

Centrality and Connectivity in Public Transport Networks and their Significance for Transport Sustainability in Cities

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Introduction

The promotion of public transport as a backbone of mobility in urban agglomerations, or at least as an alternative to the dominance of the automobile, has become a prominent policy focus in most large cities around the world. However, while some cities have been successful in shifting car journeys onto rail and buses, others are struggling despite considerable effort to make public transport more attractive.

This paper provides a brief overview of success factors for public transport and then takes the configuration of public transport networks as a vantage point for policy evaluation. The development of centrality and connectivity indicators for the public transport network of Melbourne's north-eastern suburbs delivers an instrument for assessing the congruence of the systems with the geographical structure of central areas and urban activities in these cities. It is hypothesised that a higher number of convenient transfer points and a choice of routes to users (network connectivity), as well as a high degree of spatial overlap and integration between public transport infrastructure and urban activity centres and corridors (centrality of facilities) will lead to a greater role for public transport in the mobility patterns of the city as a whole.

The paper will then look at current strategies for public transport improvements in Melbourne and other cities and quantify their impact on network connectivity and centrality. It will further introduce a planning tool for central areas, both inner urban and suburban, based on these indicators to categorise public transport access and service quality at a local level, and to evaluate and prioritise measures of improvement.

Best Practice Public Transport Systems

The significance of public transport for urban mobility in developed cities varies greatly. Public transport is used for just over 2% of all trips in Atlanta and Los Angeles, 7% of all trips in Melbourne and Sydney, 14-16% of all trips in Copenhagen, Hamburg and Toronto, and 26-31% of all trips in Barcelona, Vienna and Singapore (Kenworthy and Laube 2001). This variation is influenced, for example, by historic and current policy priorities for infrastructure development and the form of urban settlements, and the competitiveness of different modes in terms of speed and pricing (Newman and Kenworthy 1999, Gleeson, Curtis and Low 2003). Since many cities now emphasise the desirability of increasing the mode share of public transport at least in their policy rhetoric, if not their practical priorities, it has become commonplace for cities with weaker public

transport to look closely at the success factors in cities with stronger public transport. The most important of these success factors 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, Nobis 1999)
- a legible network structure that is efficient to operate, easy to navigate and offers a choice of routes wherever possible (Mees 2000, Vuchic 2005)
- a speed advantage of urban rail over road traffic along a city's main corridors (Newman 2005)
- 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)
- an institutional framework that allows for integrated, publicly accountable capital investment and service planning (Mees 2005, Mees et al 2006)

In practice however, these factors are often considered selectively, and not always fully understood. This is partly a consequence of the specific policy challenges inherent to the task at hand: for instance, a policy goal of increasing Los Angeles' public transport usage (2% of all trips) to the level of Melbourne (7%) inevitably requires a different set of measures than increasing Melbourne's usage to the level of Hamburg (15%), as stipulated in Melbourne's current metropolitan strategy (DOI 2002). Increasing Hamburg's public transport usage to the level of Vienna (30%) would call for yet another entirely different approach. Thus in Los Angeles, the focus may be on the mere existence of public transport, and its acceptability to the travelling public, for a common range of mobility needs, and the geographic concentration of some of these movements into corridors for high-performance modes. In Melbourne, the focus may be on the physical and service integration of the existing network, and its expansion to cover the entire urbanised area at equitable standards. In Hamburg, the issue of raising public transport's competitiveness with the private car in terms of speed, convenience, cost and space allocation may be the key to an increased mode share. Consequently, in terms of transport and land use integration, in Los Angeles the co-location of urban development with any type or level of public transport service may result in above-average ridership. In Melbourne, public transport around new or intensified development would need to conform to certain standards of service level and system integration to push its usage above the metropolitan average. In Hamburg, new or intensified development would need to prioritise public transport over car access with regard to urban design, station location and accessibility, and road and parking provision to make a difference.

This paper is primarily concerned with the policy challenges facing Melbourne and other cities with a comparable mode share for public transport, and will take a geographical perspective on the city-wide or regional configuration of the public transport network. In the following section, we will introduce a range of measures and indicators to explain the common observation, intuitively quite obvious, that public transport tends to perform better and attract a greater share of trips in parts of the city with high geographic centrality. Using the supplementary concept of network connectivity, we will then develop a methodology to assess programs and projects of public transport system expansion against their ability to increase levels of centrality over greater parts of the network, and against the congruence of this centrality pattern with that depicted in

strategic planning documents and supported by the movement networks of other transport modes.

Understanding Connectivity and the Congruence of Centrality in Complementary Movement Networks

The analysis of movement networks to capture mobility patterns in cities, and to assess urban design qualities associated with them, has received increasing attention in recent years. The work of Hillier and Hanson (1984) and Hillier (1996) informed the development of the Space Syntax methodology, which has since been applied in numerous cities world-wide and centres on the practice of 'axial mapping', ie. the breakdown of movement networks into line-of-sight segments. Most of these applications concentrate on the surface (street) network and investigate issues as diverse as the spatial integration of network elements, pedestrian and vehicle flows, human way-finding, social and economic vitality and criminality at a micro-scale. Porta, Crucitti and Latora (2006a) in summarising this methodology, point out that axial mapping as a topological image of urban movement spaces does in fact reverse the traditional and in some respects intuitive categorisation of network elements: it defines street segments as nodes and intersections as edges connecting these nodes. Porta et al describe this as the dual approach of analysing movement networks and assert that its strength lies in the abstraction of mapping a network's topological properties. Its weakness lies in a necessary detachment from spatial and sensory experience, particularly in the omission of distance, or spatial resistance, as the principal property of urban geography (see also Crucitti, Latora and Porta 2006).

