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Article

GIS Analysis of Adequate Accessibility to Public Transportation in Metropolitan Areas

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Abstract: The public transport system plays an important role in a city as it moves people from one place to another efficiently and economically. The public transport network must be organized in a way that will cover as many places and as much of the population as possible, and support the city's growth. As one of Australia's largest capital cities, Melbourne is growing and expanding its metropolitan area to reflect the growth in population and an increased number of activities. To date, little research has been conducted to determine the accessibility and adequacy of public transport taking into consideration the blank spot areas, the number of public transport options for each area, the population density within specific geographical areas, and other issues. In this study, a new measurement model is developed that examines public transport in residential areas and the extent to which it is adequate for the various local government areas (LGAs). An accessibility approach is adopted to evaluate the accessibility of different types of public transportation in residential areas in metropolitan Melbourne, Victoria, Australia. The results show that in most LGAs, the number of blank spots will decrease as the population density increases. This indicates that residents in lower-density areas will have less accessibility to public transportation. However, there is no indication that there is a greater level of services (such as more night-time and weekend public transportation services) in the high-density areas. This research is significant as it will point to and help to improve the areas with inadequate public transportation and other issues, taking into consideration their geographical locations and population density.

Keywords: spatial coverage; public transport access; network analysis; geographic information system (GIS); Australia

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1. Introduction

The increasing number of private vehicles on the road has caused a significant increase in air pollution and traffic jams, and a lack of parking space. Vehicle numbers far exceed normal rates around the world [1,2]. Not only has this increase exacerbated air and noise pollution; it has also produced high traffic density, contrary to government intentions [3,4]. An increase in the use of public transport may be the solution to these problems. One of the strategic objectives of many city governments is to have their citizens use public transport instead of private vehicles, as this will reduce the negative environmental impact [5,6].

However, inadequate public transport can also lead to various issues, such as parking difficulties and longer commuting times, and could create social disadvantages such as isolation, particularly for older populations, people with disabilities, and those who do not drive. These citizens may feel isolated and lonely if there is an inadequate public transport infrastructure [7–9]. Inadequate accessibility via public transport to places of learning, employment, and healthcare facilities [10], and unequal access to transportation services [11], can have a significant negative impact on society's most disadvantaged members.

Meanwhile, as the world's population continues to increase, many cities will face transport challenges. In Jakarta, with the rapid growth of the population, the number of vehicles on the roads is also increasing, and traffic congestion has become a common problem despite the availability of public transport [12,13]. Therefore, when building a public transport infrastructure, other factors must be taken into account, such as the population density. A thorough analysis of public transport and citizens' requirements is essential to the creation of an efficient public transport infrastructure.

In this paper, we investigate the accessibility of public transport, taking into account the distribution of population when measuring accessibility levels based on suburbs and LGAs. We develop a new measurement model to measure public transport accessibility and describe these indexes to increase the understanding of public transport usage in metropolitan Melbourne. We start by explaining the datasets and the statistics of the populations being studied. Then, we present the methods proposed for identifying the catchment and the blank spots using availability calculations. The results are discussed in detail in Section 5. Section 6 summarizes and discusses the main accessibility trends and results for each LGA. Section 7 concludes the paper and suggests future research directions.

2. Related Works

It is not easy to organize an alternative, user-friendly public transport system that is efficient in offering amenities and services that can ensure the quickest transit and waiting times [6]. Important factors including accessibility to stops/stations, system mobility, and connectivity with other forms of transport must be taken into account in order to design a public transport system that is user-friendly [8]. The economic dynamics, individual opportunities, and ultimately the population's quality of life are all impacted by the spatial equality of transportation systems [4,14]. In other words, inadequate territorial planning may result in social disadvantages. In this sense, the contribution of a geographic information system (GIS) to Transport Geography goes beyond the straightforward management of generic functionality [15]. A GIS provides important options for transport modeling [16], making it easier to update and interpret geographical data and to plan, analyze, control, and manage transportation systems.

In order to increase the appeal and competitiveness of public transport networks and reduce the use of private vehicles, Blythe et al. [17] looked at a wide range of emerging technologies and techniques capable of integrating various public transport modes and services at the urban and inter-city scale. In order to improve the environmental and energy efficiency of transport services, Arampatzis et al. [15] introduced a GIS-based decision support system (DSS) to analyze and assess various transport strategies. Various aspects of public transport, such as its geographic reach, regularity, comfort, and accessibility for the disabled, may call for a more thorough examination because they help to determine how effectively and fairly the service is delivered to the public.

According to a review by ref. [18], measures applied to determine public transport accessibility can be divided into three main categories: access to public transport stops, the time it takes to reach one's destination via public transport, and the stops required for public transportation [19]. The majority of accessibility studies have focused on the proximity to public transport stops and the degree of physical access. Both the journey time and the access to public transport stops should be taken into account [20]. The distance between a destination and a public transport station or the time it takes to go from A to B by public transport can also be used to gauge accessibility [21]. In this study, we determine the accessibility of public transport, taking into account the population distribution when comparing accessibility levels across suburbs and LGAs. In order to better understand how public transport is used in metropolitan Melbourne, we create a new measurement model to gauge its accessibility.

3. Public Transportation Review

The public transport network in Victoria is maintained by Public Transport Victoria (PTV), VicRoads, and the Department of Transport Victoria (https://www.ptv.vic.gov.au/footer/about-ptv/our-role-and-governance, accessed on 15 March 2022). The PTV manages three public transport modes: trams, trains, and buses [22]. Each mode has unique and specific purposes within the transport network. A tram is a vehicle that runs on tracks and provides reliable transportation within a high-density city center. Trams run at a relatively low speed and, usually, there are short distances between tram stops. In the city center, with greater traffic congestion, trams are ideal as they run easily on tracks within a **car-free zone**. In a shared road area, the trams have higher priority than other vehicles.

3.1. Tram Network

Melbourne's tramway network includes 250 km of double track, 493 trams, 24 lines, and 1763 tram stops [22], and is the largest operational urban tram network in the world. The Melbourne tram network is run by Yarra Tram, under PTV management. Figure 1a illustrates the tram line network in the metropolitan area. As is evident, there is no tram service in some of the LGAs, such as the City of Brimbank, City of Casey, and City of Melton.

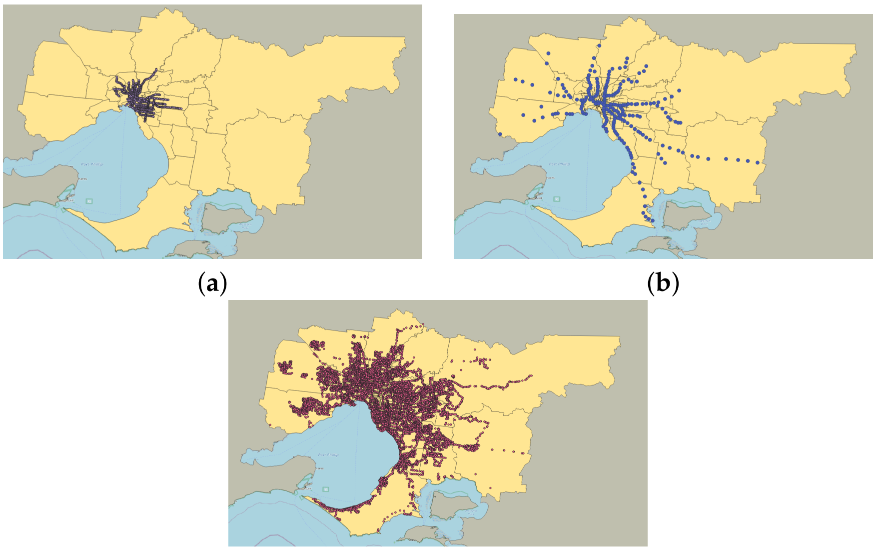


Figure 1. Trains, trams, and buses within metropolitan Melbourne. (**a**) Tram lines; (**b**) train lines; (**c**) bus lines.

3.2. Train Network

Trains offer another mode of public transport. Trains are essential to the growth of the city, particularly where most of the newly developed residential areas are built around the city outskirts. The train network is run by Metro Train under PTV management. For example, the Mernda line starts from the city area and extends to the northern metropolitan region. Figure 1b shows the train lines within the metropolitan area. As shown, the Melbourne railway network includes 17 railway lines, as well as the central City Loop [22].

3.3. Bus Network

The third public transport mode in Melbourne is buses. The bus network is run by PTV directly. The buses are designed to cover as many areas as possible where people live or engage in daily activities. The bus network in the Melbourne metropolitan area is the most extensive in terms of public transport. The metropolitan bus network has 379 bus routes in Melbourne, with 18,578 bus stops [22]. Figure 1c indicates the bus lines in the metropolitan area.

3.4. Local Government Areas in Metropolitan Melbourne

Figure 2 shows the names of the LGAs in metropolitan Melbourne. The residential areas (residential mesh blocks) in metropolitan Melbourne are shown in Figure 3b. Mesh blocks are the smallest geographic areas that are distributed and defined by the Australian Bureau of Statistics (ABS). They essentially define land uses such as primary production, residential, parks, and commercial [22]. As is evident, the residential areas in some LGAs have a greater density than other larger LGAs. For example, Yarra Ranges is located east of Melbourne and is one of the largest LGAs compared to others (e.g., Glen Eira); however, it has fewer residential areas. The population of the Melbourne metropolitan area in 2022 was 5,151,000, which is the highest in Australia [22]. Figure 3a shows the population density of the residential areas in each LGA (people per sq. km of residential area). It is clear that the density is greater in the city and its surrounding areas.

