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GIS based destination accessibility via public transit and walking in Auckland, New Zealand

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ABSTRACT

There is relatively little research on accessibility using public transit as the travel mode. Yet understanding public transit accessibility is important for encouraging mode shifts to reduce car reliance and is essential for the wellbeing of non-car households. The paper describes two measures of public transit access. The first is a combined public transit and walking accessibility index, which measures potential access to destinations via public transit and walking modes. The second is a transit frequency measure, which is a measure of transit service level in an area. These two measures extend current public transit accessibility measures by including all components of the public transit journey, calculating accessibility at the parcel level and providing a measure of public transit service. Results for the Auckland region show that although 94.4% of the urban population live in areas with medium–high public transit and walking access, only 26.5% of the urban population also have an average transit frequency of two or more trips per hour per stop. Moreover, only 5% of the urban population live in areas with an average transit frequency of more than four services per hour per stop. This work highlights the importance of including measures of transit frequency when investigating public transit access. The results also reveal the potential to use these measures to gain a more complete and realistic picture of public transit access and to explore the potential for mode substitution and accessibility for non-car households.

1. Introduction

A considerable body of research seeks to develop models and measures of accessibility, which has been defined as "the ease with which activities at one place may be reached from another via a particular travel model" (Liu and Zhu, 2004, p. 105). However there is relatively little research on accessibility using public transit as the travel mode. Martin et al. (2002) suggest that this has been due to lack of availability of public transit data and the more sophisticated modeling required due to the complexity of the journeys that can be undertaken by public transit.

Yet, accessibility by public transit modes is becoming increasingly important for two reasons. First, high levels of car travel and car dependence can have detrimental effects on both our physical health and the environment (Litman, 2003; Shannon et al., 2006). Increasing Green House Gas (GHG) emissions (Litman, 2003), traffic congestion (Litman, 1999), traffic accidents (Litman, 2003), oil price vulnerability, and physical inactivity and obesity related disorders (Sallis et al., 2004) have all been associated with increasing levels of car use. Reducing car travel to mitigate these negative effects is unlikely unless the destinations of daily life can be readily accessed via other transport modes. Thus it is important to understand whether destinations are accessible using public transit.

A second reason for the importance of public transit accessibility relates to equity issues. Regardless of the success of policies to reduce car travel and car dependence, there has always been, and will likely continue to be a segment of the population who do not have access to a private car and are reliant on public transit (Martin et al., 2008). The relative vulnerability of the public transit-reliant population – youth, elderly, marginalized – is the reason that Martin et al. (2008) have called for more attention to be paid to the incorporation of public transit into accessibility modeling.

In this research we are interested in the destinations that are accessible when people are restricted to public transit and walking modes of travel. We have addressed this question by creating a measure of public transit and walking access to a range of destinations that represent places that people travel to in everyday life. This paper reviews literature on measures of public transit accessibility, describes the calculation of a Public Transport and Walking

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Access Index (PTWAI) to destinations, describes a transit frequency measure, and presents results for the Auckland region of New Zealand.

2. Accessibility measures and public transit

2.1. Existing public transit accessibility measures

Lei and Church (2010) provide a good review of past accessibility research in general and accessibility with respect to transit in particular. Here, we only review accessibility with respect to transit. We categorize existing accessibility measures into three categories: (1) access to transit stops, (2) duration of public transit journey, and (3) access to destinations via public transit.

2.1.1. Access to transit stops

Most studies of accessibility that include public transit focus on physical access, that is proximity to a transit stop (Biba et al., 2010; Currie, 2010; Furth et al., 2007; Gutierrez and Garcia-Palomares, 2008; Hsiao et al., 1997; Kimpel et al., 2007; Lovett et al., 2002; Zhao et al., 2003). Some of these studies measure access from an administrative unit to a transit stop. Using an administrative unit as a proxy for the home of all residents within the unit can lead to errors (Currie, 2010). Attempts to address this problem have included using smaller units (Furth et al., 2007), calculating the ratio of the population within the transit stop service area with different levels of access (Gutierrez and Garcia-Palomares, 2008), and measuring accessibility from dwelling units to bus stops (Biba et al., 2010; Kimpel et al., 2007; Zhao et al., 2003).

Transit stop service areas have been calculated using both Euclidean buffers/distances and network buffers/distances, and in some instances (Zhao et al., 2003) have included barriers to walking such as rivers, lakes, walls and freeways. There is a consensus that network buffers are preferable because Euclidean buffers overestimate the service area of a stop (El-Geneidy et al., 2009; Horner and Murray, 2004).

