

An empirical analysis of transport and land-use integration: The case of public transport and apartment housing in Melbourne, Australia

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Abstract: Despite widespread policy aspirations for integrating high-density housing with public transport, what is achieved in practice is rarely measured. Furthermore, equity in public transport service provision has been given little attention in areas of high-density housing. Using Melbourne as a case study, this research tracks the development of apartment housing against public transport service provision over a 19-year period. Results show that population growth (32%) outstripped modest changes in the number of public transport services provided (5%) in the areas around new apartments, with considerable growth in apartment housing occurring (88%). However, when accounting for the introduction of larger public transport vehicles in the fleet, growth in capacity-adjusted services (35%) was found to slightly exceed population growth at a metropolitan level. Yet at a local level, considerable inequity was found in the number of capacity-adjusted services provided per person across areas and routes. Evidence was also found that apartment development has been strongly attracted to areas already well served by public transport, but with little response in terms of additional services. In the case of Melbourne, it appears that the policy intent of integrating high-density housing with public transport is a one-way mechanism only.

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1 Introduction

The integration of transport and land use remains an elusive concept, yet has long been espoused as essential for enhancing the sustainability, productivity and liveability of cities (Geurs & van Wee, 2004; Suzuki et al., 2013). Development of high-density

housing in areas of high quality public transport service provision is one example of integration (Searle, 2004; Smith, 1984), now reflected in transport and land-use planning policies in various cities globally (e Silva et al., 2023; Keys et al., 2023). This consolidation policy is supported by previous research identifying various benefits from locating housing closer to public transport, such as reduced car ownership and increased public transport use (Cervero, 1994; De Gruyter, Truong, et al., 2020; Moos et al., 2018).

Despite wide-spread and now long-standing policy aspirations for integrating high-density housing with public transport, little is known about what is achieved in practice; rarely are any outcomes reported, with a paucity of longitudinal studies (Chi & Lee, 2024; Ewing & Hamidi, 2014; Ibraeva et al., 2020). Furthermore, equity in public transport service provision, while investigated in previous studies (Amorim & e Silva, 2024; Currie, 2010; Kaeoruean et al., 2020), has been given little attention in areas of high-density housing. In response, this paper¹ tracks the development of high-density housing – namely residential apartments – against public transport service provision over time, using Melbourne, Australia, as a case study. This includes a 19-year longitudinal trend analysis (2003-04 to 2021-22) that accounts for changes in public transport vehicle capacities over time. It also includes a “needs-gap” analysis to understand the extent to which horizontal and vertical equity in public transport service provision is achieved in areas of apartment housing. Here, horizontal equity is assessed based on the number of public transport services provided per person across areas/routes (regardless of “need”), while vertical equity is assessed based on the relationship between socio-economic advantage/disadvantage and public transport service provision across areas/routes (Carleton & Porter, 2018; Delbosc & Currie, 2011).

Melbourne provides an ideal case study for this research, having experienced considerable growth in apartment housing along key public transport corridors in recent decades (Rawnsley, 2023), contributing to increases in public transport ridership and passenger crowding. During 2001-21, apartment dwelling numbers in Melbourne grew by 56%, considerably higher than detached housing growth of 31% (ABS, 2021a). Over the same period, Melbourne grew from 3.3 to 4.9 million people (ABS, 2021a), a 2.4% annual growth rate, notably higher than the OECD metropolitan average of 1-1.5% (OECD, 2020). Furthermore, Melbourne’s metropolitan planning strategy, Plan Melbourne 2017-2050, aspires to locate 70% of new housing in established (in-fill) areas close to jobs and public transport, contributing to equity and social cohesion goals, with the provision of apartment housing expected to play a major role (DELWP, 2017). More broadly, Victorian state legislation (“Transport Integration Act 2010”) requires government to demonstrate an integrated approach to transport and land-use planning, with equity as a decision making principle.

The contribution of this research is an empirical understanding of the relationship between apartment housing development and public transport service provision over time, and the extent to which this has supported (or detracted from) achieving vertical and horizontal equity. This can help to assess whether the policy and legislative intent of transport and land-use integration is being achieved, and whether this has contributed to equity in public transport service provision. In addition, to the best of the authors’ knowledge, this research is the first longitudinal analysis of its kind to account for

¹ This research builds upon a working paper (De Gruyter et al., 2024a), as well as earlier papers presented at the 103rd Transportation Research Board (TRB) Annual Meeting, 7-11 January 2024, Washington, DC, United States (De Gruyter et al., 2024b) and the 45th Australasian Transport Research Forum (ATRF), 27-29 November 2024, Melbourne, Australia (Keys et al., 2024).

changes in public transport vehicle capacities. This is particularly relevant to tram (and some train) services in Melbourne where larger vehicle types have been progressively introduced over the last 20 years. On some tram routes, passenger carrying capacity has almost doubled (Yarra Trams, 2023), thereby reducing crowding and also facilitating ridership growth.

This paper uses the term “apartments” to refer to multiple self-contained dwellings located within the same building, regardless of the type of housing tenure or management structure in place. In other countries, apartments may be known as flats, condominiums or multi-family housing.

The remainder of this paper is structured as follows. Section 2 provides a review of the literature on transport integration, including studies focused on high-density housing and public transport, as well as equity in public transport service provision. Section 3 provides context for the study through a description of Melbourne, including its population and housing characteristics, relevant policy and legislation, and public transport system. Section 4 outlines the method used to compile and analyze the data used in this study, while Section 5 presents the results. A discussion of implications is then provided in Section 6.

2 Literature review

2.1 Transport integration

Transport integration is recognized as one of the most important means for advancing sustainable transport (Givoni & Banister, 2010), commonly highlighted in transport policies worldwide (Stead, 2010). This is despite little evidence of successful outcomes and a general failure to make the transition from policy to practice (Givoni & Banister, 2010; Hull, 2008; Stead, 2004). Key barriers to policy integration, which also apply to transport, include narrow perspectives, weak or perverse incentives, lack of management mechanisms, and professional and departmental culture (Eckersten & Balfors, 2023; Geerlings & Stead, 2003). Various institutional barriers to transport integration have also been highlighted by others (Curtis & James, 2004; van Geet et al., 2019). There is also no widely accepted definition of transport integration, with the concept often meaning different things to different people (Potter & Skinner, 2000). Despite this, one commonly adopted definition is:

The organizational process through which the planning and delivery of elements of the transport system are brought together, across modes, sectors, operators and institutions, with the aim of increasing net social benefits (NEA, 2003).

Within this definition, “sectors” can range from health and education, through to environment and land-use planning.

A number of researchers have conceptualized transport integration into a number of dimensions, levels, or “rungs” on a ladder (Hull, 2005; Potter & Skinner, 2000; Preston, 2010; Stead, 2010). Here, the integration of transport and land-use planning is typically seen at a higher level with greater organizational difficulty, while the physical integration of public transport (e.g. fares, services, stops, information) is often viewed as the lowest rung on the ladder. Preston (2010) notes that while an empirical database of transport integration is emerging, most evidence is concerned with the integration of public transport. Furthermore, he highlights that the benefits of physical integration of public transport are largely based on ex-ante (before the “event”) appraisals and that ex-post

(after the “event”) evaluations are needed, particularly those that examine transport integration at higher levels (e.g. transport and land use).

Given the difficulties in achieving transport integration, Banister and Givoni (2010) suggest that “coordination” and “cooperation” may be sufficient in delivering many of the benefits of full integration. Furthermore, they note that “coordination” may be appropriate where more actors are involved, including both the public and private sector. This is particularly relevant to transport and land-use integration in cases where government controls the provision of transport services and land-use development is largely market-led, such as in Melbourne (Keys et al., 2024).

2.2 High-density housing and public transport service provision

Much research has been undertaken to understand factors that influence public transport use, particularly those that relate to the built environment (Aston et al., 2021; De Gruyter, Saghapour, et al., 2020; Ewing & Cervero, 2010; Taylor et al., 2009). These factors are typically categorized under the 3 Ds of density, diversity and design (Cervero & Kockelman, 1997), or in some cases, the 7 Ds which also include destination accessibility, distance to transit, demand management, and demographics (Ewing & Cervero, 2010). Previous research has also considered, to some extent, the relationship between high-density housing and public transport use (Moos et al., 2018; Sung & Oh, 2011), but much more limited is research that explores the relationship between high-density housing and public transport service provision (Kim & Li, 2021).

Research in the 1970s found that a minimum of 7 households per acre (17 per hectare (ha)) is needed for efficient bus service while 15 – 30 units per acre (37 – 74 per ha) is needed for rapid transit, such as rail (Pushkarev & Zupan, 1977). Another study found that a minimum of 35 people and jobs per ha were needed to support a reduction in automobile dependence through rail transit (Newman & Kenworthy, 2006). Guerra and Cervero (2010) found that light rail needs 74 people per ha to perform at the top 25 percent in terms of cost effectiveness, and heavy rail needs 111 people per ha. In their meta-analysis, Ewing and Cervero (2010) found that the elasticity of household/population density was 0.07, meaning that a 1% increase in population density is associated with a 0.07% increase in transit use. These findings indicate that while density influences transit use, other factors such as design and proximity to transit stops have stronger effects. A more recent study (Renne et al., 2016) found for every doubling of the combined population and job density within half a mile of transit stations, transit commuting mode share increased by 17.5%. In terms of walkability, a doubling of the Walk Score yielded a 27.6% increase in transit commuting. Transit service frequency also plays a critical role; a doubling of service frequency increases transit commuting by 18.6%. These findings highlight that increasing density, improving walkability, and enhancing transit service frequency near transit stations can significantly boost public transit commuting. When comparing from region to region, a doubling in the share of jobs and population accessible within walking distance of all rail stations resulted in a 38.6% boost in transit commuting. This illustrates the importance of the network effect.

Diab et al. (2020) found that a 10% increase in the number of apartments dwellings was associated with a 5% increase in public transport ridership. The authors suggest this is due to apartment housing being located in higher density areas containing a greater mix of land uses and higher levels of public transport supply, consistent with previous research (Gim, 2012). In addition, Smith (1984) showed a positive relationship between residential dwelling density and public transport use across various cities in the United States, but notes that an increase in housing density does not necessarily assure an increase in public transport service provision, particularly where free market real estate

conditions prevail. He suggests that government policy fostering the development of high-density housing should be accompanied by decisions to increase public transport service provision, allowing public transport to serve as a development catalyst (Smith, 1984). Kim and Li (2021) found that residential properties in Southern California were more likely to be densified in public transport-rich areas, not only in existing areas of high-quality public transport, but also in locations where public transport is expected to be available in the future.

2.3 Longitudinal studies of public transport service provision

Longitudinal studies of public transport service provision are rare (Ewing & Hamidi, 2014; Ibraeva et al., 2020), a key limitation being the lack of historical data (Wang et al., 2022). Furthermore, studies are often undertaken at an aggregate level, with the potential for differences to be masked within and between regional sub-areas (Kasraian et al., 2022). In general, most longitudinal studies of public transport tend to focus on ridership (Boisjoly et al., 2018; Diab et al., 2020; Dong, 2022), rather than service provision. However, previous research has also sought to understand how public transport influences land development (Kasraian et al., 2016), including property values (Bowes & Ihlanfeldt, 2001). While results vary, studies have generally found that the provision of public transport makes properties more desirable, leading to an increase in property values (Rennert, 2022). This is supported by longitudinal data from 1970 to 2010, which demonstrate a rise in gentrification indicators such as increasing property values, the influx of higher-income residents, and a shift in racial demographics around LRT stations compared to control areas (Chava & Renne, 2022). Another longitudinal analysis of rent trends from 2012 to 2016 across 23,000 census tracts near rail stations reveals that TODs with higher walkability and density experienced rent growth 30% higher than non-TOD areas. The study found that a 1% increase in population density and walkability led to rent increases of 0.05% and 0.16%, respectively, while greater distances from stations resulted in downward pressure on rents (Renne et al., 2024).