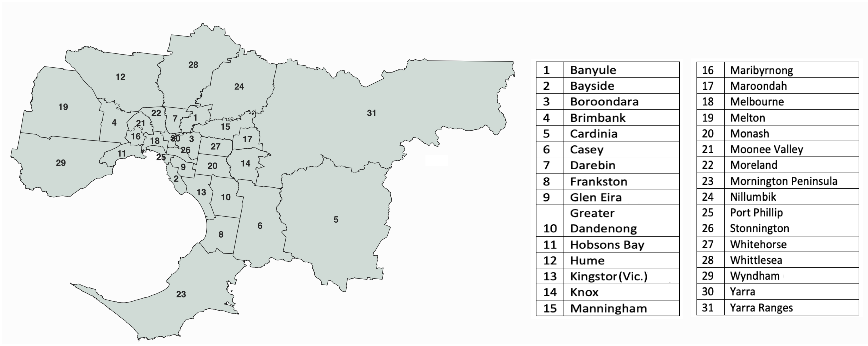
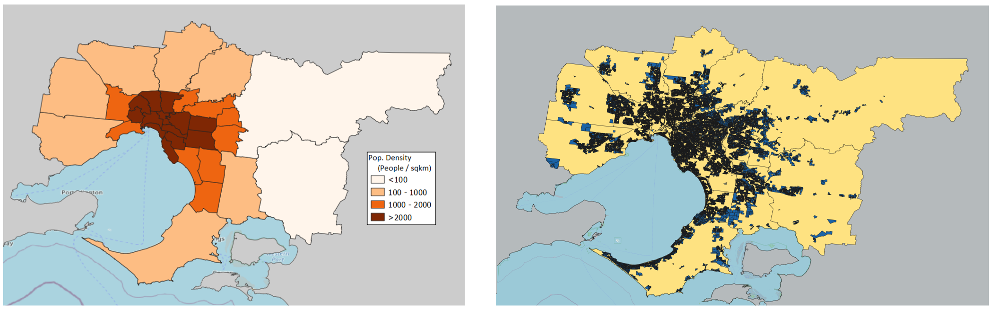


Figure 2. Local government areas (LGAs) in metropolitan Melbourne.



(**a**) (**b**)

Figure 3. The residential areas and populations in each LGA. (**a**) The population density based on LGA; (**b**) residential areas in metropolitan Melbourne.

In the next section, we conduct an extensive analysis of the quality and adequacy of transportation in metropolitan Melbourne. It will include an analysis of the ability to access (walk) public transport, the differences between modes of public transport in terms of accessibility, the source of data for the analysis, and blank spots (blank areas), which are areas whose residents have no access to any public transport. LGAs will be compared in terms of the blank spots, suburb levels, the frequency of public transport services, the number of available public transport modes, the availability of after-hours and weekend rides, and other important aspects.

4. Dataset and Method

4.1. Dataset

4.1.1. Public Transport Dataset

The General Transit Feed Specification (GTFS) is a data format that allows public transport providers to publish their timetable data in a uniform format that can be used by a wide variety of software applications. The data can be obtained through an API or downloaded as standalone data. Public Transport Victoria (PTV) is a public transport provider in Victoria that offers three transportation modes: buses, trams, and trains. As a public transport authority, PTV provides the GTFS data through their API https://www.ptv.vic.gov.au/footer/data-and-reporting/datasets/ptv-timetable-api/, accessed on 25 March 2022 and repository https://discover.data.vic.gov.au/dataset/ptv-timetable-and-geographic-information-2015-gtfs, accessed on 25 March 2022. The GTFS dataset contains eight tables that include a list of agencies that run the public transport, the routes, the stops and stations with all of the timetables, and calendar dates to provide custom schedules. In this work, we utilize the 2020 GTFS timetable from PTV for all public transport modes. The entity relationship diagram for the GRFS dataset is shown in Figure 4.

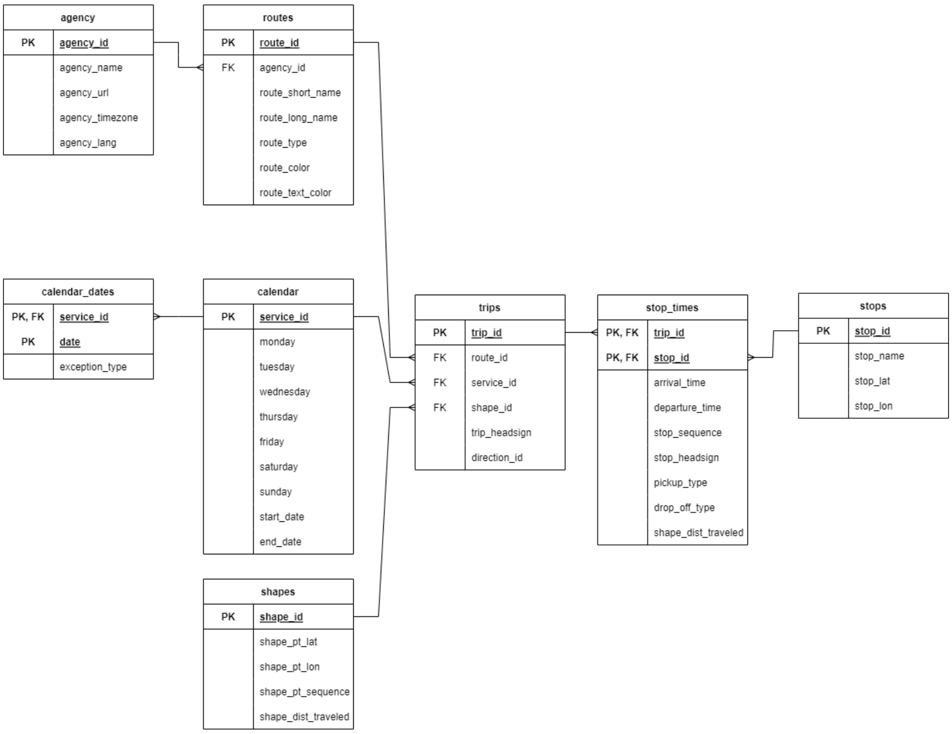


Figure 4. GTFS entity relationship diagram.

4.1.2. Road Network Dataset

Melbourne's road network was obtained from the OpenStreetMap (OSM) from the PlanetOSM repository https://planet.openstreetmap.org/, accessed on 25 March 2022. In this work, we focus only on the vehicular road types where public transport can be found https://wiki.openstreetmap.org/wiki/Key:highway, accessed on 2 April 2022. Although, as a crowd-sourced dataset, the OSM is prone to errors, the road network data show high consistency with other digital map platforms, such as Google Maps.

4.1.3. Boundary Dataset

The Australian Statistical Geography provides a framework of statistical areas used by the Australian Bureau of Statistics (ABS) to enable the publication of statistics that are comparable and spatially integrated. The ABS gives academics and researchers access to open big data. The digital boundary dataset was based on the 2016 standard and taken from the ABS repository https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1270.0.55.001July%202016, accessed on 25 March 2022. ABS has been established to provide the opportunity to gain practical experience in assessing the business, statistical, technical, computational, and other issues involving big data. There are 2310 regions throughout Australia without gaps or overlaps. The smallest geographical areas defined by the ABS are mesh blocks (MBs). There are 358,122 mesh blocks throughout the whole of Australia. This includes 113 non-spatial mesh blocks with special purpose codes. These non-spatial mesh blocks do not have a geographic boundary defining their extent, and include areas that are difficult to define in this way. Because mesh blocks are very small, they can be combined together to accurately approximate a large range of other statistical regions, called Statistical Areas Level 1 (SA1). SA1s are geographical areas comprising many mesh blocks. Most SA1s have a population of between 200 and 800 people, with an average population of approximately 400 people. Moreover, the ABS dataset includes LGAs. An LGA is a non-ABS structure of the Australian Statistical Geography Standard. Non-ABS structures are hierarchies of regions that are not defined or maintained by the ABS. LGAs are defined by the Departments of Local Government, or their equivalent in each state or territory, apart from the Australian Capital Territory. The boundary structure and hierarchy are shown in Figure 5.

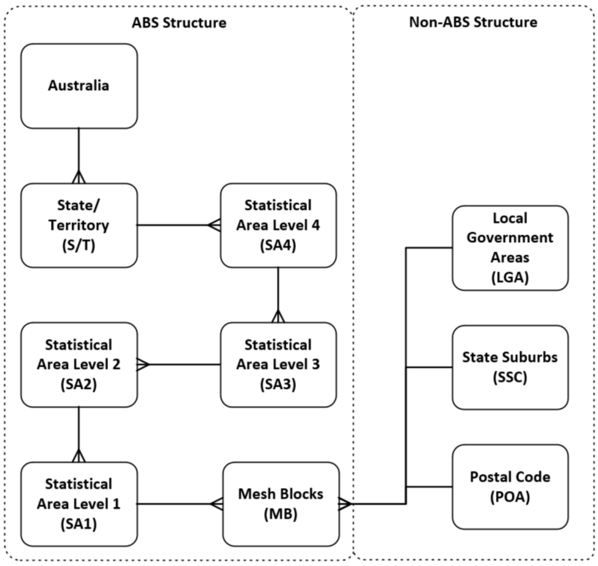


Figure 5. Boundary structures in Australia.

