, on the whole the outer metropolitan area remains characterised by a legacy of urbanisation that was either focussed on regional rail services with frequencies too low to meet the SNAMUTS 20 standard, or without much public transport orientation at all. Zuid Holland is by no means free of comparable settlement and public transport service patterns, but its multi-nuclear nature ensures that there is a lower number of regional centres than in Hamburg without services that meet the SNAMUTS 20 standard, and that these tend to be smaller than their northern German counterparts.

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

On the average 30-minute contour catchment size, Copenhagen delivers another breakout performance within the sample that reflects several observations already made earlier, namely the high speed and frequency of its suburban rail and metro network and the dense grid of bus routes in the inner area. The combination of these two factors maximises both the number of destinations that can be reached within the time window, and the number of trips for which no transfer is necessary. At considerable distance, the figures for Oporto, Amsterdam and Hamburg are relatively similar, considering that this index, like closeness centrality, can be expected to decline with growing city size and geographical complexity (and the ensuing difficulty to provide short travel times across a large settlement area). The reasons why Edinburgh and Zuid Holland trail the sample on this index are also quite straightforward: in Edinburgh, the slow average speeds on a bus-dominated network and the patchy configuration of public transport services outside the core city conspire to depress the average contour size, while in Zuid Holland, the dispersed nature of settlement across a multitude of spatially separated urban centres is the key driver for the low figure.

Betweenness centrality

The last SNAMUTS index compiled for all six case study cities tries to measure the geographical distribution of travel opportunities across the networks' nodes and route segments as generated by the land use system and the configuration and service levels of the public transport network. Betweenness is a dynamic index, acknowledging that fast and frequent services between a pair of centres will be more attractive for urban movement than slow and infrequent services between another pair of centres of similar size. The index is designed to highlight which centres and public transport routes are 'at the crossroads' of movement across the metropolitan

area, and how well different modes fare in terms of attracting such movement opportunities, not least with a view to their varying passenger capacity. The global betweenness index represents an attempt to benchmark the attractiveness of the public transport system as a whole to facilitate movement and accessibility across a case study city, and may allow for an insightful comparison within our six-city sample (Table 5).

Table 5: Betweenness centrality in the European case study cities

SNAMUTS 20	København (2009)	Hamburg (2010)	Amsterdam (2010)	Zuid Holland (2010)	Edinburgh (2011)	Oporto (2009)
Global betweenness index	2,173	1,612	1,726	844	677	736
Average nodal betweenness	83.4	51.6	55.2	24.1	33.3	34.5
Average catchment (residents and jobs) of typical path length	74,000	88,000	78,000	85,000	51,000	51,000
Segmental betweenness – rail/S-tog/S-Bahn	49.3%	27.8%	24.5%	32.4%	8.7%	1.9%
Segmental betweenness – metro/U-Bahn/LRT	10.6%	33.5%	14.1%	17.6%	-	27.3%
Segmental betweenness - tram	-	-	21.9%	30.7%	-	0.0%*
Segmental betweenness - bus	39.1%	38.3%	39.4%	19.4%	91.3%	70.7%
Segmental betweenness - ferry	0.0%	0.3%	0.0%	-	-	-
Segmental betweenness – CBD area	32.0%	24.6%	29.1%	21.3% (Rotterdam) 18.9% (Den Haag)	44.0%	46.9%

*Cable car

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

Yet, the difference in the figures between Zuid Holland and Amsterdam, where polycentrality is less pronounced than in Zuid Holland but still a critical feature of the

settlement pattern, remains striking. With a view to with Copenhagen's outstanding performance on this index, it is likely that both cities benefit strongly from a relatively intact interplay of a dense surface public transport network (dominated by trams in Amsterdam and buses in Copenhagen) and a functional pre-war, originally transit-oriented, mixed-use settlement pattern in their inner areas. In contrast, Rotterdam and Hamburg, both extensively damaged during World War II, significantly departed from this pattern during post-war reconstruction in favour of a more functionally segregated urban form with reduced urban density compared to the pre-war stock.