In contrast, a primal approach to the analysis of movement networks (Porta, Crucitti and Latora 2006b) treats intersections as nodes and street segments as edges and is therefore capable of assigning a value of distance to these edges. This is not merely in the interest of a more realistic representation of urban geography by combining topological and metric measures of the system. The primal approach also reduces the inevitable subjectivity associated with the definition of abstracted network elements in the dual approach. The authors therefore recommend the use of the primal approach for the analysis of centrality in urban movement networks, while contending that there is no one-size-fits-all measure of centrality: rather, they call for a 'Multiple Centrality Assessment' involving the incorporation of four different centrality indexes, constructed upon four different concepts of centrality (see below), into a multifaceted representation.

Before returning to this technique, however, we will briefly examine in what ways the analysis of public transport networks diverges, and requires different assumptions and definitions, from the analysis of movement networks for individual transport (ie. pedestrians, cyclists and motorists).

Firstly, public transport systems are networks of predetermined movement, that is to say, they concentrate travel demand onto particular corridors or routes. Passengers can enter and leave, or transfer between these routes freely, but they cannot make spontaneous decisions about changing direction without leaving the movement device they are in, in the way a pedestrian, cyclist or motorist can. For our purposes, this circumstance adds a layer of complexity to the network configuration. If we interpret a public transport route, in a primal graph (see above) as a corridor of nodes (stations/stops or interchange points) linked by multiple, consecutive edges (segments of route between adjacent nodes), then the path along this route has greater

prominence within the network than a random path of similar distance that would in practice require multiple transfers between different routes. In short, **our public transport network assessment needs to distinguish paths clearly by the number of transfers they incur, and apply penalties for paths with transfers over paths without transfers, due to the inconvenience and delay experienced by users.**

Secondly, not every geographical intersection between route segments (edges) in a public transport system can appropriately be treated as a node (transfer point): in short, a public transport network is not always nor necessarily planar. Routes may cross each other without stopping, or the conditions for changing between routes may be so deficient (in terms of urban design, safety or sheer walking distance) that the intersection is not perceived as a transfer point by passengers. Conversely, some intersections offer superior conditions for transfers between routes, particularly where purpose-designed facilities exist and timetables of different routes are coordinated to facilitate transfers. **Our network assessment thus needs to define standards of co-location and legibility of interchanges in order to classify them as network nodes.**

Thirdly, the concept of distance as a measure for spatial resistance, or impediment to movement, needs to be considered differently in public transport systems than for individual transport modes. For pedestrians and, to a lesser extent, cyclists and motorists, geographical distance tends to be a useful indicator for the disutility of travel: in the absence of congestion or physical barriers to movement, their speed is relatively constant, and the time spent travelling is more or less proportional to the distance travelled. In the case of public transport, speeds on different network segments can be extremely varied: it is not uncommon for a rapid rail service to cover 10 km on a dedicated right-of-way within the same time it takes a bus to cover 1 km through a congested town centre. Furthermore, the cost of travel to the user, which to a motorist consists to a significant degree of fuel cost and is thus roughly proportional to trip length, is usually at least partly dissociated from distance in public transport networks. Most systems use either flat or zone-based fare regimes, where trips of varying distance attract the same fare, and/or they rely to a high extent on periodical (weekly, monthly or annual) tickets, where there is no longer any necessary correlation at all between distance and cost, or even number of trips and cost. This paper will take the stance that **the main impediment or disutility of travel on public transport is travel time - understood not merely as in-vehicle time, but also incorporating access time, waiting time and, where applicable, transfer time.**

In the light of these premises, the practical example in this paper will:

- apply a common standard for interchanges to be counted as network nodes;
- count an edge for every pair of nodes along a continuous public transport route, like for every possible pair of pearls on a string, whether they are adjacent to each other or not. This means that the topological path length (number of edges) between any two nodes in the network is always equivalent to the number of separate vehicle boardings the trip requires (eg. a trip with two transfers requires three vehicle boardings).
- use a measure derived from average travel time along a route segment, divided by the frequency of the service (number of departures per hour per direction) as a proxy for edge length. Thus a higher-frequency service reduces the disutility of the trip while being subject to a principle of diminishing returns, which appears commensurate with the real-life experience (an increase in service frequency from two to four trips per hour generates a comparable need for additional input

of resources as, but has a greater impact on the relative attractiveness of the service than an increase from ten to twelve services per hour).

A comprehensive assessment of network connectivity thus requires a topological (number of edges in a path) as well as a metric (cumulative edge length) perspective, both of which we will explore below.