Previous studies have also investigated the co-development of public transport and land use in cities, with Levinson (2008) finding a positive feedback effect between population density and rail network density in London between 1871 and 2001. In an historical analysis of Sydney's tram network, Wang et al. (2022) found complementary and competitive links played distinct roles in shaping the tram network, while Lahoorpoor and Levinson (2022) found the tram network both influenced, and was influenced by, population growth.

In addition, significant efforts have been made to determine whether public transport service provision has kept pace with population growth over time in Australian cities. PTRG (2017) found that while total public transport service provision in Melbourne had increased by around 50% between 2001-02 and 2017-18, this had been declining on a per capita basis since 2011-12 due to significant population growth. Similar per capita declines have also been observed in South East Queensland and Adelaide, but not in Perth (PTRG, 2017).

2.4 Equity in public transport service provision

Various studies have also aimed to understand the gap between public transport service provision and need (Carleton & Porter, 2018). The concept of horizontal equity, concerned with equal service provision regardless of need (e.g. across areas), vs. vertical equity, concerned with service provision based on need (e.g. across income groups or other indicators of relative advantage/disadvantage), is particularly relevant (Delbosc & Currie, 2011).

Currie (2004) undertook a needs-gap analysis of public transport service provision in Hobart, Australia, focusing on gaps in service provision in areas where needs are high, but services are poor or non-existent. This found that residents living in outer suburbs experience the largest needs-gap. An extension of this research was applied to Melbourne using an established index of relative socio-economic advantage and disadvantage (Currie, 2010). This found a clear mismatch between public transport supply and social needs in outer suburbs relative to inner areas. Outer suburbs were found to have 75% less public transport services than inner areas, despite having some of the highest need for these services (Currie, 2010). Additional research on public transport equity in Melbourne has found that 70% of the population share only 19% of the public transport supply, highlighting considerable inequities in service provision, particularly in lower density suburbs on the urban fringe (Delbosch & Currie, 2011; PTRG, 2017).

In the United States, the concept of “transit deserts” has been explored, defined as areas that lack adequate public transport service relative to their populations that are deemed “transit-dependent.” Research by Jiao and Dillivan (2013) in four major cities in the United States found that transit deserts typically occur in neighborhoods surrounding historic downtowns, notwithstanding that downtown areas in the United States tend to have higher levels of public transport service. In addition, Kaeoruean et al. (2020) analyzed public transport demand-supply gaps in Calgary, Canada, both on an hourly basis (5am-8am) and annual basis (2013-17), finding considerable variation in gaps across the morning hours but less variation across years.

2.5 Wider allocative considerations

There are some wider considerations in relation to many studies of transport and land-use integration in which correlations between transit service provision, ridership and land-use densities are calculated. While there is a general relationship between transit service, travel demand, and its reflection in land-use preferences, this is not necessarily a deterministic relationship. In the case of public transport, decisions to add services, establish new routes, or add new infrastructure are typically made by bureaucratic allocation on the part of transport departments rather than adjusting independently to demand changes. Such decisions may encompass wider factors than simple demand, such as fiscal capacity, political preferences, and operating considerations. When service capacity improvements are made, they are often patchy in that they may serve a specific locality, but also lumpy, such as in the case of a new metro line which may take years to build but becomes operational at a single moment. Likewise land-use development is subject to similar patchiness and lumpiness. Often land-use development follows jobs or amenities to particular locations, which are not necessarily served by public transport, and development is lumpy, such as in the case of new multi-unit apartment developments. Consequently, there is strong potential for spatial and temporal mismatch between development, transit demand and service provision at the local level. However, most studies use large-n datasets at sub- or all-of metropolitan scales and apply correlative or regression based analysis which tends towards identification of linear relationships. All models are abstractions from reality and we should exercise caution in assuming that because a particular linear relationship has been identified between development and transit provision in one case that such a relationship applies deterministically in others, especially for factors that are subject to bureaucratic discretion. Rather we might realistically expect lags, divergences, gaps, and mismatches to occur in transport and land-use integration. In turn, good planning ought to avoid such errors.

2.6 Summary and research gaps

In summary, much research has explored factors associated with public transport use, particularly measures of the built environment. Needs-gap analyses of public transport service provision have also been undertaken, highlighting areas where social needs are high, but services are low or non-existent. However, less focus has been given specifically to high-density housing and its relationship with public transport service provision, despite wide-spread policy aspirations for integrating land use and transport. Longitudinal studies on this topic are particularly rare, while no public transport-related needs-gap analyses specific to high-density housing areas have been published. Using a case study of Melbourne, Australia, this research addresses these gaps through a 19-year longitudinal trend analysis (2003-04 to 2021-22) of apartment housing development and public transport service provision, followed by a needs-gap analysis specific to areas where apartment housing has been developed. In doing so, it provides an empirical analysis of transport and land-use integration, and the extent to which this supports equity in public transport provision.

3 Research context

Melbourne is the capital of the state of Victoria, located in the south-east corner of the Australian mainland. The city is home to around five million people (ABS, 2021a). Within greater Melbourne 71.4% of travel is by private vehicle, 8.8% by public transport, and 18.8% by active modes (Department of Transport and Planning, 2023c). Population growth, while occurring in greenfield developments on the urban fringe, has also been directed towards higher density areas located in the inner city. The inner Melbourne region – generally within 10 km of Melbourne’s CBD – has grown from 265,000 to 427,000 people between 2001 to 2021 (ABS, 2021a), an increase of around 160%, compared to 46% for the remainder of metropolitan Melbourne (ABS, 2021a). Over the same period, the number of apartments in inner Melbourne has increased from 55,000 to 122,000 dwellings, around 220%, compared to 27% elsewhere in metropolitan Melbourne (ABS, 2021a). Around two-thirds (63%) of all dwellings within Inner Melbourne are now apartments (ABS, 2021a). Figure 1 shows the locations of new apartment housing across metropolitan Melbourne between 2003-04 and 2021-22. This illustrates considerable growth in apartment development in Inner Melbourne, with more modest growth occurring in other parts of Melbourne.

Melbourne’s metropolitan planning strategy, Plan Melbourne 2017-2050, aspires to locate 70% of new housing in established (in-fill) areas close to jobs and public transport. Here, apartment development is expected to play a major role (DELWP, 2017). Despite this, only 53% of new housing was built in established areas during 2017-22 (Department of Transport and Planning, 2024b). Plan Melbourne 2017-2050 notes that greater housing choice, including apartments that are located close to public transport, can support equity and social cohesion goals (DELWP, 2017).

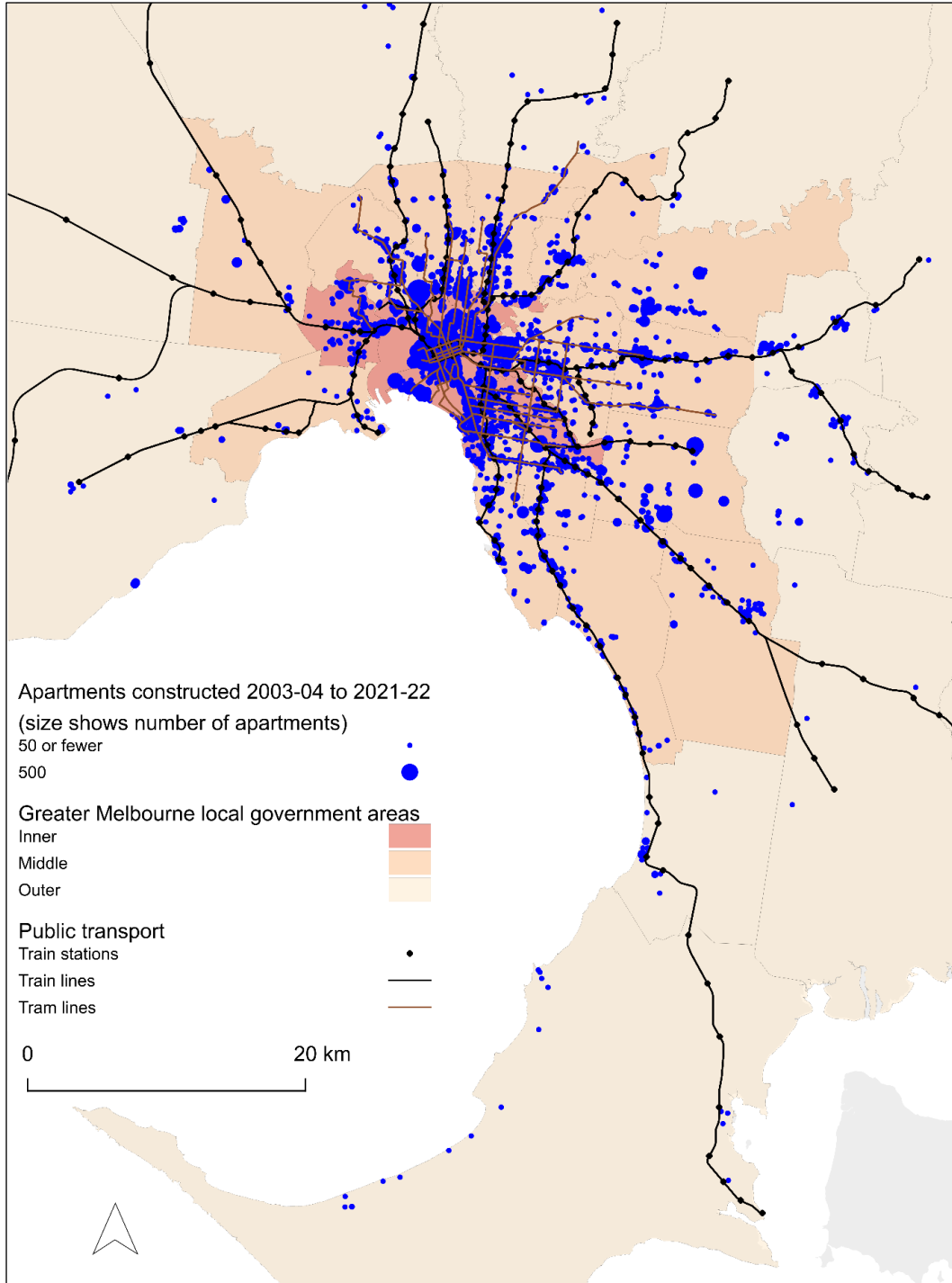


Figure 1. Locations of new apartment housing across Melbourne between 2003-04 and 2021-22

More broadly, state legislation (Transport Integration Act, 2010) requires the Victorian Department of Transport and Planning (DTP) to demonstrate an integrated approach to transport and land-use planning, with equity as a key decision making principle. It states that:

“...the transport system and land use should be aligned, complementary and supportive and ensure that (a) transport decisions are made having regard to the current and future impact on land use; (b) land use decisions are made having regard for the current and future development and operation of the transport system; (c) transport infrastructure and services are provided in a timely manner to support changing land use and associated transport demand.” (p. 33)

“The principle of equity means (a) equity between persons irrespective of their (i) personal attributes, including age, physical ability, ethnicity, culture, gender and financial situation; or (ii) location, including whether in a growth, urban, regional, rural or remote area; (b) equity between generations by not compromising the ability of future generations to meet their needs.” (p. 35)

It is also noted that Victoria has a permissive land-use planning scheme in which apartment development is largely market driven, albeit with government review and approval. On the other hand, public transport is centrally controlled and planned by government, notwithstanding that services are operated by private sector actors (Keys et al., 2024). This question of bureaucratic decision-making in relation to public transport services (and their funding) versus the market-based delivery of dwellings becomes important in relation to transport and land-use integration. Ideally under the objectives of the Transport Integration Act 2010 and the Plan Melbourne strategy, land-use development and transit service upgrades would occur in conjunction with one another. However, this integration has not systematically occurred. During the decade and a half since the TIA was legislated the Victorian Department of Transport has not yet prepared an Integrated Transport Plan. This failure was the subject of a recent Victorian Auditor General’s report (VAGO, 2021) which strongly criticized the Department. Ad hoc service improvements have been made, including to trams, but there is no necessary trigger in the TIA 2010 that requires services to be added as demand increases. Whether by bureaucratic inattention or through deliberate “sweating” of a route with growing patronage to generate operating surpluses, the potential for mismatch between growing tram service demand due to apartment development versus lagging tram service supply persists. In Victoria, there have been six state elections since 2002, with the Labor Party forming a majority government in all cases, except during a four-year period (2010-14) where the Liberal-National Coalition party were in power. Despite the dominance of the Labor Party since 2002, investment in public transport services is often politically driven. For example, in the lead-up to the 2010 Victorian state election, both parties committed to improving train services along the Frankston line, home to a number of marginal political seats (Savage, 2014). More recently, a focus on mega-infrastructure projects has tended to overshadow service upgrades to existing public transport routes/lines (Taylor, 2023).

