

Research Article

Development of a Public Transport Accessibility Index for Older Commuters: A Time-Based Approach

Kaniz Fatima ¹, Sara Moridpour ¹, and Tayebbeh Saghapour²

¹Civil and Infrastructure Engineering Discipline, School of Engineering, RMIT University, Melbourne, Australia

²Design and Social Context, School of GUSS, RMIT University, Australia

Correspondence should be addressed to Kaniz Fatima; kaniz.fatima.shawon@gmail.com

Received 17 June 2022; Revised 10 August 2022; Accepted 23 August 2022; Published 12 September 2022

Academic Editor: Indrajit Ghosh

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The development of a public transport accessibility index for older travellers using total travel time is not a subject of frequent discussion. This study proposes a public transport accessibility index (EPTAI) which considers older peoples' travel time and the populations of the second-smallest statistical areas according to census data. EPTAI identifies the level of access of the elderly to public transport (train, tram, and bus) in an urban area. The time-based EPTAI includes different trip purposes, including shopping trips (trips to shopping centres), medical trips (travel to healthcare centres), education trips (travel to education centres), and recreation trips (e.g., restaurants, parks, and cafes). The developed index is validated using statistical validation methods, including Pearson's chi-square, likelihood ratio, linear-by-linear association, Cramer's V, contingency coefficient, and phi. In addition, the performance of the developed index is compared with household survey data and the public transport accessibility level (PTAL). The results indicate that older adults' public transport access varies depending on travel time, population density, and travel destination. The proposed index can be used for future planning/expansion and modification of public transport networks in urban and regional areas to meet the travel demands of older travellers.

1. Introduction

The global number of older persons is increasing rapidly compared with younger age groups [1]. According to the United Nations [2], the population aged 65 and over was 703 million, and the elderly population is projected to double to 1.5 billion in 2050. The travel needs of the older population may be even greater than those of the younger population since they have more time for nonhome activities and need more social services and healthcare [3]. The travel behaviour of the elderly is different from that of other adults [4], and they may have different schedules than working adults. Adequate transport accessibility for the elderly is crucial for older people and those with whom the elderly interact daily, specifically where others rely upon support such as childcare and voluntary work undertaken by senior citizens [5]. Older people feel independent if transportation is readily available [6]. Older people mostly prefer private transport as a mode of mobility [7]. One of the main reasons to avoid public transport is extended travel time, including long wait-

ing time. This may be an extra responsibility for family members, particularly for younger family members. For all these reasons, the study of elderly travel needs to be separated [8] from that of other age groups.

Transport accessibility measures can identify issues on which action is required to improve the overall transport system and infrastructure. Public transport (PT) access in urban areas is a critical issue for older people. Many researchers have focused on transport accessibility [9–15]. Travel time and distance are the two most popular variables used to measure accessibility. Most proposed accessibility studies are based on distance measures [16–18]. However, travel time is a critical component that directly affects travel behaviour and choice of travel mode. If the total travel time is higher, the access level is more likely to be lower. Although time-based approaches have been considered on several occasions, they have been rarely discussed for older travellers, particularly when considering time components such as elderly walk time, total waiting time, and in-vehicle time; it is not discussed to develop indices. In addition, access to

various destinations and PT stops (for train, tram, and bus) in small geographic areas are not widely discussed for older travellers. The lack of detailed travel data on older peoples' travel behaviour is a major reason for the limited research on the accessibility to PT of this group.

This paper focuses on filling the gap in time-based PT accessibility studies for older people. In this research, people aged 65 and over are considered elderly/older people [19]. To encourage older people to use PT, adequate access to various destinations and PT stops is necessary. If a destination is reachable by older people utilising PT, there is a greater possibility of them accessing it. The objective is to develop a time-based elderly public transport accessibility index (EPTAI) to calculate access levels for older people in terms of travel time. In this study, metropolitan Melbourne datasets of older peoples' walk times, travel destinations, PT stops, total waiting times, the older population, the road network, and information at the level of the smallest statistical area are analysed to develop the EPTAI. The time-based EPTAI includes different trip purposes, including shopping trips (trips to shopping centres), medical trips (travel to healthcare centres), education trips (travel to education centres), and recreation trips (e.g., restaurants, parks, and cafes). The developed index is validated using statistical validation methods, including Pearson's chi-square, likelihood ratio, linear-by-linear association, Cramer's V, contingency coefficient, and phi. In addition, the performance of the developed index is compared with household survey data and the public transport accessibility level (PTAL) [20–22].

This paper is structured as follows. The following section (Section 2) discusses previous research studies. Section 3 describes the study area and the datasets used for the development of the index. Section 4 describes the methodology of this study. Section 5 the steps in the development of the index, including the calculation of the time and population components. Next, Section 6 presents the results and discussion and discusses older peoples' PT accessibility levels in metropolitan Melbourne according to the proposed index. Validation and Spatial Transferability of EPTAI is presented Section 7. Finally, conclusions and directions for future research are summarised in Section 8.

2. Literature Review

Transport accessibility studies can be classified into different classes and themes [23, 24], including social and transport, improvement of infrastructure, accessibility indices, and mode choice. However, to date, no best approach to the measurement of accessibility has been identified [25]. As stated previously, the two main themes of accessibility indices are time-based and distance-based measures. Table 1 provides a synthesis of distance-based accessibility index studies, while Table 2 summarizes time-based accessibility index studies.

This research study introduces an index based on time-based approaches. Although the time approach has been applied on several occasions [32, 33], for older people, time-based accessibility index is not discussed widely. Many researchers around the world have worked on older travel-

lers' active transport based on time-based measures [24, 34–45]. Some existing time-based index studies can be summarised as follows (Table 2).

Detailed research on the improvement of metropolitan Melbourne liveability has been conducted by the Department of Environment, Land, Water, and Planning [46]. This study presents a detailed plan for neighbourhoods accessible to different necessary destinations within 20 minutes. However, this study does not discuss the level of older commuters' access to metropolitan Melbourne. According to the Senior Final Report [47], the mean walking trip time for older people is 13.7 minutes, compared with 12.5 minutes for younger adults. For each destination, two thresholds, the desirable and maximum walking travel times, differ for the elderly from those of other adult groups. These values were adopted and converted from Austroads, the Association of Australian and New Zealand Road Transport and Traffic Authorities [48].

A common similarity among existing time-based studies is that none discuss the access of older travellers to PT and walking travel separately for different destinations accessed by older people. For each destination, the travel time of older people differs depending on the walk time to the destination, in-vehicle time, and average waiting time. These affect the overall accessibility level for that specific destination. For example, accessibility to healthcare centres and recreation centres differs because of the variation in travel time. Therefore, it is important to calculate each destination's accessibility level for older people separately to obtain more accurate results. Other issues for these previous studies are generally related to older peoples' mode choice preferences considering a specific larger case study area. If the PT access level is better for older travellers, preference for PT for day-to-day travel can be increased. Therefore, it is important to identify the access level for future PT access implementation and improvement. This paper also evaluates SA1s as a case study area for the analysis of more detailed access levels considering older peoples' travel.