Porta, Crucitti and Latora (2006a, 2006b) suggest a range of measures to capture the properties of networks (see also Latora and Marchiori 2002). These are:

- the **degree of a node**, understood as the number of edges converging in it. In our example, this is a significant measure, as it expresses the number of other nodes than can be reached from the node in question by way of a transfer-free public transport trip.
- the **characteristic path length**, understood as the average distance or impediment (metric), or degree of separation (topological), between all possible pairs of nodes within the network. This measure, as mentioned above, is best applied both metrically and topologically in public transport networks and is exquisitely suited for comparative network assessment, or scenarios for network reconfiguration, as explored in the next section.
- the **global efficiency**, understood as the inverse average shortest path length between any two nodes in the network. This measure is suited for fully connected as well as partially disconnected networks (the value for paths between nodes that are not connected through the network drops to 0). Global efficiency is expressed topologically, in our example, as the relative efficiency (inverse average degree of separation, or number of boardings required for the trip) compared to the efficiency of an ideal network (where a transfer-free connection is available between any two nodes). A metric indicator for global efficiency would be a comparison of actual inverse average impediment (in our example, services per hour divided by travel time in minutes) with that found in an ideal network (ie. where all routes operate at a saturated, waiting time-neutral frequency, such as every five minutes, and at their maximum conceivable speed, such as after full prioritisation over road traffic). This indicator is also useful to assess the efficiency of movement by public transport against that by car, especially in terms of travel time between nodes.
- the **local efficiency**, understood as the average efficiency of all sub-networks of nearest neighbours of each node. Local efficiency is related to the extent of clustering of nodes within a network. Using our definition of every transfer-free link between nodes forming a separate edge linking to a 'nearest neighbour', the application of this indicator is problematic, as it leads to an extent of multiple consideration of route segments that render it almost meaningless. Local efficiency can be successfully applied to public transport systems, however, if the routing of services is disregarded and the degree of each node is reduced to what are physically its 'nearest neighbours'.

From these indicators a number of different centrality indexes are derived. Each of them is applied to individual nodes, thus containing locally relevant information:

- **Degree centrality**, defined as the proportion of nodes directly connected to the node in question out of the totality of nodes within the network. In our model, degree centrality is a topological index: it measures the percentage of other

nodes that can be reached with a transfer-free trip. This index can be extended and applied separately to one-transfer trips, two-transfer trips, and so on.

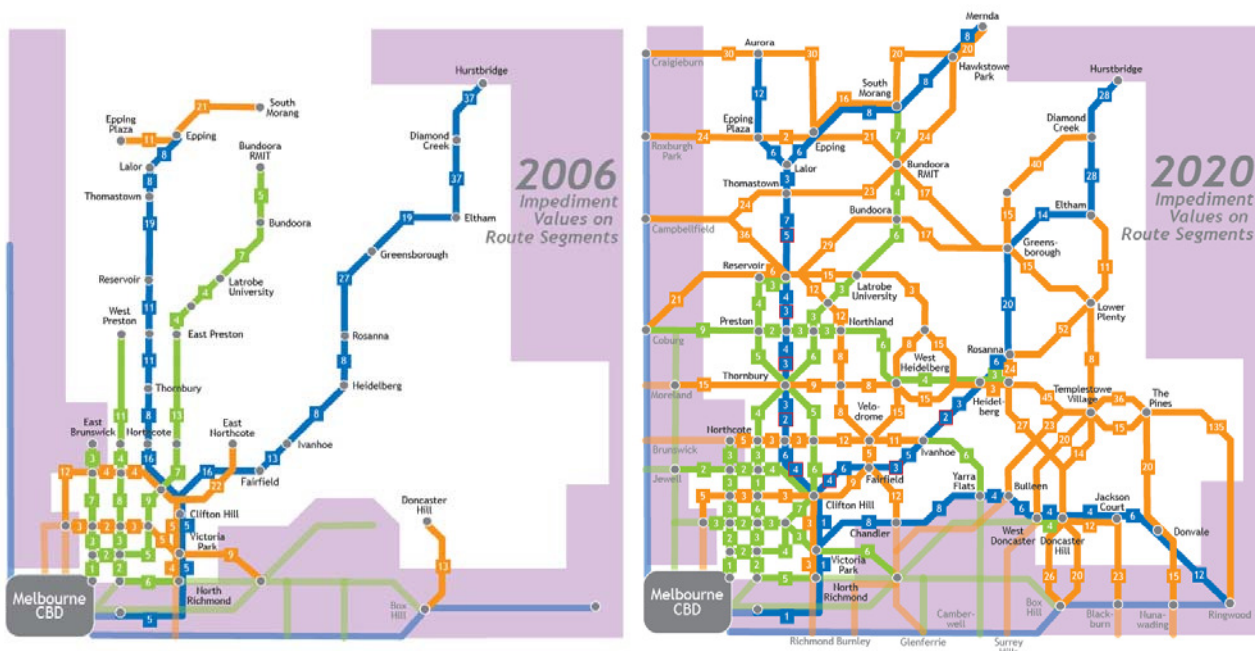
- **Closeness centrality**, defined as the inverse average distance, or impediment, between the node in question and all other nodes within the network. This metric index can be adopted to public transport networks by using an impediment measure, such as travel time divided by frequency as used in this paper.
- **Betweenness centrality**, defined as the average proportion of paths between any two nodes within the network that traverse the node in question, out of the total number of possible paths between these two nodes. This index is critical for public transport networks, since it can capture the relative importance of transfer nodes within the system, and assist in evaluating and modelling route and interchange capacity. By extension, it can be meaningfully applied to network edges as well as nodes, to measure the relative importance of route segments (see next section).
- **Efficiency or straightness centrality**, defined as the ratio of the actual inverse average shortest path length between the node in question and all other directly connected nodes, to the theoretical average shortest path length within that sample. As explained above, the theoretical shortest path length can be determined in our example by assuming idealised operating and service conditions across the network, or by using comparative data for the road system. Efficiency centrality can also be applied very meaningfully in assessing scenarios of network reconfiguration or expansion.
- **Information centrality**, defined as the relative drop in network efficiency in case the node in question is removed from the network. While this property may be of interest in public transport networks to assess the system-wide impact of service disruptions or construction work, the permanent removal of particular nodes from the network is usually not a realistic scenario, particularly where these have a function as transfer points. A far more common possibility would be the removal, addition or reorganisation of entire routes or segments of routes. An index for information centrality should therefore be applied to edges rather than nodes in public transport networks. This premise brings us back to the dual approach to network analysis elaborated on above.

