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Advancing smart urban planning: public transit connectivity and the case of melbourne's bus network

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Abstract

This study investigates the significance of public transit connectivity in promoting intelligent urban planning, utilizing Melbourne's bus network as a case study. Concentrating on the city's main growth corridors, North, Southeast, West, and Southwest, the research examines the effects of rapid population growth on the accessibility and efficiency of the bus transport system. By leveraging data from the Victorian Planning Authority and the Australian Bureau of Statistics, the study evaluates service coverage, frequency, and travel time reliability concerning key urban functions, such as access to employment, education, healthcare, and social infrastructure. The findings indicate notable spatial and temporal disparities, with the Southeast and Southwest corridors facing the most severe service deficiencies. These discrepancies obstruct the establishment of an integrated and equitable transport system, which is a vital element of intelligent urban planning. Consequently, the paper suggests specific strategies to enhance service frequency, broaden network coverage, and implement late-night operations. These proposals are designed to facilitate Melbourne's shift towards a smart, inclusive, and sustainable urban future by improving transit equity, decreasing car reliance, and bolstering connectivity in underprivileged suburban regions.

Keywords Demand-Responsive Transport (DRT), Effective city planning, Urban development, Livability, Plan Melbourne 2017–2050

1 Introduction and background

Melbourne is often cited as one of the most livable cities globally, distinguished by its robust infrastructure, cultural richness, and overall high quality of life [82, 83]. Nevertheless, the city's swiftly increasing population, especially in its outer suburban regions, is exerting significant strain on public transport systems [41]. With over 1,700 new residents moving to Melbourne weekly [4], projections indicate that the population could reach 8 million by 2051 [7], this is a trend that has continued in recent years [13]. This demographic surge is particularly evident in outer suburban Local Government Areas (LGAs) such as Casey, Wyndham, Melton, Hume, and Whittlesea, where the pace of

residential development has outstripped the expansion of public transport infrastructure, especially in terms of bus services. Melbourne's public transport network includes trains, trams, and buses, with buses playing a key role in connecting low-density and fringe areas to the rail and tram networks.

The choice of suburbs within each growth corridor, specifically those located in the Casey, Wyndham, Melton, Hume, and Whittlesea LGAs, is guided by the strategic objectives outlined in Plan Melbourne 2017–2050. This plan seeks to steer urban growth, infrastructure investment, and population increase towards specified growth zones. These designated areas are anticipated to host the majority of Melbourne's greenfield development in a coordinated, serviced, and sustainable fashion. The selection of these LGAs is not random; rather, it is strategically aligned with the vision of Plan Melbourne and the local planning frameworks. Each selected suburb embodies a blend of strategic growth designation as per the Victorian planning agenda, readiness of infrastructure, planning approvals, its role in facilitating employment decentralisation and housing supply, and, notably, its connectivity to existing and future transport infrastructure. The selection of LGAs in this research promotes a balanced strategy for population distribution, economic growth, and sustainable urban development throughout Greater Melbourne.

Although the inner suburbs of Melbourne enjoy a well-established and dependable public transport network that facilitates easy access to job centers and essential services, the burgeoning outer regions encounter substantial challenges. These challenges are likely to be intensified by anticipated population growth from 2021 to 2036, as outlined by the Department of Transport and Planning (DTP 2023 [28]) (see Fig. 1). In these rapidly developing areas, bus services are frequently characterized by infrequency, prolonged travel times, and weak organization [55]. The disparity between population growth and the corresponding development of public transport infrastructure has led to increased environmental repercussions, aggravated socio-economic disparities, and a heightened demand for equitable access to resources. Environmental repercussions include increased carbon emissions from car dependency and the expansion of urban sprawl, which both weaken and challenge Melbourne's sustainability and climate targets.

The newly developed outer corridors face considerable deficiencies in public transport, especially regarding the effectiveness and accessibility of bus operations. Residents in these burgeoning locales frequently find themselves reliant on private automobiles due to the shortcomings of the current bus networks. Issues such as infrequent service, extended travel durations, and inadequate connections to train stations, crucial conduits to the central business district, intensify this reliance. Consequently, this dependence on personal vehicles is associated with elevated transportation expenses, prolonged

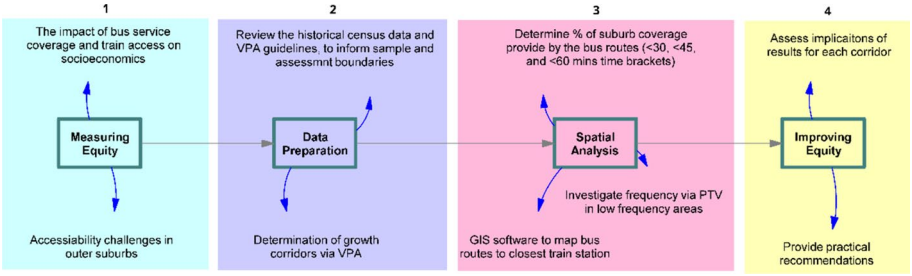

Fig. 1 The methodology process. (Source: Authors)

commuting times, and increased traffic congestion, all of which detract from the livability of these areas. Moreover, the absence of dependable public transportation appears to disproportionately impact marginalized groups, including low-income households, individuals with disabilities, and those lacking access to private transportation. This situation may exacerbate socio-economic disparities between the inner and outer suburbs.

