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Advance transit oriented development typology: Case study in Brisbane, Australia

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Abstract

Internationally, transit oriented development (TOD) is characterised by moderate to high density development with diverse land use patterns and well connected street networks centred around high frequency transit stops (bus and rail). Although different TOD typologies have been developed in different contexts, they are based on subjective evaluation criteria derived from the context in which they are built and typically lack a validation measure. Arguably there exist sets of TOD characteristics that perform better in certain contexts, and being able to optimise TOD effectiveness would facilitate planning and supporting policy development. This research utilizes data from census collection districts (CCDs) in Brisbane with different sets of TOD attributes measured across six objectively quantified built environmental indicators: net employment density, net residential density, land use diversity, intersection density, cul-de-sac density, and public transport accessibility. Using these measures, a Two Step Cluster Analysis was conducted to identify natural groupings of the CCDs with similar profiles, resulting in four unique TOD clusters: a) residential TODs, b) activity centre TODs c) potential TODs, and d) TOD non-suitability. The typologies are validated by estimating a multinomial logistic regression model in order to understand the mode choice behaviour of 10,013 individuals living in these areas. Results indicate that in comparison to people living in areas classified as residential TODs, people who reside in non-TOD clusters were significantly less likely to use public transport (PT) (1.4 times), and active transport (4 times) compared to the car. People living in areas classified as potential TODs were 1.3 times less likely to use PT, and 2.5 times less likely to use active transport compared to using the car. Only a little difference in mode choice behaviour was evident between people living in areas classified as residential TODs and activity centre TODs. The results suggest that: a) two types of TODs may be suitable for classification and effect mode choice in Brisbane; b) TOD typology should be developed based on their TOD profile and performance matrices; c) both bus stop and train station based TODs are suitable for development in Brisbane.

Keywords

Transit Oriented Development (TOD); TOD Typology; Advanced TOD Planning; Mode Choice Behaviour; Public Transport Accessibility Level (PTAL), Brisbane

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Research highlights

- Four types of neighbourhood developments were found to exist in Brisbane
- The types were validated based on mode choice behaviour of people
- Validation results suggest the suitability of two types of TODs in Brisbane
- Each type of TOD is associated with unique policy indicators (e.g. car-ownership)

1. Introduction

Transit oriented development (TOD) is a relatively recent neighbourhood development model which has been conceptualised as urban development with a combination of nodes (e.g. transit station) and places (e.g. neighbourhood) (Bertolini, 1999; Renne, 2009a). The place criterion has generally been characterised by: moderate to high density development that supports public transport (PT) services at the nodes; a mix of land uses (e.g. residential, commercial, recreational, and institutional) to facilitate and attract activity participation within the places; and well-connected street networks so that activities can be integrated with active transport (AT) (Cervero and Kockelman, 1997; Lin and Gau, 2006). This proximate and connected arrangement of land uses, therefore, reduces the need for motorised travel of people living within a TOD area. However, if people need to travel to access goods and services in other parts of a city (e.g. in other TODs), then they can choose fast, frequent, and well-connected PT services available at TOD nodes. As a result, a TOD is not just a transit station to catch PT services, but it is importantly a place to live, shop, recreate, and socialise. It is a human interaction point and an urban development process characterised by centralised decentralisation (Bertolini, 1999). These qualities of a TOD make PT services a logical alternative to private transport (Bertolini et al., 2009), and as a result, TODs have been identified as a key policy tool to discourage car-based travel to reduce greenhouse gas emissions and traffic congestion, thereby enhancing quality of life, social inclusion, health and well-being (Transportation Research Board, 2001).

The provision of land uses and transport services for a TOD requires long term planning both at the regional and local levels. Planning at the regional scale sets the spatial structure of TODs (e.g. hierarchical distribution of transport nodes, link, and activities), whereas local planning articulates the detailed plan and concentrates on the precise contents of land use types, densities and facilities (Bossard, 2002; Boufous et al., 2008). However, city planning rarely starts from an empty space, and existing land uses are an important determinant of future development (Atkinson-Palombo and Kuby, 2011). Therefore, a thoughtful analysis of today's built environment can ease facilitation of tomorrow's TOD. For example, the formation of overlay zoning in metropolitan Phoenix in 2000 facilitated TOD development after the opening of a light rail transit (LRT) in 2008 – an approach referred to as advanced TOD planning (Atkinson-Palombo and Kuby, 2011).

Zemp et al. (2011) argue that the identification of TOD potential relies on the performance assessment of the existing built environment. However, traditional assessment of the built environment for a TOD employs a binary approach focusing around train stations – i.e. whether a station area is suitable or not for a TOD (see, Bossard, 2002). This approach has been criticised for two reasons. First, it excludes other potential "development oriented transit" sites. Given that TODs are a function of both nodes and places, all neighbourhoods in a city possess some qualities for a potential TOD, irrespective of the availability of train services (Thomas and Deakin, 2008). Second, there is no "one-size-fits-all" approach to TOD development (Center for Transit-Oriented Development, 2010). Researchers are increasingly recognizing that TODs can take a variety of forms (Belzer and Autler, 2002); and individual TODs can serve different but complementary functions within a system (Atkinson-Palombo and Kuby, 2011). Therefore, the question is not whether a site is suitable or not, but rather for what type of TODs (if any) or not. Belzer and Autler (2002, p.30) argue that "it may be possible to develop a general typology of places to account for a variety of different scales (large city, small city, town), locations in the metropolitan area (central city, peripheral city, commuter town), transit type (commuter rail, frequent light rail), and other key attributes".

Few studies to date have empirically identified TOD typology in a quantitative way, despite the many associated benefits (as discussed in Section 2.1). Most of the previous classifications are based on subjective evaluation criteria of the context in which they are built (e.g. city centre, activity centre, specialist, urban, suburban, neighbourhood, commuter town centre, residential) (Calthorpe, 1993; Dittmar and Poticha, 2004; Queensland Government, 2009). These types of classifications provide for specialist functions for TODs, yet fail to take into account the built environmental characteristics that surround the TOD. As such, this generalisation of TOD functions based on subjective judgment may not be an accurate guide to the design and building of TODs (see for example, Schlossberg and Brown, 2004). We argue that a careful selection of built environmental factors and their standards for different areas in a city provide an important context for TOD development to supplement and inform a more generalised approach to a TOD typology.

The need for further research to develop typologies for TODs has also been highlighted in the literature (Jenks, 2005). Unlike train station based TOD typologies of previous studies, research has identified that TODs are equally effective in cases of bus and train services, and in particular in cities where bus rapid transit (BRT) systems operate (Kamruzzaman et al., 2013). In addition, previous studies rarely validate their generated typologies using performance indicators. Belzer and Autler (2002) have mentioned that despite having good place and node characteristics, many TODs don't function well (when measured by performance). As a result, the typology needs to be verified based on TOD outcomes (e.g. mobility choices, transit ridership, auto ownership, transportation costs, vehicle miles travelled (VMT), journey time to work, shop within the same neighbourhood) (Center for Transit-Oriented Development, 2010; Renne, 2009b). Although TOD typologies have traditionally been derived from existing built environment indicators, TODs are actually planned well in advance (for example, the case in Phoenix) (Atkinson-Palombo and Kuby, 2011). Different types of TODs should be planned as a part of the strategic future of a city, and incorporated into the long term vision. As a result, TOD typology planning cannot only be based on environmental indices because the future environment of an area is not known for planning; but should be based on other policy indicators as well--indicators that are readily available and can be projected to plan for future TOD typologies.

Based on the above discussion, the objective of this research is threefold: first, to develop a typology for existing neighbourhoods in order to understand the potential for different types of TODs in Brisbane, Australia; second, to validate the typologies with performance indicators; and third, to support the planning of advanced TOD typologies based on readily available policy indicators. Section 2 reviews the literature on the typology of TODs, aiming to develop a robust method for the development of typologies of neighbourhoods for TOD potential using Brisbane as a case study. The data and method used to derive and validate the typologies are discussed in Section 3. Results of this research are presented in Section 4, and Section 5 concludes, with implications for urban policy.

2. Literature review

2.1 TOD typology and their benefits

Developing a typology is a way to group together areas that have a common set of characteristics. Therefore, a TOD typology contains several combinations of node and place types, and all of the areas within one combination have some elements in common (Center for Transit-Oriented Development, 2010). Categorisation of TODs into typologies enhances their planning, design, and operational activities in many ways. For example, the similarities within a type allow policy makers and stakeholders to create common sets of strategies to plan or to improve performance (e.g. gentrification might be an issue in urban but not suburban TODs) (Center for Transit-Oriented Development, 2010; Jenks, 2005; Reusser et al., 2008). Classifications also support the identification of general development potentials and necessary future adaptations of whole classes and within classes. Each TOD type has a desired density, land-use mix, connectivity, and transit system function, and therefore, the typology supports the design of an optimal TOD at a given site (Zemp et al., 2011). As a result, the typology helps answer questions such as “what mixtures of uses will optimize effective mixed-use development and support location efficiency under specific conditions (for example, in areas with different levels of density)?” or “what densities and level of transit service are necessary?” (Belzer and Autler, 2002). The answers to such questions are important for effective TOD planning and design. For example, increased density has the potential to increase ridership but at the same time degrades social equity and quality of living, and therefore, a balance between these factors are important for a successful TOD (Lin and Gau, 2006). Classification also reduces management complexity for infrastructure companies by enabling the application of standards in operations and development, and securing consistency of actions across large portfolios and geographic regions. Similarly, it enables the identification of sites and actors with comparable challenges or experiences for spatial planning. Classification enables comparisons and performance assessments within the station classes, identifying successful benchmarks or highlighting needs for action (Zemp et al., 2011). Without a benchmark there will be no way to judge the quality of TODs (Belzer and Autler, 2002; Center for Transit-Oriented Development, 2010).

2.2 Method of developing TOD typology

Few TOD typologies exist in the literature. Bertolini (1999) developed a conceptual framework of a node-place typology of TOD based on train stations in Amsterdam and Utrecht in the Netherlands (Figure 1). This study developed a node index for each station using the connectivity (e.g. number of directions served and number of stations within 45 minutes of travel), frequency, and diversity of transport services (e.g. train, bus, tram). The work also fashioned a place index based on walkable distance from the stations (700 meters). The place index combines the number of residents in the area, the number of workers per each of four economic clusters (retail/hotel and catering, education/health/culture, administration and services, industry and distribution), and the degree of land use diversity. Using the node and place indices, Bertolini (1999) identified a four category typology of train stations: accessibility, stress (e.g. subject to conflict between multiple, extensive claims on a limited space), dependency, and unsustainable places (un-sustained because either node or place is stronger) (Figure 1).

More recently, Reusser et al. (2008) operationalised the node-place framework in classifying 1684 train stations in Switzerland. A total of eleven indicators were used in this study. Seven of these indicators were used to derive the node index including directions (e.g. number of end stations reachable), daily frequency, number of stations reachable within 20 minutes by train, number of end stations reachable by bus and tram, frequency of bus and tram, distance from the closest motorway access, and bike path length within 2km. The remaining four indicators were used to derive the place index: population (number of residents); full time jobs in secondary and tertiary sectors; and land use diversity (or the degree of functional mix) within the places (700 metres from the station). The node and place indicators were standardised (from 0 to 1) and summarised to form node and place indices respectively. The node and place indices were then plotted to identify whether the stations follow the node-place typology. In addition, unlike the indicators used in the node-place typology, this work identified relevant indicators based on expert questionnaires and repertory grid interviews which yielded six additional indicators (for node: number of passengers per day, ratio of the number of long distance and regional services, presence of staff; and for place: full time jobs in education, distance from town centre, and the presence of grocery, restaurants, pharmacy and florist). A two step cluster analysis was then conducted using the 17 indicators in order to classify the stations which resulted in a five cluster solution: smallest station, small stations, mid-size stations in populated areas, mid-size unstaffed stations, and large to very large stations. These classified stations were also plotted in the node-place typology. The study reported that Swiss railway stations exhibited a general balance between node and place indices (i.e. positioned close to the diagonal in Figure 1). However, the author reported that the enhanced model achieved a better fit than the node-place model in a Swiss context.