4.2. Method

The development of our framework comprises three main steps, which are (i) preprocessing, (ii) query processing, and (iii) aggregation (see Figure 6). The details of each step will be discussed below. We implemented this framework in Postgresql 12 with the PostGIS extension, and the visualizations were produced using QGIS 3.18 in the Windows 10 Professional platform using i7-8650U with 32 GB of RAM. All of the algorithms were implemented using spatial SQL.

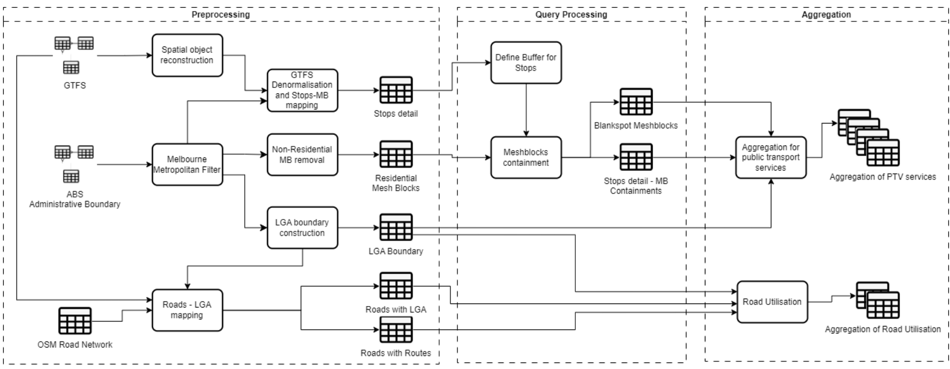


Figure 6. The processing framework.

4.2.1. Preprocessing

The preprocessing step is the heart of our work and involves the preparation of our dataset so that it can be processed in the next step.

As shown in Figure 6, we use three data sources in this work: GTFS, the ABS boundary, and the OSM road network. Since GTFS data are provided as flat files, we need to reconstruct the spatial objects, which are the stop locations and the route design. Once the spatial objects in GTFS have been reconstructed, we need to map the GTFS objects to the appropriate mesh block.

The data-mapping process requires two steps. The first is the the data mapping of ABS. This is an important step prior to the catchment analysis. We add the mesh block numbers in the stop table in order to map the data from the GTFS table to ABS datasets. Algorithm 1 illustrates the mapping process.

Algorithm 1 Data mapping algorithm

```
Input: indicate stop_id, geom, in Stop
for each stop_id of Stop do
    if mb_geom = stop_geom then
        indicate mb_code16 from mb_vic16
        set mb_code16 = mb_vic16.mb_code16
    end if
end for
```

Second is the mapping with OSM. The public transport network is designed to minimize private motorized commuting by covering as many road segments as possible. While roads are built to cover as many areas as possible, not all road segments are used for mass public transport. Since the road networks are included in the OSM dataset, we apply the overlaid method to these datasets (OSM, ABS, GTFS) to obtain the road used by the public transport network. Some roads, such as those in residential areas, are too narrow for access by public transport vehicles. Therefore, in this study, we limit our dataset to roads that are wide enough for public transport vehicles. As shown in Figure 7, to map the PTV services with the roads, for each route segment, we identify the nearest road segment (1NN (nearest neighbor)). Our road network dataset is based on the OpenStreetMap platform, and we analyze five road classifications, which are Motorway, Trunk, Primary, Secondary, and Tertiary https://wiki.openstreetmap.org/wiki/Key:highway, accessed on 2 April 2022.

(**a**) (**b**)

Figure 7. Bus line (brown), tram line (green), train line (blue), and the road line (grey). (**a**) A bus line (brown) and road line (grey); (**b**) a tramline (green) and road line (grey).

The GTFS dataset is normalized (which affects the joining process) to allow us to move to the next step. Essentially, here, we have had to minimize the join steps. A denormalization process was performed for the GTFS dataset. The GTFS dataset contains eight relations http://data.ptv.vic.gov.au/downloads/PTVGTFSReleaseNotes.pdf, accessed on 2 April 2022. This process helps to greatly improve the performance of road mapping, which is the next step. The denormalization result is shown in Figure 8.

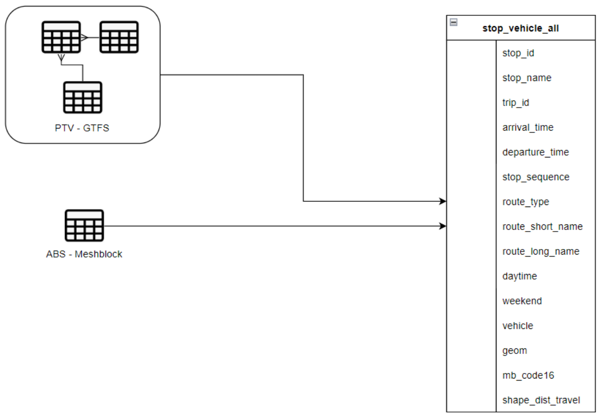


Figure 8. GTFS denormalization.

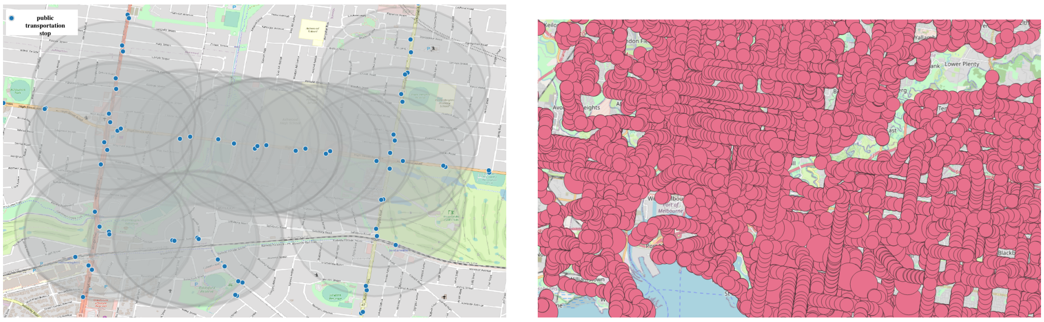
4.2.2. Query Processing

The query processing step contains two main phases: defining the buffer or catchment range for all stops, and identifying the mesh block containment in every stop catchment.

When planning a public user-friendly transport system, several crucial factors must be considered, such as accessibility to public transport stops/stations, and the connectivity with another transport mode. Easy access to public transport will encourage people to use public transport services. Therefore, we need to understand the influence of the walking distance on the use of public transport, because it is a key element in establishing fair access to public transport. The public transport location is important in allowing people to participate in a range of services and activities, and enabling easy access to work, education, health, and shopping facilities [23]. The proximity of public transport may determine the extent to which people can take full advantage of these services and facilities.

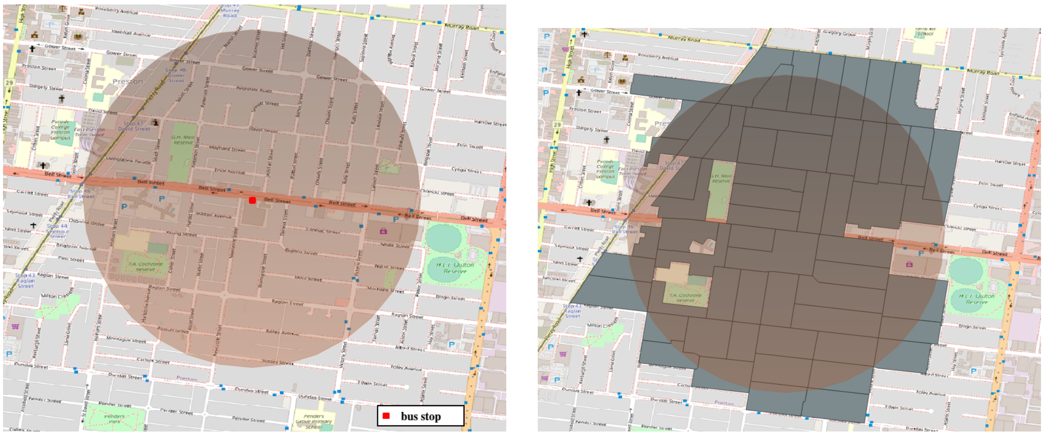
Walking distance is an important measurement, as it is the primary means used by people to travel from home to public transport access points, and it has a significant impact on public transport use. The walking distance requires a varied calculation. The New South Wales Ministry of Transport specifies that 400 m is the accessibility of a rail line and/or bus route during the day, and they also claim that people are able to reach public transport within 800 m walking distance [20,24]. However, other researchers claim that 300 m and/or 500 m is the standard walking distance to public transport [25,26]. In fact, people might walk further to a train station, but not the same distance to a bus station, so the walking distances are different for each mode/type of public transport. Therefore, in this research, we adopt the 400/800 m walking distance, and assume that people are prepared to walk up to 400 m to reach a bus/tram stop, and up to 800 m to a train station [10].

In this section, we explain the methodology used to identify the non-accessible area by PTV (known as blank spots). In Figure 6, we show the PTV stops, which may be tram, bus, or train. The public transport catchment will be created in order to determine the mesh block that intersects with the public transportation point buffer, taking into consideration the walking distance as explained above. Since the mesh blocks are usually small in size, we will consider any mesh block intersecting with the public transport point buffer. This process takes into account all mesh blocks and all surrounding public transport points of all types, which leads to a large number of intersections and overlaps, as shown in Figure 9. This enables blank spots to be determined. Figure 10 shows an example of a public transport point buffer of one point and how it intersects with the mesh blocks. Figure 11 shows an example of blank spot identification between many buffer catchments. Note that this process will handle the overlapping between the same bus and its stop stations on both sides of the road and considers one of them. Spatial SQL is used for this analysis. Algorithm 2 is used to determine the catchment for each public transport stop, while the blank spots are identified by means of Algorithm 3.