Despite growing recognition of these challenges, there remains a lack of targeted spatial analysis evaluating the performance of bus services in Melbourne's outer expanding suburbs. It is worth noting that the term expanding suburbs, used throughout this study, denote the growth corridors notion used by the Victoria Planning Authority. Previous studies have broadly addressed transport disadvantage in Australian suburbs yet often overlook localized, corridor-specific gaps in service frequency, travel time, and accessibility. This study directly addresses this gap by integrating spatial, demographic, and service-based data to assess how bus inefficiencies are contributing to inequity in rapidly expanding regions.

The central focus of this study is to assess the accessibility and effectiveness of bus services within the rapidly developing outer expanding suburbs of Melbourne. The guiding research question is: *In what ways does the efficiency of bus services in these expanding suburbs affect sustainable urban development, and what enhancements are required to improve public transport equity and decrease reliance on cars?* This inquiry aims to shed light on how existing bus services fulfill the demand for access to vital transport hubs, particularly train stations, which play a crucial role in commuting to the Central Business District (CBD) and other significant locations that offer employment, housing, education, and income opportunities. The objectives of this study are:

1. Identify gaps in bus service provision by analyzing service frequency, travel times, and coverage in outer expanding suburbs. The analysis will focus on how well bus services connect residents to major transport nodes, especially train stations, within specific timeframes: 30 minutes (satisfactory), 45 minutes (reasonable), and 60 minutes (unreasonable). This Objective supports strategic infrastructure planning in rapidly growing areas.
2. Examine the socioeconomic impacts of inadequate bus services in outer suburban areas. This will involve exploring how poor public transport connectivity may lead to increased car dependency, reduced access to employment and education, and heightened social exclusion for lower-income households and vulnerable populations. By investigating the link between transport deficiencies and socioeconomic outcomes, this study will highlight the broader consequences of bus service gaps. This Objective focuses on equity and inclusive access to employment, education, and essential services.
3. Propose strategies to improve bus service efficiency by recommending enhancements such as increasing service frequency, expanding coverage, and improving connections with other transport modes. These strategies will align with Melbourne's sustainability objectives, as outlined in *Plan Melbourne 2017–2050*, which emphasizes reducing car dependency and promoting equitable access to essential services [27], aligned with sustainable mobility and reducing car dependency in line with Plan Melbourne 2017–2050.

Plan Melbourne 2017–2050 stresses the necessity for sustainable transportation solutions to accommodate the increasing population of Melbourne [27]. It is also crucial to address the shortcomings of bus services in the outer suburbs to guarantee fair access to essential services, including healthcare, education, and employment opportunities. As Melbourne continues to expand, the establishment of efficient and accessible public transport systems will be essential for preserving the City's livability and mitigating socio-economic inequalities [37]. This research examines the accessibility and effectiveness of bus services within Melbourne's outer expanding suburbs, particularly focusing on travel durations to the nearest train stations. The study seeks to pinpoint areas that require urgent enhancements by examining the connectivity of bus networks to vital transport hubs. The results from the study provide useful insights to relevant policymakers and can inform urban planning initiatives aimed at ensuring that public transport infrastructure evolves in tandem with Melbourne's swift population growth.

2 Background and literature review

This section examines challenges and prospects present in the outer expanding suburbs of Melbourne, as well as the socio-economic ramifications stemming from insufficient bus services, and assesses effective strategies for enhancing public transport systems.

2.1 Public transport accessibility and equity

Public transport is essential for ensuring that all residents, regardless of location, have equitable access to employment, education, healthcare, and social inclusion opportunities [26, 39, 66]. Melbourne's expanding suburbs have seen substantial population increases, yet bus services in these areas remain inadequate, leading to socio-economic disparities. Public transport accessibility is a critical component of equity in urban development [49]. Accessibility refers to the ease with which individuals can reach desired services and destinations using available transport options. Geurs and van Wee (2004) [17] describe accessibility as a function of spatial proximity, travel time, and cost [35]. define equity in transport as the distribution of benefits and costs among society's members.

These principles are central to understanding why transport planning needs to move beyond the traditional Cost-Benefit Analysis (CBA), which often overlooks the social implications of transport deficiencies. With existing research showing Melbourne's outer expanding suburbs already face significant transport disadvantages, where poor bus service frequency and coverage exacerbate the inequities faced by lower-income residents [75], this can only be expected to become more critical as these expanding suburbs expand. Current CBA frameworks fail to address equity because they prioritize economic efficiency over social justice [63]. CBA typically aggregates benefits and costs at the societal level, which disproportionately favors individuals who already have higher levels of mobility and access to resources. In contrast, an equity-based approach to transport planning emphasizes accessibility gains as the key metric for evaluating the success of transport projects.