An essential element in modeling access to transit stops is the distance that people walk to get to a stop. Researchers have typically used walking distances similar to planners' rule of thumb of 400 m (0.25 mile) and 800 m (0.5 mile) for estimating the distance people will walk to a transit stop or station (El-Geneidy et al., 2009; Hess, 2009; Hsiao et al., 1997; Kimpel et al., 2007; Lovett et al., 2002) although other distances have also been used (e.g. 300 m (Mondou, 2001), 500 m (Chapleau and Morency, 2005)). Whether or not these heuristics are valid in reality has been investigated using travel survey data (Burke and Brown, 2007a, 2007b; Zhao et al., 2003). Burke and Brown (2007a, 2007b) show that for Brisbane, Australia, the trip distances walked to destinations are generally much greater than the distance conventions commonly used by planners. For example the median distance people walked from home to public transport stops was 600 m and the median distance people walked from public transport stops to end destinations was 470 m.

2.1.2. Duration of public transit journey

Studies of access to transit stops are important because getting to public transit is a key component of the public transit journey. However, it is also important to know the places people can subsequently reach when traveling by public transit. Therefore it is important to focus not only on physical access, but to include the time taken to travel between the origin and destination (Lei and Church, 2010). This is achieved by accessibility models that use travel time access via public transit to provide a measure of accessibility.

O'Sullivan et al. (2000) used isochrone analysis to investigate public transport accessibility, generating maps of areas accessible by traveling on public transit. Only recently has there been additional work in this area with Benenson et al. (2009) proposing an approach to accessibility using a detailed transportation network in Israel. Their work includes street driving time estimates, bus lines, bus stops and bus departure and arrival times, as well as real world estimates of travel speed reflecting time and location dependent congestion. Cheng and Agrawal (2010) describe an accessibility tool to calculate transit service areas in terms of travel time. In an extension of the approach used in O'Sullivan et al. (2000), Lei and Church (2010) propose a measure of transit accessibility that includes bus service time as an attribute in the GIS. Accounting for the time of day is another advance that Lei and Church's approach has over earlier models.

2.1.3. Access to destinations via public transit

The above studies measure access to locations via public transit, but do not consider the types of destinations present at these locations. As noted in the definition above, access to different activities/opportunities is an important component of overall accessibility. It goes beyond considering just the accessibility of the transportation network – i.e. the ease of getting to a place (Curtis and Scheurer, 2010). This is achieved by building on purely spatial accessibility measures via public transit described above, and incorporating access to destinations via public transit, as for example in the place based approach to accessibility described in Huang and Wei (2002). Huang and Wei calculate access via transit to urban opportunities – measured by business and industrial land parcels classified into 11 sectors. They create a transit network and compute the distance between census tracts and opportunities. A measure of bus service levels – bus runs per day between the neighborhood and the opportunity – is included in the model. An obvious limitation of this approach is the use of a census tract as an origin point.

Travel time is also used as a measure of access. Burns and Inglis (2007) create a cost surface to determine the travel cost (time) to supermarkets and fast food outlets. They calculate travel time cost for three different modes: car, bus and walking. The bus travel cost is modeled based on the road type and frequency of buses along the road.

More recent models have combined distance and travel time measures for one or more transport mode. Yigitcanlar et al. (2008) devised a GIS based Land Use and Public Transport Accessibility Index (LUPTAI). The LUPTAI measures access to common land use destinations using public transit and walking modes. The LUPTAI combines accessibility calculated for walking distances, public transit travel time, and transit service frequencies. A difference between the LUPTAI and other accessibility indices is that the outcome indices are assigned to grid cells.

Silva (2008) developed the Structural Accessibility Layer (SAL), a contour measure of accessibility, which has been found to be valuable to planners (Silva and Pinho, 2010). The SAL is calculated for spatially disaggregated sub-regions defined on a case-specific basis. For each sub-region a regional diversity of accessibility index is calculated. This is a population weighted average of the number of different destination types accessible by three transport modes – non-motorized, public transit and car. Recently Curtis and Scheurer (2010) have described an accessibility model for strategic planning – spatial network analysis for multimodal urban transport systems (SNAMUTS). This tool assesses connectivity and centrality, which is the spatial proximity to a high number and range of activities, of urban public transport networks within the land use context. Unlike other transit accessibility models which use travel time as the 'cost', SNAMUTS used average travel time along a route segment divided by the frequency of service – departures per hour

– as the cost measure. Activity nodes are used instead of destinations. The activity nodes are determined by travel survey data as non-home destinations, centers defined in land use plans or strategies, and a measure for the intensity of activities determined by walkable catchment.