3. Study Area and Dataset

The databases and study area are presented in this section to describe the process for calculating the index.

3.1. Study Area. As stated previously, metropolitan Melbourne datasets were evaluated for this study. Melbourne, the state capital of Victoria, Australia, has several public transport modes, including trains, trams, and buses. In this study, Metropolitan Melbourne Statistical Area Level One (SA1) datasets of older peoples' public transport travel were analysed. According to the Australian Statistical Geography Standard (ASGS), SA1s are the smallest level (i.e., the smallest unit to release census data) in the main structure. SA1s conform most closely to walking catchments. Metropolitan Melbourne is divided into around 10,290 SA1s, the area of which is not uniform, ranging from 0.0023 km² to 275.61 km². The population of SA1s varies from 200 to 800, with an average of approximately 400 people. A detailed map of metropolitan Melbourne

TABLE 1: Distance-based PT accessibility index study.

Index and references	Definition	Highlights
Utility-based theory: [25, 26]	Assumes that individuals maximize their utility	Individuals' accessibility is calculated based on the traveller's preferred activity opportunities/destination, rather than just the nearest opportunity/destination. A key disadvantage is that it requires extensive data collection of individuals' travel patterns and opinions
Two-point distance accessibility theory [27–29]	Counts the distance from one location to a given destination	Considers several components: network connectivity, the distance between origin and destination, service quality, elderly participation, mixed land use, service connection, and number of trips and parking
Land use and public transport accessibility (LUPTAI) [30, 31]	LUPTAI use destination-based accessibility analysis in GIS, applied datasets obtained from several sources, and use information relating to the land use destinations, the road/pedestrian, and the public transport network	It is a distance-based measure that did not calculate the effect of travel time and waiting time
Public transport accessibility level (PTAL) [20, 21]	PTAL is used in United Kingdom transport planning to assess the geographical public transport access level	PTAL is a simple, easily calculated approach that hinges on the distance from any point to the nearest public transport stop and service frequency at those stops
Service accessibility transport disadvantage index (SATDI) [18]	This research was aimed at developing a spatial index to quantify the degree of service accessibility and transport disadvantage for the elderly population of two of South Australia. The index considered the bus frequency and walking distances for the elderly	SATDI is a good measure for regional elderly public transport accessibility. However, the calculation is not straightforward for a metropolitan area with a train, tram, and bus

TABLE 2: Time-based PT accessibility index study.

Index and references	Definition	Highlights
Time-based transit service area tool (TTSAT) [42]	All travel time components from travellers' origin to destination (i.e., walk time, wait time, and in-vehicle time) are included in the travel time calculations	The population is not considered in this index. Also, it is mainly a mapping tool
Person-based measures [43]	This measures each person's travel activity within a given time frame	The calculation of this measure is mainly applicable to a small sample size
Local index of transit availability (LITA) [44]	A study of LITA used three primary time variables for calculation	Considers the frequency of the service, capacity, and coverage of service. Also considers the population

SAIs was extracted from Australian state datasets [49] using ArcMap 1071.

3.2. Datasets

3.2.1. Household Survey Data. The Victorian Integrated Survey of Travel and Activity (VISTA) is a detailed database of Victorian household travel. This detailed picture of travel informs transport and land use planning decisions made by the state government (Department of Transport Australia). VISTA datasets [50] are combined with a wide range of data, including personal characteristics of travellers (e.g., age and gender), travel variables (e.g., destination, travel mode, and time of travel), and spatial travel characteristics (e.g., statistical/geographical areas). Around 46,563 travel responses for weekdays and weekends were documented

for metropolitan Melbourne. Of these responses, 7,029 responses were from the elderly. The living area details (such as SA1 and home subregion location), travel mode, travel time, trip change, and trip destination were extracted and analysed using the statistical software IBM SPSS 26. According to VISTA data, 83% of Melbourne's older travellers prefer private transport, mainly as drivers. Around 3% of Melbourne's older people walk to their destinations. The rest (around 14%) of Melbourne's older people use public transport modes (train, tram, and bus). The VISTA datasets were used to validate the EPTAI.

3.2.2. Points of Interests (POIs). A database of detailed "features of interest" was collected from the Victorian Government open data source [49]. These features include information on various destinations/trip purposes. According to

TABLE 3: Summary statistics of travel time to each category of POI.

Time component	SA1 centroid to travel time (min)				SA1 centroid to PT stop/station travel time (min)
	Shopping centre	Healthcare centre	Education centre	Recreation centre	
Meantime	11.66	11.67	5.54	17.06	26.19
Standard deviation time	23.00	4.81	4.81	15.54	79.63

the dataset, the most common places to which the senior population group travels are shops and shopping centres, healthcare centres, and places of retirement recreation [51]. According to VISTA [50], older people mostly travel to four main categories of POIs: (1) shopping centres, (2) healthcare centres, (3) education centres, and (4) recreational centres [52]. Hence, these four most-travelled POI categories by the elderly were considered for the calculation of the index in this study.

3.2.3. Public Transport Coverage. Detailed datasets for the metropolitan Melbourne PT system, including train, tram, and bus networks, were collected from open government databases [49]. In some areas of metropolitan Melbourne, specifically in outer Melbourne SA1s, the POIs are not in the vicinity of the origins. In those cases, PT accessibility is very low as the total travel time is high. In most SA1s, the nearest bus stop is closer than the closest POI. Table 3 presents a summary of statistics on older peoples' travel times to four travel destinations/POI categories and PT stops/stations from SA1 centroids.

Table 3 reveals that the mean travel time is much higher to a PT stop than to the four POIs. The table also explains the standard deviation time is different for each POI and PT stop. Therefore, calculating individual POIs and access to PT stops for each SA1 provides more accurate accessibility measures of the travel of older people.

3.2.4. Time Data. Service frequency data were calculated from each mode's timetable during the weekdays' older travellers' peak hour travel. Older travellers' travel peak hour is between 9:30 a.m. and 3 p.m. [9]. Schedules, frequency, and in-vehicle time datasets for all three PT modes were extracted from Public Transport Victoria (PTV) [53]. The datasets show that the frequency of PT is much lower in Melbourne's outer suburbs than in the inner and middle suburbs. The frequency varies depending on SA1s, POIs, and time of day.

3.2.5. Road Network. Road network datasets were used to calculate the nearest POI and PT stop/station from the SA1 centroids. The detailed road network shapefile was collected from [49], Network_Vicmap Transport. The road network datasets were analysed using ArcMap Network Analyst Extension. ArcMap network analysis tools provide spatial analysis using data on the road network, travel directions, closest destination, closest PT stop/station, and analysis of service area.