(**a**) (**b**)

Figure 9. Catchment analysis. (**a**) An example of the catchment in a suburb (400 m buffer for each pt stop); (**b**) a catchment for the whole of Melbourne (the buffers for each public transport stop).



(**a**) (**b**)

Figure 10. One public transportation catchment example. (**a**) An example bus stop catchment (a buffer of 400 m); (**b**) a catchment that intersects with a mesh block.

Algorithm 2 Catchment algorithm

Input: indicate $stop_{id}, geom, route_{name}$
for each $stop_{id}$ of $Z[]$ **do**
  if $stop_{id}$ = 'bus' **then**
    $buffer$ (geom: 400 m)
    $buffer \rightarrow Z_i$
  end if
  if $stop_{id}$ = 'tram' **then**
    $buffer$ (geom: 400 m)
    $buffer \rightarrow Z_i$
  end if
  if $stop_{id}$ = 'train' **then**
    $buffer$ (geom: 800 m)
    $buffer \rightarrow Z_i$
  end if
end for
return $Z[]$

Algorithm 3 Blank spot algorithm

Input: indicate $stop_{id}$, $geom$, $buffer$, $route_{name}$
for each mb_i of $mb_{pt}[]$ **do**
    if $buffer_i$ intersect with mb_i **then**
        count = count + 1
        if $route_{name}$ of $stop_{id}$ are similar **then**
            count = count − 1
        end if
        mb_i = count
    end if
end for
if $mb_j = 0$ **then**
    insert mb_j in $blank_{spot}[]$
end if
return $blank_{spot}[]$

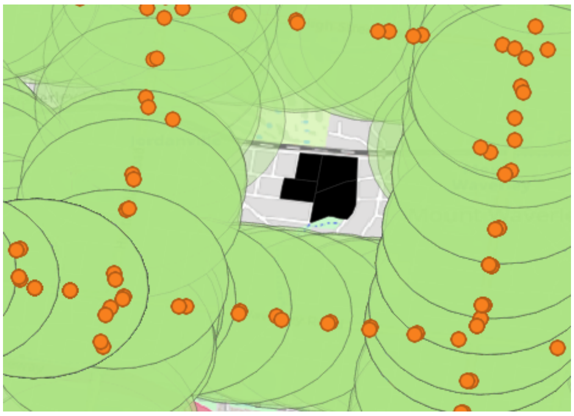


Figure 11. An example of blank spot verification between catchments.

4.3. Data Aggregation

After determining the catchment and the blank spots, data aggregation is performed in order to investigate the number of options in terms of service availability. For the availability, we consider night rides, 24-h services, weekend services, and others. In this work, we categorize the service times as morning, day, evening, and night. Morning services run from 3 a.m. to 9 a.m., day services run between 9 a.m. and 6 p.m., the evening services are between 6 p.m. and 9 p.m., and the night-time services are between 9 p.m. and 3 a.m. Note that the GTFS timetable is based on 31 h, which requires some adjustment in order to obtain the aforementioned time classifications. The aggregation for the LGAs based on the night-time or daytime rides can be performed through this categorization. For the 24-h services, we obtain any PT service that runs where the last departure time subtracted from the first departure time equals 24 h.

Interval activity refers to the interval between any departure of and arrival of a new vehicle, regardless of the number of public transport vehicles. This will give an indication of the extent to which a specific public transport stop is active. To show how active a stop is regardless of the number of vehicles arriving at each stop, the waiting time is calculated by subtracting the departure time from the next available departure time. For the public transport services that do not work during the weekend, we aggregate the services that work during Saturday and Sunday by linking the ABS and GTFS datasets.

In addition, we calculate the frequency of public transport departures from a certain stop over a 24-h period. This is done by aggregating the departure times of any public transport vehicle from a stop, which shows the frequency of public transport vehicles departing from a stop. Figure 12 indicates the public transport stops within the Maroondah City Council area.

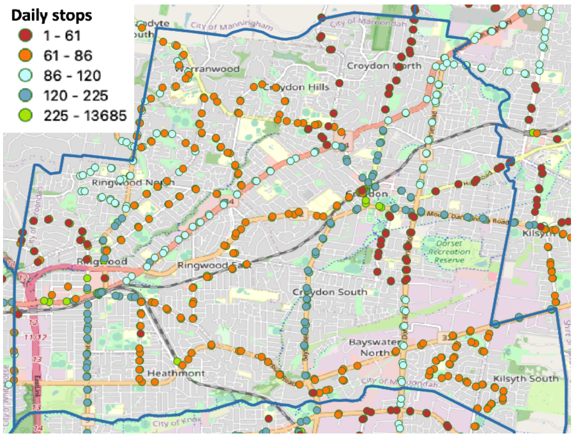


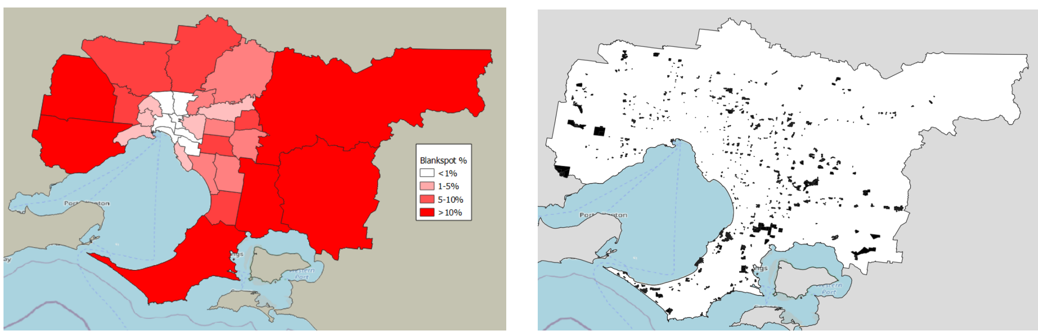
Figure 12. Maroondah City PT daily stops.

5. Results

This section is divided into four sub-sections: non-accessible areas by PTV (blank spots), road utilization/infrastructure, availability, and frequency. For better clarity, the complete interactive maps are provided https://dataset-click.github.io/public_transport/. The dataset is implemented in the PostGIS server with QGIS as the visualization tool.

5.1. Coverage and Blank Spots

In this section, we analyze the areas covered by public transport in various LGAs, taking into account the walking distance (in terms of accessibility) as explained previously. Note that, here, we have taken into account the three modes of public transport. The blank spots (blank areas) are the areas where people live but do not have access to any type of public transport in terms of the walking distance required. Figure 13b indicates the blank spots within the Melbourne metropolitan area. As shown, there are many mesh blocks that are considered as blank spots, especially in the outer LGAs. Figure 13a shows the percentage of blank spots in each LGA. As is evident, in some LGAs, more than 10% of their residential areas do not have accessible public transport. However, the LGAs in the city and inner suburbs have less than 1% of blank spots in their residential areas. However, areas such as Monash City, which has a high population density (as shown in Figure 13a), have blank spots in 5–10% of their residential areas.



(**a**) (**b**)

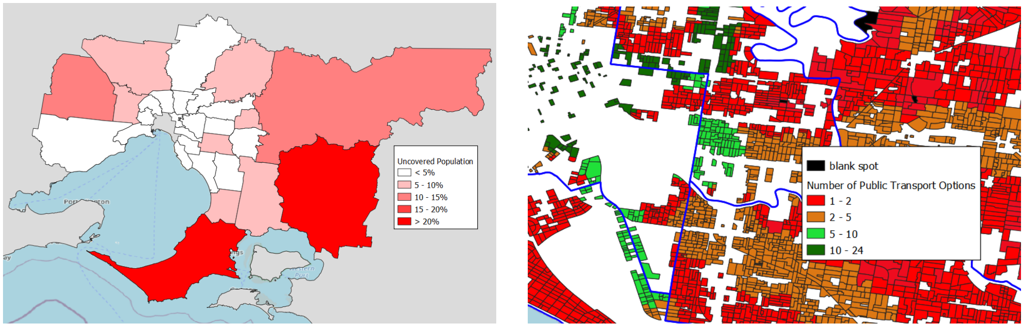
Figure 13. Blank spots within metropolitan Melbourne. (**a**) Percentage of blank spots in each LGA; (**b**) blank spots.

In Figure 13a, we can see the blank spots affecting a small number of areas. Table 1 shows that only 2173 of the residential mesh blocks are considered as blank spots, which is 5.09% of the Melbourne metropolitan residential areas.

Table 1. Blank spots by category.

Category	Total	Blank	Percentage
Industrial	1608	122	7.59%
Commercial	3123	19	0.61%
Residential	42,726	2173	5.09%
Hospital/Medical	148	4	2.70%
Education	1305	56	4.29%

Moreover, we examined those areas in metropolitan Melbourne whose population is not catered for in terms of public transport accessibility (uncovered population), as shown in Figure 14. Figure 14a shows this sector of the population in each LGA. It is clear that the city center is the smallest area (less than 5%) of the population not covered by public transport; the same percentage applies to the inner suburbs and others surrounding the city. However, the further the distance from the city, the greater is the percentage of non-coverage. For example, in the Yarra Ranges, 10–15% of the population resides in an uncovered area. The LGAs with the highest percentage of population not covered are the Mornington Peninsula and Cardinia LGA, both of which have more than 20% of the population not catered for by public transport.