Public Transport in Melbourne's North East

How can these indicators be applied in practice? An exercise in public transport network planning in Melbourne's north-eastern suburbs was commissioned by a coalition of local governments in the catchment of two existing and one planned suburban rail lines (Scheurer 2006). In accordance with a state government target to raise the share of public transport among all motorised trips within Metropolitan Melbourne from 9% in 2001 to 20% in 2020 (equivalent to 15% of all trips and thus similar to Hamburg, Copenhagen or Toronto), a greatly expanded multi-modal public transport network proposal was elaborated in close collaboration with the councils and other stakeholders. The proposal also assesses the role of activity centres, which the current metropolitan strategy identifies and seeks to strengthen (DOI 2002), in the current and future movement network and is thus interested in indexes that can capture their centrality.

Map 1 and 2 show the existing and proposed public transport networks in the corridors, including train and tram routes, and bus routes insofar they conform to a minimum

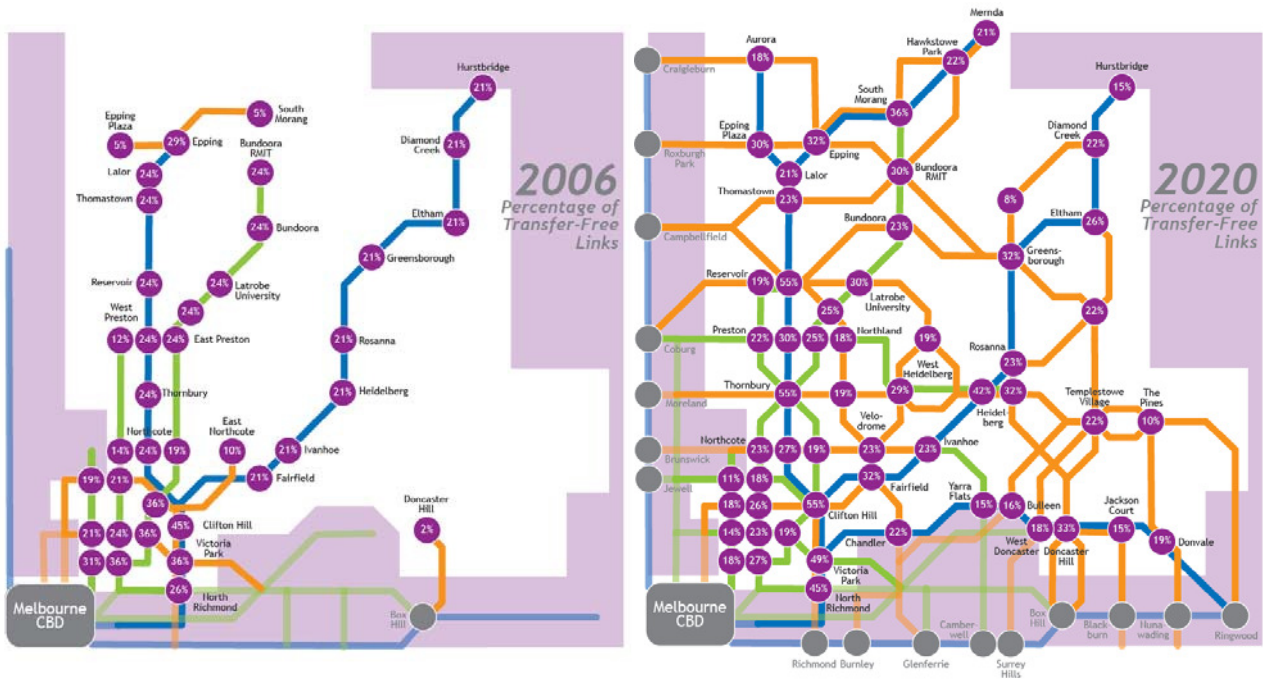
service standard. This minimum service standard has been set at: 7-days-and-evenings-per-week operation, at frequencies no less than two services per hour during the daytime (including on Sundays). In the status quo, only five bus routes fulfil this standard; however, the State Government has committed to a significant increase in service hours and frequencies across the bus network in a recent policy statement (State of Victoria 2006). Both maps also show the network nodes and the impediment scores for the network edges. Nodes have been defined as intersections between routes with co-located and legible transfer opportunities, and intermediate stops along routes within activity centres as identified in the metropolitan strategy. The impediment scores or proxy values for travel disutility, as discussed above, have been determined by dividing the average interpeak travel time in minutes by the average frequency of services per hour, and multiplied by a coefficient of 8 to achieve better readability. As the project covers only a section of Melbourne’s public transport network, edges that cross the boundary of the study area have been included in all counts, but nodes outside the study area are disregarded in calculating network performance as a whole.



Map 1, 2: Public transport networks in Melbourne’s north-east 2006 (existing) and 2020 (proposed) with impediment values on route segments, showing rail routes (blue), tram routes (green) and bus routes (orange). Impediment values in boxes framed in red refer to trains running an express stop pattern.