In a subsequent Swiss study, Zemp et al. (2011) classified 1700 railway stations using cluster analysis of 10 contextual indicators which resulted in a 7 cluster solution: central stations, large connectors, medium commuter feeders, small commuter feeders, tiny touristy stations, isolated tourism nodes, and remote destinations. This study also conducted a principal component analysis using the indicators which resulted in two components: ‘density’ (of transport and land use), and ‘use’ (of the station). The density component was calculated by standardising and summarising 6 related indicators e.g. jobs (number of jobs within a 700 metre radius), population (number of residents with a 700 metre radius), reachability (number of reachable railway stations in 20 minutes), intercity trains (number of departing intercity trains), regional trains (number of departing regional trains), buses (number of departing buses). Similarly, the use component was calculated using two indicators e.g. frequency distribution (passenger frequencies at weekends compared to weekdays), and tourism (arriving tourists per 1000 residents of the municipality). The density component was further divided into two categories to develop a node-place typology of the stations. Node index was derived by summing and standardising (Z-score) the reachability, intercity trains, regional trains, and buses indicators whereas the place index was derived based on the jobs and population indicators. The research then investigated the correlations between the clusters and the density-use typology and between the clusters and the node-place typology. Based on findings, the study claimed that the density-use typology is a methodological improvement because the typology was able to differentiate both density (i.e. traditional node and place) and use whereas the clusters with smaller stations are not well differentiated within the node-place model but are considerably differentiated in the density-use mode.

Schlossberg and Brown (2004) classified 11 TODs in Portland in terms of their pedestrian friendliness using 6 built environmental indicators at two different scales (e.g. 5 minutes and 10 minutes walk from the stations). The indicators are: quantity of accessible paths (e.g. miles of minor roads); quantity of impedance paths (e.g. miles of arterial roads), pedestrian catchments areas (PCA) or ped-shed (e.g. ratio of service area generated based on network distance and Euclidian distance from the transit stops); impedance PCA (e.g. similar to that PCA but the service area was generated by excluding the high volume, high speed corridor); intersection density, and density of dead ends. Each TOD was classified as good or poor on each indicator. If a particular TOD was ranked among the top or bottom three TODs for a given indicator, it received a positive or a negative score respectively. Total positive and negative scores for each TOD were then visualised as a prelude to their classification. The work found that two transit stops ranked highly, and three transit stops ranked poorly.

Unlike the consideration of only built environmental indicators in the previously described studies, the Center for Transit-Oriented Development (2010) has taken into account both a place indicator (e.g. use-mix) and a performance indicator (e.g. household VMT) in order to develop TOD typologies in the USA. The use-mix indicator was calculated as the percentage of workers within half a mile radius of train stations relative to the overall count of residents and workers. The derived use-mix indicator was classified into residential, balanced, and employment categories (Figure 2). The household VMT indicator was based on a regression analysis technique that used nine independent variables including household income, household size, commuters per household, journey to work time, household density, block size, transit access, and job access. The derived VMT was subsequently classified into five categories to represent different levels of performance of the transit zones (Figure 2). Subsequently, the performance and place indicators were combined to form a 15 category typology of TODs. The framework has been applied to approximately 3,760 existing transit station areas in 39 regions across the USA. Using additional performance based normative matrices (e.g. journey time to work, auto ownership), the work reported that overall, most transit stations perform better than or at the national average, outperforming the typical non-transit-oriented places. Variations, however, exist between low VMT and high VMT transit stations as well as different place categories (e.g. low VMT places are associated with low rates of auto ownership).

Atkinson-Palombo and Kuby (2011) developed a TOD typology and applied it for the evaluation of spatial distribution of overlay zoning policy around 27 LRT stations areas in Metropolitan Phoenix. The station areas were defined as those land parcels within a 1/2-mile walking distance of LRT stations using the street network. The work conducted a factor analysis of 13 indicators in order to reduce the multicollinearity in the data which resulted in a 5 factor solution. The indicators were related to the characteristics of node (e.g. whether the station has a park-and-ride facility, or an airport based station, or a terminal), people (e.g. number of jobs, population, household income, % of owner occupied housing units, and % of people with bachelor degree), and places (e.g. parcels with residential, vacant, TOD-compatible, TOD-incompatible categories). The resultant factors were then grouped using the hierarchical cluster analysis technique which resulted in a five cluster solution: transportation nodes, high population rental neighbourhoods, areas of urban poverty, employment and amenity centres, and middle-income mixed use. Using ANOVA, this study showed that land parcels subjected to overlay zonings were disproportionately distributed across the classes (e.g. most in areas of urban poverty and least in transportation nodes).

Three observations are emergent from the prior reviews. First, built environmental variations exist even within the well established TODs (e.g. in Portland) which suggests that TODs can, and should be classified according to built environment indicators. Second, despite the arguments that the conceptualisation of TOD typologies would benefit a number of policy areas, including design, planning, and operations, the development and application of TOD typologies are limited. A few studies have developed typologies, but they have not been applied to test specific TOD policies; whereas other studies have monitored TOD performances and the spatial equity of policies. Therefore, a considerable potential exists to apply and test TOD typologies in other policy contexts. Third, the studies that have developed typologies have not been verified using any performance indicators. For example, Schlossberg and Brown (2004) classified TODs based on pedestrian friendliness. However, the work has not been verified to determine if the level of friendliness is associated with the level of actual walking. In contrast, the Center for Transit-Oriented Development (2010) used performance as an indicator for the development of typologies. We argue that the performances are outcomes of TOD types, which are also not readily available, and therefore, they have little relevance for use as input for the classification.

3. Data and methods

3.1 Study area

This research develops typologies of neighbourhoods in Brisbane (Queensland) in order to assess their potential for different types of TODs. One of the long term strategic visions for the Queensland Government (2008) is to build Queensland as a strong, green, smart, and healthy state by reducing congestion and by cutting one-third of its current carbon emissions. The South East Queensland (SEQ) Regional Plan 2009-2031 provides specific policy guidelines to meet these stated goals (Queensland Government, 2009). One of the policy guidelines is to facilitate development in a more “compact way” through locating self-contained activities in well defined nodes along existing and planned transport corridors. The Plan identifies these nodes and activity centres as prime candidates for TODs. The Plan also outlines 21 key principles to be applied for site selection and construction of TODs in SEQ (Table 1). However, not all of these principles are suitable for the identification / development of TOD typologies from the perspective of the built environment (e.g. safety, social diversity, continuity). Based on the TOD typology literature as discussed earlier, and based on Table 1, the following principles are important in determining a TOD typology in this context: availability and connectivity (intermodal) of public transport services; land use mix (diversity); residential density; land use intensity for employment; and pedestrian connectivity.

The Queensland Government (2010a) has focused on TODs as a means to influence travel behaviour to shift from car-based travel to more sustainable modes of transport. To quantify the extent of needed shifts in travel, in 2006 a 'typical' individual in SEQ made 2.5 walk/bicycle trips, 1.5 trips using public transport (e.g. bus, train, ferry), and 21 trips using the car in an average week. In contrast, the targets in SEQ for 2031 are to: a) double the share of active transport trips (such as walking and cycling) from 10% to 20% of all trips; b) double the share of public transport from 7% to 14% of all trips, and c) reduce the share of trips taken by private motor vehicles from 83% to 66%. In order to achieve these travel behaviour targets through TODs and other means, the Queensland Government (2010a) has committed to spend $227 billion on a variety of priority areas in transport sector between 2011 and 2031.

Guided by the above policy documents, a comprehensive approach has been taken to facilitate the implementation of TODs within Brisbane (Brisbane City Council, 2013). The Queensland Government has started working with Brisbane City Council in order to plan and implement a number of TODs within the Council's jurisdiction e.g. Yeerongpilly, Coorparoo, Bowen Hills, Northshore, Hamilton, Fitzgibbon and Woolloongabba (Queensland Government, 2010a). However, the Queensland Government (2010b) also recognised that TODs are not "one size fits all". Based on a review of good practices around the world, the government identified that the following types of TODs can be developed in the region: city centre, activity centre, specialist activity centre, urban, suburban, and neighbourhood TOD. A design guideline has also been provided for the construction of these TODs as outlined in Table 2. More specifically, the design parameters vary from the centre to the periphery in three levels: (i) core (200m), (ii) primary walking catchments (200-400m), and (iii) secondary walking catchments (400-800m). Given the policy attention that TODs in general, and the typology of TODs in particular have received in Brisbane and Southeast Queensland, this research is particularly timely and relevant to identify areas in Brisbane with potential for different types of TODs so that these neighbourhoods can be nurtured and growth can be directed to meet the targets for different typologies. More importantly, verifications are also needed with respect to the extent to which the existing built environmental conditions are supportive of the adopted typologies. TOD typologies are very much context dependent (Reusser et al., 2008; Sung and Oh, 2011), and therefore, the best practices from other places might not be transferable, or the best option for SEQ.

3.2 Data

Three types of data were used in this research: a) spatial datasets to derive built environmental indicators and subsequently to derive typology of neighbourhoods in Brisbane; b) survey questionnaire data to use as performance indicators to validate the typologies; and c) the 2011 census data to support the advanced TOD typology planning based on readily available datasets. Based on the literature and the principles identified for TODs in SEQ as shown in Table 1, six built environmental indicators were included in the analysis: public transport accessibility level (PTAL), net employment density, net residential density, land use diversity, intersection density, and cul-de-sac density. Therefore, the PTAL represents the quality of nodes and the remaining five indicators represent the quality of places. Although both intersection density and cul-de-sac density represent network connectivity levels of an area, the former is positively associated whereas the latter is negatively associated with the walkability of TODs (Cervero and Gorham, 1995; Stangl and Guinn, 2011). Spatial analyses were conducted to derive the built environmental indicators using the following spatial/non-spatial datasets:

- physical road network data downloaded from the Queensland Government Information Services website (http://dds.information.qld.gov.au/dds/);
- cadastral parcels with land use classification data collected from the Brisbane City Council;
- locations of public transport stops downloaded from the Australian Government Open Database website (http://data.gov.au/);
- published public transport timetables downloaded from the Tranlink website (http://translink.com.au/); and
- the place of work data (2011 census data) downloaded from the website of the Office of Economic and Statistical Research, Queensland Government (http://www.oesr.qld.gov.au/).

The validity of the derived typologies was examined based on the mode choice behaviour of people living in these areas. Individuals' mode choice data were collected as a part of the HABITAT (**H**ow **A**reas in **B**risbane **I**nfluence Heal**T**h and **A**c**T**ivity) panel survey (see, Burton et al., 2009 for more infomation).