(**a**) (**b**)

Figure 14. The blank spots of the Melbourne metropolitan area. (**a**) Uncovered population; (**b**) MB catchment and LGA.

Figure 14b shows an example of a mesh block catchment in the Melbourne metropolitan area. As is evident, some mesh blocks have zero public transport figures, as shown in a block color. The red indicates that residents have one or two public transport options in each mesh block. The dark green indicates the mesh block with the greatest number of public transport options, in excess of ten.

5.2. Road Utilization/Infrastructure

The road utilization is shown in Table 2. The tertiary road is over 4000 km long, and is the longest road within the metropolitan area. This is followed by secondary and primary roads, and motorways. The shortest road type is the trunk (901 km). Figure 15 indicates the overall road utilization. Figure 15a shows the road network infrastructure in metropolitan Melbourne and all available public transport routes. Figure 15c gives the percentage of road utilization in each LGA. The highest utilization (over 75%) is in the LGAs depicted in dark green, while the second-highest utilization of roads occurs in the surrounding city areas, which have 60–75%. Meanwhile, the Cardinia LGA has the lowest road utilization (less than 25%).

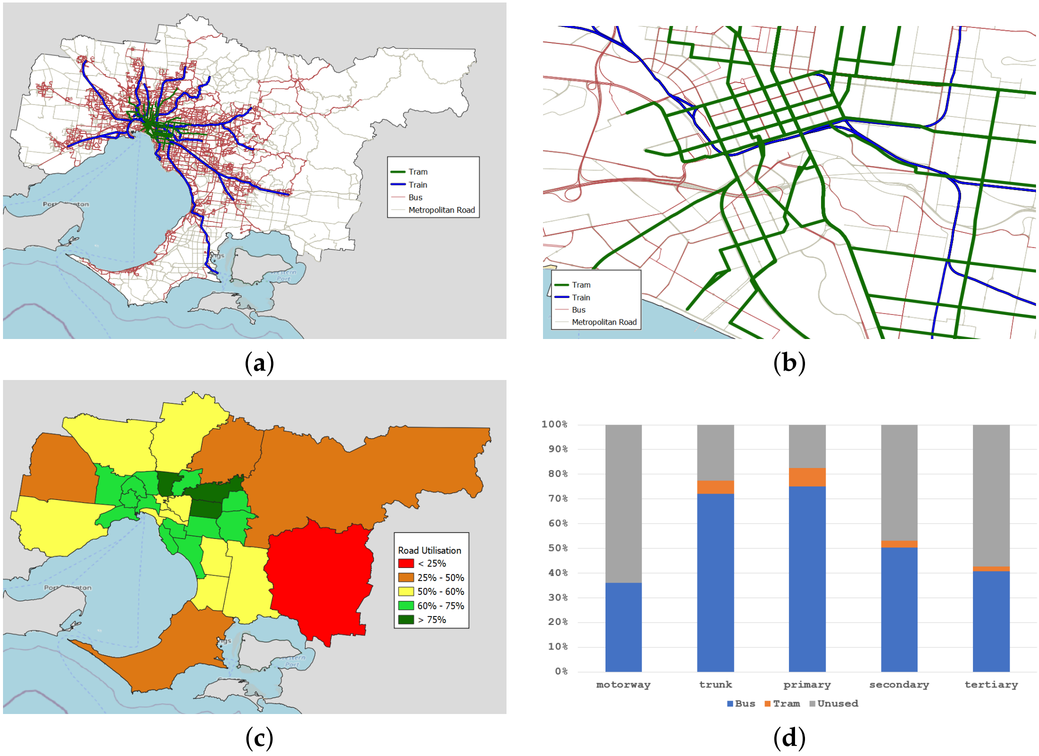


Figure 15. Roads utilized by public transport vehicles. (**a**) PTV and road network; (**b**) example PTV network in CBD; (**c**) road utilization by LGA; (**d**) road utilization by OSM road type.

Table 2. Road utilization by OSM type.

Road Type	Length (km)	Bus (km)	Tram (km)	Unused (km)
Motorway	1208	435	0	772
Trunk	901	649	49	203
Primary	1588	1191	121	277
Secondary	2131	1072	60	999
Tertiary	4017	1632	81	2304

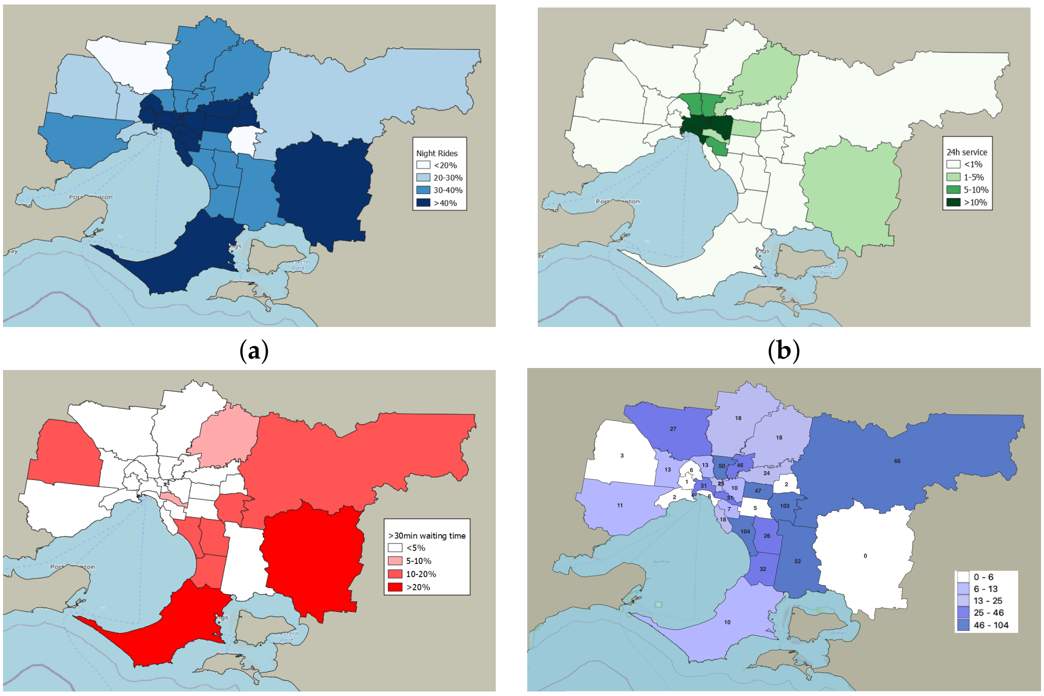
The road utilization is shown in Figure 15b, where the bus network is depicted by the brown line, the tram rail is shown in green, and the train rail network is shown in blue. A public road without any public transport route is shown in light grey.

The road utilization is shown in Figure 15d. Primary roads have the highest utilization, with almost 80% of the roads being part of the public transportation network. The trunk roads are the second most utilized, with more than 70% of the road sections being part of the public transport network. The secondary and tertiary road types have only 52% and 41% utilization, respectively, whereas the motorway has the lowest utilization, as only 36% of the road section comprises part of the public transport network. Although not all roads carry public transport, the area in which a road is located might be within the public transport catchment. The coverage and public transport catchment will be discussed in the Section 5.3.

5.3. PTV Availability

In this section, we examine the availability of public transport in the Melbourne metropolitan area. Availability refers to the time at which public transport can be accessed. While the majority of the population performs their daily activities during daylight hours on weekdays, there are those who require public transport at different times. Clearly, public transport networks focus on providing services during daylight hours on weekdays, when demand is high. Since some of the population needs public transport services outside these hours, this section discusses the availability of public transportation at night, on weekends, and for 24-h services. The waiting time for services on weekdays and weekends will be compared and discussed. Availability includes all public transportation modes (buses, trains, and trams) throughout the metropolitan Melbourne area.

Figure 16a shows the number of night rides for all public transport modes (train, trams, and buses) in each LGA. Note that night rides refer to public transport that operates between 9 p.m. and 12 a.m. As indicated, less than 20% of all public transport services offer night rides in the Knox and Hume LGAs. However, more than 40% of all public transportation services in Mornington Peninsula, Cardinia, Yarra, and CBD offer night rides. There is a rate of 20–30% for LGAs such as the Yarra Ranges and Melton.



(**a**) (**b**)

(**c**) (**d**)

Figure 16. The availability of public transportation in Melbourne metropolitan area from different aspects. (**a**) Night rides; (**b**) 24-h availability; (**c**) active interval; (**d**) weekend availability.

Figure 16b shows the percentage of bus services available 24 h per day in each LGA. As indicated, in LGAs such as Monash, Hume, Knox, Casey, and Wyndham, less than 1% of their buses offer a 24-h service. On the other hand, LGA areas such as Cardinia have around 1–5% of their buses operating for 24 h, while LGAs near the city have more than 10% of their buses offering a 24-h service.

Figure 16c shows the active interval rates of the public transport services in each LGA. Here, we aim to show how active the stop is; the waiting time indicates the time of waiting until any public transport vehicle leaves the stop. For example, for more than 20% of the public transport services in the Mornington Peninsula and Cardinia, people will need to wait more than half an hour for a bus (regardless of the bus number). In the City of Stonnington, for 5–10% of bus services, the waiting time for a bus is more than half an hour. In other LGAs, such as Casey, Pt Phillip, Boroondara, Darebin, and Moreland, less than 5% of their bus services have a waiting time that exceeds 30 min.