In Melbourne, the inadequacies in bus services in the expanding suburbs highlight the need for an accessibility-driven approach. As Di Ciommo and Lucas [30] argue, equitable transport planning must account for how transport accessibility affects vulnerable populations. Accordingly, a poor transport system can limit residents' ability to access

essential services such as employment and education [59]. The findings of this research are consistent with broader concepts and discussions in the literature that emphasize the importance of public transport in promoting social equity [70].

The spatial inequality in Melbourne's transport network is a significant issue, particularly in the city's expanding suburbs. While the inner suburbs benefit from well-established public transport infrastructure and high-profile transport infrastructure investments such as the Suburban Rail Loop East, including trains, trams, and buses, the outer suburbs face substantial gaps in service provision. This uneven distribution of transport services forces many residents in expanding suburbs, who are already at a socio-economic disadvantage, to rely on private vehicles, which in turn increases household transportation costs, commute times, and environmental impact [6, 26].

The Southeast and Southwest corridors experience the most severe limitations in bus service provision, restricting access to the central business district (CBD) and key employment hubs [21]. Public transport accessibility is also crucial for residents' quality of life, as it influences their ability to participate in economic, social, and educational activities [40, 53]. The outer suburbs' reliance on infrequent and inefficient bus services connecting them to Melbourne's radial train network compounds social isolation. Addressing these spatial inequalities is essential for making Melbourne's growth sustainable and inclusive, ensuring that public transport evolves alongside population growth ([14, 56, 57]).

Considering the above literature, there remains a limited understanding of how service levels vary across different suburbs, and how transport disadvantages and lack of service coverage overlap in expanding suburbs. This study addresses this gap by undertaking a suburb-specific analysis of bus service accessibility in Melbourne's outer suburbs. It is worth noting that although this study does not explicitly test a theoretical model, it is informed by the principles of transport justice 61, which emphasize the fair allocation of transport services concerning social need. This perspective helps contextualize disparities in service access across Melbourne's outer suburbs.

2.2 Socioeconomic impacts of inadequate public transport

In Melbourne's expanding suburbs, lengthy commute times and poor connectivity between bus services and train stations make it challenging for residents to reach the CBD and other major employment hubs, where job opportunities are concentrated [6, 23]. This issue disproportionately affects low-income households, which are less likely to own private vehicles and thus rely heavily on public transport. Research consistently shows that inadequate public transport access can severely limit employment opportunities, restricting individuals' ability to pursue better-paying jobs [16, 32].

The absence of reliable bus services in Melbourne's outer suburbs increases transportation costs, creating additional financial strain for residents already facing economic challenges. Households in these areas often allocate a greater portion of their income to commuting expenses. Lucas et al. [59] argue that this transportation burden can trap individuals in low-paying jobs, as the limited reach of public transport networks prevents them from accessing higher-paying employment opportunities in better-connected areas. Over time, this cycle of disadvantage reinforces existing socio-economic inequalities and deepens the divide between inner and outer suburbs. Expanding bus networks and improving connectivity to train stations are essential for improving

economic mobility and reducing socioeconomic disparities in Melbourne's expanding suburbs (Scholl et al. [78], [25]).

Building on earlier insights by Allard and Danziger [5] and Sanchez, Shen and Peng [77], more recent work continues to provide valuable insights into the relationship between public transport and job accessibility [1], which is highly relevant to Melbourne's situation. Their findings demonstrate that expanding bus service coverage and increasing frequency can significantly improve access to employment for suburban residents. In addition to limiting access to employment, inadequate public transport significantly contributes to social exclusion and isolation [38]. Social exclusion occurs when individuals or groups are systematically marginalized from full participation in society due to a lack of resources or opportunities. In Melbourne, the absence of efficient public transport in outer suburbs disproportionately affects vulnerable populations, including the elderly, people with disabilities, and low-income families [58]. These groups, who are often dependent on public transport, face a heightened risk of exclusion when services are infrequent or inaccessible. Residents in Melbourne's expanding suburbs who cannot afford private vehicles or rely on unreliable bus services are often unable to participate in community activities, access healthcare services, or maintain social connections.

The infrequent and unreliable bus services, combined with long travel times, create significant barriers to accessing healthcare, which then results in delayed treatments and poorer health outcomes [30]. This issue is particularly pronounced for individuals with limited mobility or those from economically disadvantaged backgrounds, who are more reliant on public transport. As Martens and Di Ciommo, [62] argue, transport equity must encompass accessibility to essential services such as healthcare. Beyond healthcare, inadequate public transport also limits access to education for residents in Melbourne's expanding suburbs. Schools, universities, and vocational institutions are often located in areas that are difficult to reach without reliable transport services. This creates barriers for students, particularly those from low-income households, who depend on buses to commute to school. Pereira et al. [70] note that transport inequity can contribute to educational disparities, as students from disadvantaged backgrounds may struggle to access learning opportunities. expanding suburbs.