Note that unlike previous research studies that predominantly focused on transit stations to define neighbourhood boundary (e.g. 700m from train stations), this research used census collection districts (CCDs) as the unit of analysis in order to include potential "development oriented transit" sites into the analysis. CCDs were the smallest statistical unit used in Australia as at the 2006 national census. This research initially derived data from 1740 CCDs in Brisbane. Consequentially, six CCDs were excluded from analysis due to a lack of residential / employment opportunities located within these CCDs. A boundary of 800m was used in this study, despite the lack of an agreed boundary for TOD precincts in the literature. As discussed in Section 2.2, a number of authors from Europe used a 700m boundary from transit stops (Bertolini, 1999; Reusser et al., 2008; Zemp et al., 2011); whereas most American studies used a range between ¼ mile (400m) and ½ mile (800m) radius from transit stations (Atkinson-Palombo and Kuby, 2011; Center for Transit-Oriented Development, 2010; Schlossberg and Brown, 2004). Some Canadian studies suggest a range between 400m and 600m from transit stop (The City of Calgary, 2004). Given that the precinct boundary is very much context dependent, this research used 800m (10 minutes walking distance) as recommended in the Queensland policy documents in determining the precinct boundary (see, Table 1 and Section 3.1). As a result, an 800m network distance buffer was generated from the centroid of each CCD based on walkable[1] road network in Brisbane in order to derive the built environmental indicators for each CCD. The average sizes of the CCDs and the buffers were found to be 56 hectares and 71 hectares respectively which indicate that most of the CCDs were located within the 800m buffer. Further analysis shows that only 15% of CCDs had an area larger than the size of their buffer. However, a larger portion of these CCDs were located within the buffer, and as a result, it was expected that the essential built characteristics of these CCDs were captured. Note that the buffer method was not used for the calculation of the net employment density indicator rather this was calculated based on CCD boundary. This is due to the fact that unlike individual work location data, the places of work data were available in an aggregated format.

The TOD typologies were developed based on existing built environmental indicators (e.g. density, diversity). One of the objectives of the typology development was to understand which types of TODs are the most efficient in Brisbane (e.g. TOD type A, B, and C). However, the typology does not indicate which areas in Brisbane (e.g. neighbourhood X, Y, and Z) are suitable for TODs in the future, since the future built environment of an area is unknown, and therefore a future typology cannot be derived. Rather, the built environment of an area needs to be guided / developed according to their potential typology – which requires advanced TOD typology planning. As a result it is important to understand which type of TOD is associated with what type of policy indicators (e.g. land value) – not the built environmental indicators. These indicators should be readily available (e.g. the census data in this case) and can also be projected.

A range of policy indicators were derived from the 2011 census (e.g. gender, age, household income, car ownership, rent, mortgage, household size etc). These are readily available and were downloaded from the website of the Australian Bureau of Statistics (http://www.abs.gov.au/). Note that the downloaded indicators were related to the Statistical Area Level 1 (a new geographic classification system that was introduced in the 2011 census) which were converted into the corresponding CCDs (see, http://www.abs.gov.au/websitedbs/d3310114.nsf/home/correspondences). Only 1479 CCDs out of 1740 in Brisbane were matched correctly using this method. The datasets were used to associate relevant policy indicators for advanced TOD typology planning.

3.3 Methods

3.3.1 Derivation of public transport accessibility levels (PTALs)

The literature indicates that traditionally the node index has been developed by combining a few common indicators such as the frequency of transport services, their connectivity level (direction), and

[1] Non-walkable roads such as the motorway, highway, ferry, ramp etc. were excluded from the analysis.

diversity of transport services (e.g. bus, train). These three indicators were taken into account in a form of PTAL to measure accessibility of transport services for each CCD – a method well documented in the literature and applied (see, Kamruzzaman et al., 2013; Transport for London, 2010; Wu and Hine, 2003). Briefly, bus stops and train stations that were located within the buffer of each CCD were identified. Access (walk) time to these stops/stations was considered as 10 minutes (maximum walking distance 800m with average walking speed 4.8km/h). Unique transport routes that pass through each of these stops/stations were then identified. Where a route occurs twice or more - because it serves more than one stop within the network buffer – only one stop was considered for that route. Morning peak hour frequency on a typical weekday (Monday) of the identified services was calculated using published timetable data (number of services per hour). This estimate was derived by halving the total number of services between 7:00am and 9:00am. Since a public transport service runs in two directions – inbound and outbound in the case of Brisbane, only the inbound direction was considered because the highest frequency was found in this direction in the morning. For each route, schedule waiting time (SWT) was calculated using the following formula:

$$SWT = 0.5 \times (frequency / 60).$$

A reliability factor was then added to SWT (2 minutes for buses and 0.75 minutes for rail services) in order to derive average waiting time. Average waiting time and access time were summed to calculate total access time. The total access time was then converted to an Equivalent Doorstep Frequency (EDF) (EDF = 30/total access time). This conversion treats access time as a notional Average Waiting Time as though the route was available at the "doorstep" (Transport for London, 2010). Routes often travel in parallel for some distance so the range and frequency of destinations are likely to be less than that suggested by the number of routes included in the calculation. In addition, travellers often are required to change routes in order to reach a desired destination, which can add significant delays to the journey. As a result, as indicated in the literature, the EDF values were halved for all but the most frequent route for each transport mode, which compensates for the above issues. The resultant EDF values were then summed for each mode which generated mode specific PTAL – in this case bus and train. The mode specific PTALs were subsequently summed to get an overall public transport accessibility level (PTAL) for each CCD (Figure 3). Therefore, the PTAL method takes into account the spatial accessibility of PT services (whether PT services are located within the 800m buffer or not), frequency of services, connectivity to opportunities (different routes), and reliability of services across different modes.

Given that the size of TOD precincts has been contested in the literature, the PTAL scores were also derived using a 600m network distance buffer for each CCD. The paired sample *t* test results show that the average PTAL was significantly higher when the 800m buffer was used (5.67) than that of the 600m buffer (4.28). This is expected because more stops and routes were located within the 800m buffer when compared with the 600m buffer. Despite these differences, a significant correlation was found to exist in the PTALs associated with the two spatial scales which signify the representativeness of either scale in this context (Figure 4). However, the 800m buffer was operationalised in this research given its policy emphasis.

3.3.2 Derivation of place indicators

The derived place indicators neatly fall into the '3Ds' of Cervero and Kockelman (1997): a) density (e.g. net employment density, net residential density); b) diversity (e.g. land use mix/diversity); and c) design (e.g. network connectivity – intersection density, cul-de-sac density). Net employment density was calculated based on the number of jobs located within a unit area of employment generating land uses (e.g. commercial, industrial) located within a CCD (e.g. number of jobs/hectares) (Figure 5a). As a result, land uses that are not suitable for employment (e.g. residential, water bodies) were excluded from this calculation. Net residential density was measured using the number of residential units located within a unit area of residential zoned land (e.g. unit/hectares) within the buffer of each CCD (Figure 5b) (Frank et al., 2005). Land use diversity was measured using the following formula of Simpson's diversity index in which the higher value represents more diversity of land uses (value ranges from 0 to 1) (Kamruzzaman and Hine, 2013; Simpson, 1949):

$$\text{Land use diversity} = 1 - \Sigma(a \;/ A)^2 ,$$

where *a* is the total area of a specific land use category (e.g. residential) within the buffer of a CCD, and A is the total area of all land use categories within the buffer. Five land use classes were considered for the analysis: residential, commercial, institutional, recreational, and industrial. Figure 5c outlines the land use diversity levels for different CCDs in Brisbane. Intersection density was measured based on the number of 3 or more way intersections located within a unit area of the buffer for each CCD (e.g. number/hectares), whereas cul-de-sac density was calculated using the number of dead ends located within a unit area of the buffer (e.g. number/hectares) (Figure 5d).

3.3.3 Derivation of neighbourhood typologies

Cluster analysis was identified to be a preferred method for generation of TOD typologies in previous studies (Reusser et al., 2008; Zemp et al., 2011). As a result, the TwoStep Cluster analysis was conducted to identify natural groupings of the neighbourhood in terms of their TOD profiles. However, prior to conducting the cluster analysis, a correlation analysis was conducted amongst the six built environmental variables (Table 3). The analysis shows that although most relationships appeared in expected directions, some atypical relationships also existed. For example, although a negative correlation between intersection density and cul-de-sac density was expected, analysis revealed a weak positive correlation (0.089). This finding suggests that for some neighbourhoods, both indicators are equally present, and exclusion of any of these indicators misrepresents the neighbourhood as a potential TOD. As a result, all six indicators were retained for further analysis. To make this measure less sensitive to outliers, the 5% highest and lowest scores were set equal to the 95th and 5th percentile point respectively based on the literature (De Vos et al., 2012; Schwanen and Mokhtarian, 2004).

3.3.4 Validation of the typologies

Renne (2009b) developed a six dimensional framework to monitor and evaluate TOD outcomes including: 1) travel behaviour, 2) the economy, 3) the natural environment, 4) the built environment, 5) the social environment, and 6) the policy context. This research used the first dimension to validate a

TOD typology. Belzer and Autler (2002) have highlighted that the locational efficiency of TODs should be reflected in mobility choices of people. As a result, it was hypothesized that if an area is typified as ‘good’ for a potential TOD, people living in that area would use more PT and AT than automobiles. For this reason, mode choice behaviour data were needed to validate the generated typologies. This research used mode choice data collected as a part of the HABITAT survey from adults (aged between 40 and 70 years) living in 200 CCDs from Brisbane. The HABITAT study was purposely designed to examine changes in the health and related behaviours of a “baby boomer” cohort (born between 1946 and 1965), and as a result, younger age individuals were not included.

The 200 CCDs were randomly selected from the 1740 CCDs in Brisbane (about 11.5%). Although the HABITAT panel survey collected data in three phases (2007, 2009, and 2011) from 11036, 7866, and 6901 adults, only the 2007 version of the data were utilised in this paper in order to maintain a higher sample size. Respondents were asked to indicate ‘on most weekdays (Monday to Friday), which type of transport do you mainly use to get to and from places?’ Respondents were given the following five options to choose from: a) public transport; b) car or motorcycle; c) walk; d) bicycle; and e) other. Respondents were also instructed to select only one option from the above. The walk and bicycle modes were combined together to represent AT. As a result, the mode choice behaviour became a four-category dependent variable in this research. It was possible to identify whether the differences in mode choice behaviour are significant between different types of neighbourhood using non-parametric statistical tests for the categorical dependent variable. However, analysis based on just one factor (typology of CCDs in this case) may conceal influences arising from other explanatory factors. In order to overcome these weaknesses, multinomial logistic regression analysis was conducted in Stata (version 11), controlling for other confounding effects in the model.

Numerous research studies have identified that residential-self selection is a significant confounding factor that often creates a spurious relationship between built environmental factors (e.g. TODs) and travel behaviour (e.g. mode choice), both in this context (Kamruzzaman et al., 2013), and elsewhere (Handy et al., 2006b; Handy and Clifton, 2001; Pinjari et al., 2007; Schwanen and Mokhtarian, 2005). It is defined as an individual’s inclination to live in a particular neighbourhood based on their ability, attitudes, and preferences (Guo and Chen, 2007; Pinjari et al., 2007). Research has identified two sources of residential self-selection: a) socio-demographics, and b) attitude and preference (Mokhtarian and Cao, 2008). For example, non-car owning households may choose to live in TODs in order to use PT services. Thus, TODs do not influence the use of PT in this case but it merely facilitates the use. Rather it is the constraint of an individual’s lack of access to a motor vehicle which has a more direct influence on the choice. Similarly, despite owning a car, individuals with a positive attitude and perception towards PT may intentionally choose to live in a TOD. As a result, TODs merely facilitate their acting on their preferences and the observed behavioural differences for these individuals are largely due to differences in travel attitudes, not urban form differences—although the effect will be captured by urban form variables in the absence of variables reflecting residential self-selection in a model.