Figure 2 shows an example of apartment growth along a typical tram corridor in Melbourne between 2009 and 2019. Here, the number of tram services along this corridor increased from around 141,000 annual services to around 157,000 annual services, or 11%, during 2009-19 (PTV, 2023a). This is despite the considerable growth in apartment housing that can be seen, which along the northern section of the corridor which Figure 2

relates to, resulted in the number of apartments doubling from around 3,500 to 7,000 dwellings (Department of Transport and Planning, 2023b).

Melbourne's public transport network comprises 17 train lines, 24 tram routes and around 400 bus routes. Train and tram services generally operate every 5-10 minutes in peak periods, while bus services operate less frequently, typically every 10-30 minutes (PTV, 2023b). To encourage more diverse and dense development near high-quality public transport, Melbourne's planning scheme defines a Principal Public Transport Network (PPTN), comprising all train stations, all tram routes, and a small number of bus routes with a relatively high peak service frequency (Department of Transport and Planning, 2023a), as shown in Figure 3.



Figure 2. Apartment growth along a tram corridor in Melbourne between 2009 (top) and 2019 (bottom)

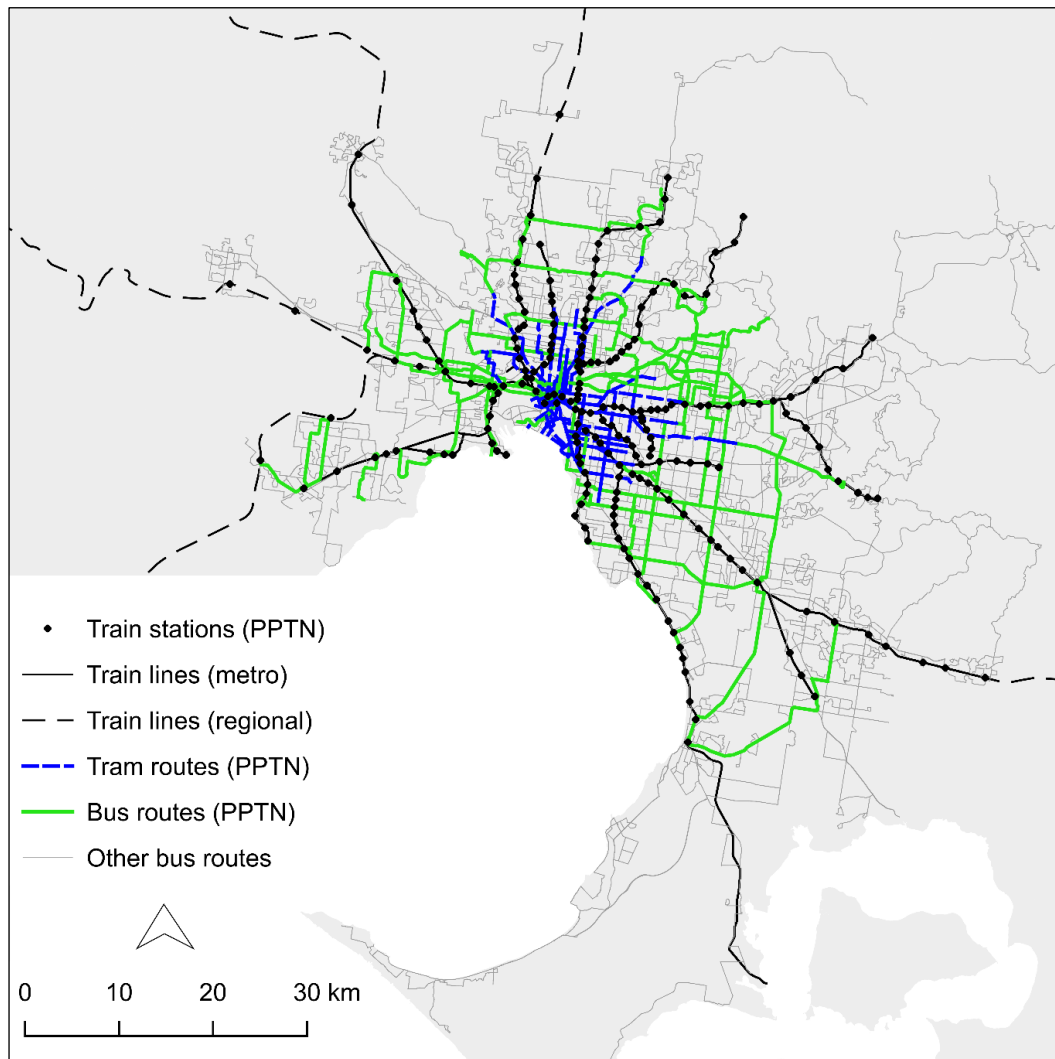


Figure 3. Melbourne's public transport network. *Note:* PPTN = Principal Public Transport Network

Public transport use accounts for 8.8% of all trips across metropolitan Melbourne, but around 16% of all trips in the Inner Melbourne region (Department of Transport and Planning, 2023c). Public transport ridership in Melbourne reached an all-time high in 2018-19, increasing by more than 50% since 2003-04, with a total of 570 million trips across train (243 million), tram (205 million) and bus (122 million) services (see Figure 4). However, like many cities, public transport ridership in Melbourne declined significantly with the COVID-19 pandemic, with ridership still recovering. As of May 2024, public transport ridership in Melbourne was around 80% of pre-pandemic levels (Department of Transport and Planning, 2024a). The approximately one-third patronage growth from 2006 to 2012 is noteworthy within Melbourne's transport planning. This new demand placed pressure on the metropolitan rail network to which the Victorian Government responded in 2015 by initiating a new underground rail line. That line will open in 2025 marking a nearly two-decade lag between initial demand surge, planning response, and infrastructure commissioning.

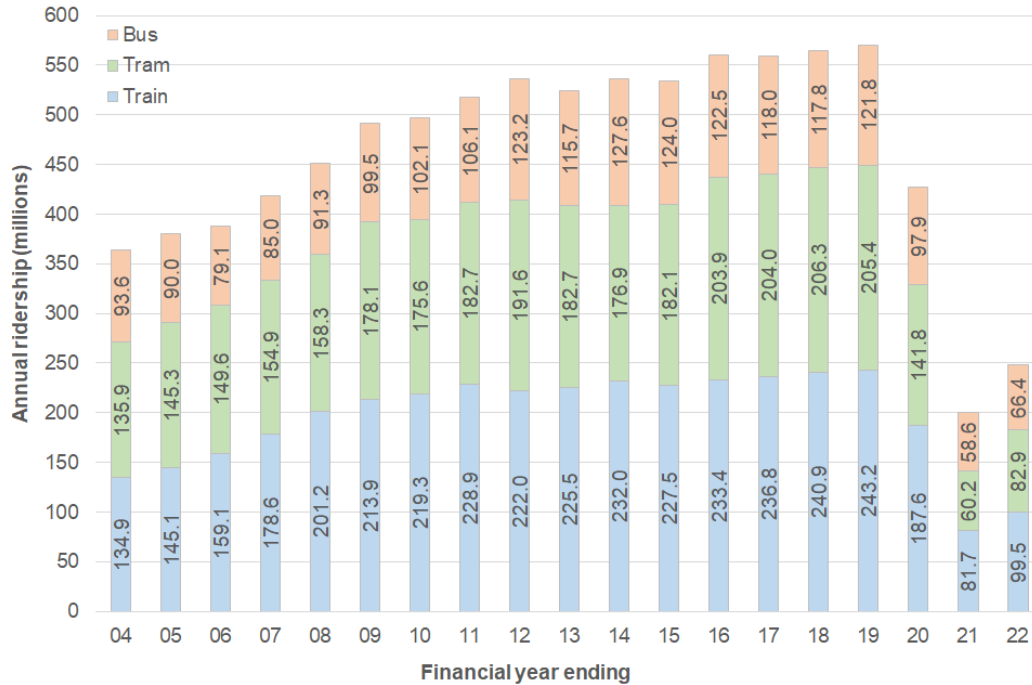


Figure 4. Annual public transport ridership in Melbourne by mode, 2003-04 to 2021-22

4 Method

This section describes the method used to compile and analyze annual data on apartment housing activity and public transport service provision in Melbourne. The study period chosen was 2003-04 to 2021-22, reflecting the availability of data on apartment housing activity. This timeframe also reflects a period in which considerable growth in apartment housing was experienced in Melbourne, as well larger public transport vehicles, particularly trams, being introduced on the network. Public transport service provision data used in this research was provided under a data sharing agreement and so permission is required to share the final dataset compiled for this research.

4.1 Compilation of apartment housing data

Annual data on construction of apartment housing developments (containing 10 or more dwellings), including their address location, was sourced from the Department of Transport and Planning (DTP) (Department of Transport and Planning, 2023b). Data was available for each Australian financial year (1 July to 30 June) between 2003-04 and 2016-17, and for calendar years between 2017 and 2021. To provide consistency in the use of financial years, housing developments completed in calendar years from 2017 onwards were split equally between financial years straddled by the relevant calendar year. This was considered reasonable based on a separate analysis of monthly dwelling building approvals data (ABS, 2023) which showed that, for the financial years of 2011-12 to 2021-22, 47% of approvals were granted in January to June, and 53% in July to December.

The annual dataset classified dwellings before 2017 as detached, attached 1 storey, attached 2 or 3 storey, attached 4+ storey, or unknown, and from 2017, as detached, apartments, townhouses, or unknown. Developments were considered to be apartments if

they were explicitly classified as attached 4+ storey or apartments, or if their site density was at least 100 dwellings/ha. A density criterion was considered desirable to avoid excluding unknown or misclassified apartment developments. A site density of 100 dwellings/ha was considered appropriate as it aligned closely with the attached 4+ storey and apartment classifications, with around 96% of dwellings classified as such having at least that density. Site densities below 100 dwellings/ha aligned more closely with the townhouse classification.

The annual dataset excluded greenfield developments on Melbourne's urban fringe. However, a separate analysis of greenfield development activity (Department of Transport and Planning, 2023b) found only two out of 1,300 apartment housing developments (0.2%) within 800 meters of Melbourne's PPTN were in greenfield locations. The annual dataset also excluded housing developments with less than 10 dwellings. A separate analysis of building permit activity (VBA, 2023) showed that around 6% of dwellings with a density of at least 100 dwellings/ha were for developments of less than 10 dwellings. This suggests that the number of dwellings drawn from the annual dataset may understate actual dwellings by around that amount.