2.2. Transit service frequency

Service frequency, a critical aspect of accessibility, can vary markedly between peak and non-peak commuting times. Several studies have included measures of transit service level either as a complement to transit access measures or as an independent measure. There are two general approaches to measuring transit service frequency. The first excludes public transit that does not meet a minimum standard of service. For example an accessibility planning tool developed in Perth Australia by Curtis and Scheurer (2010) adopted a minimum service frequency standard of 30 min or better during weekday inter-peak. Similarly, in Jones et al.'s (2008) study of the relationship between hospital access and the stage of cancer at diagnosis and survival, sections of the road network with a bus service running at least every hour in the daytime from Monday to Saturday were identified along with patients who lived within 800 m of these routes.

The second approach includes all public transit trips when assigning a measure of service frequency. For example Currie (2010) uses the number of trips per week for each stop, whereas Mondou (2001) and Yigitcanlar et al. (2008) categorize transit service frequency by how often a bus/train arrives (e.g. at least every 15 min, at least every 30 min, and 30 min and more). Lovett et al. (2002) use a combination of service frequency and population size. Bus accessibility is classified based on the percentage of the population with access to a certain number of return bus services per day. For example, they define a moderate level of bus accessibility as at least 50% of residents having one or more return daytime services each weekday.

In summary, a comprehensive time-based measure of public transit accessibility needs to take account of the time taken to reach a transit stop, waiting times, the duration of the public transit journey, and the destinations available at the end of a trip. There is less research covering these latter two components of the public transit journey and very few studies take account of all components of the public transit journey. Those that do are often limited by calculating access to aggregated areas such as administrative boundaries. Including public transit service levels in accessibility analysis is rare, even though the number of public transit trips is an important factor in estimating accessibility in a meaningful way.

We build on existing public transit accessibility research by calculating two measures of public transit access. The first is a Public Transit and Walking Accessibility Index (PTWAI), which is a measure of potential access between land parcels and destinations via public transit (buses, trains and ferries) and walking modes. It accounts for all components of the public transit journey as discussed above, calculates access to disaggregate destinations, and works at the land parcel level, which is an improvement on calculating access for larger administrative areas. The PTWAI uses actual public transit route data to calculate access to a variety of common everyday destinations for a range of travel times. Time has been selected as the metric of accessibility based on evidence that it is perhaps more important than distance or cost in choosing travel modes (Frank et al., 2008; Salon, 2009). Additionally, time is closer to people's experience than distance (Lovett et al., 2002). With regard to public transit the important factors to users are travel time and service frequency (Curtis and Scheurer, 2010). Indeed, service level is the key factor driving public transit patronage in New Zealand (Wang, 2011). The PTWAI is based on travel time and includes a standard waiting time at each transit stop. However, it does not include a measure of service level/frequency. To address this limitation a complementary second measure of transit frequency has been calculated. The transit frequency measure is the average number of distinct public transit journeys through each transit stop.

3. Study area

The study area is the Auckland region, in the North Island of New Zealand (Fig. 1). The 440,993 Ha study area comprises what were, until amalgamation in November 2010, the southern part of Rodney District Council, the northern part of Franklin District Council and all of North Shore City, Waitakere City, Auckland City Manukau City, and Papakura District Council. At the 2006 census, the study area had a usually resident population of 1,298,757 people and comprised both urban (1,248,105) and rural (51,652) populations. Islands were excluded from the study area, with the exception of Waiheke Island, which has a sizeable residential population.

4. Method

4.1. Creating a multi-modal transit network

We used ArcGIS 9.2 to create a multi-modal network combining transit and walking modes using travel time as the network impedance. Transit data for buses, trains and ferries were obtained from the Auckland Regional Transport Authority. These data included transit stops, routes and schedules which were used to create the transit component of the network. Transit data were provided for a Friday and included travel times between each stop on each route. The scheduled travel times were used to calculate a transit travel time for each transit segment of the network. In addition, a wait time of 10 min was included at each transit stop where there was a change in transport mode or public transit route. This time is comparable to the average 'arrive to wait' time of 7 min