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

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

Edinburgh and to a lesser extent Oporto remain strongly dependent on buses for the bulk of their public transport system's ability to service mobility needs arising from the land use system. In Oporto, the metro system, developed only over the last 15 years, arguably remains incomplete and is in fact subject to ambitious expansion plans. In Edinburgh, the role of its relatively extensive heavy rail infrastructure for frequent suburban services remains underdeveloped, though here too, plans are underway to address this (as well as introduce a light rail system).

The segmental betweenness scores for the CBD area – percentage of travel opportunities to, from or passing through the central city - can be expected to drop with growing city size and polycentricity, as well as a network configuration that offers attractive alternative travel paths for cross-suburban journeys. Within our sample, high-capacity orbital transport links are arguably best developed in Amsterdam, yet it is Hamburg that comes out with the lowest segmental betweenness figure for the CBD, perhaps primarily due to its larger size and a flatter

hierarchy in network significance (nodal betweenness) between the dominant CBD node (both cities' respective Central Station) and other rail hubs in its vicinity in Hamburg than in Amsterdam.

Discussion and Conclusions

The SNAMUTS analysis of the land use-transport systems in six European city regions has shown Copenhagen to achieve a top ranking on every accessibility indicator with the exception of network coverage, on which it comes second after Amsterdam. But does Copenhagen's stellar performance in this assessment elevate the Danish capital to the status of a model city, a benchmark for European best practice in public transport accessibility?

Some of Copenhagen's success factors can be traced to more immutable features of urban form, such as its position on an island which effectively limits its possible outward expansion to less than half the city's circumference, and the absence of major geographical or administrative barriers on the land side of the island that would impede the existence and effectiveness of high-quality orbital links to complement the radial corridors that shaped the city's historic development.

But there are also public transport network and service planning choices behind Copenhagen's good standing in the comparison of SNAMUTS results. The three most critical factors in this regard appear to be:

- the presence of an expansive heavy rail (suburban rail and metro) network with high service frequencies – every 5 minutes or better during business hours on all routes in the inner area, and every 10 minutes or better practically everywhere else – a standard that out of the six-city sample, only Hamburg can match;
- the presence of a random-access grid of surface routes covering the medium- to high-density, mixed-use inner neighbourhoods without leaving deliberate gaps where parallel rail lines exist – a standard also found in Amsterdam and Den Haag (mostly tram-based), Edinburgh and Oporto (mostly bus-based), but not in Hamburg and Rotterdam.
- the presence of fast orbital routes in middle and outer suburbs whose service frequency matches that of radial train lines, and whose travel times are shorter than those of transfer trips through the central city using the radial routes.

This is not to say there was no room for improvement in Copenhagen's public transport system – there remain conspicuous geographical gaps in the rail system, and some bus routes are congested or insufficiently prioritised over motorised traffic. Some of these shortfalls are being addressed by metro extensions currently under construction, and by plans to convert the busiest orbital bus route to light rail.

The comparison between the two medium-sized cities, Oporto and Edinburgh, demonstrate some of the shortfalls associated for cities in this category from relying excessively on buses for urban public transport. Edinburgh has by far the highest operational input but produces what is arguably the poorest accessibility profile in the sample. A comparative look at Oporto illustrates the efficiency gains in terms of operational resources as well as accessibility performance that can be achieved by

introducing light rail as a higher-capacity mode for the city's key corridors (a step Oporto only took during the 1990s and which remains far from complete).

Some open questions remain. For instance, what would be the outcomes in terms of accessibility performance if public transport service intensity per capita in Hamburg was lifted to the level of Copenhagen (a more than 40% increase)? Would Hamburg draw even with or even outperform its northern neighbour? And further, how does Rotterdam's and Hamburg's failure to provide a full random-access surface network across their inner areas relate to the unique characteristics these two cities share – namely, accommodating Europe's two largest seaports within their boundaries as well as, out of the sample examined in this paper, being precisely the two cities that suffered a major discontinuity to their urban development in the mid-20th century due to wartime destruction and subsequent rebuilding in a very different form?

Future SNAMUTS investigations and an expansion of the European sample to incorporate Barcelona, Munich, Vienna and Zurich will serve to address these questions in more detail.

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