Figure 16d shows the public transport services (all modes—trains, trams, and buses) in each LGA that do not operate during the weekend. As shown, areas such as Monash and Cardinia have the lowest number of public transport services that do not work during the weekends. However, areas such as Knox and Kingston have over 100 public transport services that do not operate during the weekend.

5.4. PTV Frequency

Figure 17 indicates the average stop transit (or frequency) in each LGA for all public transport modes. The Yarra Ranges and Cardinia have an average of fewer than 100 transits of public transport at each stop in a day. Areas such as Casey and Frankston have an average of 100–150 transits of public transport at each stop in a day. As shown, areas around the city center have more than 250 transits of public transport at each stop in a day.

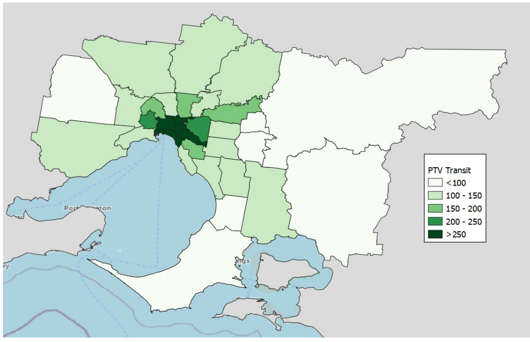


Figure 17. Stop transit average in each LGA.

6. Discussion

In this section, we discuss the results of the comprehensive analysis of public transport in the city of Melbourne and the metropolitan areas. As is clear from Tables A1–A3 (see Appendixes A–C), the center of Melbourne (C) is the best placed in terms of public transport availability and accessibility. Moreover, despite its small size, the city area does not have any blank spots, which also indicates that there is no population without any access to public transportation. However, there are some LGAs where 22% of residents do not have access to public transport. However, this section takes a broader perspective by considering the relationship between the blank spots and public transportation services, and major factors such as the density, the size of LGA, and the population density, among others.

Figure 18 shows that with the increase in the LGA size, there is some increase in the number of blank spots. For example, the Yarra Ranges is the largest LGA and has 9.6% of blank spots, whereas Monash City has around 4.2% of blank spot areas. However, since we consider only the radiational MB (see Figure 19), we can notice that the number of blank spots is not affected by an increase in the number of MBs.

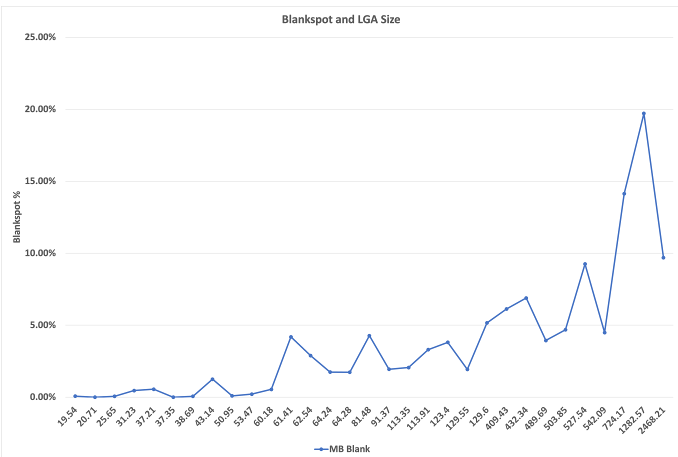


Figure 18. Blank spots and the size of the LGA area.

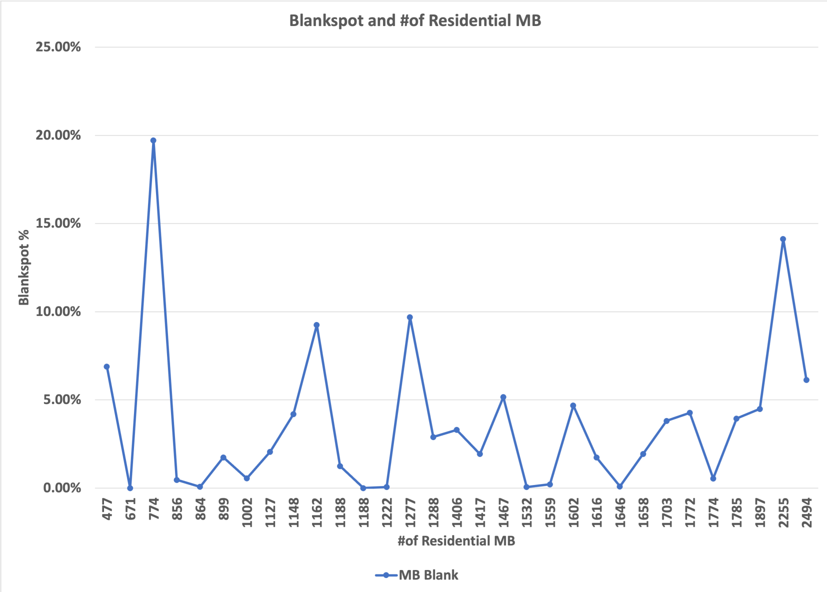


Figure 19. Blank spots and number of residential MBs.

Figure 20 shows that with the increase in density, we notice a decrease in the number of blank spots. This is an important observation as it indicates that in less-dense areas, there will be less accessibility to public transport. For example, Moreland, which has a high density, has only 0.09% of blank spot areas, whereas a low-density LGA such as Cardinia has a very high number of blank spots (around 19.7%). Another example is the Yarra Ranges, which has 9.6% blank spot areas. Figure 21 shows that an increase in population does not affect the blank spot areas.

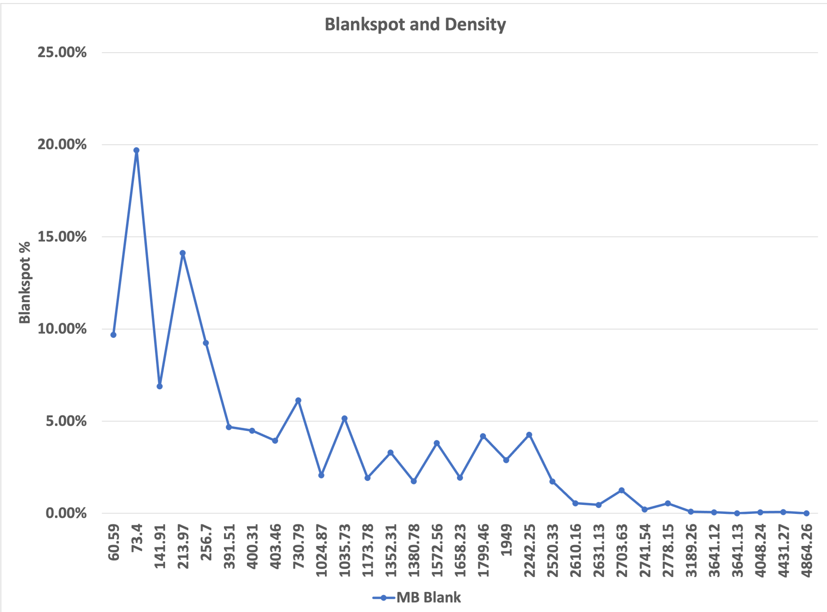


Figure 20. Blank spots and LGA density.

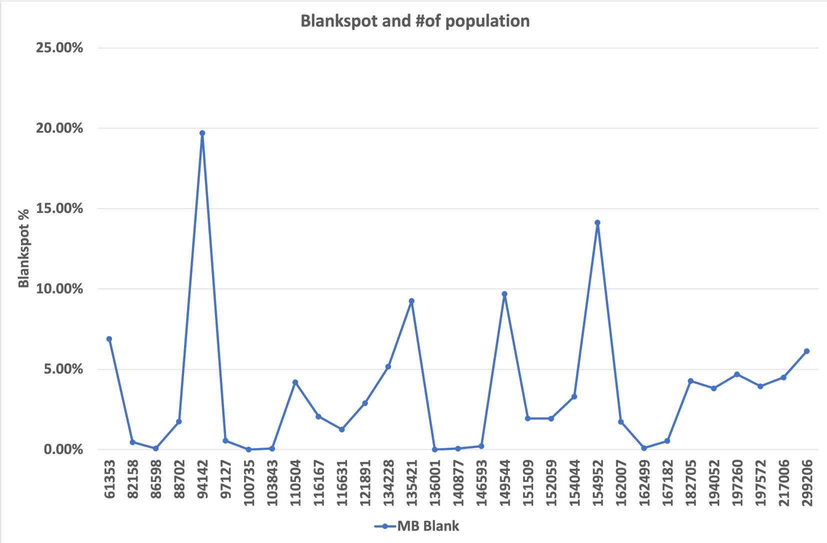


Figure 21. Blank spots and the population.

Figure 22 shows that with an increase in density, the number of services (such as weekend buses, public transport at night, and others) actually does not appear to be affected. However, as shown in Figure 23, it appears that with an increase in the density, the 24-h services (trams, trains, and buses) will increase.