4.2 Compilation of public transport service provision data

Annual data on numbers of scheduled train services by line was sourced from DTP from 2003-04 to 2021-22 (PTV, 2023a). Line-level data was converted to station-level data based on information available from DTP for 2016-22, with the assumption that stopping patterns for 2016-22 were representative of earlier years back to 2003-04 (which is considered a reasonable assumption in Melbourne). Route changes over the analysis period consisted only of adding new train stations and extending lines based on data from Vicsig (Vicsig, 2023), with no train stations closing during the analysis period. Vehicle capacity adjustments over the analysis period were based on separate information supplied by DTP. In general, a mix of 3-car and 6-car trains were used on some lines until full 6-car running was introduced in 2010; nominal capacity for trains on all lines was increased from 798 to 900 passengers by a program of replacing seats with standing room in 2017; and capacity on two lines was increased by progressive introduction of high capacity 7-car trains with capacity of 1,100 passengers in 2021. Using the example of where the nominal capacity for trains was increased from 798 to 900 passengers by replacing seats with standing room, the vehicle capacity adjustment factor was 1.13 ($=900/798$), which was later multiplied by the number of annual train services to determine the number of capacity-adjusted annual train services.

Annual data on the number of scheduled tram services by route was also sourced from DTP from 2003-04 to 2021-22 (PTV, 2023a). Route-level data was matched with individual tram stops, based on current stop locations specified in General Transit Feed Specification (GTFS) data, and adjusted for route changes over time. A total of 19 separate tram route changes over the analysis period (some involving multiple routes) were identified and reviewed in discussion with the tram operator, Yarra Trams. Two changes could not be addressed as they related to temporary disruptions where substitute services were not captured in the DTP dataset. The remaining 17 changes were addressed by matching individual tram stops to the relevant route configuration. Capacity adjustments over the analysis period were based on information supplied by Yarra Trams, showing the allocation of different tram classes to individual routes at each depot over time. Nine different classes of trams have operated in Melbourne over the analysis period, with capacities ranging from 55 to 180 passengers. Over time, higher capacity trams have been introduced on many routes, though occasionally at the expense of swapping lower capacity trams to other (perhaps less used) routes.

Annual data on the number of scheduled bus services by route was only available from DTP from 2017-18 to 2021-22 (PTV, 2023a), so this information was instead drawn from GTFS data (by month) which was available from 2015-16 onwards. A comparison of the DTP and GTFS data for bus services showed that they either matched exactly, or were within 5% of each other, for 91% of route/month combinations. The number of bus route changes far exceeded the number of tram route changes, with around 900 bus route changes since 2015, but many were minor relocations of individual stops rather than substantive changes. Using the GTFS data, the number of bus services on each route calling at each stop was determined. Capacity adjustment information was obtained from discussions with DTP and bus operators (CDC and Kinetic), which revealed that only three routes had seen capacity changes over the 2015-16 to 2021-22 period. On those routes, some standard rigid buses with a capacity of 70 passengers had been replaced by articulated buses with capacity of 110 passengers.

The data compilation process for public transport services produced a series of tables containing the following for each year: (1) number of scheduled services for any train station, tram stop or bus stop, and (2) capacity factors to be applied to determine the number of capacity-adjusted services.

4.3 Data analysis

Scripts in R were developed to calculate the annual number of apartment dwellings and corresponding number of public transport services for selected areas, which could range from a single apartment building to a public transport line/route or local government area, or for metropolitan Melbourne as a whole. Processing and analysis were undertaken using RStudio 2022.12.0 running R 4.2.2. Figure 5 outlines the process. An online dashboard was also developed to allow users to view results, including maps of apartment locations, for selected areas: <https://apartments-melb.shinyapps.io/dashboard/>.

The annual number of public transport services for the apartment dwellings in a selected area was calculated by (1) identifying train stations, tram stops and bus stops within 800 meters walking distance of the apartment dwellings in the area, (2) finding the number of scheduled annual services for those stations and stops, and their capacity-adjusted numbers, and (3) aggregating the number of public transport services for stations or stops on each line within the selected area, with and without capacity adjustments. Stations and stops within 800 meters walking distance were identified using OpenStreetMap, with 800 meters chosen for consistency with transport-related policies in Melbourne and previous research (DELWP, 2017; Kim et al., 2016).

For tram and bus services, results were returned by route, so that a single tram or bus stopping at multiple stops within the area was counted only once. Train services, by contrast, were returned by station, and required aggregation to avoid double-counting where a single train stopped at multiple stations within the area. This was achieved by taking the highest station count for each line and summing the line counts. Adjustment was needed where two lines meet at a junction station and then continue on a combined line. In this case, the combined line count was the higher of (1) the sum of the highest station counts for each of the two separate line segments, and (2) the highest station count for the combined line segment.

Using the data on the number of annual public transport services within 800 meters of apartment dwellings, an annual longitudinal trend analysis was undertaken from 2003-04 to 2021-22. This allowed the development of apartment housing against to be tracked against public transport service provision over time, with and without vehicle capacity adjustments. The analysis was undertaken for selected areas, including key public transport routes/lines, local government areas, and metropolitan Melbourne as a whole.

While the analysis could have also been undertaken for activity centers within metropolitan Melbourne, use of the selected areas was already found to sufficiently demonstrate how the results vary across different areas. Also, it is noted that satellite towns are typically located outside of metropolitan Melbourne and so were not captured by the dataset which was limited to the metropolitan area.

In addition to the longitudinal trend analysis, a needs-gap analysis was also undertaken. This required the compilation of two additional variables: population, and an Index of Relative Socio-economic Advantage and Disadvantage (IRSAD). These variables were sourced from the Australian Bureau of Statistics (ABS, 2021a) for each of the selected areas, but within 800 meters of stations and stops that are within 800 meters of apartment dwellings only. The IRSAD is an established index between 1 and 10 describing the extent of relative advantage or disadvantage in an area, with a high score indicating a relatively high incidence of advantage and a relatively low incidence of disadvantage (ABS, 2021b). The index is based on a combination of 25 different variables related to advantage and disadvantage (e.g. income, education, occupation) (ABS, 2021b) and was weighted by population for each of the selected areas. For the needs-gap analysis, horizontal equity was assessed by calculating the number of annual public transport services per person over time in the selected areas. This helped to assess the extent to which public transport service provision is equitable across areas, regardless of “need.” Vertical equity, on the other hand, assessed the extent to which public transport service provision is equitable based on “need,” through exploring the relationship between IRSAD and the number of annual public transport services available in the selected areas.

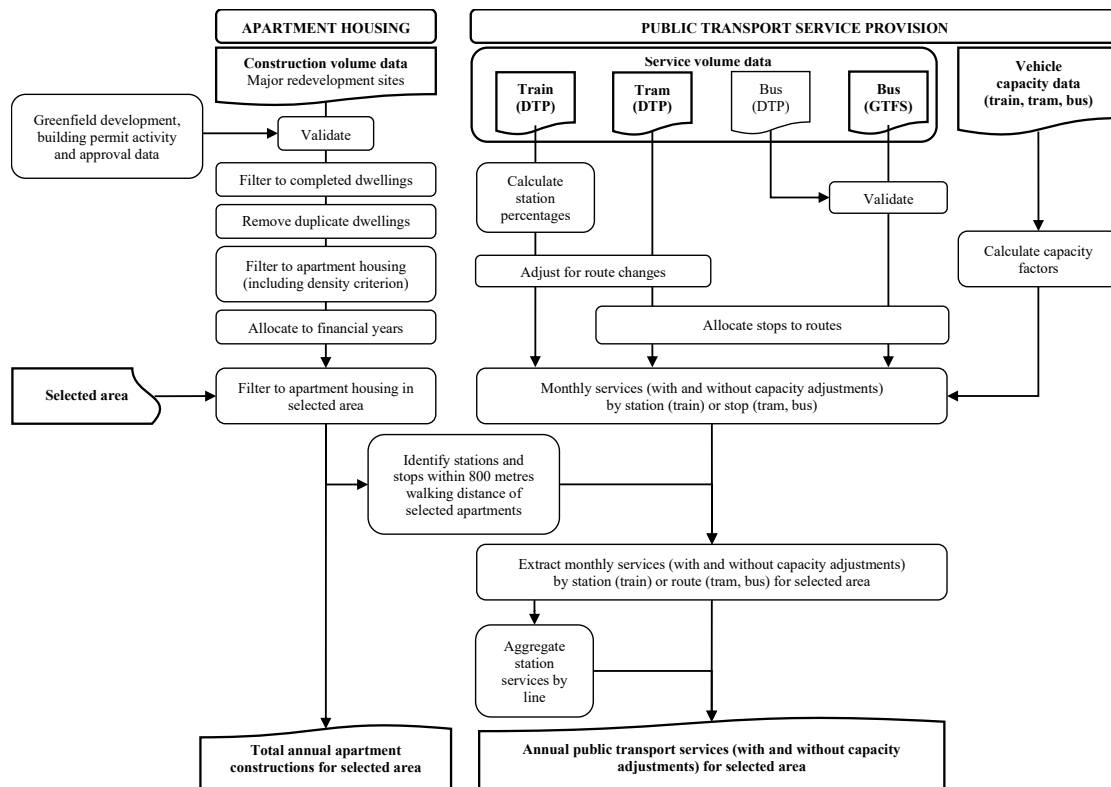


Figure 5. Process for calculating number of annual apartment dwellings and public transport services for selected area. *Note:* DTP = Department of Transport and Planning, GTFS = General Transit Feed Specification

5 Results

The results are presented in three main parts: (1) the longitudinal trend analysis of apartment housing activity and public transport service provision (2003-04 to 2021-22), (2) the needs-gap analysis for horizontal equity, and (3) the needs-gap analysis for vertical equity. With the exception of the needs-gap analysis for vertical equity, the results focus on train and tram services only due to the lack of bus service provision data before 2015-16. However, where bus services are included (from 2015-16 onwards), the results are largely consistent with those for train and tram services only (from 2003-04 onwards). The results with bus services included (from 2015-16 onwards) are therefore provided separately in Appendix A.

In addition, the analysis is based on the number of annual public transport services passing through each selected area and does not account for the distance covered by those services (i.e. service-km). This was intentional to reflect service provision from an apartment resident's perspective (e.g. number of services operating within 800 meters), but results in a decrease in the number of tram services along a small number of routes that were merged. It is also acknowledged that public transport service provision can be measured in other ways, e.g. a cumulative opportunities approach to reflect the ability of residents to reach key destinations such as jobs, schools and shops.

5.1 Longitudinal trend analysis

Figure 6 shows how public transport service provision across metropolitan Melbourne (within 800 meters of apartment dwellings) has tracked against total population (also within 800 meters of apartment dwellings), alongside apartment housing development, between 2003-04 and 2021-22. The values are indexed to 2003-04 for ease of comparison, with public transport services including train and tram only due to the lack of bus service provision data before 2015-16. As can be seen in Figure 6, population growth (32%) outstripped modest changes in the annual number of public transport services provided (5%), with considerable growth in apartment housing occurring (88%) between 2003-04 and 2021-22. A slight reduction in population growth can be observed after 2019-20 due to internal migration away from Melbourne and reduced international arrivals associated with the COVID-19 pandemic (ABS, 2022). While annual train and tram service provision remained relatively stable over the analysis period, generally within $\pm 5\%$ of 2003-04 levels, this grew by around 35% when adjusting for changes in public transport vehicle capacities, slightly surpassing population growth by 2021-22. In addition, a period of larger growth in capacity-adjusted public transport services can be observed between 2013-14 and 2016-17. This corresponds to the introduction of larger tram vehicles on some routes during this period, combined with the nominal capacity for trains on all lines being increased from 798 to 900 passengers in 2017.