3.2.6. Population Data. Population is one of the important attributes for measuring transport access. Many researchers used population as an important contribution to the access

TABLE 4: Population summary of metropolitan Melbourne SA1s.

Population in SA1	Minimum*	Maximum	Standard deviation	Mean
Elderly	0	778	48.578	82.260
Total population	0	4354	208.076	435.843

*Minimum population is zero because the Melbourne Airport SA1 does not have any population.

level identifications [54]. In Greater Melbourne, 14% of the total population is identified as elderly [55]. Population datasets for older people were extracted from census data. The census datasets were extracted from the Australian Urban Research Infrastructure Network [56]. Table 4 presents a summary of the population statistics of metropolitan Melbourne SA1s.

The elderly population is not consistent for all SA1s. For instance, some inner Melbourne SA1s have a low population density of the elderly. Similarly, some outer Melbourne SA1s have high population densities of the elderly. Therefore, consideration of the older population is necessary to calculate the EPTAI and provides more accurate accessibility results for specific SA1s.

4. Methodology

The development of the elderly accessibility index comprised two steps. The first step involved the calculation of the time component, and in the second step, the population component was calculated. The framework for the calculation of travel time is also presented in Figure 1.

In the proposed EPTAI, the total travel time is divided into four segments: (1) walk time to a public transport stop/station, (2) wait time at the stop/station, (3) in-vehicle travel time, and (4) walk time from the stop/station to the final destination/POI. Therefore, in the development of the EPTAI, travel time was calculated as follows.

- (i) If the POI is not within walking range of a PT stop/station, more than one PT mode may be used for travel. Therefore, the total travel time includes (1) walk time from the SA1 centroid to the nearest PT stop/station, (2) average wait time at the stop/station, (3) in-vehicle travel time, (4) walk time to the PT stop/station nearest to the destination POI, (5) average wait time at the stop/station, (6) in-vehicle travel time to destination POI, and (7) walk time to destination POI

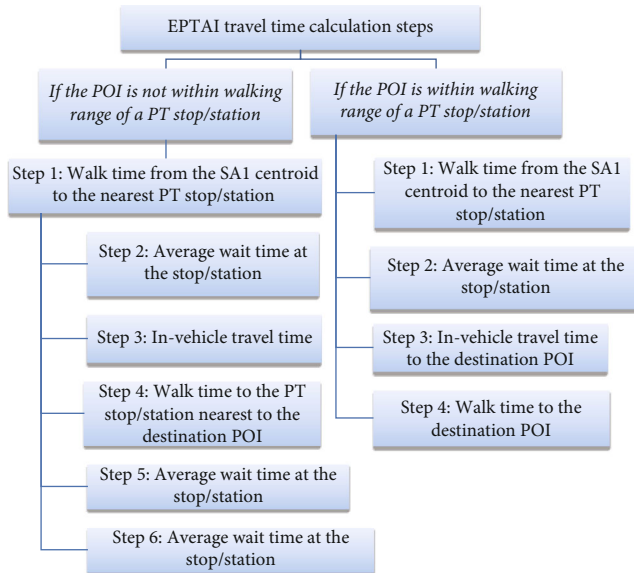


FIGURE 1: The framework EPTAI travel time calculation steps.

- (ii) If the POI is within walking range of a PT stop/station, the total travel time includes (1) walk time from the SA1 centroid to the PT stop/station, (2) average wait time at the stop/station, (3) in-vehicle travel time to the destination POI, and (4) walk time to the destination POI

5. EPTAI Development

5.1. Accessibility Index Parameters. To calculate the EPTAI, the centre of the SA1 polygon is identified for all SA1s. The total travel times between SA1 centres and POIs are separately calculated using open data sources. Datasets are analysed using IBM SPSS 26 and ArcMap 1071. The network travel time is measured from the centre of the SA1 to the closest PT stop/station and the POI. For instance, if a specific SA1 has more than one healthcare centre within the threshold of the walk time of older commuters, the nearest healthcare centre is considered for index development. In addition, the nearest PT stop for this healthcare centre is considered for the calculation of travel time.

5.1.1. Walk Time (WT). The older commuters' walking speed of 0.70 m/sec (2.52 km/hr) is used to calculate walk time. This value is consistent with the existing literature on the average walking speed of older people [57, 58]. The walk distances to the nearest PT stop/stations from the SA1 centroid and POIs are measured using ArcMap 1071.

5.1.2. Average Waiting Time (AvWT). The average wait time is between the arrival time to the nearest PT stop/station and the arrival of the service. For each selected route, the average wait time is considered to calculate the PT transport frequency. For instance, if a service runs every 10 minutes, the service frequency is 6 per hour. In this case, the AvWT

is 5 minutes. The AvWT is estimated as half the headway (i.e., the time interval between services), as shown in

$$\begin{aligned} \text{AvWT}_{\text{SA1}} &= 0.5 * (60F_i) + 0.5 * (60F_j), \\ \text{AvWT}_{\text{SA1}} &= 0.5 * (60F_i) \text{ if } F_j = 0, \end{aligned} \quad (1)$$

where AvWT_{SA1} is the average waiting time (in minutes) for an SA1 to a specific POI, F_i is the frequency of PT mode to the POI, and F_j is the frequency from the PT stop/station to the connecting PT mode to the destination POI. If the POI is within walking range, $F_j = 0$.

5.1.3. In-Vehicle Time (InVT). InVT is a significant travel time variable. In-vehicle time is the total travel time spent in a transport mode. In this study, in-vehicle time is calculated using the public transport journey planner (<https://www.ptv.vic.gov.au/journey>). InVT is calculated for all POIs and each trip separately.

5.1.4. Total Travel Time (TTT). The total travel time is the summation of walk time (WT), average wait time (AvWT), and in-vehicle travel time (InVT). Equation (2) presents the TTT calculation. The total travel time is calculated for each SA1 (10,289 SA1s in metropolitan Melbourne) separately.

$$\text{TTT} = \text{WT} + \text{AvWT} + \text{InVT}. \quad (2)$$

For each category of POI, the TTT ratio is calculated as a weighted value of TTT for each POI with respect to TTT for all categories of POI. For instance, to calculate the TTT ratio for shopping centres, the TTT for the shopping centre, and the TTT for the other three POIs (healthcare, education and recreation centre) are considered. Equations (3)–(6) are used to calculate the TTT ratio for four POI categories.

$$\text{TTTRatio}_{\text{POI1}} = \frac{\text{TTT of POI1(Shopping centre)}}{\text{TTT of (POI1 + POI2 + POI3 + POI4)}}, \quad (3)$$

$$\text{TTTRatio}_{\text{POI2}} = \frac{\text{TTT of POI2(Healthcare centre)}}{\text{TTT of (POI1 + POI2 + POI3 + POI4)}}, \quad (4)$$

$$\text{TTTRatio}_{\text{POI3}} = \frac{\text{TTT of POI3(Education centre)}}{\text{TTT of (POI1 + POI2 + POI3 + POI4)}}, \quad (5)$$

$$\text{TTTRatio}_{\text{POI4}} = \frac{\text{TTT of POI4(Recreation centre)}}{\text{TTT of (POI1 + POI2 + POI3 + POI4)}}. \quad (6)$$

5.1.5. Older Population (P_{ratio}). Population density is a significant measure for the calculation of public transport and walking accessibility measures [28, 32, 40, 59–61]. However, consideration of the elderly population for EPTAI is not very common. To enhance the accuracy of the EPTAI, the population ratio of SA1 is normalised (see Equation (7)), as the

TABLE 5: Chi-square test results.