In order to account for the first sources of the self-selection effect, a number of socio-demographic factors were included in the multinomial logistic regression model including age, gender, car-availability, level of education, household size, health status, and living arrangements. These variables have a significant impact on mode choice behaviour in this context (Kamruzzaman et al., 2013). These were collected as a part of the HABITAT survey. In addition, to account for the second sources of residential self-selection effect, data related to respondents' living preferences were also collected as a part of the survey. Respondents were asked to indicate the importance of 14 items in their decision to move into their current address on a 5-point Likert scale (1 – not at all important to 5 – very important). Based on the scores of their responses, factor analysis was conducted in order to extract the fundamental dimensions spanned by these 14 items using the principle axis factoring with oblique rotation method. Similar approaches have been used in previous studies in order to control for self-selection effect both in Australia (Giles-Corti et al., 2013); and elsewhere (Cao et al., 2007; Handy et al., 2005; Handy et al., 2006a). An initial result showed that 4 out of the 14 items had low communalities which were excluded and the factor analysis was rerun. The analyses resulted in a 4 factor solution as shown in Table 4. The extracted factors suggest that respondents choose a particular neighbourhood because of their: a) accessibility and mobility options; b) natural environment; c) child centric facilities; and d) ease of access to work and city. The scores associated with these factors were included in the model in order to control for self-selection. Despite the initial sample sizes of 11036 individuals, the analytical sample reduced to 10013 individuals after excluding cases with missing value(s).

3.3.5 Associating policy indicators for advanced TOD typology planning

The collected census indicators were continuous in nature, whereas the cluster analysis resulted in discrete TOD typologies. As a result, a multinomial logistic regression analysis was conducted in Stata to investigate whether the indicators vary significantly between different TOD types.

4. Results

4.1 Typology of TODs in Brisbane

The cluster analysis resulted in four unique clusters (Figure 6). The cluster quality chart indicates that the overall model quality is in the "Fair" range. Net employment density was found to have greater influence in forming the clusters followed by net residential density, and PTALs. Based on the mean contributions of different indicators as shown in Figure 6, the four clusters can be interpreted as:

- **Cluster 4 - Neighbourhoods featuring the quality of an existing residential TOD:** 257 CCDs (15%) in Brisbane were identified as having the quality of a residential TOD. The average net residential density of this cluster was 35 units per hectare. As a result, they met the minimum residential density criteria for almost all types of TODs as suggested in the Queensland Practitioners' Guide (see, Table 1 and 2). However, note that a residential density of 35 units / hectare is far below the density reported for TODs in Seoul (Sung and Oh, 2011), but similar to those reported in Santa Clara, CA or in Puget Sound, WA (Queensland Government, 2010b). The average PTAL score of the neighbourhoods in this cluster was 8.72, which is the highest amongst all the clusters. Note again that a 8.72 PTAL score is not very high when compared to PTALs in London (see, Transport for London, 2010), but a typical score for smaller cities like Belfast (Wu and Hine, 2003). The findings clearly support the well-established view reported in the literature that TODs are context sensitive (Bailey et al., 2007; Loo et al., 2010). The cluster also has a modest diversity level with a mean diversity score of 0.55. This finding suggests that, on average, more than two types of land uses are present in each neighbourhood within the cluster. As a result, few employment opportunities are also located within these neighbourhoods (e.g. 8 jobs/hectare). The cluster also has the highest intersection density level. Figure 6 shows that almost a three-way (or more) intersection is present within a hectare of land in the neighbourhoods in addition to the negligible amount of cul-de-sacs (0.13 per hectare). However, at this stage, it is not known whether the above TOD design factors are efficient enough to influence behavioural outcome in this context – these are discussed in the following sub-section.

- **Cluster 2 - Neighbourhoods featuring the quality of an existing activity centre TOD:** 171 CCDs (10%) in Brisbane were identified as having the quality of an activity centre TOD. The average net employment density of this cluster was 65 jobs per hectare. Although the number of jobs required for the successful operationalisation of an activity centre TOD has not been specified in the context of Queensland, Frank and Pivo (1994) noted that a significant modal shifts from single occupancy vehicle use to transit use and walking occur with between 20 and 75 employees per acre (i.e. between 50 and 172 employees per hectares) in the USA. As a result, the 65 jobs per hectare can be said to have met the number of jobs required for an activity centre type TOD. In addition, based on research findings from cities around the world, Newman and Kenworthy (2006) reported that minimum threshold of 35 residents and jobs per hectare is needed to create an environment that supports a vibrant mix of activities and usage of public transport and walking over driving. This threshold was exceeded for the neighbourhoods in this cluster (e.g. 65 jobs + 33 residential units = 89). Note also that these neighbourhoods nearly met the minimum population density criteria for this type of TOD in Queensland (Table 2) although further infill or high rise developments are expected within the cluster. In addition, as suggested in Tables 1 and 2, these neighbourhoods have the highest mix of land uses (0.57). Similar to residential TODs (Cluster 4), these neighbourhoods also possess good quality public transport services (PTAL: 7.62), with well-connected road networks. Therefore, it is critical to understand which types of TODs in Brisbane have a greater potential to influence travel behaviour: i.e. residential or activity centre? This is discussed in the following sub-section.

- **Cluster 3 - Neighbourhoods featuring the quality of potential TODs:** A larger group of CCDs in Brisbane have the potential to develop as a TOD. A total of 809 (more than 46%) CCDs fall into this group. A significant effort is needed to transform these CCDs into full fledged TODs. For example, on average these neighbourhoods have 18 dwelling units per hectare. As a result, a 50% increase in design density would meet the required density criteria for suburban or neighbourhood type of TODs in Queensland. Currently, these CCDs have a mean PTAL score of 3.84 which is almost half of the PTALs for cluster 4 or Cluster 2. This finding suggests that a twofold improvement in public transport services is necessary in order to transform these neighbourhoods into a full-fledged TODs like cluster 4. The best aspect of these neighbourhoods is that transit services exist within the proximity of these CCDs – therefore, only quality needs to be improved for these services (e.g. frequency). A twofold increase in employment is also necessary to develop these CCDs into a Cluster 4. Cluster 3 places have better street connectivity levels in Brisbane (0.64 intersection per hectare) with only fewer cul-de-sacs (0.09 per hectare), and with a moderate diversity level (0.47).

- **Cluster 1 - Neighbourhoods requiring both land use and transport investment to qualify as a TOD:** Around 29% of CCDs (497) in Brisbane do not qualify for a TOD. Despite having moderate land use diversity and connectivity levels, these neighbourhoods lack both transport services and other place-related qualities (e.g. density).

Figure 7 outlines the spatial distribution of the four clusters in Brisbane. It shows that the different clusters are located next to each other, which indicates that different types of TODs can be developed in a hierarchical order. Figure 8 presents each cluster with a limited geographic background (e.g. different parts of Brisbane, train stations, BRT stops). Figure 8a demonstrates that residential clusters (Cluster 4) are rarely located within the Inner Brisbane area rather these neighbourhoods are located mainly within the Northwest Inner Brisbane and Southeast Inner Brisbane areas (i.e. next to the Inner Brisbane area). In contrast, the activity centre TODs are mainly located within the Inner Brisbane area (Figure 8b). However, some pockets of activity centre type TOD exist in outer parts of Brisbane (e.g. Chermside, Inala, Wynnum, Northgate) (Figure 8b). However, these outer pockets are well recognised as service/activity centre in Brisbane. In addition, some outer neighbourhoods also possess the quality of a residential TOD in Brisbane (e.g. Sunnybank Hills, Chermside) (Figure 8a). Thus, it is not logical to refer to TOD types according to city location (inner city verses suburban).

Also notable is that the residential TOD clusters appear mainly along the train and BRT line corridors in Brisbane. - This finding, however, does not necessarily suggest that TODs should be located proximal to train stations or BRT stops. Evidence in Figure 8a shows that some neighbourhoods may possess the characteristics of a residential type of TOD, despite being situated far away from train stations or BRT stops (e.g. Carindale, Chermside). Similarly, some activity centre types of TODs are also located away from train stations and BRT stops (e.g. Forest Lake, Carina, Chermside). These clusters are associated with high frequency regular bus transit stations and corridors.

Cluster 3 in Figure 8c indicates that potential TODs are located in a North-South corridor within the Brisbane region. However, Wynnum is a clear exception to this pattern – perhaps due to the availability of train services there. This finding suggests that a lack of high quality transport services along East-West corridors hinder the development of TOD types of neighbourhoods in Brisbane. Figure 8c also shows that the potential TOD neighbourhoods are mainly located in the outer parts of

Brisbane. However, despite having the quality, the clusters cannot be labelled as a TOD (potential), if they do not function well when measured by performance (Belzer and Autler, 2002). The following section presents the validation results of the identified clusters.

4.2 Validation of the typologies

Renne (2009b) has highlighted that the performance of TODs should be measured by comparing: a) TODs vs. other TODs, b) TODs vs. non-TODs, and c) TODs vs. regional average. In the absence of regional average data, the first two criteria were used to validate the clusters in this research – i.e. comparisons were made between: a) residential TODs (cluster 4) and activity centre TODs (cluster 2); b) residential TODs (cluster 4) and potential TODs (cluster 3); and c) residential TODs (cluster 4) and non-TODs (cluster 1). Table 5 outlines descriptive statistics related to mode choice behaviour of people living in the four clusters, whereas Table 6 presents the results obtained from the multinomial logistic regression analysis of mode choice behaviour. Given that CCDs within the Cluster 4 possess the quality of residential TODs, this category was set as reference category in the model. As a result, the mode choice behaviour of people living in other three clusters was compared with the mode choice behaviour of people living in Cluster 4. Considering the built environmental qualities of the clusters, it was expected that people living in Cluster 3 (potential TODs) would exhibit a lower PT, and AT usage followed by people in Cluster 1 (non-TODs). However, it was expected that people living in Cluster 2 (activity centre TOD) would exhibit a complex behaviour. A lower PT utilisation was postulated for this group because unlike people in residential TODs, higher order goods and services are located within their neighbourhoods, and as a result, they don't need to travel longer distances. However, they were expected to walk more due to the availability of different types of opportunities (e.g. jobs) within the neighbourhoods.

A significant model emerged from the multinomial regression analysis. The explanatory power (19%) of the model was found to be defensible in the literature for this type of analysis. As expected, the relative risk ratios (RRRs) in Table 6 shows that people living in Cluster 1 (i.e. non-TODs) were 1.4 times less likely to use the PT and 4 times less likely to walk and cycle when compared to people living in Cluster 4 (residential TODs). Table 3 also shows that people in Cluster 3 were 1.3 times less likely to use the PT. However, this finding was significant only at the 0.1 level. Nevertheless, people living in cluster 3 were 2.5 times less likely to walk and cycle. Therefore, the built environment clearly affected the walking propensity of people living in these neighbourhoods.

The findings also suggest that these neighbourhoods could reach the directed policy targets (e.g. doubling the share of active transport trips) if they were developed as a fully-fledged residential TOD. However, unlike the hypotheses, little difference was found to exist in mode choice behaviour of people living between Cluster 2 (activity centre TOD) and Cluster 4 (residential TOD), suggesting that both residential TODs and activity centre TODs are equally effective in enhancing the use of more sustainable modes of transport. The findings, therefore, validate the typology of neighbourhoods developed in this research. More importantly, the findings suggest that different types of TODs have the ability to influence mode choice behaviour – even after controlling for residential self-selection.

4.3 Indicators of advanced TOD typology planning

Table 7 shows the results obtained from a multinomial logistic regression analysis that identifies the differences in policy indicators between the clusters. It is clear from Table 7 that median neighbourhood income is not a suitable indicator for advanced TOD typology planning because none of the income-related indicators were found to have a significant association with the clusters. Similarly, citizenship is not a significant predictor for TOD typology planning in Brisbane. Other than income and citizenship indicators, all other indicators were found to be significant. Based on the information presented in Table 7, the following observations can be formulated:

- Residential type of TODs are more homogeneous neighbourhoods, whereas activity centre type of TODs are more socially and commercially diverse communities.
- Neighbourhoods with more educated residents are less likely to be supportive for activity centre types of TODs;
- Neighbourhoods with disproportionately more younger aged residents are more likely to be supportive of activity centre types of TODs;
- Neighbourhoods with larger sized households are good candidates for potential TODs;
- Neighbourhoods with fewer private dwellings are good candidates for activity centre types of TODs; and
- Residential areas where more than 15% of residents do not own private vehicles are suitable for both residential TODs (15-18%) and activity centre TODs (>18%).