Notwithstanding the changes in public transport vehicle capacities that have taken place, the results provide little evidence that the number of annual public transport services have changed in response to increases in apartment housing development. Rather, apartment development has been attracted towards areas that were already served by public transport. This is illustrated by Figure 7 which shows that, at a local government area level, more apartment dwellings were built between 2003-04 and 2021-22 in areas that already had a high level of public transport service provision in 2003-04.

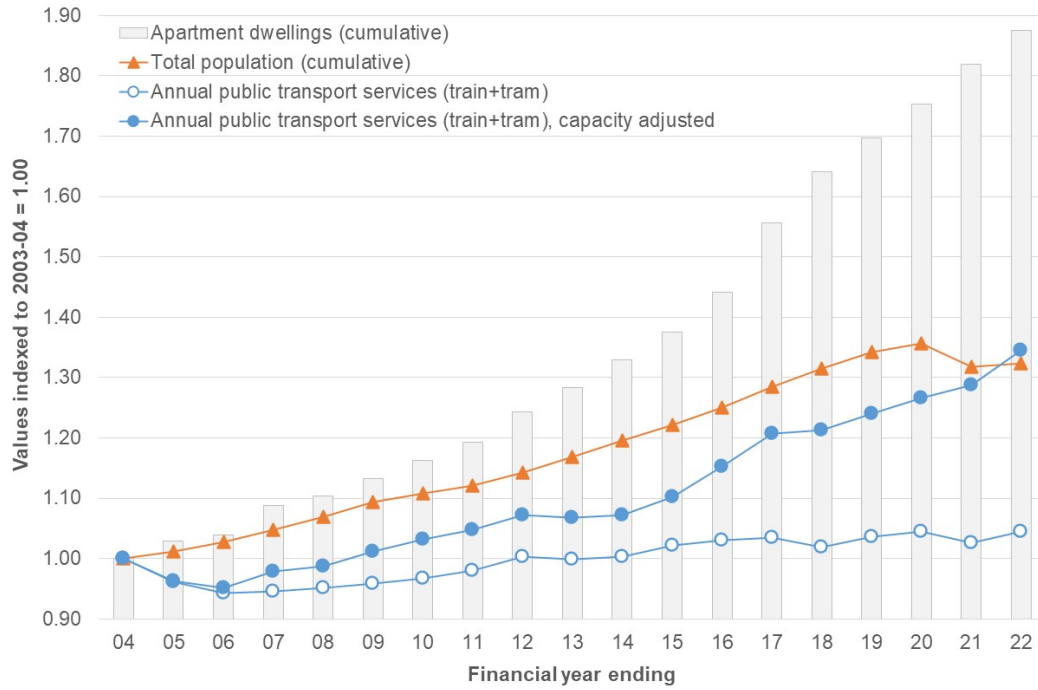


Figure 6. Trend analysis for metropolitan Melbourne of apartment housing development and total population vs. public transport services (train, tram) within 800 m of apartment dwellings (2003-04 to 2021-22)

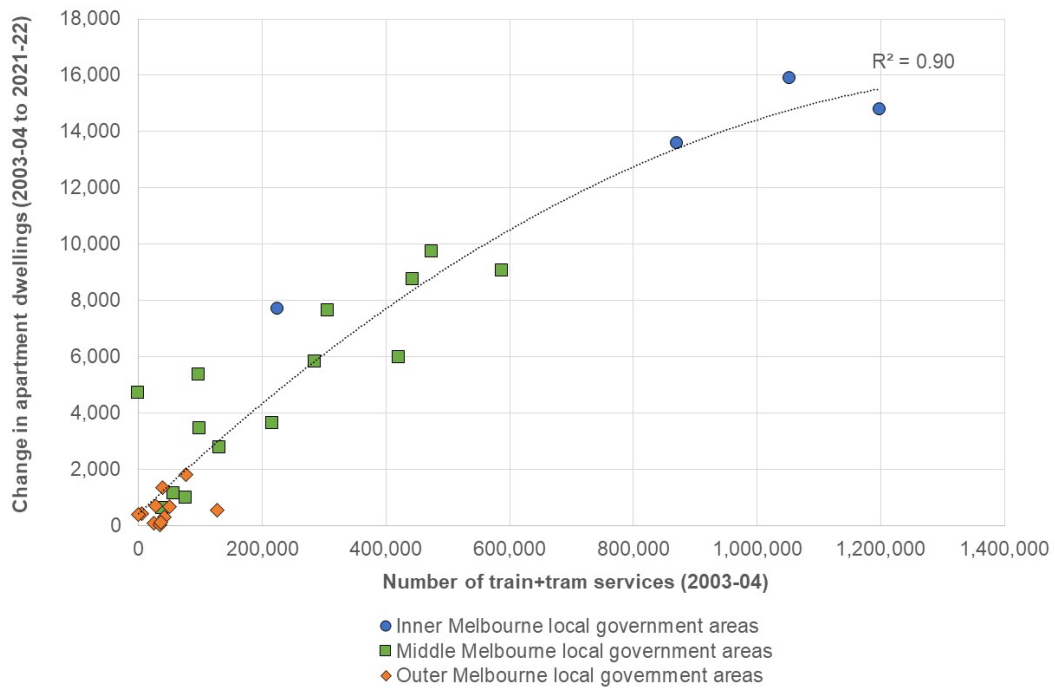


Figure 7. Annual public transport services (tram, train) in 2003-04 across local government areas within 800 m of apartment dwellings vs. change in number of apartment dwellings (2003-04 to 2021-22). Note: excludes City of Melbourne as an outlier which had more than 76,000 new apartment dwellings

Figure 8 shows the percentage change in total population (within 800 meters of apartment dwellings) and capacity-adjusted annual public transport services (also within 800 meters of apartment dwellings), alongside the percentage change in apartment dwellings, in each local government area in Melbourne between 2003-04 and 2021-22. For ease of comparison, local government areas are grouped into inner, middle and outer Melbourne, as illustrated in Figure 1. This grouping is consistent with the monitoring and analysis of housing outcomes by the Victorian Government (DELWP, 2018) and in line with other transport and land-use research previously undertaken in Melbourne (De Gruyter et al., 2014). Inner Melbourne generally refers to local government areas located within 10 km of Melbourne's CBD, where higher density housing is more prevalent, and where the majority of Melbourne's tram network operates. Middle Melbourne generally refers to areas located 10-20 km from Melbourne's CBD, reflecting lower density areas and a greater presence of bus services, but with higher density precincts around some train stations. Outer Melbourne generally refers to areas located more than 20 km from Melbourne's CBD, including low density greenfield development on the urban fringe and more limited public transport services in the form of buses and trains. As can be seen in Figure 8, for inner Melbourne, the growth in capacity-adjusted annual public transport services has generally kept pace with population growth, except for the local government area of Melbourne where population growth has far exceeded public transport service provision. Growth in apartment dwellings in the local government area of Melbourne has also been considerable at around 250% between 2003-04 and 2021-22. In middle Melbourne, the growth in capacity-adjusted public transport services exceeded population growth in most local government areas (10 out of 14), with considerable growth also occurring in apartment dwellings (up to around 200% in the local government area of Manningham). In outer Melbourne, designated growth areas located on the urban fringe (Melton, Wyndham, Whittlesea, Hume, Casey) have experienced high levels of population growth which has mainly been directed towards lower-density (detached) housing, reflecting modest growth in apartment housing. The growth in capacity-adjusted public transport services in outer Melbourne has not kept pace with population growth in around half of the local government areas (6 out of 11). Overall, the results shown in Figure 8 highlight inconsistencies in the growth of public transport services relative to the growth in population (and apartments) across local government areas in Melbourne.

Figure 9 shows the same type of information as Figure 8, but at a public transport line/route level. In most cases, the growth in capacity-adjusted train services exceeded population growth, alongside considerable growth in apartment dwellings (e.g., Footscray, with an increase of >1,000%). Results for tram routes are more varied: some experienced a decrease in service provision, while others experienced a substantial increase that exceeded the growth in total population along the route.

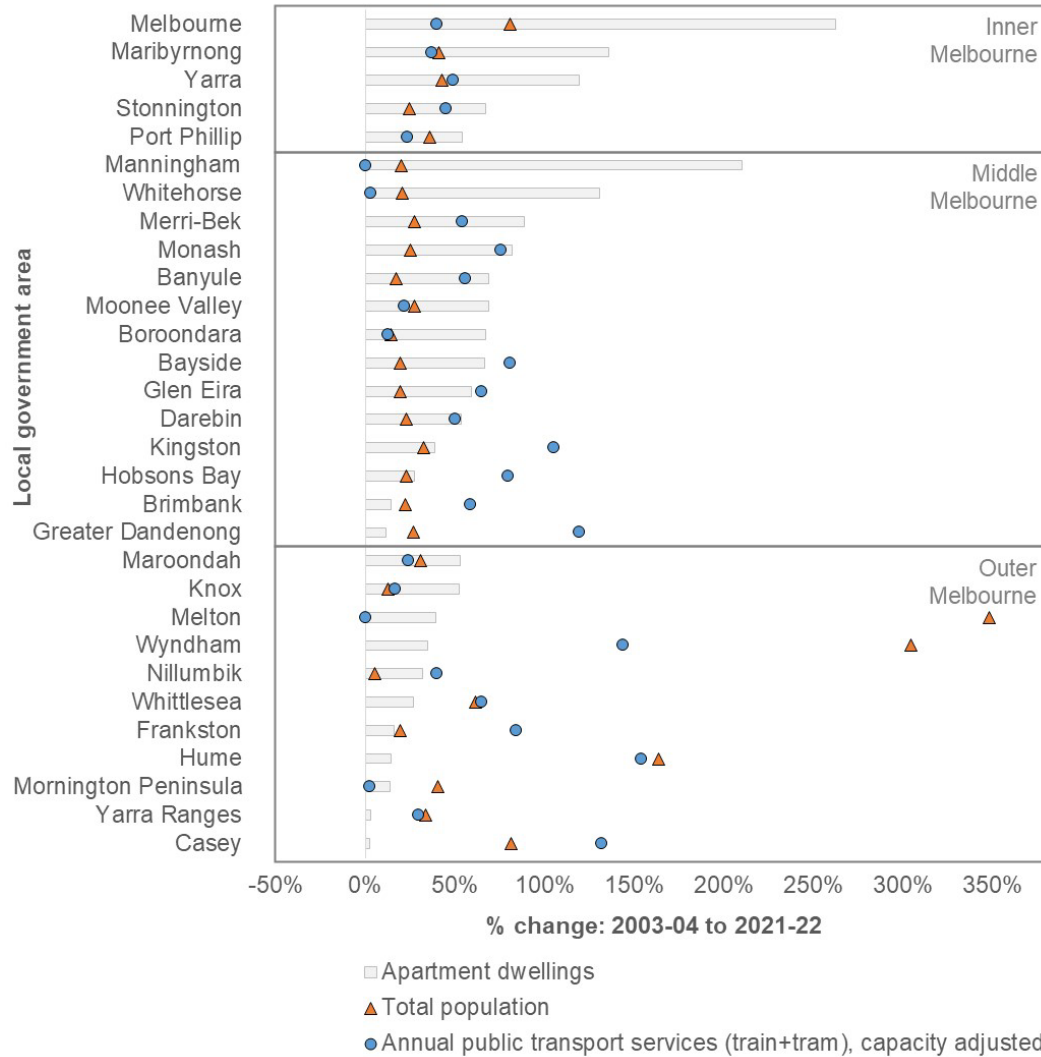


Figure 8. Change between 2003-04 and 2021-22 across local government areas in apartment dwellings, total population, and public transport services (train, tram) within 800 m of apartment dwellings