POI/destination	Validation method	Statistics value	df	<i>p</i> value
Shopping centre	Pearson chi-square	41766.00	21	0.001
	Likelihood ratio	32039.01	21	0.001
	Linear-by-linear association	2785.00	1	
Healthcare centre	Pearson chi-square	49580.00	25	0.001
	Likelihood ratio	36777.10	25	0.001
	Linear-by-linear association	3555.10	1	
Education centre	Pearson chi-square	51450.00	25	0.001
	Likelihood ratio	36875.00	25	0.001
	Linear-by-linear association	3244.00	1	
Recreation centre	Pearson chi-square	41160.00	20	0.001
	Likelihood ratio	3237.00	20	0.001
	Linear-by-linear association	1678.18	1	

No. of valid cases/number of analysed SA1s: 10289.

older population is low in each SA1 compared to the total population.

5.1.6. Development of Accessibility Index Equation. The EPTAI is a multiple of travel time and population. All the distances are measured in kilometres, and the times are in minutes. The proposed accessibility index is presented in

$$EPTAI = \sum_{j=1}^4 (TTT_{\text{ratioPOI}})(P_{\text{ratio}} * 102), \quad (7)$$

where TTT_{ratioPOI} is the total travel time ratio for a specific POI (Equation (8)) and P_{ratio} is the population ratio (Equation (9)).

$$TTT_{\text{ratioPOI}} = \frac{TTT \text{ of Specific POI}}{\sum_1^4 TTT \text{ of POI}_j}, \quad (8)$$

where j is the ranges from 1 to 4 comprising the four main categories of POI for the elderly, TTT is the WT to nearest PT stop/station + $InVT$ + $AvWT$ + WT to nearest stop/station of POI + $AvWT$ for POI travel + $InVT$ for POI travel + WT to POI, and TTT is the WT to nearest the PT stop/station + $InVT$ + $AvWT$ + WT to POI (if WT to the nearest stop/station of POI is 0).

$$P_{\text{ratio}} = \frac{\sum_1^n \text{Elderly Population}}{\sum_1^n \text{All group Population}}, \quad (9)$$

where n is the number of SA1s.

The index is grouped into six main categories, (1) very poor, (2) poor, (3) moderate, (4) good, (5) very good, and (6) excellent, based on the calculated values of EPTAI. These categories measure the levels of access to PT for the elderly. The quantile classification method was used to identify categories for EPTAI. The quantile method is a suitable method for both index comparison/classification and map reading [62].

TABLE 6: Symmetric measure test results.

POI/destination	Validation method	Value	<i>p</i> value
Shopping centre	Phi	2.00	0.001
	Cramer's V	1.00	0.001
	Contingency coefficient	0.90	0.001
Healthcare centre	Phi	2.23	0.001
	Cramer's V	1.00	0.001
	Contingency coefficient	0.92	0.001
Education centre	Phi	2.23	0.001
	Cramer's V	1.00	0.001
	Contingency coefficient	0.91	0.001
Recreation centre	Phi	2.00	0.001
	Cramer's V	1.00	0.001
	Contingency coefficient	0.90	0.001

5.2. EPTAI Assessment. Cross-tabulation (crosstab) statistical tests were conducted using IBM SPSS 26 to measure the correlation between the observed VISTA trip data and the accessibility values for each SA1 measured by the EPTAI. Crosstab analysis uses the p value to determine whether to reject or accept the correlation among the variables. Statistical analysis is conducted separately for each POI. Cross-tabulation analysis, chi-square, likelihood, and linear-by-linear association were applied to evaluate the accuracy of the EPTAI using IBM SPSS 26. These statistical measures are consistent with the statistical measures used in the literature [60, 63–65]. These tests measure the correlations between the components used in the EPTAI calculation. If the calculated p value is less than 0.005, it can be assumed that the result of the statistical test is significant, and the variables are correlated with each other. Table 5 presents the crosstab analysis results between the six EPTAI categories (very poor, poor, moderate, good, very good, and excellent) and the observed PT usage by the elderly.

TABLE 7: Chi-square-based measure comparison for EPTAI and PTAL.

POI/destination	Validation method	EPTAI		PTAL	
		Value	<i>p</i> value	Value	<i>p</i> value
Shopping centre	Chi-square	41766.00	0.001	35490.00	0.001
	Likelihood	32039.01	0.001	30059.00	0.001
Healthcare centre	Chi-square	49580.00	0.001	53860.00	0.001
	Likelihood	36777.10	0.001	39474.00	0.001
Education centre	Chi-square	51450.00	0.001	48975.00	0.001
	Likelihood	36875.00	0.001	35886.00	0.001
Recreation centre	Chi-square	41160.00	0.001	39160.00	0.001
	Likelihood	32317.00	≤0.001	31170.45	≤0.001

According to Table 5, the *p* values are less than 0.005 for all four POI categories. Therefore, the accessibility measures calculated by the EPTAI and older travellers' PT usage are correlated. Table 6 presents the symmetric measures for all four POIs.

The symmetric measure test describes the correlation between more than two variables. Phi, Cramer's V, and the contingency coefficient are symmetric measure tests. All three symmetric measures test the *p* value (limit between -1 and 1) and indicate the relationship between variables. The EPTAI categories, the older population, and the older commuters' PT usage were evaluated using the symmetric measure test. The available datasets for elderly PT usage in metropolitan Melbourne are very limited, and this also affects the results of the index assessment. Due to the limited valid datasets, the variables are less dependent on each other but still show correlations, and the *p* value is close to the limit (-1). As stated previously, no elderly time-based accessibility index has been reported to date which measures access levels. Therefore, the accuracy of the developed EPTAI was compared with an existing index, the public transport accessibility level (PTAL). PTAL is a well-established approach to measuring PT access levels. The method was first introduced in 1992 to measure the density of the PT network in Greater London [66]. PTAL is widely recognised all over the world and has been reviewed and used by different transport researchers/practitioners worldwide [14, 20–22]. PTAL considers walking time from destinations to PT stops/stations, service frequency, and average wait time, calculates the total access time, and converts it into the equivalent doorstep frequency [14, 22]. However, the proposed EPTAI also considers in-vehicle time, the elderly population, and road network information in the calculation of the index. To compare EPTAI and PTAL, PTAL was calibrated for older commuters using metropolitan Melbourne datasets. PTAL was calculated for all 10,289 SA1s and different modes of PT (train, tram, and bus) to maintain consistency and provide a valid comparison. Table 7 presents and compares the results of crosstab, chi-square, and likelihood tests for EPTAI and PTAL.