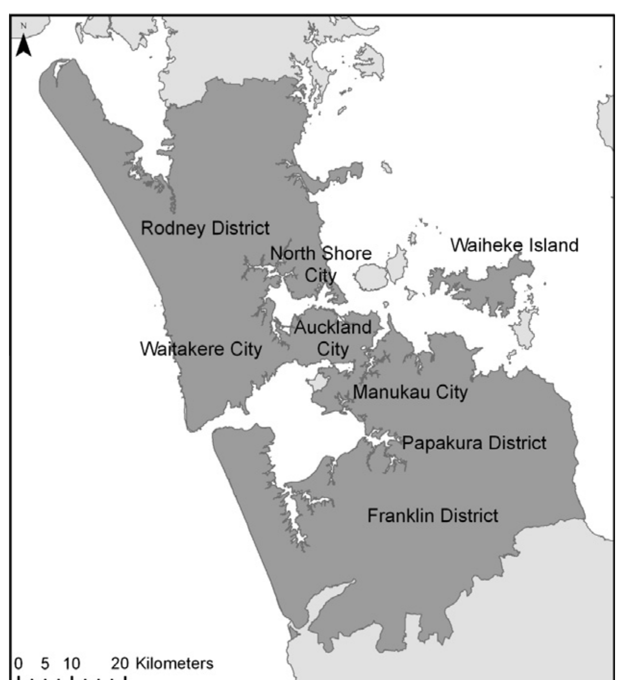

Fig. 1. Study area, Auckland region, New Zealand.

Table 1
Land use destinations.

Domains	Destination types	Count	Source	Date
Education	Preschools	547	Ministry of Education	2008
	Primary schools	392	Ministry of Education	2008
	Intermediate schools	245	Ministry of Education	2008
	Secondary schools	120	Ministry of Education	2008
	Tertiary institutes	9	Ministry of Education	2008
Financial	Banks and ATMs	512	www.koordinates.com	2008
	Post offices	105	www.koordinates.com	2008
Health	Accident and emergency	18	www.koordinates.com	2008
	General practitioners	463	Ministry of Health	2006
	Pharmacies	381	www.koordinates.com	2008
	Hospitals	18	Ministry of Health	2008
Shopping	Supermarkets	218	www.koordinates.com	2008
	Convenience stores	1041	www.koordinates.com	2008
Social and recreational	Cinemas	24	www.koordinates.com	2008
	Cafés and restaurants	2327	www.koordinates.com	2008
	Parks (access points)	4885	Land information New Zealand (modified)	2006
	Beaches (access points)	1463	Land information New Zealand (modified)	2006

found in a study of arrival characteristics of New Zealand public transit passengers (Lester and Walton, 2010). The 'arrive to wait' time is the amount of time a passenger plans to arrive before their intended public transit service.

Road network data were used to create the walking component of the network. A walk travel time for each road segment was calculated using the length of the road segment and a walking speed of 78 m/min. The walking speed is based on data from field observations of walking speeds in Auckland (Finnis and Walton, 2008).

4.2. Land use destinations

Data for 17 different land use destinations were obtained from a variety of sources and grouped into five domains: education, financial, health, shopping and social/recreational (Table 1). These domains and destinations represent common everyday destinations for which data was readily available and correspond to the main destinations in the New Zealand Household Travel Survey (Ministry of Transport, 2009).

4.3. Calculating accessibility

Transit and walking accessibility was calculated from every destination (e.g. every school) for each of the 17 destination types to land parcels in the Auckland region. Land parcels classified as water, road and rail were excluded from the analysis.

For each destination, service areas were calculated for five travel times using the walking and transit network (Table 2). Fig. 2 illustrates how the service areas were calculated for an example destination and an example travel time. The service area is a combination of a 50 m Euclidean buffer around the road centerlines and a 50 m buffer around the transit stops that are accessible from the destination within the given travel time. All land parcels within the service areas were assigned an accessibility score from 0 to 4, based on the travel times shown in Table 2. A score of 0 indicates a travel time exceeding 60 min travel by transit and on foot along the road network to get to the destination. A score of 4 represents high accessibility and means that the destination is accessible within 10 min transit and walking travel. Parcels greater than 50 m away from a road were allocated the average accessibility scores of their neighboring parcels in order to ensure they were assigned an accessibility score.

This resulted in each land parcel being assigned 17 accessibility scores (i.e. a score for each destination type) ranging from 0 to 4. A domain accessibility score was calculated by averaging the accessibility scores for all destinations within each domain. The final PTWAI value was calculated for each land parcel by summing the five domain accessibility scores. Averaged domain accessibility was calculated prior to calculating the PTWAI to ensure that each domain has equal weighting in the final index. The PTWAI for each parcel is a value ranging from 0 to 20 (Table 3).

Table 2
Accessibility scores and travel times.