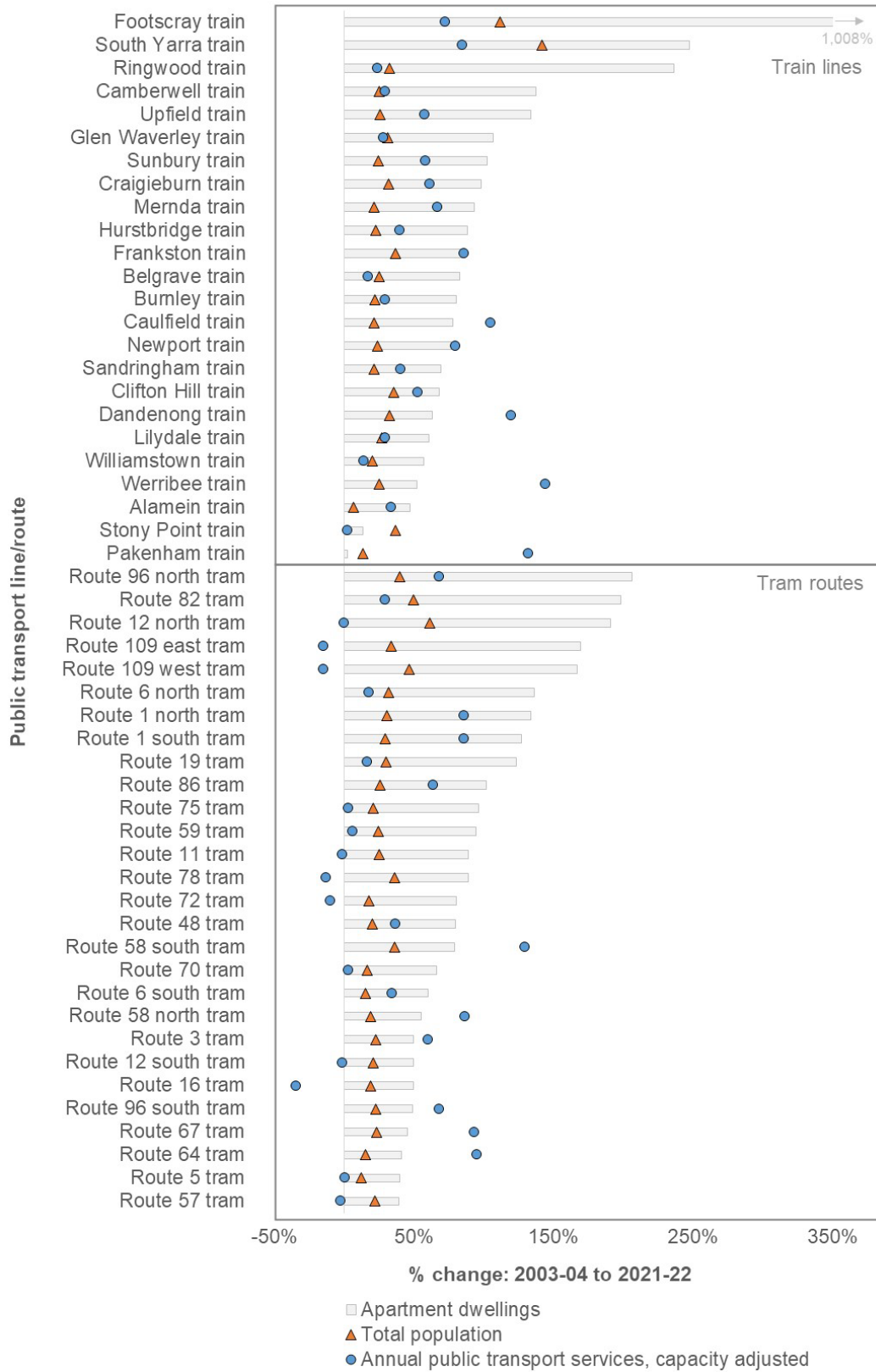


Figure 9. Change between 2003-04 and 2021-22 across public transport lines/routes in apartment dwellings, total population, and public transport services (train, tram) within 800 m of apartment dwellings

5.2 Needs-gap analysis for horizontal equity

To assess the extent of horizontal equity in public transport service provision in metropolitan Melbourne, Figure 10 shows the number of annual public transport services provided per person (within 800 meters of apartment dwellings), with and without capacity adjustments, between 2003-04 and 2021-22. While the number of annual public transport services per person has decreased from around 1.3 services/person in 2003-04 to 1.0 service/person in 2021-22, the capacity-adjusted figures are relatively stable over time around 1.2-1.3 services/person. This implies that horizontal equity in public transport service provision, when capacity adjustments are incorporated, is largely met at a metropolitan-wide level over time.

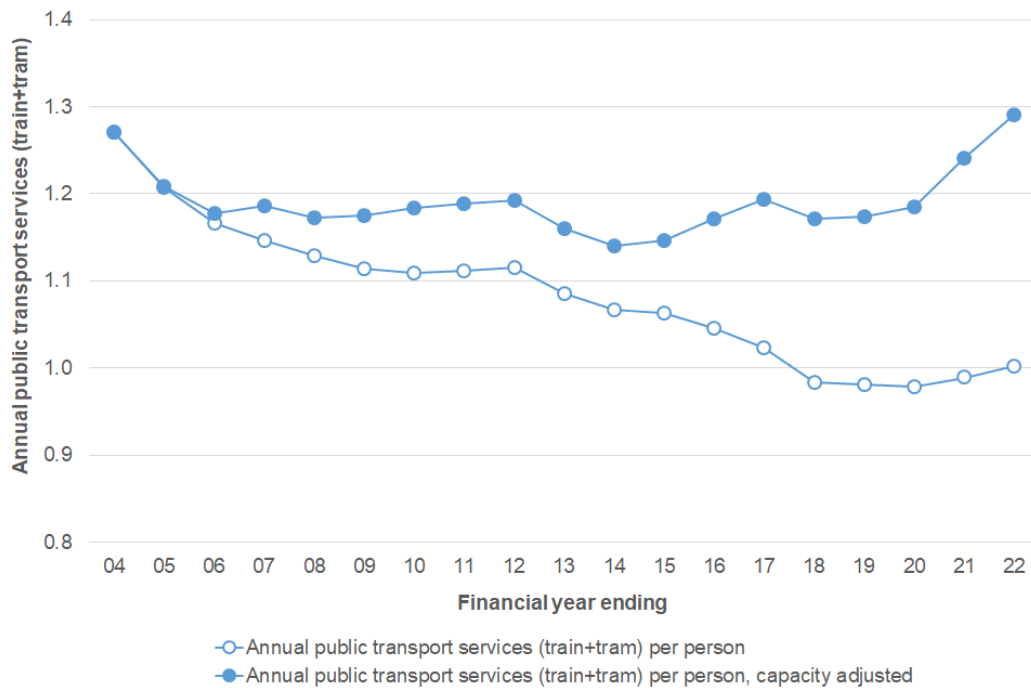


Figure 10. Annual public transport services (tram, train) per person within 800 m of apartment dwellings across metropolitan Melbourne (2003-04 to 2021-22)

Figure 11 shows the number of capacity-adjusted annual public transport services provided per person (within 800 meters of apartment dwellings) in each local government area in Melbourne in 2003-04 and 2021-22, along with the percentage change in apartment dwellings during this period. As can be seen, considerable variability exists across local government areas in the number of capacity-adjusted public transport services provided per person. Not only do some local government areas receive considerably more services per person than others, some experienced an increase in the number of services per person (between 2003-04 and 2021-22) while others experienced a decline. In general, most local government areas in inner Melbourne tend to receive a higher level of public transport service provision per person (around 5-15 services per person) than most located in middle and outer Melbourne (around 1-4 services per person). However, it is noted that when bus services are included from 2015-16 onwards (see Figure A6 in the Appendix), outer areas tend to receive a comparable level of public transport service provision per person to inner areas, yet disparities still exist between

local government areas. These findings suggest that horizontal equity in public transport service provision is largely unmet at a local government area level in Melbourne.

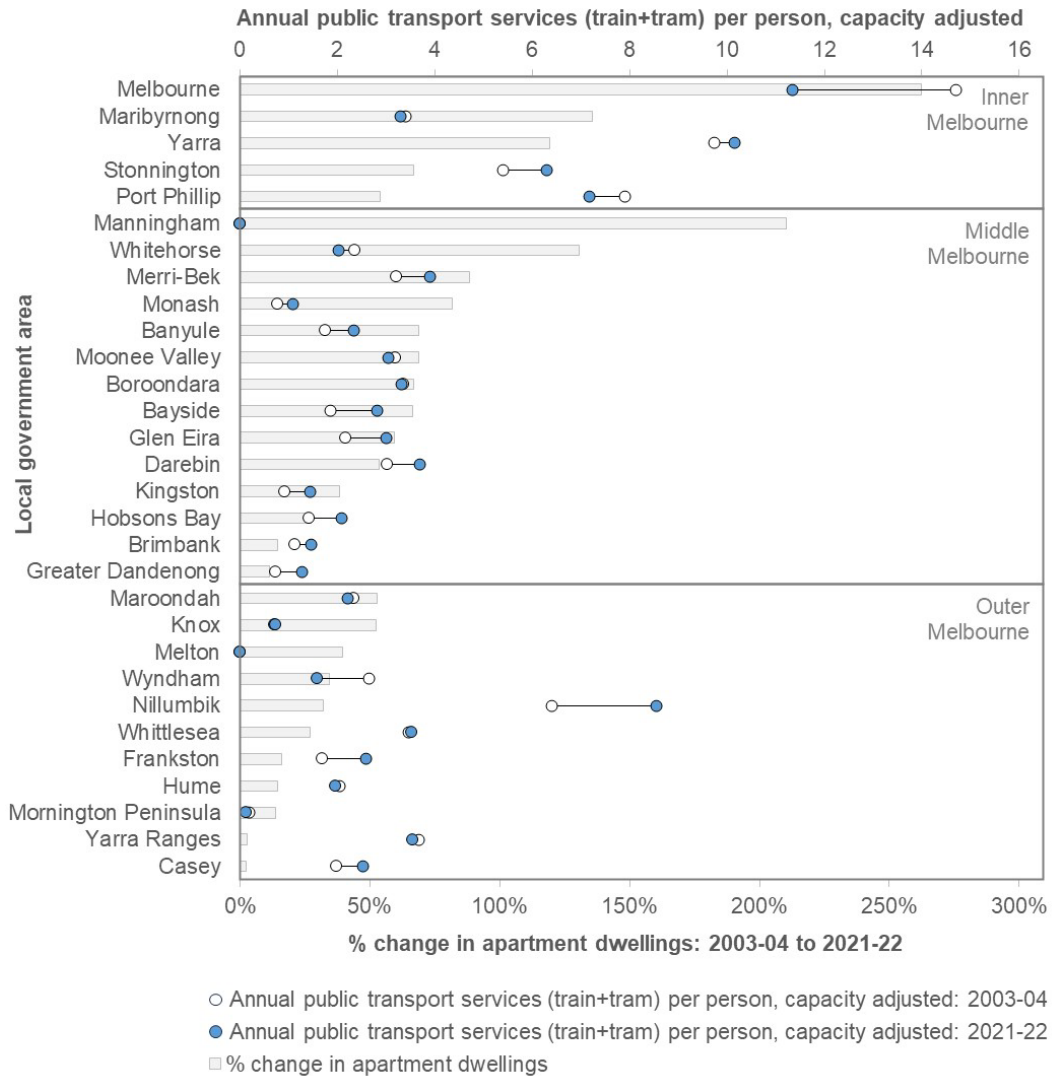


Figure 11. Change between 2003-04 and 2021-22 across local government areas in apartment dwellings and annual public transport services (train, tram) per person within 800 m of apartment dwellings

Figure 12 shows the same type of information as Figure 11, but at a public transport line/route level. Again, considerable variation is found across lines/routes where some received more services per person than others, and where both increases and declines were experienced between 2003-04 and 2021-22. This therefore suggests that horizontal equity in public transport service provision is largely unmet at a line/route level.