The test results show similarities between both measures. From Table 7, $p < 0.005$ indicates that both EPTAI and PTAL are statistically significant. Table 7 shows that the

EPTAI results are more accurate than those of PTAL and more accurately replicate the observed older commuters' PT usage to access shopping, education, and recreation centres. However, PTAL values are more accurate in measuring accessibility to healthcare centres.

6. Results and Discussion

Table 8 presents a summary of the results of older peoples' accessibility levels for the four main travel destinations in metropolitan Melbourne SA1s.

Table 8 shows the results for index range, SA1 number, and PT accessibility for SA1s in percentages. The index range value was calculated using Equation (7). As mentioned before, the indices were classified into six categories of access level: very poor, poor, moderate, good, very good, and excellent. The index classification presents the level of access of the elderly to PT, where a higher index value means greater travel time and lower public transport accessibility for older people. If an SA1 is classified at a very poor level, it indicates that a longer travel time is required to reach that specific destination from a specific SA1. Individual calculations were conducted for all SA1s considering four POIs. Table 6 shows that around 50% of the total of 10,289 SA1s have very poor to moderate levels of shopping centre access for older people. Only around 16% of all SA1s are assessed as having excellent shopping centre accessibility for older commuters.

Moreover, similar results were observed for healthcare centres, education centres, and recreation centres. Around 33.2% of the total number of 10,289 SA1s have very poor and poor access levels for healthcare centres in relation to PT travel by older people. In some SA1s, comparatively close destinations are assessed as having poor PT access levels. For education centres, around 33.27% of the total of 10,289 SA1s have very poor and poor levels of PT access for older commuters. In the case of recreation centres, more than 36.98% of the 10,289 SA1s have very poor and poor PT access levels for older people. One of the main reasons for these poor accessibility levels is that comparatively close facilities take more time to reach by PT, as it does not cover all the destinations in SA1s. Therefore, older people need more walk time and effort to reach their destinations. This

TABLE 8: Summary of elderly PT accessibility.

POI/destinations	Accessibility	Index ranges and levels					
		Excellent	Very good	Good	Moderate	Poor	Very poor
Shopping centre	Index range	>2.096	2.906-4.813	4.813-6.919	6.919-9.759	9.759-14.755	<14.755
	SA1 number	1682	1692	1722	1715	1746	1732
	PT accessibility for SA1s (%)	16.34	16.44	16.73	17.15	16.96	16.38
Healthcare centre	Index range	>1.203	1.203-2.001	2.001-2.886	2.886-4.089	4.089-6.170	<6.170
	SA1 number	1723	1729	1694	1729	1705	1707
	PT accessibility for SA1s (%)	16.74	16.80	16.46	16.80	16.57	16.63
Education centre	Index range	>1.231	1.213-2.048	2.048-2.953	2.953-4.185	4.185-6.315	<6.315
	SA1 number	1726	1734	1706	1700	1721	1702
	PT accessibility for SA1s (%)	16.78	16.85	16.58	16.52	16.73	16.54
Recreation centre	Index range	>1.269	1.269-2.118	2.118-3.059	3.059-4.339	4.339-6.767	<6.767
	SA1 number	1249	1381	1863	1991	1890	1915
	PT accessibility for SA1s (%)	12.14	13.42	18.11	13.35	18.37	18.61

Total analyzed SA1s = 10,289.

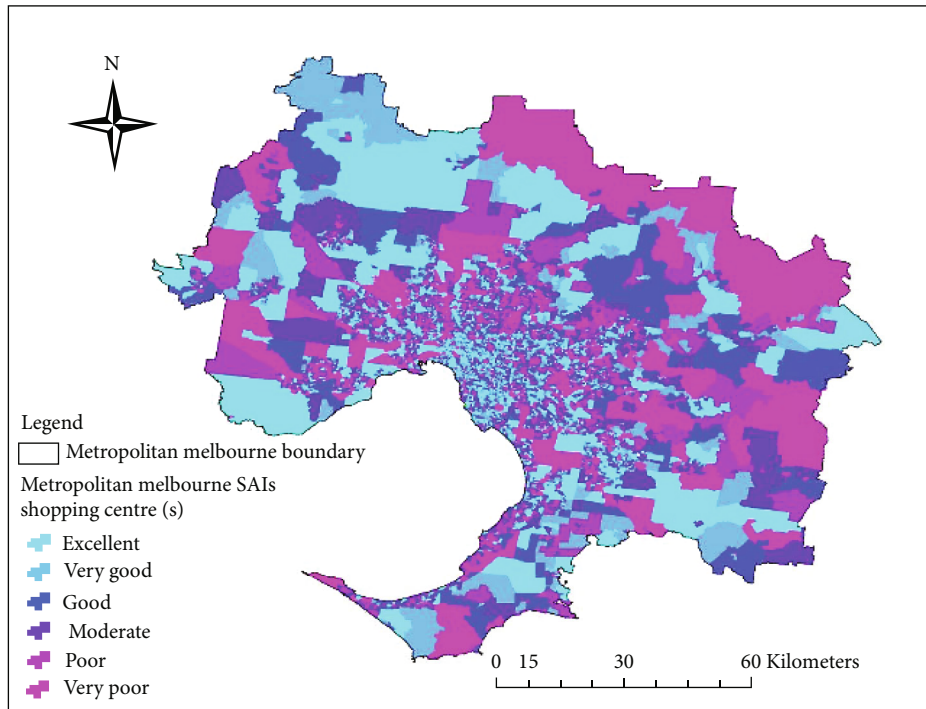


FIGURE 2: Older people public transport accessibility index for shopping centre(s) (<https://desktop.arcgis.com/en/arcmap/latest>) [67].

may be one of the main reasons that older commuters avoid PT and prefer private transport.