Our first nodal index, degree centrality, has been plotted on both networks as the percentage of nodes across the system that can be reached from the node in question without a transfer. Map 3 and 4 show these indicators. It should be noted that the definition of transfer-free trips is not without ambiguity, particularly in more complex networks where a choice of routes exists between most pairs of nodes. In some of these cases, a transfer trip may result in shorter travel times and the use of modes with higher service frequency and/or higher performance and passenger comfort (especially rail) for a greater portion of the trip than a transfer-free connection. It can be expected that different groups of system users will make different choices in this context: for example, a young, able-bodied person with constraints on her time budget may embrace the opportunity to transfer in return for faster movement, while an elderly or frail person with an ample travel time budget may prefer the transfer-free connection even if

it results in longer travel times. In our model, we have opted for a compromise: Wherever a pair of nodes is connected by a single edge (transfer-free trip) this option has been included regardless of the cumulative impediment value. Wherever a pair of nodes is connected by a minimum of two edges, the path with the lowest cumulative impediment value has been chosen, regardless of the number of transfers required.



Map 3, 4: Degree centrality indexes for nodes in the existing (2006) and proposed (2020) public transport networks in Melbourne's north-east

The average degree centrality (percentage of nodes within the network that can be reached without a transfer) for all nodes in the 2006 network is 23%. In the 2020 network, this figure reaches 25%. While this difference appears unspectacular, the absolute figures behind these percentages highlight that the number of nodes grows from 38 (of which 12 meet the standard for legible transfer points) to 60 (of which 54 are legible transfer points) from the 2006 to the 2020 network. The average degree centrality, again measured in absolute values, grows from 9.8 transfer-free edges to 18.4. Thus this index, in capturing the impact of network reconfiguration, needs to be plotted against a common benchmark to be meaningful.

To facilitate such comparison, an efficiency index has been used and displayed in Map 5. The global efficiency of the network, as explained above, can be measured by adding inverse impediment values for each nodal relation, and extracting the ratio of the result to a hypothetical scenario in which connectivity has been maximised and travel disutility minimised. Out of a range of possible 'ideal worlds' in this respect, we have chosen to investigate on-the-ground performance against a scenario in which each trip relation is transfer-free, ie. all pairs of nodes on the network have a direct connection between them, while the impediment values for the route segments remain the same. In practical terms, this indicator shows to what extent the transfer-free routes contained in the network do indeed serve the most accessible trip relations, that is to say, trip relations with low impediment values.

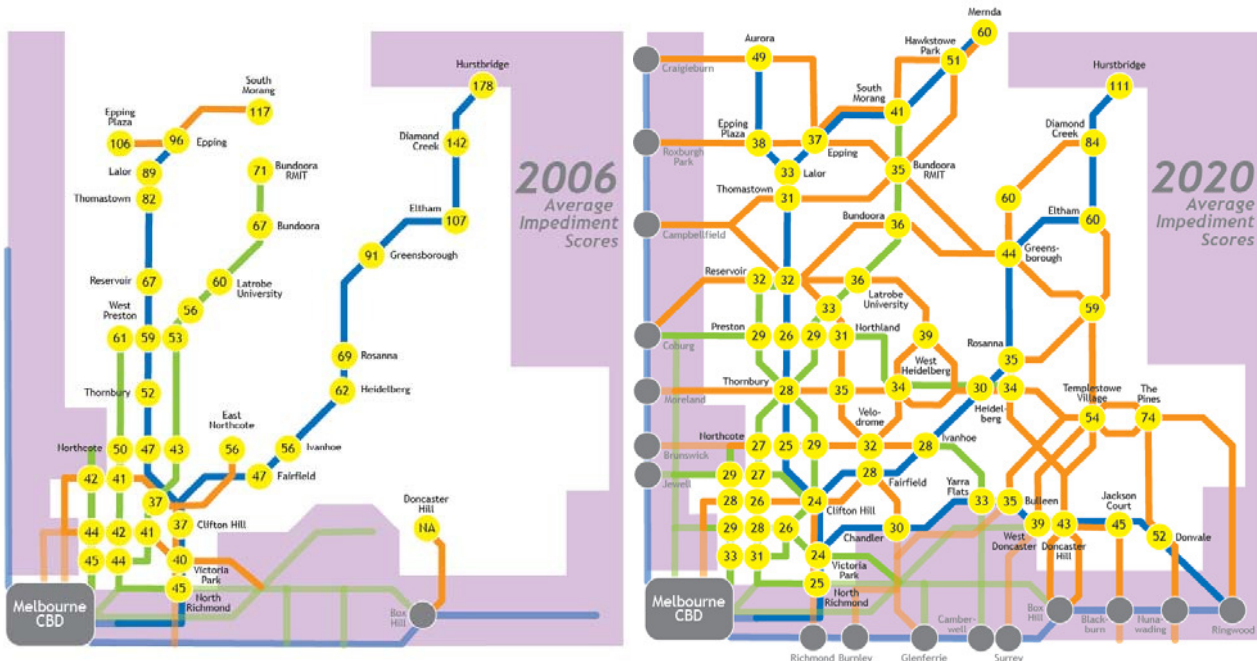
Assessed in their own right, the 2006 network in Melbourne's north-east achieves a global efficiency of 51%, while in the 2020 network, this figure drops to 46%. Thus both

networks achieve around half the efficiency of a system where a direct link exists between any two nodes (Latora and Marchiori 2002), an impressive result given that such an idealised system would probably require service levels several dozen times higher than the actual cases. However, we are still comparing apples with oranges: the far greater complexity of the 2020 network and thus its greater reliance of transfer trips to minimise impediment are not done justice by these findings. Map 5 therefore attempts a direct comparison between the absolute efficiency counts for each network and displays by what factor the efficiency specific to each node increases or decreases through the transformation of the 2006 network into the 2020 network. Using this technique, global efficiency increases three-fold, remarkably similar in magnitude to the projected increase in system ridership and required expansion of system capacity. Local efficiency increases for practically every node, with the sole exception probably due to an ‘edge effect’ (see below).