2.3 Existing strategies for improving bus services

One of the key barriers to public transport usage in Melbourne's outer suburban areas, particularly in rapidly growing suburbs like Clyde North, Tarneit West, and Truganina, is the long travel times caused by infrequent bus services and poor connectivity to train stations. Residents often rely on private vehicles due to the unreliability of public transport, leading to increased traffic congestion and environmental impacts. Expanding bus routes to cover newly developed residential areas and increasing the frequency of services can make public transport a more viable option for daily commuting, thereby reducing car dependency [22]. Additionally, improving connectivity between bus services and other modes of transport, such as trains and trams, is essential for creating an efficient, integrated network [25, 50]. To address these challenges, in one of the earlier studies, Glaeser and Kahn [44] conclude that urban planners must prioritize the expansion of bus services in areas experiencing high population growth, which is supported by the research in high-growth areas in Seoul by Cervero and Kang [18].

Demand-Responsive Transport (DRT) systems provide a flexible and efficient alternative to fixed-route bus services, especially in low-density suburban areas where traditional services are underutilized [76]. In Melbourne, one notable implementation of DRT is the FlexiRide service, which operates in suburbs including Melton South, Tarneit North, Rowville, and Mooroolbark, among others. FlexiRide allows passengers to book a ride via an app or phone, with the bus adjusting its route based on demand, picking up and dropping off passengers at designated points within the service area [29]. This flexibility enables public transport providers to maintain coverage in areas where fixed-route buses may not be cost-effective. FlexiRide is particularly useful in Melbourne's outer expanding suburbs, where population density is low, and fixed-route buses may not be viable. Studies show that such services can significantly enhance public transport accessibility by connecting residents to key transport hubs, such as train stations, reducing their reliance on private vehicles [34, 71]. DRT helps decrease traffic congestion and lowers greenhouse gas emissions by reducing car dependency and offering a more adaptable public transport solution [66]. This aligns with *Plan Melbourne 2017–2050*, which prioritizes sustainable growth and the promotion of public transport to reduce the city's environmental impact (Victorian Government 2017). Research highlights that DRT systems, including FlexiRide, are particularly beneficial for vulnerable populations, such as the elderly and people with disabilities. The ability to request rides on demand, coupled with accessible vehicles, ensures that these groups have equitable access to essential services [76]. However, challenges remain in the integration of DRT services like FlexiRide with existing public transport networks [42]. Mulley et al. (2020) [67] stress the importance of ensuring seamless connectivity between DRT services and traditional modes of transport, such as trains and buses. Furthermore, the success of DRT systems relies on the availability of user-friendly booking platforms and sufficient public awareness of the service [69].

Tailoring public transport to low-income households, elderly residents, people with disabilities, and those who rely on public transport to access essential services is a core aspect of transport equity, ensuring that all residents have equitable access to the opportunities and resources they need to thrive [19, 21]. One approach to providing tailored services for vulnerable populations is the introduction of DRT systems, which offer flexible and adaptable transport options that can be adjusted to meet the specific needs of passengers. Moreover, DRT provides a personalized and accessible transport option for those who may struggle with traditional public transport systems by allowing passengers to book services in advance or on demand [76].

Focusing on inclusiveness, as Foth et al. [34] suggest, requires ensuring that public transport systems cater to the specific mobility needs of these groups. Providing reduced fares or subsidies for low-income families can alleviate the financial burden of public transport, making it more accessible and affordable for those who need it most [53]. Improving physical accessibility is equally important for ensuring transport equity [36]. Bus services must be accessible for passengers with mobility impairments by providing wheelchair-accessible buses, installing ramps and lifts at bus stops, and ensuring buses are equipped with appropriate signage and audio-visual aids to assist passengers with disabilities. Such measures are critical for ensuring that all residents, regardless of physical ability, can use public transport services safely and comfortably [19, 20, 76] stress

the importance of inclusive design, which plays a key role in making public transport systems functional for all.

Beyond infrastructure gaps, recent research highlights broader declines in bus ridership, which have significant implications for service planning and equity. Studies such as Yu et al. [84] show that ridership dynamics are shaped by nonlinear interactions between service quality, urban form, and socioeconomic variables. In suburban and outer metropolitan areas, declining ridership may reflect both limited-service provision and mismatched planning priorities, rather than a true lack of demand. These insights support the need for nuanced, context-sensitive strategies to improve public transport accessibility and rebuild usage.