In addition to the above census indicators, Table 7 identifies additional spatial indicators that are significantly related to TOD typologies. For example, distance to the CBD plays a role in determining the type of TOD, as does distance to the coast line.

5. Discussion and conclusions

This research represents one of several attempts in the literature to develop typologies of neighbourhoods with respect to TODs and their effectiveness. While the case studies are based on TODs in Brisbane, Australia – the proposed approach yields a generalisable method for evaluating prospective TOD sites through the selection of built environmental indicators. A number of findings can be deduced from this research, either directly or indirectly, that have significant implications for TOD research. At the broad scale, evidence from this research clearly reinforces TOD as a means to promote sustainable travel behaviour. The mode choice behaviour of people living in TOD neighbourhoods in Brisbane demonstrates that they are significantly more likely to use public and active transport. The findings, therefore, support the focused TOD policy in South East Queensland.

Within the context of our research - the Queensland Government is aiming to develop six types of TODs in Brisbane (city centre, activity centre, specialist activity centre, urban, suburban, neighbourhood). However, the existing city structure reveals that Brisbane's neighbourhoods possess only four types of TOD efficiency indicators. Within these four, the research suggests that the TOD efficiency of one type of neighbourhood (cluster 1) has limited potential for effectiveness. This finding was further verified when their influence on mode choice behaviour was found to be quite minimal. As a result, investment in these areas to develop as a TOD would be questionable in the short term, despite the location of some of the neighbourhoods is in the city centre area (Figure 8d). The subjective and anecdotal geographical approach used for the classification of TODs (e.g. city centre) needs to be supplemented with built environmental indicators to sharpen the locational criteria for TOD development.

The remaining three types of neighbourhood clusters are comprised of elements that support the location of a (potential) TOD. The built environmental indicators between the three are clearly distinguishable. One type reflects the character of existing residential TODs because residential density satisfies the design standard required for Queensland (e.g. 35 units per hectare), with better public transport services (PTALs 8.72), and street connectivity (intersection density 0.77 per hectare). Land use diversity in these areas is also in the acceptable range (0.55). However, this cluster has limited employment opportunities (7.5 jobs/hectare). A second cluster has all the qualities for a residential TOD but possesses high employment density (65 jobs/hectare), justifying its designation as activity centre TOD in this research. The third cluster possesses the quality of a potential TOD, because although the built environmental indicators in these areas are not as pronounced as the other two clusters, they have the potential to influence behaviour. These areas can be further developed to form a TOD of any of the six types used in Brisbane. However, such a generalised classification is a lost opportunity. For example, Forest Lake is located at the outskirts of the city – and is classified as a suburban TOD. Yet, based on our findings, this site has much more capacity and has the potential to develop as a comprehensive activity centre type of TOD.

The findings here suggest that deeper insights are needed into how different people living in different land-use types engage in travel. Cleary a “one-size fits all” approach to TOD does not seem to be supported. Evidence indicates that residential TODs and their residents will engage in travel somewhat differently than residents in an activity centre type of TOD. However, their travel engagement varies significantly from residents living in cluster 3 type of TODs. The characteristics that support cluster 4 and 2 types of TOD are important for policy and strategic planning. For example, evidence for this research indicates that the cluster type is critical for TOD success. Neighbourhoods that have a cultural mix, lower education levels, and younger aged people with less car ownership and fewer private dwellings should be targeted for a cluster 2 type of TOD (activity centre).

Thus, long term strategic planning needs to account for policy indicators (eg. public housing) in order to inform TOD design indicators (eg. density, diversity). Given the costs associated with this type of infrastructure development – it is critical that forecasting be based on strong empirical research to support projections. Further research needs to explore in greater depth the fundamental drivers of the different observed behaviour in each of the cluster 2, 3 and 4 TOD typologies. In addition, the mix of land uses in the clusters and the varying percentages of types of mixes (commercial and residential) may be important in the development of a typology. This research did not differentiate in the relative percentage mix of land uses and assumed a linear relationship between the built environment indicators (e.g. density, diversity) and TOD outcomes. In reality, as evidenced in other context, the relationship may not be linear (Frank and Pivo, 1994). Further research should seek to categorise the indicators used in this research for the derivation of TOD typologies and investigate their impacts.

This paper has examined the use of built environmental indicators to develop a typology and form the basis for locational analysis of TODs. Built environmental indicators offer a rigorous and quantitative approach to justify development decisions for TODs. We consider this critical for evidence-based decision making and land use planning. Much of the international research on TODs is not developed on the basis of quantitative findings and relies on generalised geographical approaches with little scientific support.

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Tables

Table 1: TOD principles for SEQ (Queensland Government, 2009)

Major components	Sub-components	Principles
Location	Infrastructure and services levels	• Locate development around nodes or corridors where infrastructure capacity exists or can be created • Prioritise locations with high levels of transit service frequency.
	Development levels	Ensure TOD occurs at a scale that is appropriate for the location.
	New development	Apply TOD principles in new communities where transit nodes exist or are proposed.
Land use	Type	Ensure transit oriented development precincts are dominated by land uses that support transit.
	Extent	Transit oriented development precincts focus on the area within 5 to 10 minutes of the transit node considering the nature of the topography.
	Density	Incorporate higher density residential uses in transit oriented development precincts to increase vitality and provide more convenient access to services and transport. Use the following baseline density guidelines: ▪ activity centres: 40–120 dwellings per hectare (net) or greater ▪ suburban and neighbourhood locations: 30–80 dwellings per hectare (net) or greater ▪ priority transit corridors: 40 dwellings per hectare (net) or greater
	Intensity	Incorporate high-employment intensities and a mix of employment opportunities.
	Mix	• Provide and integrate a mix of uses to create a greater variety of services catering for the diverse needs of a vibrant community. • Provide timely and convenient access to services and facilities required to support people's daily needs, including an appropriate mix of commercial and retail services, jobs, community infrastructure and open space relevant to the context of the surrounding area.
	Continuity	Encourage continuous activity in transit oriented development precincts to provide a sense of vitality and safety.
Design	Adaptability	Ensure development delivers a built form that is robust and flexible, allowing development to be adapted or redeveloped over time to vary uses, increase densities or increase employment intensity.
	Built form	Ensure development features high-quality subtropical design that maximises amenity, street activity and pedestrian connectivity.
	Public realm	• Provide for a high-quality public realm to meet the needs of the surrounding community, including open space, pedestrian areas and transit access. • Deliver design that promotes social interaction and inclusion, physical activity and a sense of place and identity.
	Integration	Ensure design seamlessly integrates transit nodes and the community.
	Safety and accessibility	• Ensure development promotes a high sense of personal and community safety, and equitable access to all public areas.
	Parking	• Locate, design, provide and manage car parking in TOD precincts to support walking, cycling and public transport accessibility.
Transport	Mode share	Create an increased mode share for walking, cycling and public transport by providing high levels of accessibility and public amenity within precincts and to stations and surrounding areas for cyclists and pedestrians, with priority for pedestrians.
	Efficiency	Facilitate a high level of intermodal connection.
Social	Social diversity and inclusion	• Ensure development creates an environment that supports social inclusion and diversity of different age, cultural, employment and income groups. • Provide a mix of housing types, tenures and affordability to support social diversity. • Promote physical and social connections between new and existing communities. • Ensure community development initiatives are carried out as an integral part of community building.
Process	Coordination	Planning for development in transit oriented development precincts requires the coordinated effort of all stakeholders, including state agencies, local government and the development industry.
	Community engagement	Engage with the community likely to experience change early and throughout planning and development processes to promote a sense of ownership and involvement.
	Timeframes	Transit oriented development outcomes take time to deliver, and precincts mature over time.

Table 2: Suggested design parameters for different types of TODs in Queensland (Queensland Government, 2010b)

TOD type	Dwelling density (number of dwellings per hectare)	Land use diversity	Commercial plot ratio[a]	Transit
City centre	100+ / 300+	Residential 30%, commercial 40%, retail 20%, community 10%	5:1	-Peak hour frequency: 15 minutes -Off-peak frequency: not more than 30 minutes -18-24 hour transit services -Dedicated routes
Activity centre	40+ / 140+	Residential 50%, commercial 25%, retail 15%, community 10%	3:1	
Specialist activity centre	40+ / 120+	At least 20% residential, at least 10% retail, commercial or community	2:1	
Urban	60+ / 180+	Residential 60%, commercial 25%, retail 10%, community 5%	3:1	
Suburban	30-80 / 100+	Residential 70%, commercial 10%, retail 15%, commercial 5%	2:1	
Neighbourhood	30-60 / 80+	Residential 90%, commercial 2.5%, retail 5%, community 2.5%	1:1	

[a] Plot ratio is an identical concept to the floor area ratio (FAR). It is a ratio of gross floor area to the area of a site. Therefore, the measure has no unit. For example, a 5:1 commercial plot ratio means that a 1000 m^2 plot should be developed with 5000 m^2 of commercial floor space.

Table 3: Correlations amongst built environmental indicators

Indicators	Net employment density	PTALs	Net residential density	Land use diversity	Cul-de-sac density	Intersection density
Net employment density	-	.344**	.404**	.300**	.045	.180**
PTALs		-	.630**	.386**	-.103**	.461**
Net residential density			-	.412**	-.030	.518**
Land use diversity				-	-.098**	.211**
Cul-de-sac density					-	.089**
Intersection density						-
N						1734

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4: Pattern matrix showing main reasons for choosing the current address as a place to live

Items	Factors			
	Accessibility and mobility of places	Natural environment	Child centric facilities	Ease of commuting
Closeness to public transport	0.746	-0.024	0.070	0.033
Ease of walking to places	0.690	0.215	-0.022	-0.026
Wanted to live close to shops	0.668	-0.105	0.045	0.250
Closeness to open space (e.g. parks)	0.121	0.856	0.074	-0.108
Near to green-space or bushland	-0.056	0.686	0.013	0.178
Closeness to schools	0.118	0.029	0.749	-0.124
Closeness to childcare	-0.074	0.026	0.612	0.133
Closeness to the city	0.038	0.104	-0.058	0.598
Closeness to work	0.010	-0.004	0.099	0.530
Access to freeways or main roads	0.203	-0.006	0.034	0.492
% of variance explained	33.884	8.933	6.409	4.463
Total variance explained (%)				53.869
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.				0.794
Extraction Method				Principal Axis Factoring
Rotation Method				Oblimin with Kaiser Normalization
N				10013

Table 5: Descriptive statistics showing mode choice behaviour of people living in different types of clusters

Transport modes	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Overall	
	Count	Column%	Count	Column %	Count	Column %	Count	Column %	Count	Column %
Car or motorcycle	3819	88.6	370	74.0	3722	81.5	437	68.6	8348	83.4
PT	368	8.5	63	12.6	596	13.1	119	18.7	1146	11.4
AT	99	2.3	62	12.4	213	4.7	75	11.8	449	4.5
Other	24	0.6	5	1.0	35	0.8	6	0.9	70	0.7
Total	4310	100	500	100	4566	100	637	100	10013	100.0

Table 6: Multinomial logistic regression analysis results showing mode choice behaviour of people living in types (cluster) of neighbourhood (CCDs) in Brisbane