Figures 2–5 illustrate the spatial distribution of elderly PT access levels for metropolitan Melbourne in relation to four main trip purposes. Figures 2–5 are developed using ArcMap 1071 (<https://desktop.arcgis.com/en/arcmap/latest>) [67]. The spatial distribution of elderly PT accessibility levels is presented in different colours using the quantile classification method. A lower value indicates excellent accessibility, and a higher value represents poor access. Figure 2 shows that PT access by the elderly to shopping centres is not

always easy. Shopping centres generally cover a wide area, and the PT route to a shopping centre route from the place of origin is not straightforward. This increases the total travel time (TTT). Change of travel mode may be necessary to reach shopping centres from different SA1s. Changing mobility mode increases the TTT because of the increase in *AvWT* and *InVT*, which decreases the accessibility level. Analysis of the spatial distribution of access to shopping centres (Figure 2) reveals that some Melbourne SA1s are classified as having excellent access levels. This specific SA1s may be serviced by very good bus access, or they

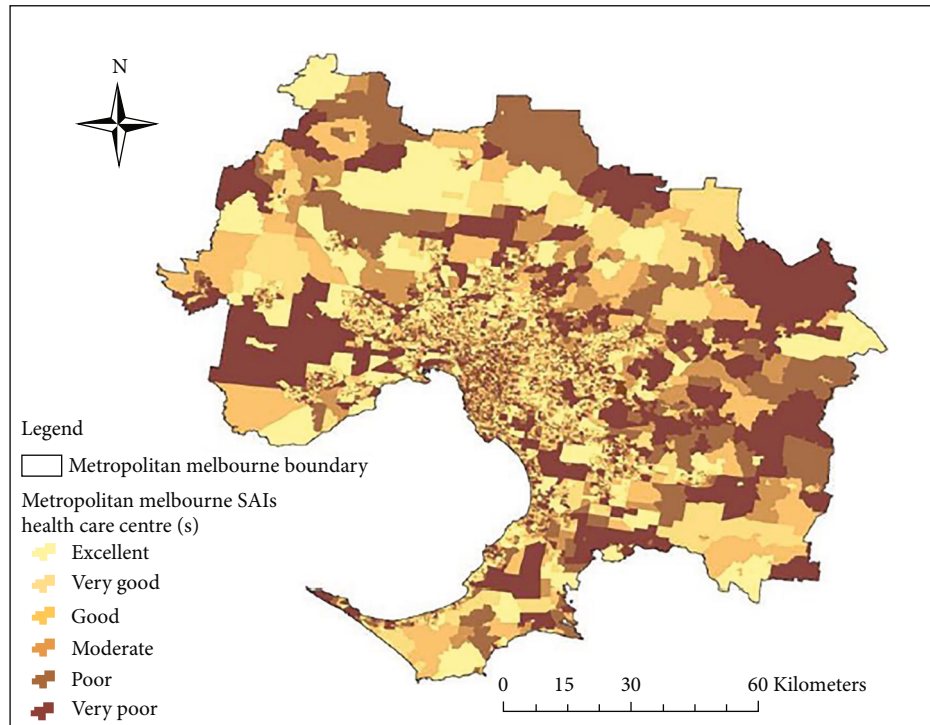


FIGURE 3: Older people public transport accessibility index for healthcare centre(s) (<https://desktop.arcgis.com/en/arcmap/latest>) [67].

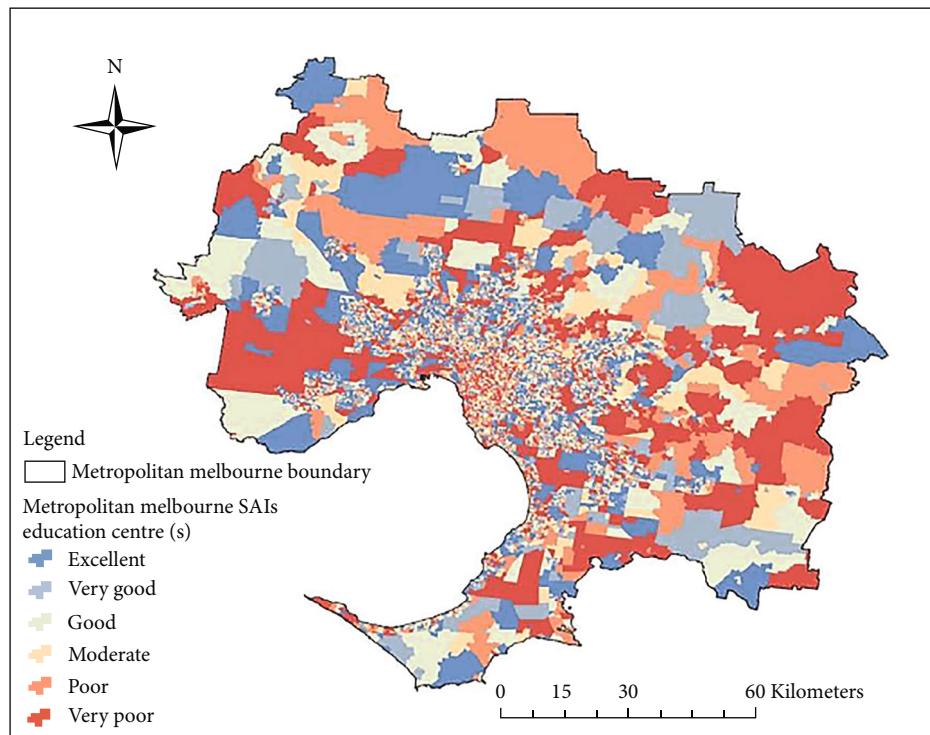


FIGURE 4: Older people public transport accessibility index for education centre(s) (<https://desktop.arcgis.com/en/arcmap/latest>) [67].

may be within the walking thresholds of train stations. A similar pattern is observed for the other three destination categories (refer to Figures 3–5). However, education and recreation centres have better coverage in all Melbourne SAIs (Figures 3–5). A substantial portion (8%) of the total

travel of the elderly involves education escort, specifically for primary school children [50, 52]. As primary schools are zoned, children are most likely to attend primary school in the area where they live. From public transport network datasets, most education centres are closer than PT stops/