Accessibility score	Travel time (min)
0	>60
1	40–60
2	20–40
3	10–20
4	0–10

4.4. Aggregating the accessibility index

The land parcel level accessibility scores were aggregated by averaging across each meshblock[1] to give a meshblock level PTWAI score. A total of 8634 meshblocks were included in the analysis. On average there were 43 parcels in each meshblock. The aggregated meshblock level scores allow comparisons with other meshblock level data (e.g. census data, NZ Deprivation Index) and easier visualization at the city scale. Calculating the index at the more disaggregate land parcel level and then aggregating to the meshblock level goes some way to avoiding potential aggregation errors (Apparicio et al., 2008).

4.5. Calculating transit frequency

We also created a measure of public transit service level for each meshblock using the data on transit stops (bus, train, ferry) and scheduled transit trips. Each transit stop was assigned a frequency value representing the number of trips through the stop during the entire day. Meshblocks were buffered by 400 m. The average number of trips per hour per stop were calculated for each meshblock to create the *transit frequency* measure. The above process was repeated for commuting hours (7–9 am and 4–6 pm) and non-commuting hours (6–7 am, 9 am–4 pm and 6 pm–midnight).

[1] A meshblock is the smallest census area used in New Zealand. Urban meshblocks contain around 100 people.

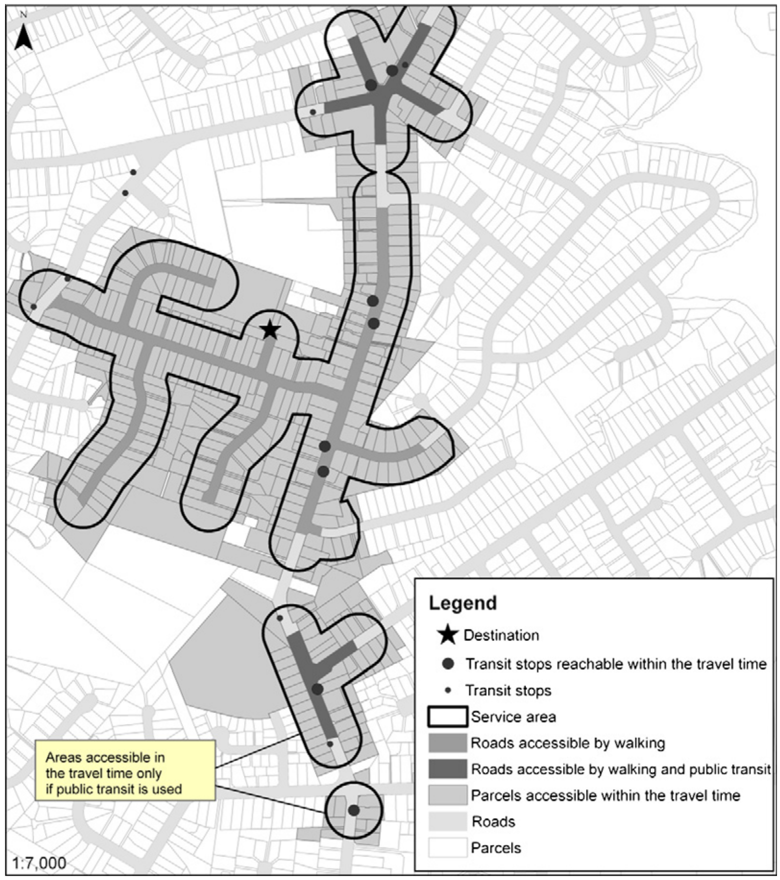

Fig. 2. Example service area calculation.

Table 3
PTWAI score descriptions.

PTWAI score	Label	Description
0–4	Very low	Accessible within a travel time >60 min on average
5–8	Low	Accessible within a travel time between 40–60 min on average
9–12	Medium	Accessible within a travel time between 20 and 40 min on average
13–16	High	Accessible within a travel time between 10 and 20 min on average
17–20	Very high	Accessible within a travel time <10 min on average

5. Results

Although the possible scores for PTWAI range from 0 to 20, the actual scores have a minimum of 1.8, a maximum of 19.9, and a median of 12.1 (Table 3). Of more interest are the relative differences in the PTWAI scores for different locations. The relative differences can be shown by mapping the PTWAI scores (Fig. 3). Fig. 3 shows the North Shore of Auckland with four neighborhoods labeled: Beach Haven, Northcote, Takapuna and Cheltenham. Takapuna and Northcote have relatively high public transit and walking access, whereas Beach Haven and Cheltenham have lower public transit and walking access.