Finally, addressing the needs of vulnerable populations requires actively involving these groups in transport planning and decision-making processes. Engaging communities to understand their unique challenges and priorities ensures that transport services are designed with their needs in mind. This participatory approach to transport planning leads to more inclusive and equitable outcomes by ensuring that the voices of vulnerable populations are heard and their needs addressed [2, 54]. Such an approach promotes equity and improves the effectiveness of public transport in meeting the diverse needs of Melbourne's residents.

3 Research methodology

This section delineates the research methodology and techniques employed to evaluate the efficiency of bus services within the expanding suburbs of Melbourne. These corridors, as defined by the Victorian Planning Authority (VPA) and referred to as expanding suburbs throughout this study, are scrutinized using data obtained from the Australian Bureau of Statistics (ABS) to create a thorough understanding of the demographic and socioeconomic characteristics of each corridor. The objective of the research is to pinpoint specific areas within these corridors where bus services fall short of providing adequate connections to essential transport hubs, such as train stations, which facilitate access to Melbourne's central business district (CBD). The outcomes of this study offer recommendations aimed at enhancing public transport accessibility and service quality for the rapidly expanding populations in these regions.

Further, this research employs a quantitative approach, utilizing numeric and spatial analysis to evaluate bus service coverage and efficiency in the expanding suburbs. There are traces of qualitative methods, which are solely based on narrative synthesis and evaluation from the existing literature throughout the study. This method is suitable for analyzing complex urban transport networks and their impact on population mobility. Quantitative analysis involves gathering demographic data on the identified expanding suburbs, focusing on factors such as population size, employment rates, economic performance, and current transport modes to work. These indicators provide a profile of each corridor and highlight areas that may have greater transport needs. Figure 1 presents the methodology process of this research.

3.1 Research methods and data sources

The research relies on various data sources, including population and socioeconomic data from ABS and geographic data from the VPA, to determine the expanding suburbs and boundaries that are investigated. The ABS data provide insight into the population

characteristics of the expanding suburbs, covering key variables such as population size to understand the density and distribution of residents in each corridor, the method of transport to work to assess reliance on public versus private transport modes as well as multiple statistics to determine the economic profile of the region such employment rate, average income and rent as a portion of income. Travel Time Isochrones are fed with the locations of the relevant train stations within each allocated growth corridor, which provides direct access to Melbourne's CBD. These stations act as primary nodes for public transport users, and the efficiency of bus services connecting to these stations is critical for residents' overall mobility.

Spatial analysis is conducted using Geographic Information System (GIS) software, TravelTime, to map bus service areas around train stations. The goal is to assess the extent of bus service coverage based on specific time thresholds: 30 minutes (satisfactory), 45 minutes (reasonable), and 60 minutes (unreasonable). These thresholds support the evaluation of how well buses connect residents to arterial train stations within a feasible timeframe, incorporating up to 15 minutes of walking time to the nearest bus stop. Moreover, travel beyond 45 minutes often leads to reduced willingness to use public transport and increased car dependency; reaching the city center takes 30 minutes for most people, deemed as a satisfactory threshold, and is informed by related planning benchmarks as delineated in Marchetti [60]. This method helps identify areas where bus services are either insufficient or inefficient, leading to recommendations for targeted improvements. The notions of frequent, infrequent and sufficiency, and insufficiency can be interpreted differently in various contexts. Nonetheless, in this study, public thresholds were considered measures used within Transport Victoria service standards and are consistent with user expectations for reliable, accessible urban transport (PTV 2024, [23, 24]).

The TravelTime tool was configured to simulate typical weekday travel conditions using scheduled timetables and average traffic levels. The analysis focused on three assessment times: 9:00 am (weekday peak), 11:00 pm (weeknight), and 12:00 am (weekend). A 15-minute walk to the nearest bus stop was set as the maximum catchment distance. Transfer wait times were derived from published bus and train schedules. However, the tool does not account for real-time delays, cancellations, or service disruptions. This standardized setup enabled consistent comparisons across various inner urban regions. The 9:00 am weekday peak time reflects standard commuter patterns aligned with typical work and school hours, which captures the highest demand for employment-related travel. The 12:00 pm weekend timeframe was selected to represent midday activity for non-work-related trips, such as access to retail, healthcare, and social destinations. These times provide a representative contrast between peak commuting and general weekend mobility needs, including those of shift workers and transport-dependent populations.

A GIS-based program, TravelTime, maps bus routes in each growth corridor, and key train stations are reflected as isochrones. This software assesses service coverage using time-based analysis, calculating travel times from residents' homes to the train stations. Results for three travel time thresholds are recorded: 30 minutes, 45 minutes, and 60 minutes. Variables such as a maximum 15-minute walking time restriction (900 seconds) are incorporated into the code. For peak hour (9:00 am) and weekend (noon) scenarios, travel times are calculated relative to arriving at the station, while for weeknight

(11:00 pm) scenarios, they reflect departing from the station. This spatial analysis reveals which areas of the expanding suburbs are underserved by the current bus network. The study identifies where public transport investments are most urgently needed to support the growing populations in these corridors by examining how effectively buses connect to arterial train stations. Following this, the frequency of areas served by a single bus route is analyzed to determine how well they accommodate the surrounding population.