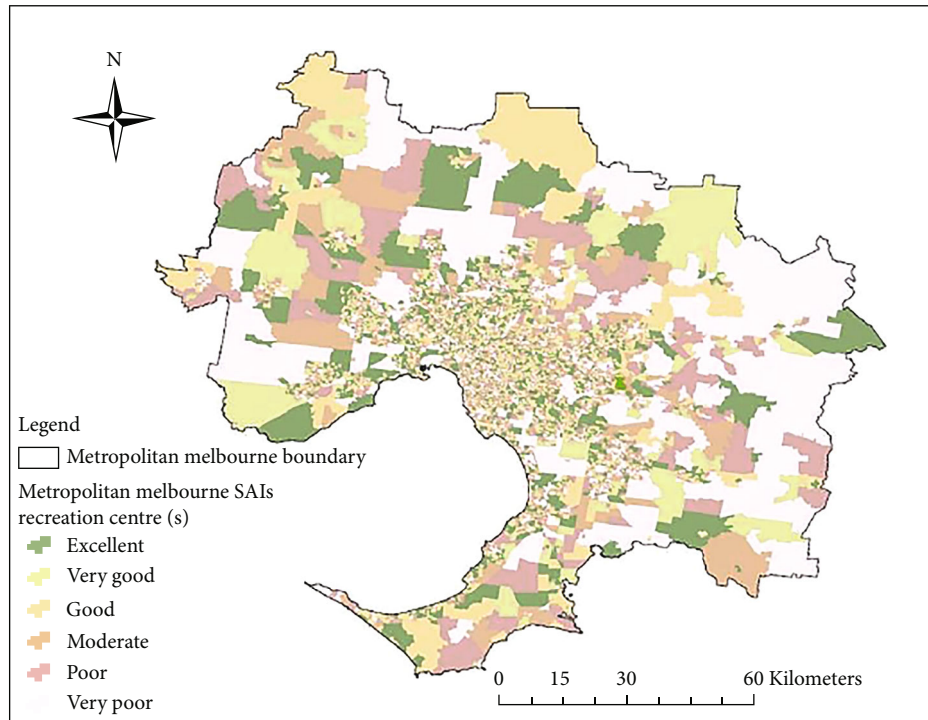


FIGURE 5: Older people public transport accessibility index for education centre(s) (<https://desktop.arcgis.com/en/arcmap/latest>) [67].

stations from the SA1 centroid. Similarly, in some SA1s, recreation centres are closer than PT stops/stations from the SA1 centroid (Figure 5). Therefore, older travellers may walk to these education/recreation centres instead of using PT.

Moreover, the PT accessibility of the elderly varies depending on total travel time, travel destination, and the population of a specific area. The results indicate that some SA1s and POIs are located near PT stops/stations, but these PT stops/stations may not be within the walking thresholds of older commuters, which affects access levels. The access levels might be suitable for other adults while they may be poor for older people. EPTAI can be considered as a measure to identify the worst PT access areas for the elderly. Therefore, the measurement of PT access levels for the elderly will assist urban planners and policymakers in applying strategies to improve PT accessibility for this age group.

7. Validation and Spatial Transferability of EPTAI

7.1. Validation of EPTAI. A study by Fatima et al. [41] presents detailed spatial and temporal dependency of older peoples' travel mode preference, trip time, and neighbourhood using the bivariate Pearson correlation theory and hot spot analysis technique. This study identified the dependency of trip duration, time of the day, geographical areas, and PT access over transport mode preference of older people. The temporal analysis results indicate that transport mode preference can vary depending on older peoples' trip purposes, although in some cases older travellers may prefer PT as the main transport mode depending on specific trip durations and times of the day. For instance, older people have

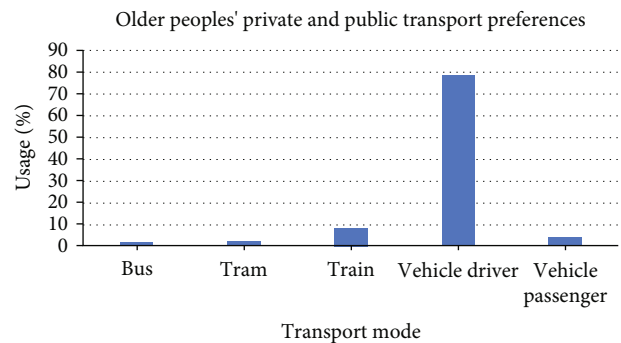


FIGURE 6: Older peoples' public and private transport mode preferences.

a greater possibility of preferring public transport over private transport during shopping trips between 10:00 and 11:00 a.m. Figure 6 represents the summary of older travellers' public and private transport mode preferences.

The analysis results of this study also interpret that the reliance on PT is greater mostly during the morning peak time (between 10:00 a.m. and 11:00 a.m.) or afternoon (between 5:00 p.m. and 6:00 p.m.). Additionally, lower trip duration has a strong correlation with preferring PT over the private mode of transport.

7.2. Spatial Transferability of EPTAI. EPTAI is also applicable to other geographic and statistical areas. A study by Fatima et al. [68] presents the older peoples' PT accessibility for three home subregions (inner, middle, and outer) of metropolitan Melbourne. Table 9 represents the summary of the

TABLE 9: Summary of elderly PT accessibility comparison.

	Melbourne elderly PT access (%)				
	Very low	Low	Moderate	Good	Excellent
Shopping centre (shopping centre coverage: inner 26.58%, middle 34.17%, outer 39.25%)					
Melbourne inner	5.60	5.70	16.00	46.00	26.70
Melbourne middle	9.80	10.56	23.00	33.00	23.64
Melbourne outer	41.16	23.33	18.75	11.70	5.06
Healthcare centre (healthcare centre coverage: inner 30.07%, middle 28.91%, outer 41.02%)					
Melbourne inner	4.33	6.65	13.66	37.88	37.48
Melbourne middle	8.66	9.78	5.77	44.04	31.75
Melbourne outer	31.93	28.55	17.00	11.67	10.85
Education centre (education centre coverage: inner 21.25%, middle 32.22%, outer 46.53%)					
Melbourne inner	4.46	5.66	15.66	35.77	38.45
Melbourne middle	3.45	3.85	19.56	31.56	41.58
Melbourne outer	24.56	17.73	16.78	21.65	19.28
Recreation centre (recreation centre coverage: inner 26.74%, middle 28.83%, outer 44.43%)					
Melbourne inner	4.36	8.64	16.74	25.83	44.43
Melbourne middle	13.36	8.71	10.87	29.34	47.72
Melbourne outer	28.19	24.95	18.86	16.77	11.23

EPTAI assessment within the metropolitan Melbourne home subregion.

From Table 9, around 40% of healthcare centres are covered by the Melbourne outer region, while the inner region covers around 30% and the middle region 29%. But the elderly PT accessibility is poor and very poor in most of the outer region. Sometimes to reach the closest facilities elderly are required to change bus services twice. However, for education centres and recreation centres, the access level is slightly better in Melbourne's outer region. The reason is the number of these two POIs' coverage is higher than the shopping centres and healthcare centres.

Another study by Fatima et al. [40] evaluates PT access and POIs' coverage using EPTAI to identify the older peoples' accessibility level within Melbourne metropolitan local government areas (LGAs). Table 10 represents the summary of the EPTAI assessment within the metropolitan Melbourne LGAs.

Table 10 shows that most of the inner and middle LGAs are categorized as moderate, good, and excellent categories towards the destinations. However, most of outer Melbourne has very low public transport access to its destinations. Most of the inner LGAs, such as the City of Melbourne, City of Port Phillip, City of Stonnington, and the City of Yarra, observed a satisfactory level of elderly PT access towards the four destinations. Only around 9% of SA1s within these LGAs consist of the very poor and poor access category. However, for the outer region, LGAs show an opposite level of PT access. Most of the outer part LGAs identified as only 5-7% excellent category. Around 70% of the outer region, LGAs are classified as a very poor and poor category.