Explanatory factors	Main mode of transport used (ref: car)								
	Public Transport			Active Transport			Other		
	RRR[a]	z	p>|z|	RRR	z	p>|z|	RRR	z	p>|z|
Neighbourhood type (ref: Cluster 4 – Residential TOD)									
Cluster 1 (Non-TOD)	**0.72**	**-2.08**	**0.04**	**0.26**	**-5.91**	**0.00**	0.67	-0.77	0.44
Cluster 2 (Activity Centre TOD)	<u>0.70</u>	<u>-1.71</u>	<u>0.09</u>	1.12	0.39	0.70	0.94	-0.10	0.92
Cluster 3 (Potential TOD)	<u>0.76</u>	<u>-1.72</u>	<u>0.09</u>	**0.40**	**-4.34**	**0.00**	0.70	-0.72	0.47
Reasons for choosing neighbourhood									
Accessibility and mobility of places	**2.66**	**15.55**	**0.00**	**1.97**	**7.31**	**0.00**	1.04	0.17	0.87
Natural environment	**0.85**	**-3.41**	**0.00**	0.99	-0.19	0.85	0.86	-0.91	0.36
Child centric facilities	**0.78**	**-4.10**	**0.00**	0.88	-1.45	0.15	1.01	0.05	0.96
Ease of commuting	**0.74**	**-5.50**	**0.00**	**0.73**	**-3.27**	**0.00**	<u>1.47</u>	<u>1.81</u>	<u>0.07</u>
Female (ref: male)	0.94	-0.70	0.48	**0.58**	**-5.14**	**0.00**	**0.54**	**-2.61**	**0.01**
Age (continuous)	**0.98**	**-3.33**	**0.00**	**0.96**	**-4.49**	**0.00**	1.00	0.07	0.94
Car availability (ref: yes, always)									
Yes, sometimes	**7.66**	**18.92**	**0.00**	**8.74**	**12.80**	**0.00**	<u>2.70</u>	<u>1.87</u>	<u>0.06</u>
No	**37.52**	**18.11**	**0.00**	**36.77**	**14.12**	**0.00**	**40.96**	**9.87**	**0.00**
Do not drive	**23.55**	**18.09**	**0.00**	**27.21**	**15.24**	**0.00**	**19.66**	**6.44**	**0.00**
Education: graduate (ref: up to year 12)	**1.49**	**5.44**	**0.00**	**1.38**	**2.74**	**0.01**	**0.36**	**-2.73**	**0.01**
Health status (ordinal)	1.01	0.21	0.84	**1.44**	**5.90**	**0.00**	0.85	-1.00	0.32
Household size (continuous)	**0.91**	**-2.47**	**0.01**	<u>0.90</u>	<u>-1.79</u>	<u>0.07</u>	1.06	0.51	0.61
Employment status (ref: non-working)									
Working part time	**1.36**	**2.49**	**0.01**	**0.64**	**-2.84**	**0.01**	0.73	-0.70	0.48
Working full time	**3.16**	**9.71**	**0.00**	0.90	-0.81	0.42	**1.84**	**1.96**	**0.05**
Living arrangement (ref: living alone)									
Couple with no kids (ref: living alone)	**0.65**	**-4.24**	**0.00**	0.83	-1.39	0.17	0.90	-0.35	0.72
Couple with kids (ref: living alone)	**0.55**	**-4.84**	**0.00**	**0.63**	**-2.85**	**0.00**	0.65	-1.16	0.25
Log pseudolikelihood									-4649.78
Wald Chi^2									**1992.35**
Pseudo R^2									0.19
N									10013

[a] RRR – Relative Risk Ratio
[b] Bold coefficients are significant at the 0.05 level.
[c] Italic coefficients are significant at the 0.1 level.
[d] Dimmed coefficients are not significant.

Table 7: Multinomial logistic regression analysis results showing the differences in policy variables between different TOD types

Explanatory factors	Outcome variable: classification of CCDs (ref: cluster 4 - residential TODs)								
	Cluster 1			Cluster 2			Cluster 3		
	RRR[a]	z	p>|z|	RRR	z	p>|z|	RRR	z	p>|z|
Median mortgage repayment per month	1.000	-1.450	0.148	0.999	-2.080	0.037	1.000	-2.010	0.045
Median personal income per week	1.001	1.160	0.247	1.003	3.160	0.002	1.001	1.110	0.266
Median total family income per week	--	--	--	--	--	--	--	--	--
Median total household income per week	--	--	--	--	--	--	--	--	--
Median rent per week	--	--	--	--	--	--	--	--	--
Male (%)	1.041	0.960	0.335	1.088	2.340	0.019	1.052	1.540	0.123
Born in Australia (%)	0.904	-2.760	0.006	0.921	-2.320	0.020	0.999	-0.030	0.979
Speak in English at home (%)	1.143	4.240	0.000	1.100	2.950	0.003	1.069	2.320	0.020
Australian citizen (%)	--	--	--	--	--	--	--	--	--
Year 12 completed (%)	0.896	-4.950	0.000	0.938	-3.190	0.001	0.913	-4.840	0.000
Median age	1.002	0.060	0.952	0.920	-3.030	0.002	0.965	-1.610	0.107
Average household size	14.735	4.550	0.000	2.158	1.290	0.199	2.934	2.030	0.042
Average person per bedroom	0.001	-4.030	0.000	0.420	-0.560	0.575	0.663	-0.290	0.771
% of people live in private dwelling	1.013	0.570	0.571	0.959	-2.820	0.005	0.992	-0.470	0.640
% of people live in detached dwelling	0.994	-0.700	0.483	1.018	1.980	0.048	1.007	0.920	0.359
% of dwelling own zero vehicle	0.876	-4.320	0.000	1.081	3.650	0.000	0.976	-1.090	0.277
Distance to motorway	--	--	--	--	--	--	--	--	--
Distance to coast	1.001	2.300	0.022	1.000	0.930	0.350	1.000	1.270	0.203
Distance to water body (e.g. Brisbane River)	--	--	--	--	--	--	--	--	--
Distance to CBD	1.001	6.750	0.000	1.001	2.120	0.034	1.000	4.250	0.000
Log likelihood									-1161.99
LR chi^2									1261.70
Pseudo R^2									0.35
N									1479

[a] RRR – Relative Risk Ratio
[b] Dimmed coefficients are not significant for that cluster.
[c] Dash represents that the variable is not significant for any of the cluster.

Figure captions

Figure 1: Node-place typology of train stations (adopted from Bertolini, 1999)

Figure 2: Performance based typology of transit oriented development (adopted from Center for Transit-Oriented Development, 2010)

Figure 3: Clusters and outliers of good and poor PTALs in Brisbane[1].

Figure 4: Correlation of the PTAL scores between different scales of measurement

Figure 5: Spatial patterns (cluster/outliers) of the derived place indicators in Brisbane[2]

Figure 6: Cluster analysis results showing the types of neighbourhoods in Brisbane

Figure 7: Spatial distribution of CCD clusters in Brisbane

Figure 8: Spatial distribution of each cluster within different parts in Brisbane

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[1] The cluster and outlier analysis were conducted using the inverse distance conceptualisation of spatial relationship. This method is suitable for continuous data and in situations where the closer the features are in space, the more likely they are to influence each other. A fixed distance band was used to generate the clusters/outliers because the datasets were polygonal in nature (CCDs) with a large variation in size. The Multi-Distance Spatial Cluster Analysis (Ripley's k-function) tool in ArcGIS was used to derive an appropriate distance band that exhibited maximum spatial autocorrelation. HH – a significantly high value CCD is surrounded by several significantly high value CCDs, HL - a significantly high value CCD is surrounded by several significantly low value CCDs, LH – a significantly low value CCD is surrounded by several significantly high value CCDs, LL – a significantly low value CCD is surrounded by several significantly low value CCDs, Not Significant – no significant difference between the value of a CCD and the values of surrounding CCDs).

[2] HH – a significantly high value CCD is surrounded by several significantly high value CCDs, HL - a significantly high value CCD is surrounded by several significantly low value CCDs, LH – a significantly low value CCD is surrounded by several significantly high value CCDs, LL – a significantly low value CCD is surrounded by several significantly low value CCDs, Not Significant – no significant difference between the value of a CCD and the values of surrounding CCDs.