3.2 Data analysis

The demographic and spatial data are analyzed to comprehensively understand each growth corridor's transport needs. For each corridor, the proportion of bus service coverage is compared to those who face travel times exceeding 45 or 60 minutes. This comparison allows for the identification of transport gaps in specific areas. Statistical data are employed to examine correlations between population characteristics such as employment and bus service coverage. This helps determine whether certain demographic groups are disproportionately affected by poor services. The analysis culminates in a set of recommendations for improving bus services in the expanding suburbs. These recommendations focus on how to enhance Melbourne's bus services to meet the growing population's needs and improve access to key transport nodes. Accordingly, the socio-economic implications were explored using an interpretive lens, which draws on spatial comparisons between accessibility patterns and key demographic indicators to highlight areas of disproportionate transport disadvantage.

To guide the structure of the analysis, a conceptual framework (Fig. 2) was developed to illustrate the key relationships between population growth, bus service deficits, transport behavior, and socioeconomic outcomes. Although not empirically tested, it provides a systems-based lens for interpreting the spatial and demographic patterns identified in this study.

As depicted in Fig. 2, the causal loop diagram illustrates the dynamic interconnections between population growth, the quality of transport services, and the related socio-economic effects in the outer suburbs of Melbourne. Positive feedback loops are represented

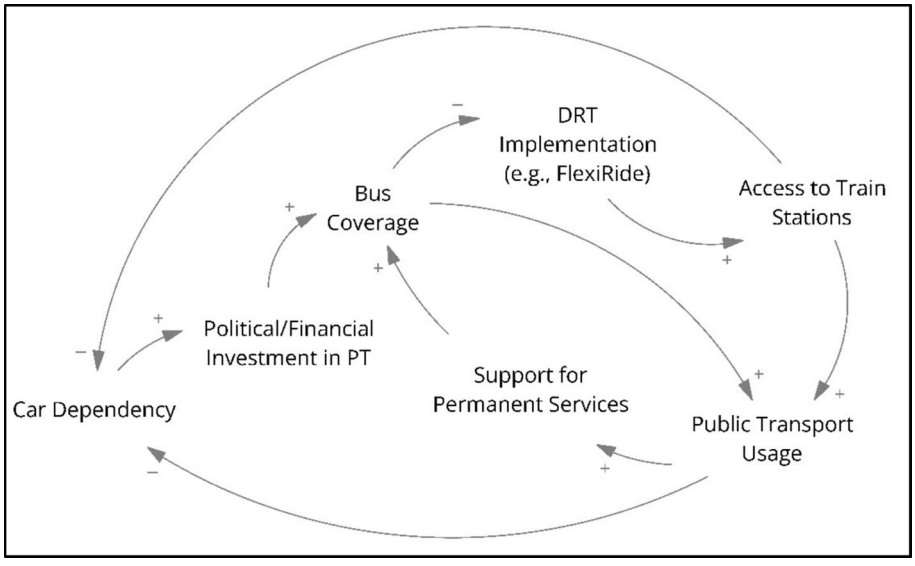

Fig. 2 Conceptual framework illustrating feedback loops (Source: Authors)

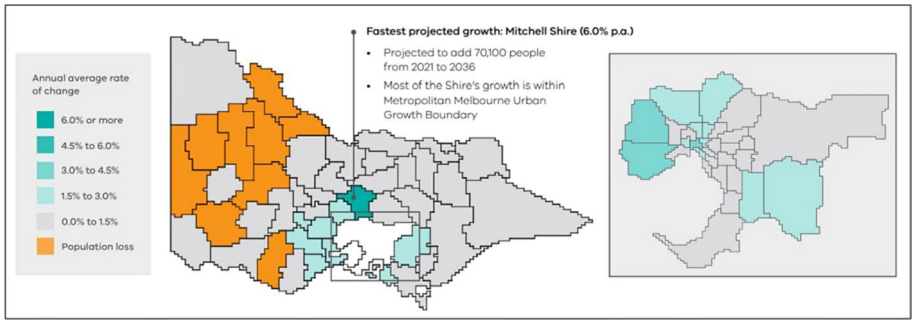

Fig. 3 Annual average rate of population change: Metropolitan and regional local government areas 2021 to 2036 (Department of Transport and Planning Victoria 2023 [28])

Fig. 4 Top five population growth: 2021 to 2036, metropolitan and regional local government areas (DTP 2023)

by arrows marked with a plus (+) sign, which signify reinforcing relationships, whereas negative feedback loops are indicated by minus (–) signs, reflecting balancing effects. While the diagram emphasizes significant interactions and directional influences among the variables, a comprehensive causal tracing and quantification of the feedback mechanisms were outside the purview of this study.