The PTWAI scores are markedly different for urban and rural meshblocks. Urban meshblocks are those defined as 'Main Urban Area' and 'Satellite Urban Area' in the Statistics NZ urban/rural profile (Statistics New Zealand, 2005). As expected the urban meshblocks have higher PTWAI scores than the rural meshblocks, with urban meshblocks ($n = 8547$) having a median PTWAI score of 12.1, compared to a median PTWAI score of 3.3 for rural meshblocks ($n = 87$).

Transit frequency correlates with PTWAI scores for urban meshblocks. Meshblocks with higher PTWAI scores have a higher frequency of public transit at all times of day (Fig. 4). Not surprisingly transit frequency is higher during commuting hours than non-commuting hours.

Using New Zealand census 2006 data for the Auckland region we calculated the percentage of the population who live in meshblocks with different levels of public transit accessibility. Table 4 shows the percentage of the urban population resident in meshblocks by PTWAI score and trip frequency. As indicated 94.4% of the urban population live in meshblocks that have medium to very high PTWAI scores. However, if we include the transit frequency measure, only 26.5% of the urban population have medium–very high PTWAI scores *and* have at least two transit trips per hour per stop (Table 4). Conversely, 67.9% of the urban population live in meshblocks with medium–high access to destinations, yet have an average trip frequency of less than two trips per hour per stop. Moreover, only 5% of the urban population have adequate levels of service (i.e. four or more services an hour on average).

When we consider the transit frequency during commuting hours only the percentage of the urban population that have medium or high PTWAI scores and a transit frequency of two or more trips per hour per stop increases to 63.1% for trips during commuting hours (Table 5).

6. Discussion and conclusion

We developed two measures of public transit access: the PTWAI, a measure of potential access to destinations via public

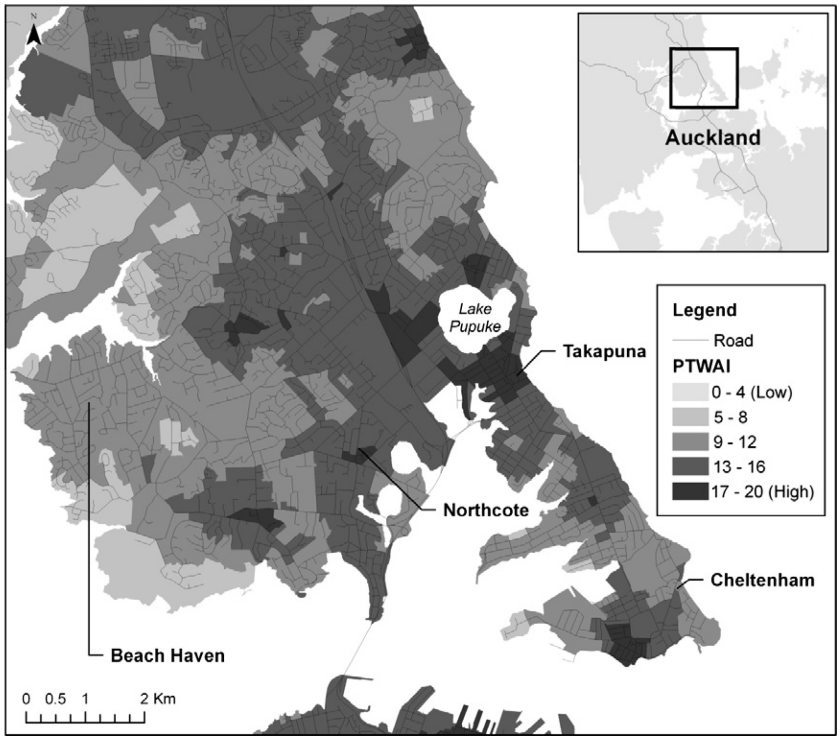

Fig. 3. PTWAI scores for the North Shore of Auckland.

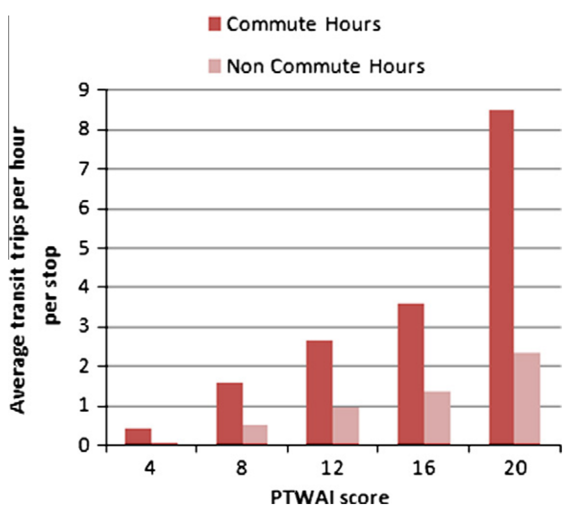

Fig. 4. Transit service frequency by PTWAI score for urban meshblocks.