Map 5: Factors of local efficiency gain for nodes in the 2020 network over the 2006 network. Circles without figures depict nodes that do not appear in the 2006 network.

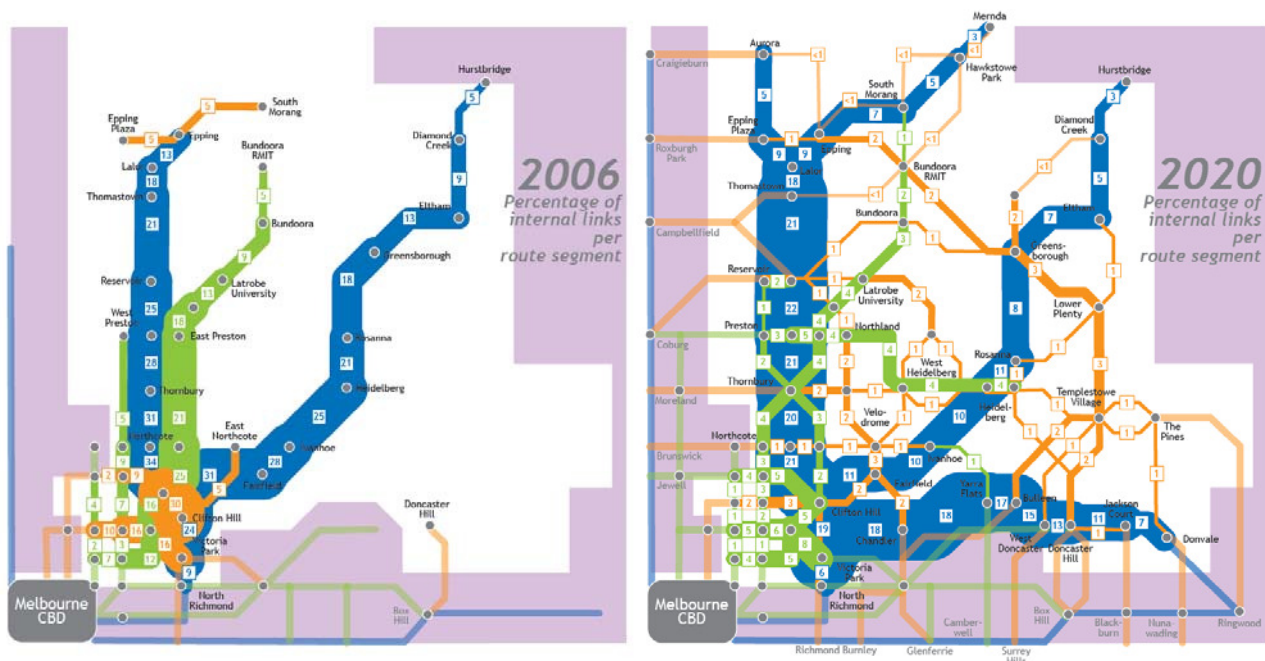
Maps 6 and 7 show a measure for closeness centrality, representing the average proxy distance or travel impediment (travel time divided by service frequency per segment) between a node and all other nodes within the network. In this example, the measure has not been inverted, so a lower value indicates greater centrality.



Maps 6, 7: Closeness centrality indexes for nodes in the existing (2006) and proposed (2020) public transport networks in Melbourne's north-east

The average impediment between any two nodes on the 2006 network has a value of 66, compared to 38 on the 2020 network. The difference shows the result of three simultaneous improvements to the network: increased frequencies of services, greater speed through the introduction of express services on train routes and prioritisation over traffic for trams and buses, and the greater connectivity of the network as a whole, reducing travel impediment on many orbital links where the travel path can follow geographical desire lines more closely. Note that both maps show a slight 'edge effect' particularly near Melbourne's CBD (which has been excluded from the study area), with average impediments rising at the nodes along radial routes closest to the CBD. This result is counter-intuitive and unlikely to be observable if the methodology was applied to Melbourne's public transport system in its entirety.

Maps 8 and 9 construct a betweenness centrality index, though in our case, the network elements in question are not nodes but edges, or to be more precise, those edges that connect immediately adjacent nodes or 'nearest neighbours' (see maps 1 and 2). This is because in expansion programs for public transport systems, the most significant constraints tend to be the capacity of route segments of the existing network, and the cost of constructing additional routes, particularly where they contain dedicated rights-of-way (Vuchic 2005). The betweenness centrality index captures the relative importance of each segment for the network as a whole by measuring the percentage of paths between all possible pairs of nodes on the network that traverse this segment. As in Maps 3 and 4, this index contains assumptions about the route passengers will opt for on trips where they have more than one choice, and lends itself to separate application for different user groups.