4 Results and analysis

This section presents the results of the study, focusing on the efficiency and accessibility of bus services in Melbourne's four expanding suburbs: North, Southeast, West, and Southwest. Each corridor has been selected and restricted in line with data from the Victorian Planning Authority and the respective Department of Transport. Bus service coverage, frequency, and travel times will be investigated.

4.1 Selection of expanding suburbs

The VPA has identified four expanding suburbs in an 18-month-long development [81]. These include the South-East, North, Sunbury, and West. The Western growth corridor is predominantly split between two Local Governing Areas (Melton City Council and Wyndham City Council), and the Northern growth corridor is split between Hume and Whittlesea Councils. The Department of Transport and Planning has also published population expectation statistics in 2023, which highlight Casey, Hume, Whittlesea, Melton, and Wyndham Councils as the largest LGAs for population growth by 2036 (Figs. 3 and 4) (Department of Transport and Planning 2023) [28]. Therefore, for this paper, the following expanding suburbs will be assessed: South-East: Casey Council, North: Hume City Council (Predominant), City of Whittlesea (Secondary), West*: Melton City Council, and South-West*: Wyndham City Council.

4.2 Selection of growth corridor boundaries

In determining the spatial area for each of the expanding suburbs in this assessment, a visual mapping approach using GIS software and planning overlays was employed to identify the most relevant regions for analysis. This approach allows for flexibility in capturing natural variations within the geographic data, and at the same time, remains consistent with strategic growth boundaries outlined in planning documents such as Plan Melbourne 2017–2050. By using this method, the assessment focuses on regions that visually align with key criteria, e.g., population growth, land use patterns, proximity to transport, ensuring that the chosen area is appropriate and relevant to the needs of the population now and shortly. While precise measurements are important in certain contexts, the use of a best-fit spatial approach provides adaptability when dealing with real-world geographic complexities, especially in regions that do not neatly conform to established boundaries. This method has been applied with careful judgment, supported by relevant spatial data, to ensure the selected area is appropriate. As a result, the boundaries have been unequivocally confined to the following Fig. 5a–d.

Figure 5a illustrates the northern growth corridor within the Hume City Council and City of Whittlesea, encompassing Roxburgh, Epping, Craigieburn, Mickleham, Wollert, and Donnybrook. Figure 5b depicts the western corridor under the Melton City Council, including Melton, Cobblebank, Rockbank North (Aintree), and Rockbank South. Figure 5c presents the south-western corridor governed by Wyndham City Council, covering Wyndham Vale, Tarneit, Tarneit West, Werribee, and Hoppers Crossing. Figure 5d outlines the south-eastern corridor within Casey Council, comprising Clyde, Clyde North, Cranbourne, Cranbourne North, Narre Warren South, Junction Village, and Botanic Ridge. A comprehensive analysis of the population trends across these growth corridors is discussed in the subsequent sections.

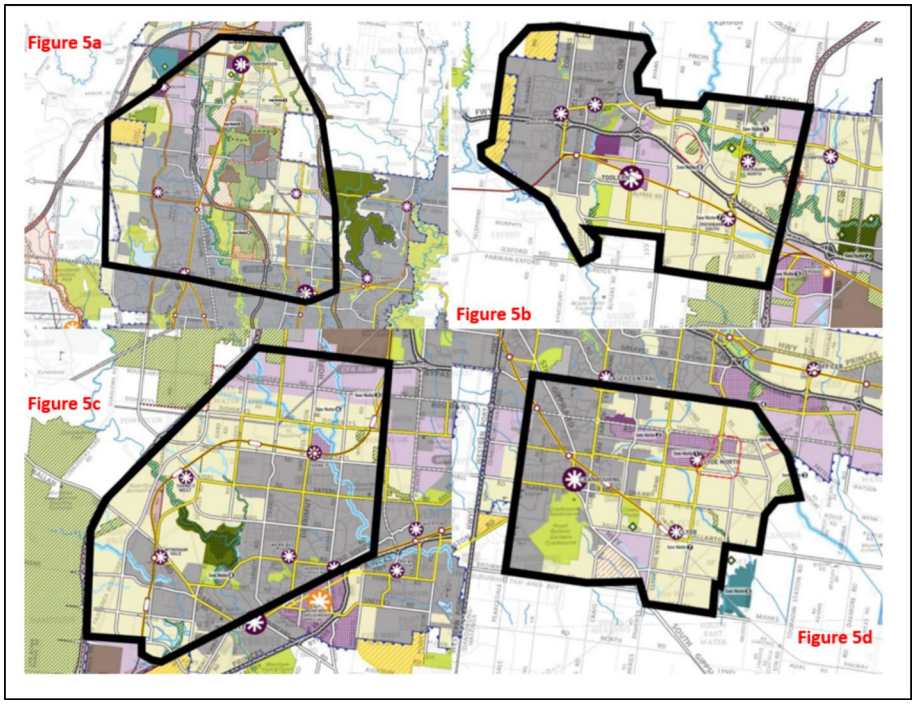

Fig. 5 Victorian planning authority growth boundaries (Victorian planning authority 2012)