Figure 1

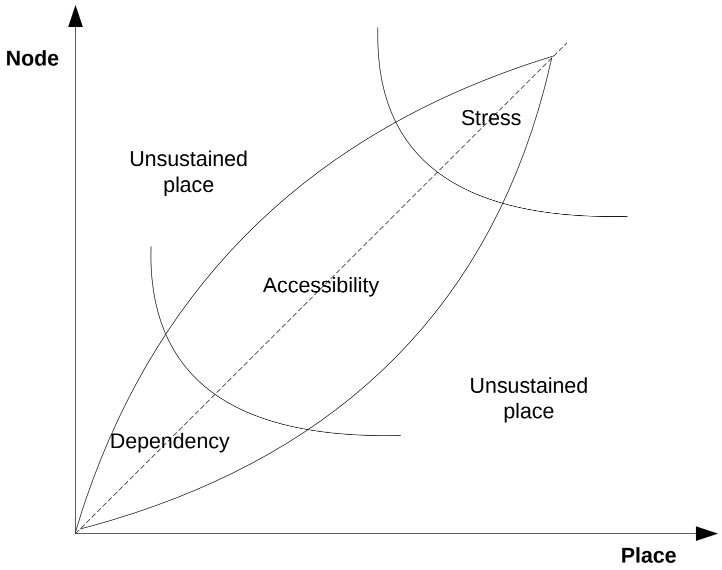

Node
Stress
Unsustained place
Accessibility
Unsustained place
Dependency
Place

Figure 2

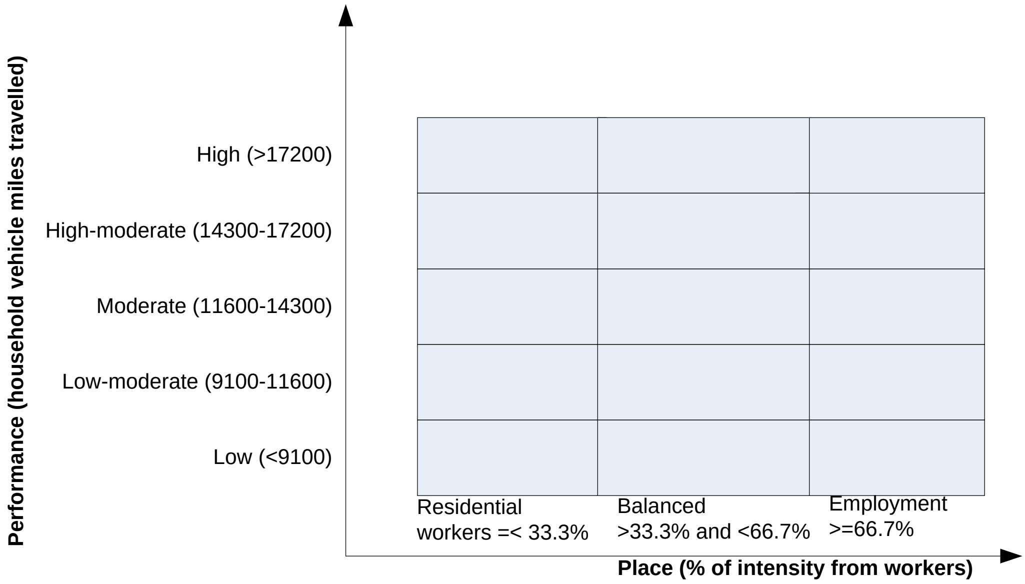
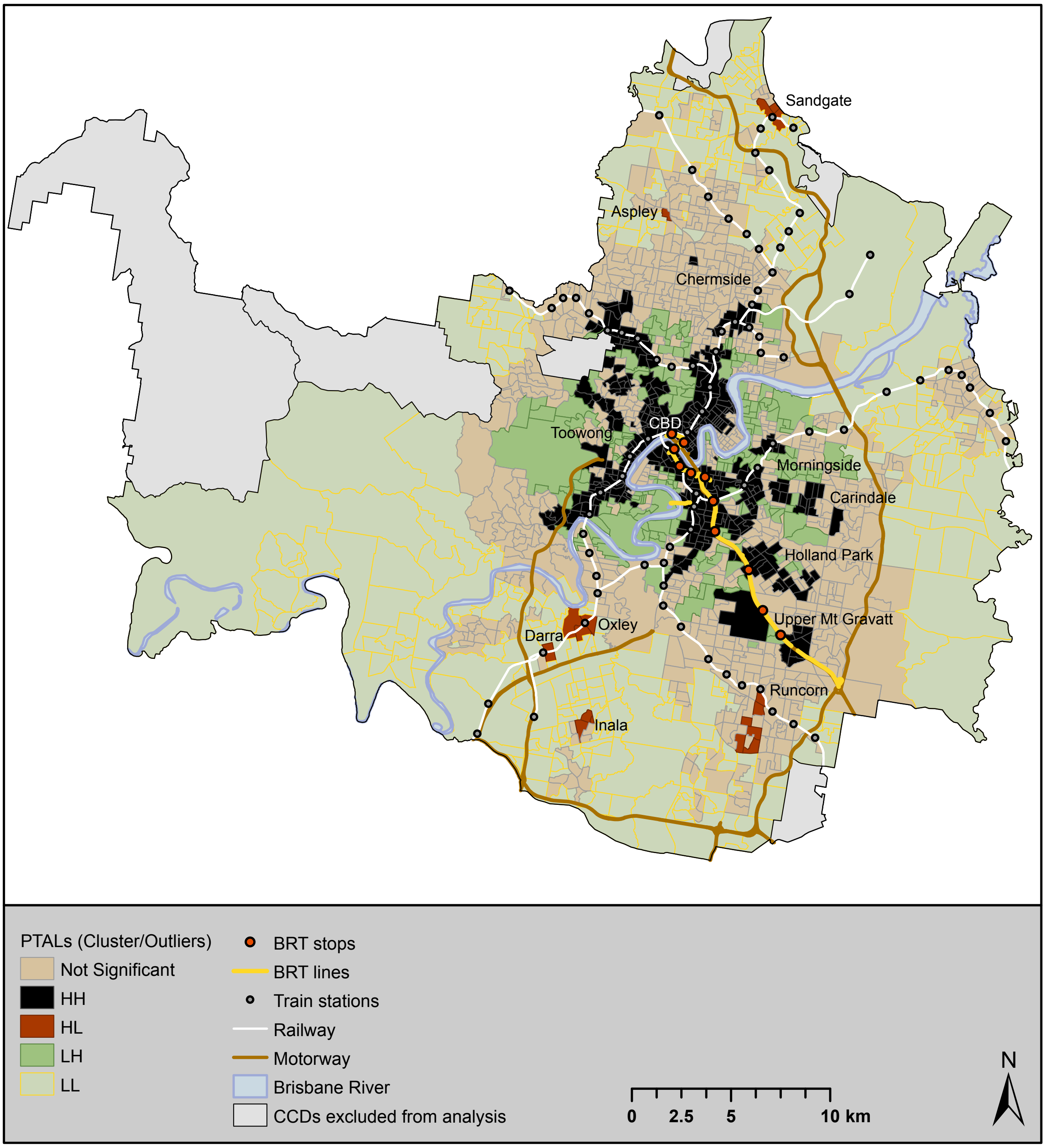

Performance (household vehicle miles travelled)
High (>17200)
High-moderate (14300-17200)
Moderate (11600-14300)
Low-moderate (9100-11600)
Low (<9100)
Residential
workers =< 33.3%
Balanced
>33.3% and <66.7%
Employment
>=66.7%
Place (% of intensity from workers)

Figure 3



Sandgate
Aspley
Chermside
CBD
Toowong
Morningside
Carindale
Holland Park
Upper Mt Gravatt
Oxley
Darra
Runcorn
Inala
PTALs (Cluster/Outliers)
Not Significant
HH
HL
LH
LL
BRT stops
BRT lines
Train stations
Railway
Motorway
Brisbane River
CCDs excluded from analysis
0
2.5
5
10 km
N

Figure 4

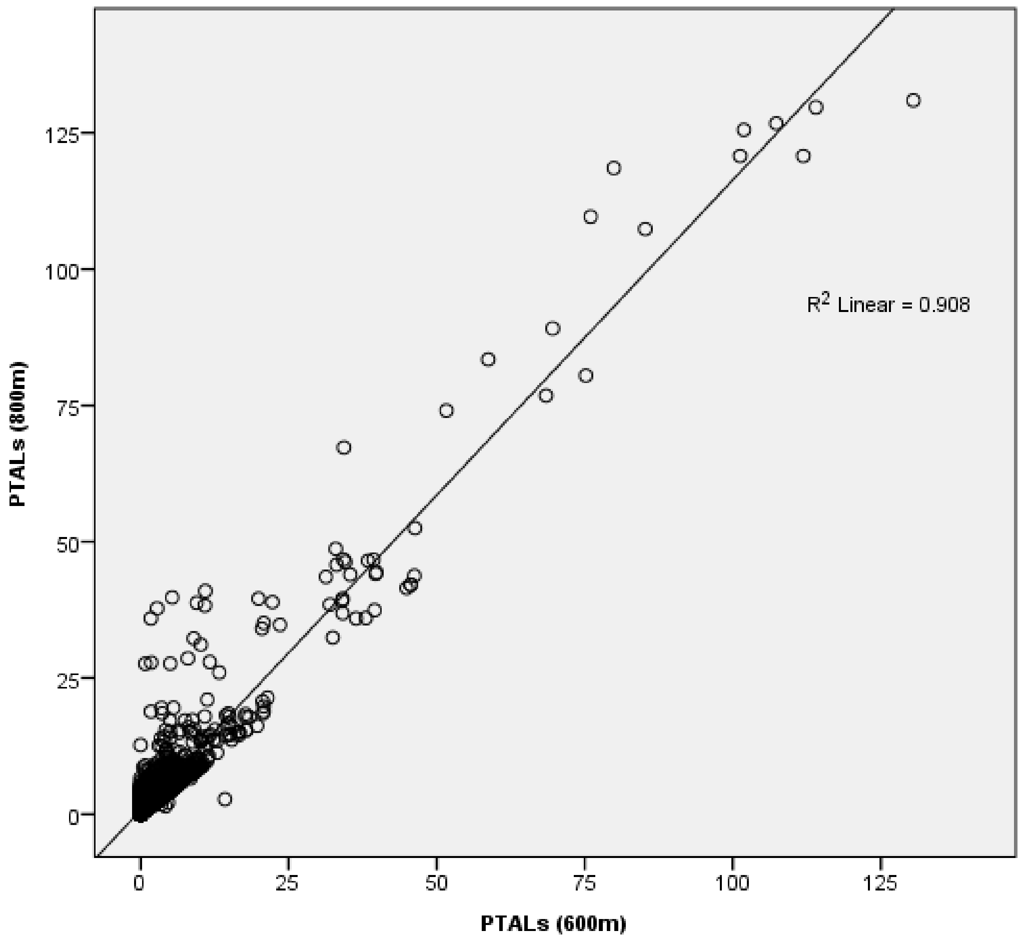


Figure 5

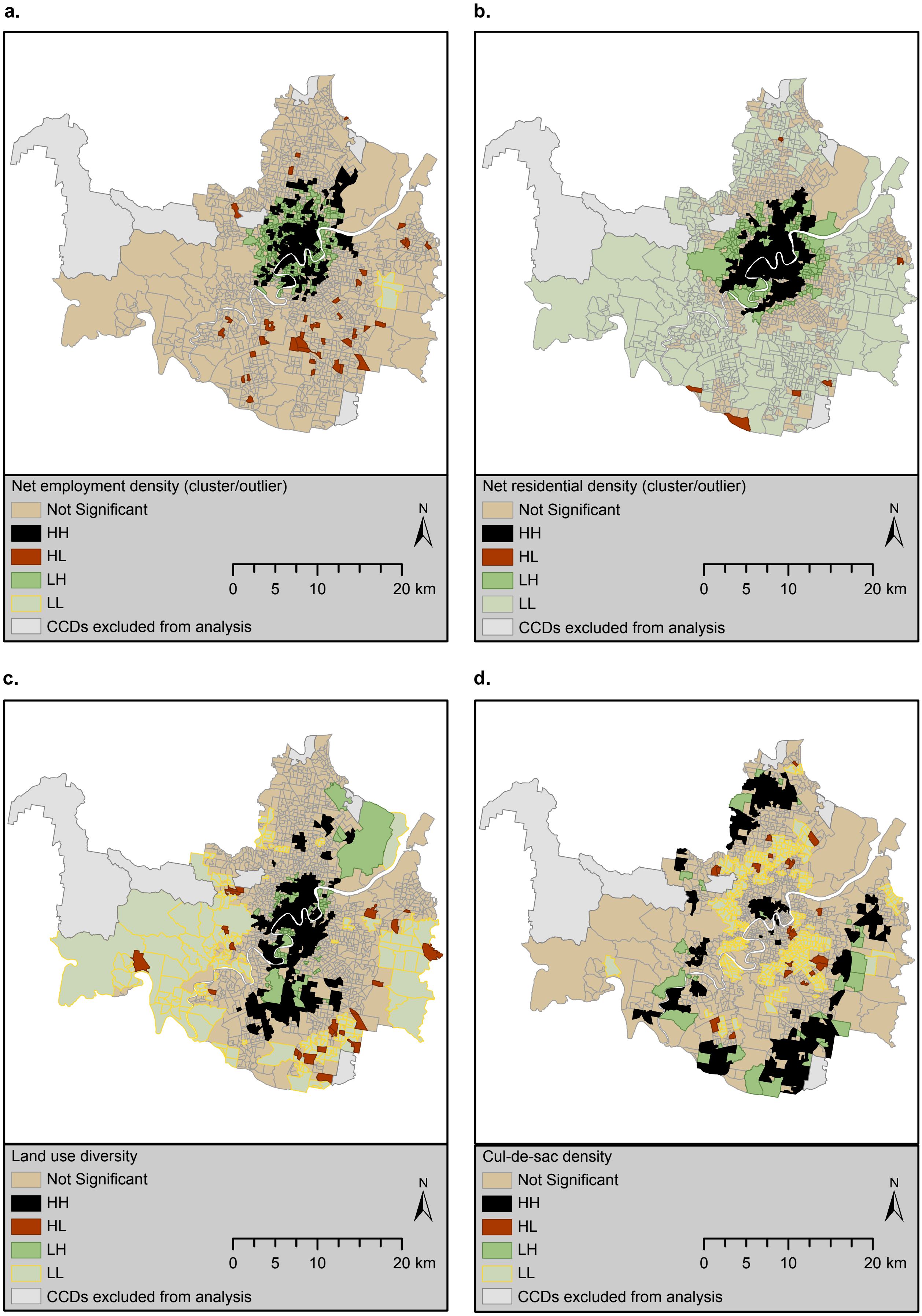

a.
b.
c.
d.
Net employment density (cluster/outlier)
Not Significant
HH
HL
LH
LL
CCDs excluded from analysis
N
0
5
10
20 km
Net residential density (cluster/outlier)
Not Significant
HH
HL
LH
LL
CCDs excluded from analysis
N
0
5
10
20 km
Land use diversity
Not Significant
HH
HL
LH
LL
CCDs excluded from analysis
N
0
5
10
20 km
Cul-de-sac density
Not Significant
HH
HL
LH
LL
CCDs excluded from analysis
N
0
5
10
20 km