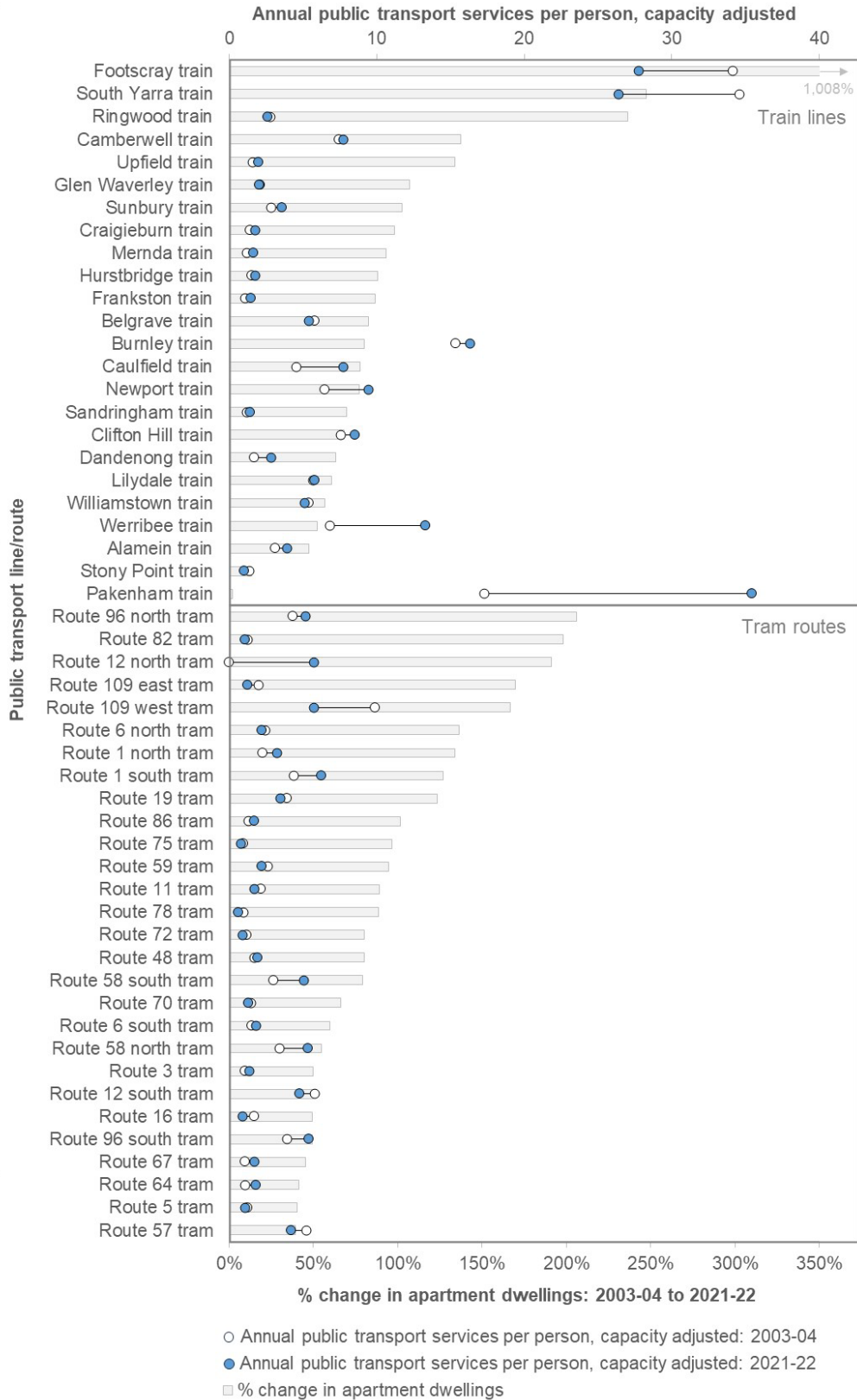


Figure 12. Change between 2003-04 and 2021-22 across lines/routes in apartment dwellings and annual public transport services (train, tram) per person within 800 m of apartment dwellings

5.3 Needs-gap analysis for vertical equity

To assess the extent of vertical equity in public transport service provision, the number of annual public transport services in 2021-22 (within 800 meters of apartment dwellings) in each local government area and along each public transport line/route was compared against the population-weighted Index of Relative Socio-economic Advantage and Disadvantage (IRSAD) for each area/line/route. These results include services for all three modes of public transport in Melbourne: train, tram and bus.

Figure 13 shows that local government areas with a higher IRSAD (higher incidence of advantage) tend to have a higher level of public transport service supply, although the relationship is relatively weak ($R^2 = 0.36$). While inner Melbourne local government areas tend to have a higher level of public transport supply and a higher IRSAD value, and the opposite is generally true for outer Melbourne, the results for middle Melbourne are more scattered. However, Melbourne's population is not evenly spread across its local government areas, so it is more appropriate to consider public transport supply on a per person basis, as shown in Figure 14. This shows that there is no clear relationship with the IRSAD value, indicating that more advantaged areas do not necessarily receive greater public transport supply per person than less advantaged areas, and vice versa. This implies that the socio-economic status of an area appears to have no influence on the allocation of public transport services on a per person basis.

Similar results are found at a line/route level, indicating that lines/routes located in more advantaged areas do not necessarily offer more services per person than those in less advantaged areas, and vice versa (see Figure 15 and Figure 16).

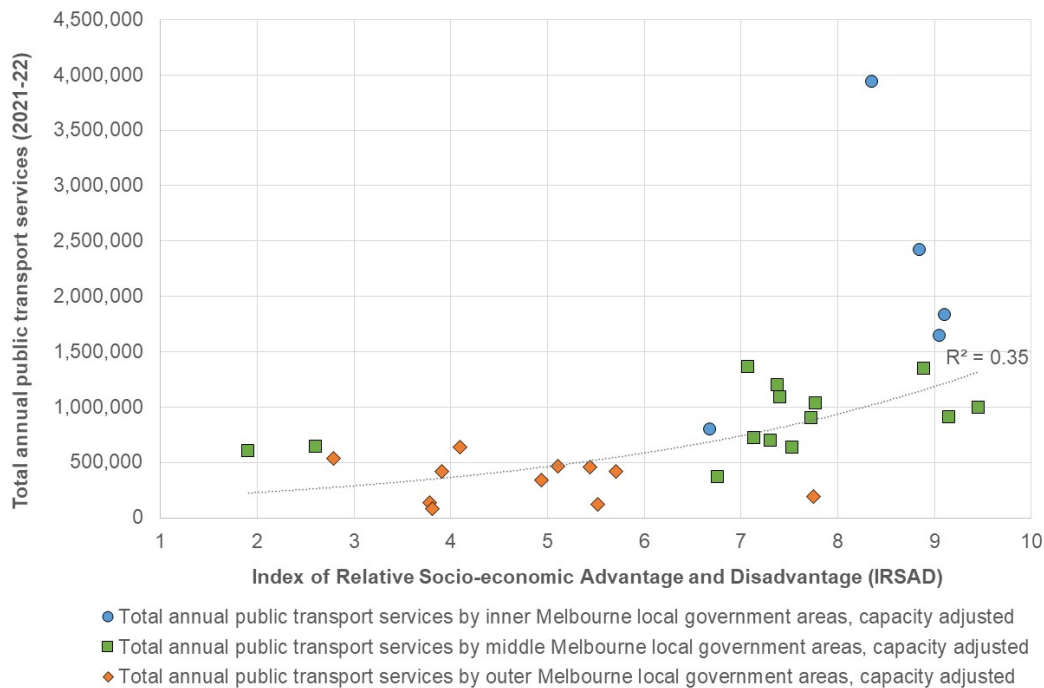


Figure 13. Total annual public transport services by local government area (inner, middle, outer) within 800 m of apartment dwellings (2021-22) vs. relative advantage/disadvantage

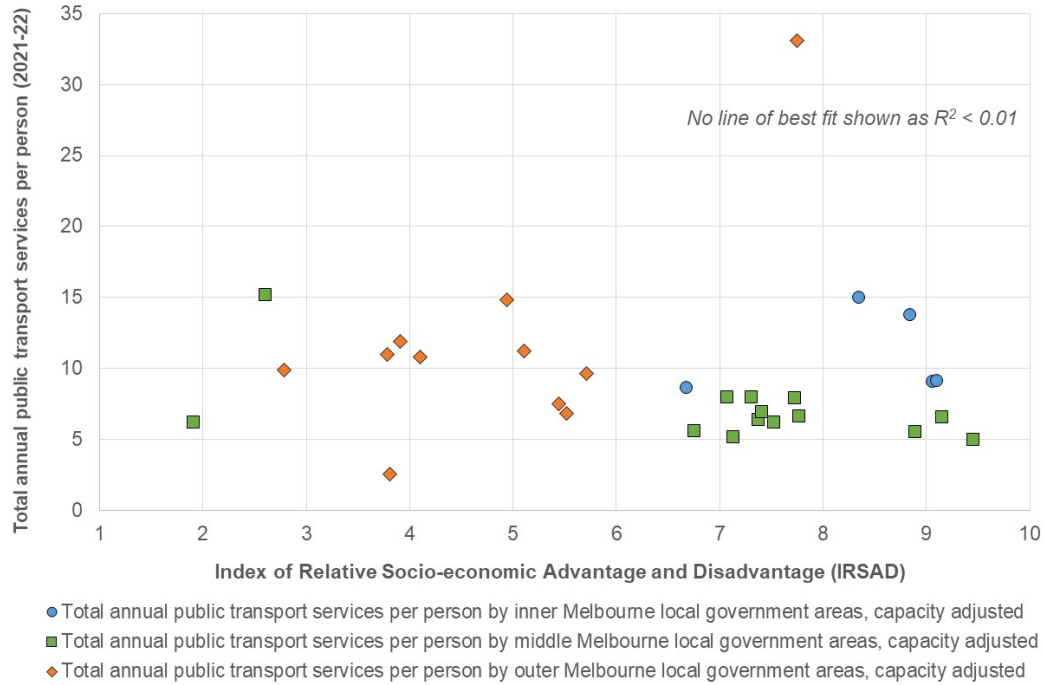


Figure 14. Total annual public transport services per person by local government area (inner, middle, outer) within 800 m of apartment dwellings (2021-22) vs. relative advantage/disadvantage