Table 4
Percentage of the urban population by PTWAI categories and trip frequency for all hours for urban meshblocks.

PTWAI score	Transit frequency (%) Average trip frequency per hour per stop				Total (all trip frequencies) (%)
	<1	1–2	2–4	⩾4	
Very low: 0–4	0.9	0.1	0.0	0.0	1.0
Low: 6–8	3.4	0.8	0.4	0.0	4.6
Medium: 9–12	18.0	18.8	7.3	0.5	44.6
High: 13–16	11.1	18.5	12.4	2.1	44.1
Very high: 17–20	0.3	1.2	1.7	2.5	5.7
Total (all PTWAI scores)	33.7	39.4	21.8	5.1	100

transit and walking, and transit frequency, a measure of actual transit trips through an area. The PTWAI builds on and extends existing public transit accessibility measures by including all components of the public transit journey, calculating access to disaggregate destinations, and calculating accessibility at the land parcel level. It is a useful tool for exploring public transit accessibility and it provides the ability to investigate both overall public transit accessibility and the public transit accessibility of a single domain or destination type. Because accessibility is calculated at the parcel level it allows for investigation at a variety of scales (parcel level, meshblock level and a variety of possible aggregations). Thus the PTWAI could be useful for neighborhood level studies and for citywide and regional studies. The transit frequency measure provides a useful complement to the PTWAI and the combination of the two measures is more representative of real access than either alone.

These two measures allowed us to explore geographic aspects of public transit accessibility in the Auckland region. Of particular interest is the finding that although 94.4% of the urban population in the Auckland region can, on average, reach all destination types in less than 40 min of travel time via walking and public transit, only 26.5% of the urban population also live in areas that have at least two transit trips per hour per stop. By comparison, during commuting hours 61% of the urban population can reach destinations in under 40 min and have at least two transit trips per hour per stop. This indicates that Auckland's public transit system is designed for peak hour commuting and not to support the trips required for non-work travel. Also of note is the finding that only 5% of the urban population live in areas with an average transit frequency of more than four services per hour per stop. This analysis highlights the importance of including a measure of public transit frequency in accessibility analysis.

The two measures described in this paper could help identify areas where it is feasible for people to substitute non-car modes of travel and maintain a reasonable level of accessibility to

Table 5
Percentage of the urban population by PTWAI categories and trip frequency for commuting hours for urban meshblocks.

PTWAI score	Transit frequency (%) Average trip frequency per hour per stop				Total (all trip frequencies) (%)
	<1	1–2	2–4	⩾4	
0–4 (low access)	0.9	0.0	0.0	0.0	1.0
6–8	1.7	1.5	0.9	0.5	4.6
9–12	6.4	12.5	18.3	7.3	44.6
13–16	2.9	9.0	18.2	14.0	44.1
17–20 (high access)	0.1	0.2	1.1	4.3	5.7
Total (all PTWAI scores)	12.0	23.3	38.5	26.2	100

destinations given the current public transit system and destination locations. For example, mode substitution is likely to be more feasible in locations with high PTWAI and transit frequency scores. Attempts to encourage mode substitution in locations with low PTWAI or low transit frequency are likely to be unsuccessful or to result in transport related exclusion. The PTWAI and transit frequency measures also provide insight into locations where public transit improvements should be prioritized to increase the overall destination accessibility of Auckland's population; the same locations where it would be detrimental for non-car and other vulnerable households to live currently. We intend to use the PTWAI and transit frequency measures to examine the relationship between non-car and high deprivation households and public transit accessibility.

There are several assumptions implicit in the PTWAI. The first is that accessibility and transit frequency do not vary across a parcel. The PTWAI was calculated at the parcel level in order to limit aggregation errors (Apparicio et al., 2008). Although this is an improvement over calculating the PTWAI for larger administrative areas, accessibility and transit frequency may still vary across a parcel. This is particularly likely for larger parcels. The PTWAI assumes that the most accessible location on a parcel represents the entire parcel. This is not necessarily true, and may lead to an overestimation of accessibility. Ideally accessibility and transit frequency could be calculated from individual dwellings. However, as well as requiring accurate dwelling data sets this would require much greater computational capacity.