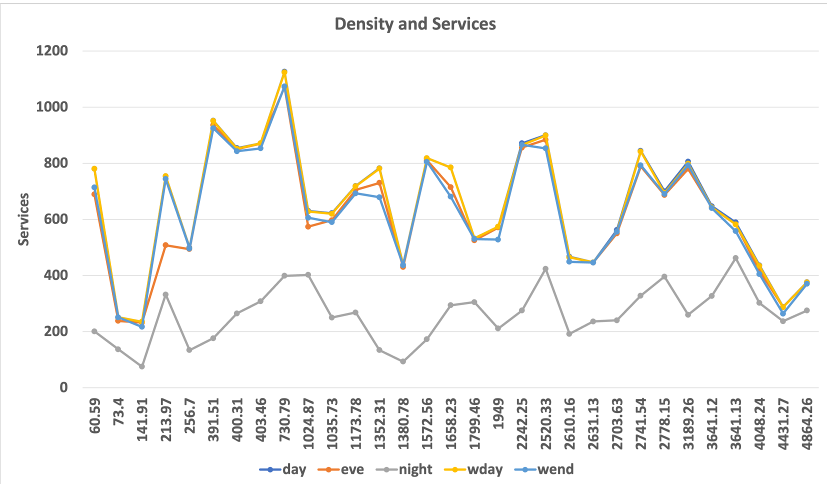


Figure 22. Services and LGA density.

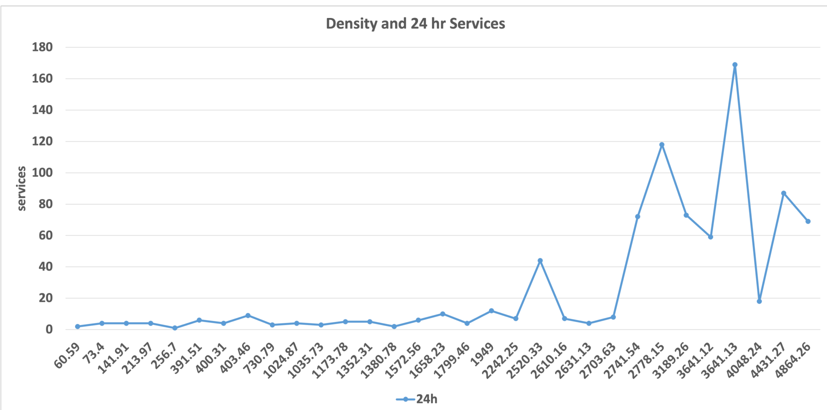


Figure 23. LGA density and 24-h services.

Figure 24 shows that with an increase in population, the number of public transport services is affected and increases. However, in each LGA, the night rides are not affected by a population increase. Similarly, as shown in Figure 25, the 24-h services do not appear to be affected. Figure 26 shows that with an increase in the LGA size, the number of public transport services is not affected. For example, LGAs such as Kingston and Knox have services similar to those of a smaller LGA such as Moreland.

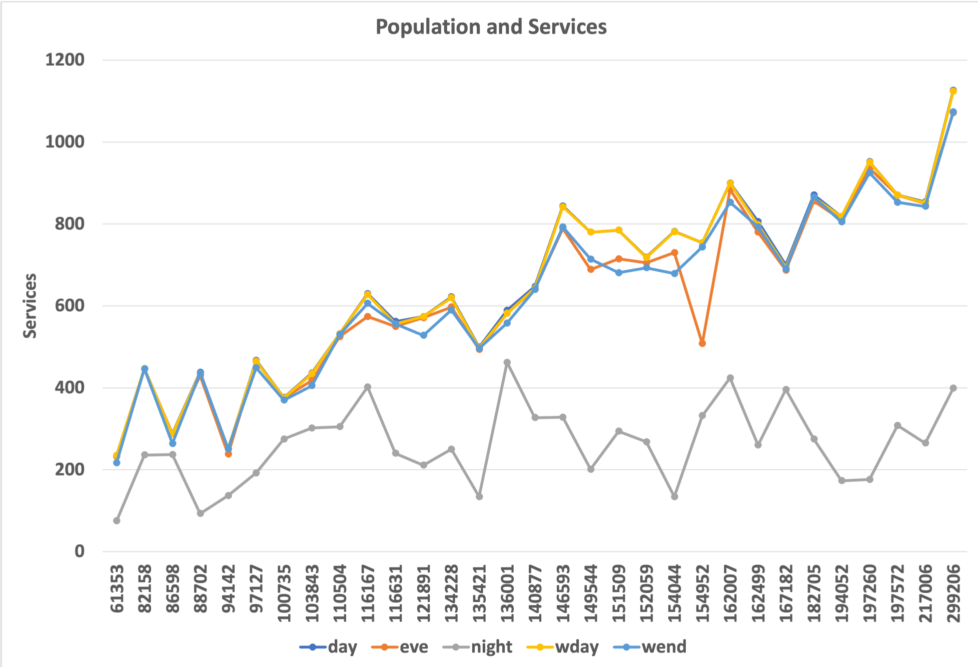


Figure 24. Population and services.

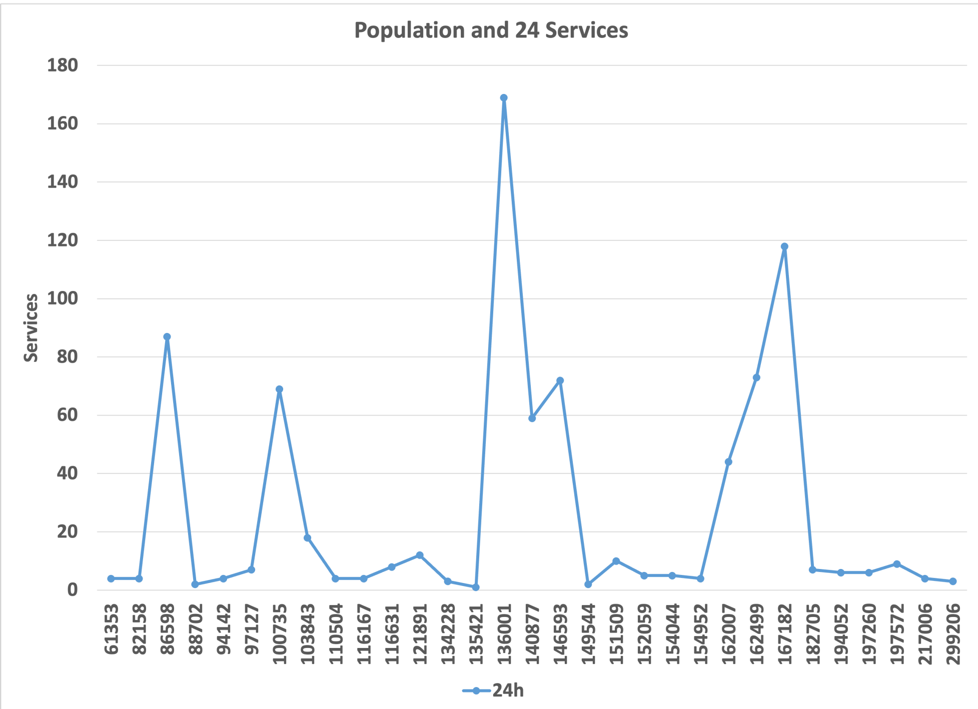


Figure 25. Population and 24-h services.

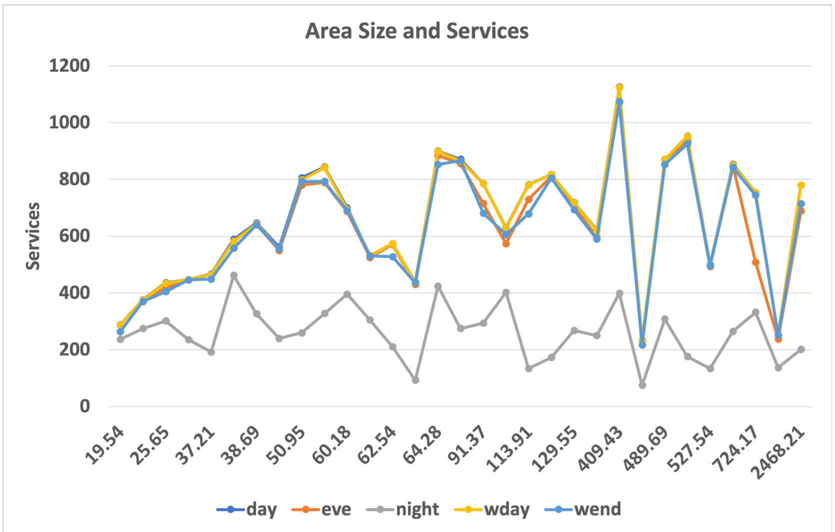


Figure 26. Services and LGA size.

7. Conclusions and Future Work

Citizens often use public transport in the Australian city of Melbourne. An essential aspect of city development planning is determining where public transportation facilities such as train stations, bus stops, and parking facilities should be located. The aim of this research was to investigate the accessibility of public transport, taking into account the distribution of population when measuring accessibility levels based on suburbs and LGAs. The paper presents a new measurement model to measure the adequacy of public transport and its accessibility in order to acquire a better understanding of public transport usage in metropolitan Melbourne. We examined the extent to which various LGAs have public transport coverage, as well as accessibility in terms of walking distance, in order to identify any areas that have no access according to PTV (the blank spots). We also investigated the parts of the population in the Melbourne metropolitan area for whom public transport is not available or not easily accessible, and those sections of roads utilized by public transport in various LGAs. Moreover, the paper reveals the availability of public transport services at different times (daylight hours on weekdays, and evenings, nights, and weekends), as well as the availability of 24-h public transport services. Additionally, we compared public transport in various LGAs in terms of the waiting time and frequency of services on weekdays and weekends. Importantly, the results indicate that in high-density areas, the number of blank spots is smaller than in LGAs with less density. This suggests that people in less populated areas have reduced accessibility to public transportation. Moreover, there is some indication that the larger the LGA, the greater will be the number of blank spots. Finally, the population density and the size of the LGA do not have any impact on public transport services in terms of their availability during daylight hours, evenings, nights, and weekends.