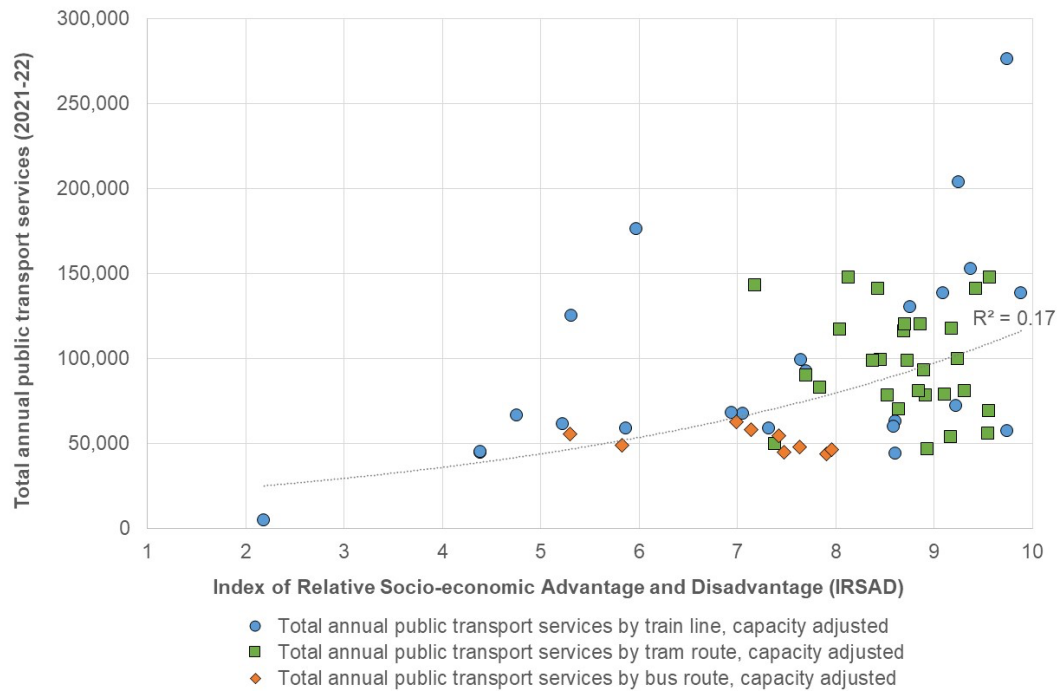


Figure 15. Total annual public transport services by line/route (train, tram, bus) within 800 m of apartment dwellings (2021-22) vs. relative advantage/disadvantage

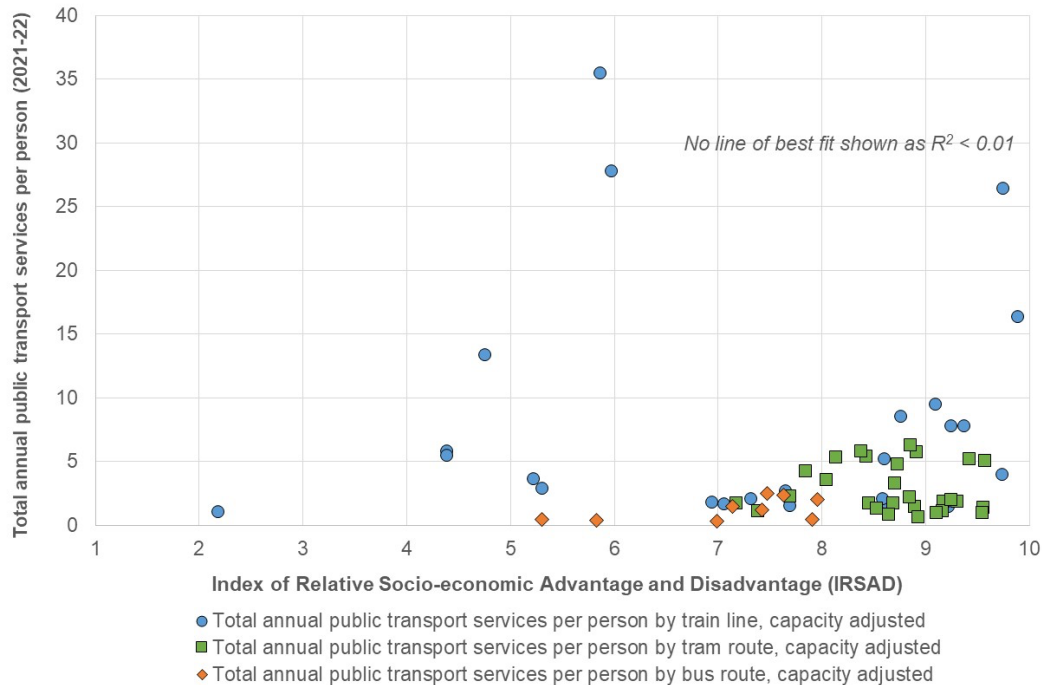


Figure 16. Total annual public transport services per person by line/route (train, tram, bus) within 800 m of apartment dwellings (2021-22) vs. relative advantage/disadvantage

6 Discussion and conclusions

This research has tracked the development of apartment housing against public transport service provision over a 19-year period, using Melbourne as a case study. A “needs-gap” analysis was also undertaken to measure equity in public transport provision in areas of apartment housing. Results showed that population growth (32%) outstripped modest changes in the number of public transport services provided (5%) in the areas around new apartments, with considerable growth in apartment housing occurring (88%) over the 19-year period. Little empirical evidence was found that public transport services have changed in response to increases in apartment housing development. Rather, urban consolidation has been directed towards areas already served by public transport – an example of one-way integration only between transport and land use. This is despite the presence of state legislation for integrating transport and use planning (Transport Integration Act, 2010) backed by supportive planning policy (DELWP, 2017), and a recent combination of formerly separate transport and planning departments into a single Department of Transport and Planning (Keys et al., 2024). The research findings are broadly consistent with previous research in the UK which has found that transport tends to be reactive to, rather than integrated with, land-use planning (Stead, 2004). It is also consistent with research in the US, where an increase in housing density was found to not necessarily assure an increase in public transport service provision (Smith, 1984). The findings also align with previous research in Australia which has found declines in public transport services per capita over time, due to significant population growth (PTRG, 2017).

In contrast, when incorporating vehicle capacity adjustments to account the introduction of larger public transport vehicles in the fleet, growth in capacity-adjusted public transport services within 800 meters of apartment dwellings was found to slightly

exceed population growth at a metropolitan level (35% vs. 32%). However, the move to larger public transport vehicles is partly due to the long-run modernization of Melbourne's tram fleet to low-floor, accessible vehicles, rather than in response to increases in population and apartment housing. Furthermore, considerable variation was found in the results across individual local government areas and public transport lines/routes, consistent with the extra capacity driven by a fleet modernization agenda. This implies that horizontal equity, expressed by annual capacity-adjusted public transport services per person, has been met in areas of apartment housing at a metropolitan level over time, but is largely unmet across individual local government areas or public transport lines/routes. For example, most local government areas in inner Melbourne received 5-15 annual public transport services per person compared to 1-4 services per person in most local government areas in middle and outer Melbourne. The issue of horizontal equity not been met at smaller geographical scales has been raised in previous research (Carleton & Porter, 2018; Kasraian et al., 2022), where studies undertaken at an aggregate (e.g. metropolitan) level have been found to mask differences between sub-areas. This highlights the importance of measuring equity at both the metropolitan and local level.

Little to no relationship was found between public transport service supply and the Index of Relative Socio-economic Advantage and Disadvantage (IRSAD). From an equity perspective, this is considered promising as it implies that more advantaged areas within 800 meters of apartment housing do not necessarily receive greater public transport supply per person than less advantaged areas within 800 meters of apartment housing, and vice versa. This finding contrasts previous studies which tend to consider all residential areas, regardless of housing type, typically finding that residents living in outer suburbs have lower public transport service supply combined with lower levels of socio-economic advantage, in contrast to those living in the inner suburbs (Currie, 2004, 2010; Delbosc & Currie, 2011). While the results of the current study imply that vertical equity in public transport service provision is largely met for those living within 800 meters of apartment housing, a progressive policy may call for less advantaged areas that have a greater need for public transport to receive a greater supply of services, relative to more advantaged areas.

One of the key implications of the research findings is that increases in public transport service provision need to be better aligned with, and more responsive to, population growth associated with the development of new apartment housing. In Melbourne, as well as other jurisdictions experiencing rapid population growth, new apartment housing should be supported the introduction of new public transport services to avoid passenger overcrowding on existing services and to ensure equity in public transport service provision. Here, continued monitoring of new housing development, population, and levels of public transport service provision is essential to inform future planning and service rollout. This should include the preparation of transport impact assessments that quantify public transport trip generation associated with new apartment housing (De Gruyter, 2019; Kim et al., 2017) so that the impacts of new housing on the public transport network can be better understood and addressed at the outset. This can be facilitated by a vision-led approach to transport and land-use planning, increasingly known as the Decide and Provide paradigm, by deciding on a preferred future for a development, and then providing the means to help realize that future (TRICS, 2021). This is particularly important in the context of cities seeking to promote urban consolidation and limit outward growth on the fringe.

Another key implication is that greater efforts need to be directed towards addressing horizontal inequities in public transport service provision at a local area and route/line level. This is relevant to many cities where public transport services are not evenly

distributed on a per person basis across the metropolitan area. Here, continued monitoring of horizontal equity in public transport service provision over time provides an important tool for understanding the extent to which this is being achieved. In Melbourne, a further consideration is the linear radial nature of much tram corridor apartment development. While public transport capacity increases and higher service frequencies are beneficial, further consideration needs to be given to new route provision that provides for multi-directional travel beyond the radial corridors. This is important to support reduced car ownership that can improve apartment design by avoidance of incorporated car parking provision. But car-free housing in part depends on public transport that can serve the multi-directional trips that car use provides. While buses sometimes play this role, they are often viewed as an inferior mode by public transport users in Melbourne and so investment in bus network reform is needed to help overcome this issue.

While this study has contributed to understanding the relationship between apartment housing development and public transport service provision, and the extent to which this has supported equity, it is also subject to some limitations. First, the extent to which apartment housing has shaped public transport service provision over time (if at all) could not be assessed due to lack of data on other factors that may influence public transport service provision, such as ridership, crowding, and political and investment decisions. In particular, historical data on ridership and crowding was not available in Melbourne for most of the study period and for each mode of public transport. Future research in other jurisdictions could therefore seek to incorporate these factors in a panel regression with fixed effects to understand their relative contribution to public transport service provision over time. In addition to traditional econometric models, recent developments in predictive modelling – such as XGBoost and the state-of-the-art transformer-based model TabPFN – offer promising alternatives. TabPFN, in particular, has demonstrated impressive accuracy in tabular data settings with limited samples and complex interactions by using pretrained prior knowledge and zero-shot inference (Hollmann et al., 2025). While these methods do not yet replace causal inference frameworks, they can be used in conjunction with tools like synthetic control methods to help estimate treatment effects and model non-linear dependencies. In future work using jurisdictions with more complete datasets, it is proposed that such approaches be explored to improve the robustness and explanatory power of the analysis. There is also scope to better understand how factors such as ridership, crowding and political decisions are associated with equity in public transport service provision relative to apartment development. More generally, the timing of apartment development relative to public transport service provision could be explored in more detail in future research using a time-series analysis. In addition, given the different operational characteristics and user perceptions associated with each public transport mode, a separate analysis could seek to understand how mode each is influenced by and/or contributes to apartment development, while noting that data on bus services for Melbourne was only available from 2015-16 onwards. Second, there is the policy and planning question of why the integration of apartment housing and public transport in Melbourne has been a one-way phenomenon only. Future research could seek to answer this question, including what is needed for it to become a responsive two-way mutually supporting planning mechanism. Broader questions also remain about whether the public transport response (or the lack of response) to housing development in Melbourne has been adequate to fulfil broader policy objectives of sustainable development such as the 15/20-minute city. Future research could seek to explore these issues in greater detail, both from a resident and planning agency perspective. Third, while the analysis explored differences across local government areas and public transport lines/routes, it was limited to metropolitan Melbourne only. Future studies

could undertake similar analyses in other cities and regions and also track the provision of other (non-transport) services and facilities over time, e.g. parkland, schools.

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Author contribution

The authors confirm their contribution to the paper as follows: conceptualization: C. De Gruyter, E. Keys; methodology, formal analysis, investigation: C. De Gruyter, S. Pemberton; validation: C. De Gruyter, S. Pemberton, E. Keys; data curation, visualization: S. Pemberton; writing – original draft, review & editing: C. De Gruyter, S. Pemberton, E. Keys, J. Dodson, J.L. Renne; project administration, funding acquisition: C. De Gruyter.

Appendix

Appendix available as a supplemental file at <https://doi.org/10.5198/jtlu.2025.2667>.

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