The second assumption is that the 50 m buffer used in PTWAI can be traversed instantaneously, which may lead to an overestimation of accessibility. In other words, first the PTWAI calculates the roads accessible within the available time and then it buffers these roads by 50 m. Consequently it does not account for time taken to traverse this additional 50 m. The third assumption is that the road network is an adequate representation of where people can walk. Information on sidewalk presence and formal and informal walking paths are not included in the PTWAI. This may lead to over or underestimations of accessibility. The fourth assumption is that walking times are only dependent on distance, ignoring barriers that may influence the duration of the walk such as variability in terrain and waiting times at road crossings and major intersections. The final assumption is that a person waits for 10 min at each transit stop. In reality this waiting time may vary for different stops and, assuming a person does not plan their public transit according to the schedule, this waiting time will be dependent on the service frequency. The transit frequency measure goes some way to addressing this.

In addition to these assumptions the PTWAI has limitations. Firstly, the 17 destinations were selected because they are common household travel destinations that data was readily available for. However, there are important omissions most notably: work destinations and visiting family/friends. In New Zealand, work destinations account for 9.1% of total trips by all modes taken in a year (Ministry of Transport, 2009) and 22% of all travel by public transport (Ministry of Transport, 2010, p.12). Work destinations were excluded from the PTWAI due to lack of data. Nonetheless, transit and walking access to workplaces is likely to be well represented by this index because people work at most of the destinations in the index and because many of the destinations in the index (e.g. cinemas, cafes, banks) are located where people work. Visiting family and friends is another important component of travel. In New Zealand, 27% of social and recreational trips taken in a year are to visit family and friends (Witten et al., 2009). This destination was not included in the index because it is difficult to represent the location of family and friends. In future work these locations could be represented by incorporating a measure of accessibility to residential areas.

A second limitation is that the PTWAI method has intensive computational requirements. For example, to calculate the service area for a destination type with a larger number of features and the 60 min travel time could take in the order of 40–60 h.[2] Due to the inability of ArcGIS to process very large datasets often the file had to be split into several parts in order to perform the service area calculations. Calculations for destination types with smaller datasets and shorter travel times did not take as long (e.g. ranging from 10 min to a couple of hours). Whether or not it is necessary to calculate accessibility at the level of individual dwellings is an important question. At one level it depends on the purpose of the study and it may be impractical and unnecessary in many instances. At another level we do not know how results might be impacted by the level of disaggregation. An important area for future research is assessing the differences in accessibility measures calculated at different spatial scales. A third limitation is the transit frequency measure. The measure used here is a basic one and could be improved by considering the number of routes per stop. A fourth limitation is that maximum walking distances to stops were not modeled. This means that the PTWAI includes walking distances to stops that may be greater than those commonly walked in reality. A fifth limitation is that the aggregate index is constructed by adding the averages of the domains. This means that, for example, primary schools will be less important than banks in the aggregate index. Unfortunately the problem of constructing an aggregate index from multiple components is a difficult problem and other ways of constructing the aggregate index would lead to different problems. For example, simply summing all 17 components to arrive at an aggregate index, would mean that education (with five components) weights more heavily than shopping (with only two). Any aggregate results should be viewed with this in mind. This limitation can be addressed by viewing disaggregate results, which is one of the strengths of this approach. Further limitations are that the PTWAI has only been calculated for a Friday and the reliance on the accuracy and availability of suitable destination data.

Despite these limitations the PTWAI and transit frequency measures provide us with valuable insights into public transit accessibility. Although the PTWAI has similarities with existing measures,

[2] The PTWAI was calculated on a workstation with an Intel Zeon Quad Core E5450 3.0G 12M 1333 processor and 2 × 2 Gb RAM.

notably the LUPTAI and SAL, it provides an original approach to the issue of measuring public transit accessibility. Comparisons between these different public transit accessibility measures would be a useful contribution to this field. In addition, future investigations in this area could improve on the PTWAI and other measures reviewed here by addressing the assumptions and limitations discussed above. Advances in data availability and resolution and greater computational power will allow for similar studies to be more easily applied in practice. Increased computational power will also allow for calculations of public transit accessibility from individual dwellings for specific times of day and integrating actual public transit schedule data. Finally, the PTWAI and transit frequency measures both represent important components of accessibility. Our results indicate that future work in improving the transit frequency measure and in combining the PTWAI and transit frequency measure is warranted.

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