In future work, this analysis model will be applied to other cities for the purpose of comparison. Additionally, as there might be some changes due to fewer COVID-19 restrictions, we will investigate the impact of relaxed regulations on overall PTV coverage.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Information on the local government areas (LGAs) of metropolitan Melbourne. Each row represents an LGA, and the remaining seven columns contain, respectively, the land area in square kilometers (sqkm), population (Pop), population density (Psqkm), number of mesh blocks (MB), number of residential mesh blocks (MBR), percentage of blank spots (MBBl), and percentage of the population at blank spots (PB).

Table A1. LGAs population and blank spot details.

LGA	sqkm	Pop	Psqkm	MB	MBR	MBBl	PB
Bayside (C)	37.21	97,127	2610.16	1278	1002	0.55%	0.55%
Boroondara (C)	60.18	167,182	2778.15	2237	1774	0.54%	0.57%
Brimbank (C)	123.40	194,052	1572.56	2256	1703	3.81%	5.25%
Cardinia (S)	1282.57	94,142	73.40	1121	774	19.71%	22.17%
Casey (C)	409.43	299,206	730.79	3051	2494	6.13%	7.47%
Darebin (C)	53.47	146,593	2741.54	1923	1559	0.21%	0.24%
Frankston (C)	129.60	134,228	1035.73	1900	1467	5.16%	7.72%
Hobsons Bay (C)	64.24	88,702	1380.78	1265	899	1.74%	2.61%
Hume (C)	503.85	197,260	391.51	2074	1602	4.68%	5.72%
Kingston (C) (Vic.)	91.37	151,509	1658.23	2217	1658	1.94%	2.96%
Knox (C)	113.91	154,044	1352.31	1729	1406	3.30%	4.20%
Manningham (C)	113.35	116,167	1024.87	1405	1127	2.06%	2.73%
Maribyrnong (C)	31.23	82,158	2631.13	1096	856	0.46%	0.72%
Maroondah (C)	61.41	110,504	1799.46	1383	1148	4.19%	5.67%
Melbourne (C)	37.35	136,001	3641.13	1323	671		
Monash (C)	81.48	182,705	2242.25	2179	1772	4.27%	5.21%
Moonee Valley (C)	43.14	116,631	2703.63	1526	1188	1.25%	1.53%
Moreland (C)	50.95	162,499	3189.26	2106	1646	0.09%	0.15%
Mornington Peninsula	724.17	154,952	213.97	3248	2255	14.13%	20.46%
Nillumbik (S)	432.34	61,353	141.91	740	477	6.89%	8.13%
Port Phillip (C)	20.71	100,735	4864.26	1582	1188		
Greater Dandenong	129.55	152,059	1173.78	1864	1417	1.93%	2.78%
Whitehorse (C)	64.28	162,007	2520.33	1969	1616	1.73%	2.13%
Whittlesea (C)	489.69	197,572	403.46	2232	1785	3.94%	4.18%
Wyndham (C)	542.09	217,006	400.31	2274	1897	4.49%	4.99%
Yarra (C)	19.54	86,598	4431.27	1378	864	0.07%	0.05%
Banyule (C)	62.54	121,891	1949.00	1555	1288	2.89%	3.62%
Melton (C)	527.54	135,421	256.70	1449	1162	9.25%	10.34%
Glen Eira (C)	38.69	140,877	3641.12	1714	1532	0.06%	0.07%
Stonnington (C)	25.65	103,843	4048.24	1597	1222	0.06%	0.09%
Yarra Ranges (S)	2468.21	149,544	60.59	1868	1277	9.69%	12.37%

Appendix B

This table shows public transportation information for the local government areas (LGA) of metropolitan Melbourne. Each row represents a factor with eleven columns. The first column represents the number of public transportation stops for all LGAΣSt. Column 'Day' represents the number of stops operating during the day. The third and fourth columns represent how many stops operate in the evening (E_v) and at night (N_i) for every LGA. The fifth and sixth columns show how many public transportation stops operate on weekdays (W_d) and at weekends (W_e). The seventh column represents how many public transportation stops operate for 24 h. The eighth, ninth, tenth, and eleventh columns represent the active interval times of the public transportation services in each LGA: five, fifteen, thirty, and more than thirty minutes to access another public transportation service (regardless of public transportation service number).

Table A2. LGAs' public transportation service details.

LGA	ΣSt	Day	E_v	N_i	W_d	W_e	24 h	w_5	w_{15}	w_{30}	w_{30+}
Bayside (C)	467	467	465	192	465	449	7	65	262	122	18
Boroondara (C)	700	700	687	396	694	690	118	321	125	250	4
Brimbank (C)	818	818	810	173	818	805	6	62	411	308	37
Cardinia (S)	251	251	238	137	251	251	4	5	78	105	63
Casey (C)	1126	1126	1072	399	1124	1074	3	77	532	458	59
Darebin (C)	844	844	789	328	842	793	72	200	520	121	3
Frankston (C)	622	622	597	250	620	590	3	42	178	325	77
Hobsons Bay	438	438	430	93	436	436	2	40	233	162	3
Hume (C)	952	952	936	176	951	925	6	70	445	407	30
Kingston (C)	785	785	715	294	785	681	10	36	439	180	130
Knox (C)	782	782	730	134	781	679	5	53	442	184	103
Manningham	630	630	574	402	628	606	4	134	297	176	23
Maribyrnong	447	447	446	236	447	446	4	129	227	91	0
Maroondah (C)	532	532	525	305	532	530	4	18	233	271	10
Melbourne (C)	589	589	582	462	582	558	169	409	116	61	3
Monash (C)	871	871	856	275	865	866	7	139	458	269	5
Moonee Valley	562	562	550	240	556	556	8	171	193	172	26
Moreland (C)	806	806	780	260	798	793	73	170	371	242	23
Morn-Peninsula	754	754	508	332	754	744	4	20	109	361	264
Nillumbik (S)	235	235	232	75	235	217	4	13	112	92	18
Port Phillip (C)	376	376	375	275	375	370	69	206	98	65	7
Gre-Dandenong	719	719	705	268	718	693	5	55	251	312	101
Whitehorse (C)	900	900	884	424	899	853	44	139	556	162	43
Whittlesea (C)	871	871	870	308	871	853	9	70	534	262	5
Wyndham (C)	854	854	850	265	852	843	4	13	217	587	37
Yarra (C)	288	288	287	237	287	264	87	220	25	42	1
Banyule (C)	574	574	571	211	574	528	12	93	298	182	1
Melton (C)	499	499	494	134	497	496	1	5	172	245	77
Glen Eira (C)	647	647	642	327	643	640	59	159	307	173	8
Stonnington (C)	436	436	418	302	434	405	18	267	91	44	34
Yarra Ranges (S)	780	780	689	201	780	714	2	31	204	421	124

Appendix C

This table shows public transportation information for the local government areas (LGA) of metropolitan Melbourne. Each row represents a factor with eleven columns. The first column represents the number of public transportation stops for all LGAs. The 'Day' column represents the number of stops operating during a day. The third and fourth columns represent how many stops operate in the evening and at night for every LGA. The fifth and sixth columns show how many public transportation stops operate on weekdays and weekends. The seventh column represents how many public transportation stops operate for 24 h. The eighth, ninth, tenth, and eleventh columns represent the active interval times of the public transportation services in each LGA: five, fifteen, thirty, and more than thirty minutes to access another public transportation service (regardless of public transportation service number).

Table A3. PTV road utilization details in each LGA.

LGA	Road (km)	PTV Usage	Bus Usage	Tram Usage
Banyule (C)	170.00	65.82%	65.81%	1.19%
Bayside (C)	120.27	64.43%	63.88%	1.26%
Boroondara (C)	214.60	58.49%	44.93%	17.49%
Brimbank (C)	421.73	65.75%	65.75%	
Cardinia (S)	604.33	18.88%	18.88%	
Casey (C)	674.43	51.89%	51.89%	
Darebin (C)	151.55	79.68%	72.70%	13.06%
Frankston (C)	304.35	55.02%	55.02%	
Glen Eira (C)	132.09	70.67%	63.05%	11.06%
Greater Dandenong (C)	371.46	52.33%	52.33%	
Hobsons Bay (C)	182.97	66.26%	66.26%	
Hume (C)	591.11	56.30%	56.30%	
Kingston (C) (Vic.)	250.78	69.53%	69.53%	
Knox (C)	283.80	68.50%	68.50%	
Manningham (C)	203.42	76.50%	76.50%	
Maribyrnong (C)	109.34	70.77%	70.77%	5.63%
Maroondah (C)	176.90	69.79%	69.79%	
Melbourne (C)	307.59	68.36%	55.05%	26.54%
Melton (C)	407.51	35.95%	35.95%	
Monash (C)	250.18	71.51%	71.51%	
Moonee Valley (C)	157.42	68.09%	64.11%	11.55%
Moreland (C)	156.22	74.25%	70.06%	11.78%
Mornington Peninsula (S)	769.61	31.47%	31.47%	
Nillumbik (S)	278.36	30.76%	30.76%	0.01%
Port Phillip (C)	148.16	57.99%	49.00%	18.56%
Stonnington (C)	115.29	53.89%	32.05%	26.01%
Whitehorse (C)	191.92	81.95%	81.03%	10.29%
Whittlesea (C)	448.72	55.65%	55.64%	0.60%
Wyndham (C)	564.34	54.42%	54.42%	
Yarra (C)	116.27	55.17%	33.97%	26.29%
Yarra Ranges (S)	847.99	38.23%	38.23%	

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