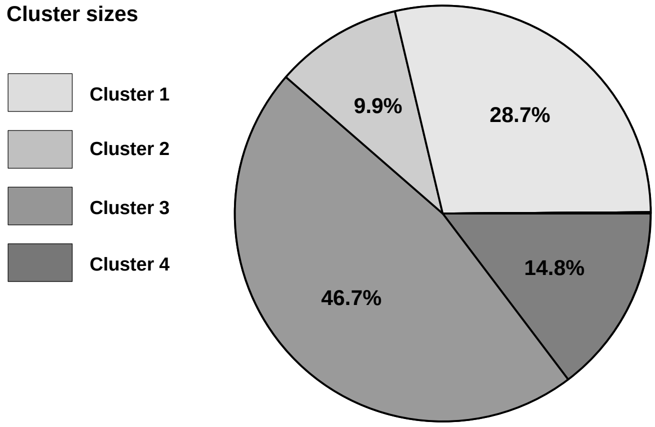
Figure 6

Model summary

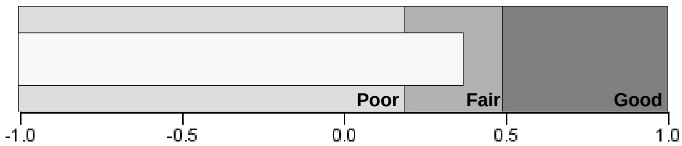
Algorithm	TwoStep
Inputs	6
Clusters	4

Size of smallest cluster	171 (9.9%)
Size of largest cluster	809 (46.7%)
Ratio of sizes: largest to smallest cluster	4.73

Cluster sizes



Cluster quality



Silhouette measure of cohesion and separation

Input (predictor) importance

1.0 0.8 0.6 0.4 0.2 0.0

Cluster	1	2	3	4
Label	Non-TOD	Activity Centre TOD	Potential TOD	Residential TOD
Size	28.7% (497)	9.9% (171)	46.7% (809)	14.8% (257)
Inputs	Employment density 2.66	Employment density 64.85	Employment density 3.63	Employment density 7.48
	Residential density 12.67	Residential density 32.72	Residential density 17.67	Residential density 35.44
	PTALs 1.65	PTALs 7.62	PTALs 3.84	PTALs 8.72
	Cul-de-sac density 0.22	Cul-de-sac density 0.16	Cul-de-sac density 0.09	Cul-de-sac density 0.13
	Land use diversity 0.32	Land use diversity 0.57	Land use diversity 0.47	Land use diversity 0.55
	Intersection density 0.52	Intersection density 0.74	Intersection density 0.64	Intersection density 0.77

Figure 7

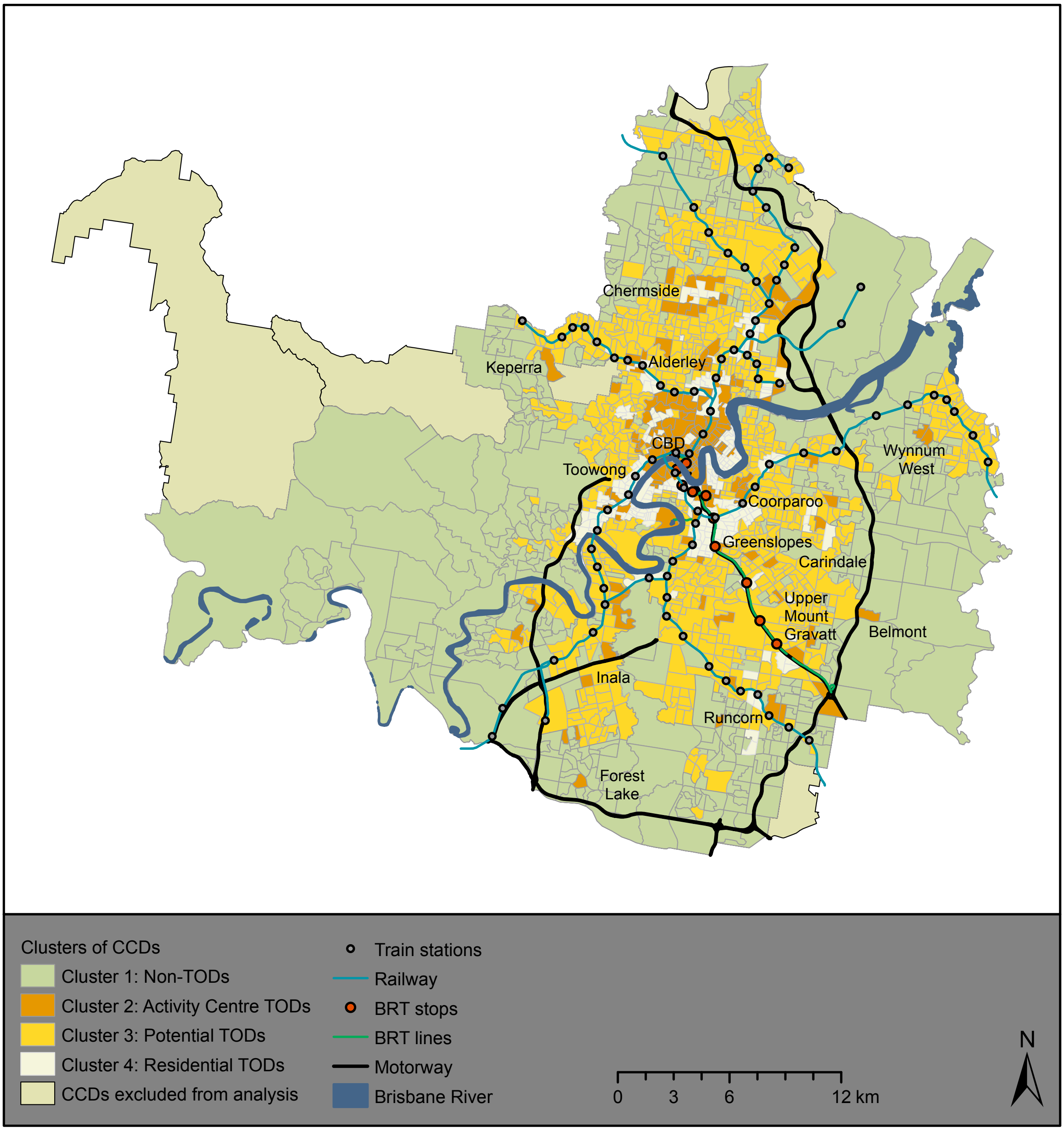
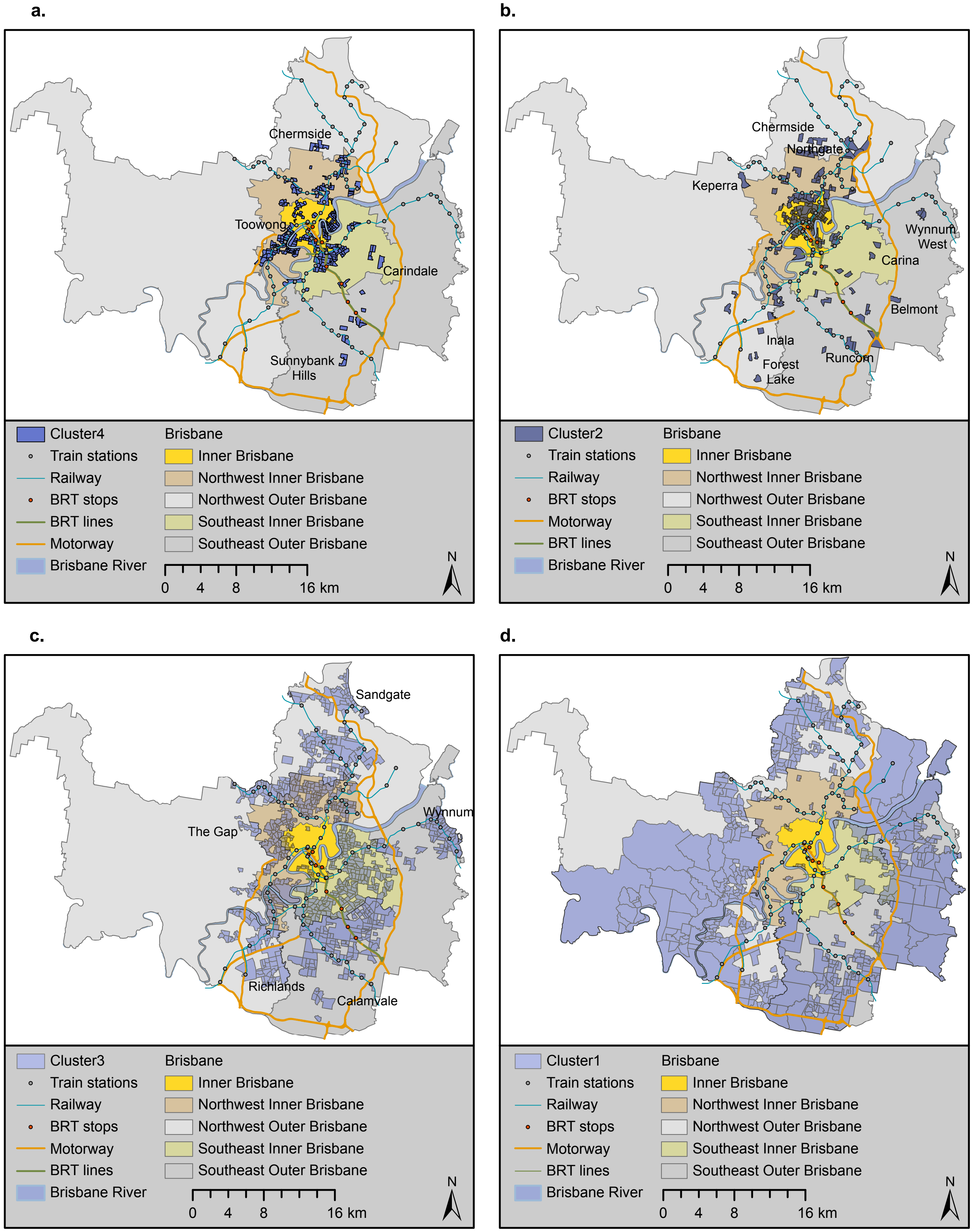

Chermside
Keperra
Alderley
CBD
Toowong
Coorparoo
Greenslopes
Carindale
Wynnum
West
Upper
Mount
Gravatt
Belmont
Inala
Runcorn
Forest
Lake
Clusters of CCDs
Cluster 1: Non-TODs
Cluster 2: Activity Centre TODs
Cluster 3: Potential TODs
Cluster 4: Residential TODs
CCDs excluded from analysis
Train stations
Railway
BRT stops
BRT lines
Motorway
Brisbane River
0
3
6
12 km
N

Figure 8


a.
Chermside
Toowong
Carindale
Sunnybank Hills
Cluster4
Train stations
Railway
BRT stops
BRT lines
Motorway
Brisbane River
Brisbane
Inner Brisbane
Northwest Inner Brisbane
Northwest Outer Brisbane
Southeast Inner Brisbane
Southeast Outer Brisbane
0 4 8 16 km
N
b.
Chermside
Northgate
Keperra
Wynnum West
Carina
Belmont
Inala
Forest Lake
Runcorn
Cluster2
Train stations
Railway
BRT stops
Motorway
BRT lines
Brisbane River
Brisbane
Inner Brisbane
Northwest Inner Brisbane
Northwest Outer Brisbane
Southeast Inner Brisbane
Southeast Outer Brisbane
0 4 8 16 km
N
c.
Sandgate
Wynnum
The Gap
Richlands
Calamvale
Cluster3
Train stations
Railway
BRT stops
Motorway
BRT lines
Brisbane River
Brisbane
Inner Brisbane
Northwest Inner Brisbane
Northwest Outer Brisbane
Southeast Inner Brisbane
Southeast Outer Brisbane
0 4 8 16 km
N
d.
Cluster1
Train stations
Railway
BRT stops
Motorway
BRT lines
Brisbane River
Brisbane
Inner Brisbane
Northwest Inner Brisbane
Northwest Outer Brisbane
Southeast Inner Brisbane
Southeast Outer Brisbane
0 4 8 16 km
N