Maps 8, 9: Betweenness centrality indexes for the existing (2006) and proposed public (2020) transport networks in Melbourne's north-east, showing the percentage of all node-to-node paths fully within the network passing through the route segment in question.

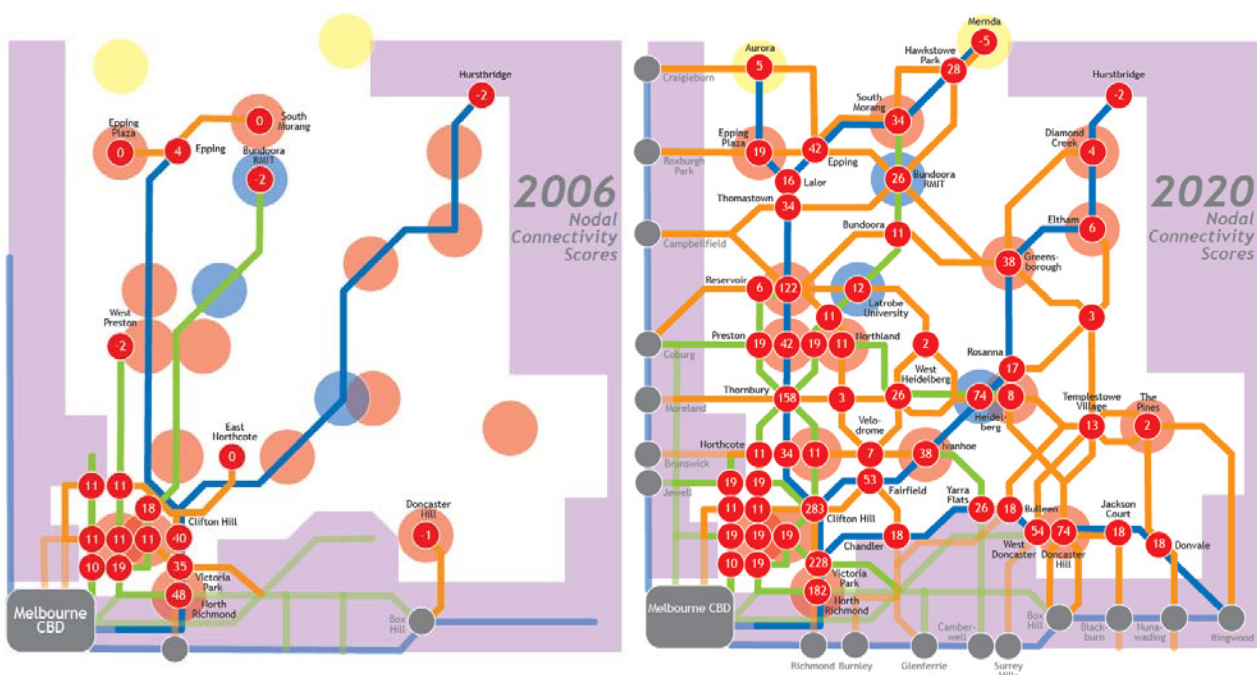
In this assessment, the betweenness values of edges crossing the boundaries of the study area have not been displayed (as these edges are defined not to attract paths between two nodes within the study area and thus only generate paths to or from themselves, at a constant percentage value inverse to the total number of nodes). This index shows clearly how a more complex and interconnected network is capable of diffusing some travel demand away from its trunk routes and thus of achieving more geographically balanced passenger flows with fewer squeeze points for capacity. In the 2020 network, the betweenness scores for radial train and tram routes vary little inward of Thomastown, Latrobe University, Rosanna and Bulleen, while in the 2006 network, there is a continuous crescendo all the way to Clifton Hill. A related insight from this index is the significance of the three proposed orbital tram routes, and the orbital bus route from Doncaster via Greensborough to Epping, for the congruence of the network, indicating a strong potential for these routes to create new connections and thus access new markets for public transport. Conversely, the bus routes proposed north of Epping and the link between Thomastown, Bundoora RMIT and Hawkstowe Park have a weaker than expected position in the network as a whole. Finally, the 2006 figures assign an extraordinary role for a relatively short segment between Clifton Hill train station and a nearby tram and bus interchange at Queens Parade. Shown on the map as a bus link, in practice this distance would likely be walked by most transferring passengers; however, the pedestrian amenity between these locations is so poor that it can safely be assumed that not many passengers will actually make a transfer there. Thus the role of Clifton Hill for network connectivity, even in the 2006 network, may well be significantly underutilised. In the study that informed these indicators, this circumstance has prompted a proposal of consolidating the two interchanges in one location (Scheurer 2006).

These three findings also help to illustrate the limitations of the betweenness centrality index as it stands now, and highlights opportunities for further refinement. In particular, the treatment of each path between a pair of nodes on the network as equal disregards

the varying potential of passenger flows between nodes, a weakness of tools for spatial accessibility analysis discussed in detail by Baradaran and Ramjerdi (2001). Some nodes have a greater number of residents, and/or a greater number or broader range of destinations than others, which obviously influences their propensity to generate trips. Further, it can be expected that passenger flows between any two nodes decline with growing distance, or impediment, of the trip: most people will not travel to a grocery store, or a hairdresser, or a childcare centre that requires significantly more time and effort to get to than a more accessible alternative. Hence, a more accurate betweenness centrality index would attempt to include a weighting factor for paths, for example by introducing correlations to the catchment size of the nodes in question, and to the travel time/service frequency (impediment score) of the journey between them.