7.3. Application of EPTAI. This study applied GIS techniques to objectively measure PT access levels for older travellers in

a metropolitan region. The EPTAI provides a practical means of measuring levels of accessibility within metropolitan areas. The results of EPTAI access levels can be used to better understand older people's accessibility requirements and preferences and the availability of PT modes. The findings indicate that the availability of PT in inner Melbourne SA1s is high, and PT can be accessed by all three modes (bus, train, and tram). However, PT in outer SA1s is generally limited to buses. The results of EPTAI analysis can be referred for the extension of bus services based on older peoples' travel needs. EPTAI also may apply to geographical standards other than SA1 (Section 7.2). The procedure for developing the index can be used for any public transport mode in urban areas or regional cities. The index can also be used for other destinations that older people visit frequently.

In many transport models, several variables including socioeconomic characteristics are considered independent variables. Therefore, a weighted accessibility index is easily applicable to identify access levels and predict future travel behaviour. Depending on access levels, travel information can be updated, including the locations of frequently visited POIs, maps, alternative routes to reach popular destinations, estimated travel time, and estimated time of travel specifically for older travellers. Geographical areas classified as having very poor and poor levels of PT access can be prioritised to upgrade services. The information can be circulated on public buses, by real-time trackers or in printed schedules.

Since EPTAI considers the elderly population, the results provide precise access levels for specific geographical areas for this age group. Based on the results, transport planners can plan a separate shuttle service for older people to minimise total travel time. The shuttle service may run on a

TABLE 10: Summary of Melbourne LGAs' older peoples' PT accessibility comparison.

Region	LGA name	PT access level within specific LGAs (%)				
		Very low	Low	Moderate	Good	Excellent
Inner Melbourne	City of Melbourne	4	5	18	46	27
Inner Melbourne	City of Port Phillip	4	6	17	46	27
Inner Melbourne	City of Stonnington	5	4	19	46	26
Inner Melbourne	City of Yarra	4	6	17	48	25
Middle Melbourne	City of Banyule	9	9	24	35	23
Middle Melbourne	City of Bayside	7	11	23	33	26
Middle Melbourne	City of Boroondara	7	11	23	33	26
Middle Melbourne	City of Darebin	7	11	26	33	23
Middle Melbourne	City of Glen Eira	9	11	23	34	23
Middle Melbourne	City of Hobsons Bay	8	10	24	31	27
Middle Melbourne	City of Kingston	6	10	23	37	24
Middle Melbourne	City of Manningham	7	11	22	34	26
Middle Melbourne	City of Maribyrnong	8	8	23	36	25
Middle Melbourne	City of Monash	9	7	23	37	24
Middle Melbourne	City of Moonee Valley	8	7	23	38	24
Middle Melbourne	City of Moreland	9	10	23	34	24
Middle Melbourne	City of Whitehorse	9	10	23	33	25
Outer metropolitan	City of Brimbank	42	24	18	11	5
Outer metropolitan	Shire of Cardinia	43	23	18	11	5
Outer metropolitan	City of Casey	41	23	18	12	6
Outer metropolitan	City of Frankston	42	23	17	11	7
Outer metropolitan	City of Greater Dandenong	41	23	18	12	6
Outer metropolitan	City of Hume	45	24	19	9	3
Outer metropolitan	City of Knox	43	23	18	11	5
Outer metropolitan	City of Maroondah	46	26	15	8	5
Outer metropolitan	City of Melton	46	26	18	6	4
Outer metropolitan	Shire of Mornington Peninsula	48	28	19	3	2
Outer metropolitan	Shire of Nillumbik	43	23	16	12	6
Outer metropolitan	City of Whittlesea	41	23	15	16	5
Outer metropolitan	City of Wyndham	41	27	22	4	6
Outer metropolitan	Shire of Yarra Ranges	42	24	18	9	7

different timetable than the existing PT schedule to popular destinations. The EPTAI may also be suitable for the measurement of PT accessibility for physically disabled commuters. EPTAI can also be modified for other adult commuters according to travel time thresholds and population densities. Urban planners, transport policymakers, and local councils may use this index to evaluate and modify PT routes and stop/station locations to provide more access to different PT users. To measure the accessibility for other PT user groups, travel time modification, population distribution, and mostly travelled POIs can be applied using this proposed index.

The EPTAI is applicable to newly developed areas where the older people's walk time and population size can be considered for equal transport access opportunities, specifically for older and disabled commuters. The EPTAI indicates a clear location and area where the improvements are needed most for public transport services and can be actioned

according to the needs of the target population group. Land use distribution for older peoples' accommodation and frequently visited POIs can be planned using EPTAI.

8. Conclusions and Future Research Directions

This study proposes a time-based EPTAI to measure the level of access to PT of elderly commuters. The index variables and calculation procedure are explained for each POI/destination from the SA1 centroid. For each SA1, the EPTAI is used to measure the level of access of the elderly to PT. In addition, statistical validation methods and observed travel data from VISTA are used to evaluate the accuracy of the index in measuring PT accessibility for the elderly. Finally, the proposed index is compared with an existing popular PT accessibility index, PTAL, for comparison and validation.

The proposed index is time-based and uses available census data to validate the measures. The time-based index emphasises the travel time of older commuters using PT to different destinations. Lower accessibility to public transport may have a negative impact on additional facilities and social activities. With low access levels, the elderly are more likely to avoid the use of PT as a travel mode. An increase in total travel time may lead them to search for a private mode of transport. The EPTAI calculation examines a very small geographical area as the travel origin and includes a count of the elderly population. The findings also indicate that PT is more accessible to older people in Melbourne's inner SA1s than in outer SA1s. However, for older people, the level of access to PT is not always higher where the PT coverage is better.

This paper proposes a PT accessibility index for the elderly. However, the procedure for developing the index is used for four different main POIs (based on travel datasets). The index can also be used for other destinations that older people visit frequently.

The present study did not consider access to private transport from each SA1 centroid to the nearest PT stop/station or from each POI to the nearest stop/station. The study also did not consider the daily cost in terms of transport usage. Future research studies can consider these factors.

Data Availability

All data generated or analysed during this study are included in this published article. These datasets are publicly available from different sources.

Disclosure

A preprint has previously been published [46] in Research Square. The preprint can be accessed through the following link: <https://www.researchsquare.com/article/rs-1570936/v1>.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

K.F. and S.M. conceptualized the study. K.F. contributed to the methodology. K.F. was responsible for the software. K.F., S.M., and T.S. validated the study. K.F. participated in formal analysis. K.F. and S.M. participated in the investigation. K.F. and T.S. provided resources. K.F. contributed to data curation. K.F. wrote the original draft preparation. K.F., S.M., and T.S. wrote, reviewed, and edited the manuscript. S.M. and T.S. supervised the study. All authors have read and agreed to the published version of the manuscript.

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