The final index presented here is a more free-wheeling exercise, derived from a street connectivity indicator developed for an urban design-based context analysis of local areas (ISTP et al 2006). This indicator allocates a value to each point on the network that is equivalent to the number of physical connections into adjacent nodes, minus two. Thus a four-way intersection has a value of two, an intermediate point along a street has a value of zero, and a dead-end (cul-de-sac) has a value of minus one. For this index, we will depart from our earlier definition of each transfer-free connection between any two nodes as a separate edge and only consider the physical links emanating from each node (rail tracks, tram tracks or roads carrying a bus line). The resulting connectivity value has been multiplied by the number of departures per hour on each mode, and a mode-specific coefficient derived from the ratio of seat capacity per vehicle and average load factor as identified in Kenworthy and Laube (2001). In the Melbourne case, this coefficient is 1 for rail, 0.3 for tram and 0.1 for bus (meaning that a tram in Melbourne carries on average three times, and a train ten times the number of passengers a bus does). Obviously, these ratios are specific to the conditions within the public transport network under consideration, and would be expected to vary between cities with different vehicle fleets and flows of travel demand, as well as over time, as vehicles are renewed and the role of each mode within the system changes.

Map 10 and 11 display these connectivity scores for each node, and further identify the higher-order activity centres from the metropolitan strategy (DOI 2002).



Maps 10, 11: Nodal connectivity indexes for in the existing (2006) and proposed (2020) public transport networks in Melbourne's north-east, showing the location of activity centres as identified in the metropolitan strategy (red circles - principal and major activity centres, blue circles - specialised activity centres (university and hospital campuses), yellow circles - growth area activity centres)

According to this model, the average nodal connectivity score in the existing network (2006) is 11.3, based on a total of 19 network nodes (with a cumulative score of 203). In the proposed network (2020), the average score climbs to 35.5 and is based on a total of 57 network nodes (with a cumulative score of 2,024). If the index is reliable, then, we can point to an extraordinary synergy effect from the proposed network extensions: in return for an approximate growth in the level of vehicle-km across the three modes by a factor of two to three, and the construction of 42 km of additional rail routes with 13 new stations as well as 33 km of additional tram routes, a ten-fold increase in network connectivity is achieved.

This efficiency, however, is to some extent the result of a network structure that does not always conform to the hierarchy of activity centres, that is to say, the public transport nodes with the highest scores are not necessarily located in the most important suburban centres. In some cases, this is a result of pragmatism: the insertion of transfer nodes with multi-modal co-location can be achieved with a much lower outlay of resources in Thornbury and Clifton Hill than in one of the activity centres elsewhere along the same corridor and is therefore more likely to occur. In other cases, the figures highlight the untapped potential of activity centres as network nodes. For example, the activity centre of Reservoir does not currently feature as a major public transport interchange in State Government plans to improve orbital links and bus services in the study area (State of Victoria 2006), but appears to be geographically well-placed to fulfil such a function from this assessment. Lastly, the identification of suburban activity centres within the metropolitan strategy is not necessarily unambiguous and has been criticised for a certain degree of arbitrariness (Mees 2003). For example, the centres of Northland and The Pines consist of little more than conventional 'big-box' shopping centres. Their potential for urban consolidation in the spirit of the metropolitan strategy, encompassing higher-density residential development, a greater range of business and social activities and reduced dependence on the car for access, may be limited in comparison to activity centres where a broader spectrum of town centre uses, and a more pedestrian- and public transport-oriented urban environment are already present. Thus the assessment of public transport network connectivity in activity centres can also assist in steering the process of consolidation in these centres, accepting that different types of activity centres require different consolidation policies, with different outcomes and different future roles for public transport access.

Outlook: Transit-Oriented Urban Development and Development-Oriented Urban Transit

This paper has assessed the applicability of centrality and connectivity indexes developed for the analysis of urban street systems, to public transport networks. By testing a framework of Multiple Centrality Assessment developed by Porta, Crucitti and Latora (2006b) on proposals for network expansion in several public transport corridors in suburban Melbourne, it was found that these indexes can be employed in meaningful ways to inform policy choices about public transport network design, infrastructure investment and service improvements, as well as the integration of public transport

routes and stations with the urban environment, particularly activity centres. This integration of public transport and land use has received widespread attention in recent years with the promotion of transit-oriented development, most prominently in car-oriented cities investing in new or upgraded public transport systems and seeking to diversify travel patterns away from the car (Bernick and Cervero 1997, Dittmar and Ohland 2004).

The network analysis of public transport systems, as sketched in this paper, attempts to expand on the pursuit of transit-oriented development by taking a complimentary, reverse perspective: Can the growth of public transport systems in many cities be directed in ways that makes rail, trams and buses more suitable to serve the majority of mobility needs for users of transit-oriented development? In other words, can transit become more development-oriented or responsive to the changing urban context, including in scenarios where high-performance, fixed-route modes such as heavy or light rail are required for the magnitude of the transport task and/or the expectations of users?

This quest raises a number of political and practical implications, ranging from funding regimes for public transport infrastructure and operations, institutional arrangements between planning agencies, operators, the development industry and the general public, the social and cultural acceptability of, as well as economic pressures (in an era of rapidly rising fuel prices) for an increased role of public transport at the expense of the car. The indicators developed in this paper are designed as a potential tool for decision makers to view the role of public transport, and its correlation to urban growth and redevelopment, in a more systemic and holistic manner.

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