4.3 Growth corridor population data analysis

This section interprets the demographic and socioeconomic data from Melbourne's four expanding suburbs and evaluates how these factors influence the urgent need for more efficient bus services. The data presented in Table 1 (adopted from ABS 2021, and Department of Transport and Planning 2023 [28]) offers valuable insights into key categories that link transport accessibility and car dependency. These categories have been selected due to the following:

- Income distribution and socioeconomic disparities – Lower-income households are more reliant on public transit due to limited access to private vehicles (Martens 2016). Research shows that public transport accessibility significantly impacts employment opportunities for low-income households, as unreliable or insufficient services often limit their ability to reach job centers, particularly in suburban areas [47].
- Population growth – Population growth places considerable strain on public infrastructure, including transport networks, exacerbating the already stretched bus services within urban expanding suburbs, limiting the ability of residents to access essential services (Hensher and Mulley 2015 [48]).
- Housing affordability – Research highlights that lower-income renters, especially those in high-rent regions, often rely on affordable public transport as a means to manage their limited disposable income [23, 24]. However, when public transport is insufficient, these residents may be forced to spend a disproportionate amount of their income on car ownership or face limited access to economic opportunities [70].
- Car dependency and public transport usage – As public transport options become less reliable or infrequent, households are forced to rely more on private vehicles, contributing to both increased household costs and environmental impacts [64]. In expanding suburbs with low public transport usage rates, such as Melton and Casey, addressing these service gaps is critical to reducing car dependency and improving overall transport equity [75].

4.3.1 Income distribution and socioeconomic disparities

The income distribution data (Table 1) highlights significant disparities across the four expanding suburbs. Wyndham has the highest median weekly household income ($2,023), while Hume has the lowest ($1,703), with Casey ($1,918) and Melton ($1,887) falling in between. These figures suggest varying levels of economic vulnerability,

Table 1 Growth corridor population (data from DTP, 2023, and census results [8–11]

Category	Vic	South-east Casey	Southwest Wyndham	West Melton	North		
					Hume	Whittlesea	Avg
Population 2021	–	369,560	296,320	181,350	246,920	231,830	239,375
Population 2036	–	527,480	472,120	349,390	356,000	335,370	345,685
Population growth (2021–2036)	–	42.7%	59.3%	92.7%	44.2%	44.7%	44.4%
Median weekly income ($)	1,759	1,918	2,023	1,887	1,703	1,768	1,735
Unemployment rate (%)	5.0%	5.7%	6.8%	6.5%	7.5%	5.9%	6.7%
Rent as % of income	30.9%	28.3%	27.9%	34.0%	37.1%	32.7%	34.9%
Public transport usage (%)	4.4%	3.3%	5.9%	3.7%	4.3%	4.8%	4.6%
Car ownership (vehicles per household)	1.9	2.1	1.9	2.1	2	1.9	1.95
Households with no car (%)	7.5%	2.9%	3.6%	3.2%	4.4%	4.2%	4.3%

particularly in Hume and Whittlesea, where lower-income households are more likely to rely on affordable public transport to access employment, education, and essential services.

In Hume, the unemployment rate is recorded at 7.5% (Table 1), which is considerably above the Victorian average of 5%. This implies that a significant segment of the local populace may encounter obstacles to securing employment, particularly in the absence of dependable public transportation. Residents with lower incomes and those who are unemployed generally depend more on affordable and efficient transport solutions, particularly bus services, to access job opportunities. Nevertheless, the data reveal that the utilization of public transport remains persistently low across all areas, which raises important questions regarding the sufficiency, availability, and effectiveness of the current bus services in fulfilling the needs of the community.

4.3.2 Population growth and strain on infrastructure

The population growth forecasts (Table 1) show dramatic increases across all four corridors, which will place substantial strain on existing transport infrastructure by 2036:

- Melton is projected to nearly double, growing by 92.66% from 181,350 in 2021 to 349,390 in 2036 [10].
- Wyndham will grow by 59.33%, reaching 472,120 by 2036 [12].
- Hume and Whittlesea will experience 44.18% and 44.66% growth, respectively [9].
- Casey will see a 42.73% increase, reaching 527,480 by 2036 [8].

This projected growth, particularly in Melton and Wyndham, highlights the urgent necessity for strategic investments in public transport infrastructure. The bus services in these areas are expected to expand to address the growing demands of a rapidly increasing population. If these services do not improve, these regions may experience heightened car dependency, traffic congestion, and environmental challenges.

4.3.3 Housing affordability and rent as a percentage of income

Rent as a percentage of household income is another critical factor affecting transport equity in these regions. The data reveal that Hume (37.1%) and Melton (34%) (Table 1) have the highest rent burdens, well above the Victorian average (30.9%). This suggests that a significant portion of residents in these regions are financially stretched, which often correlates with greater reliance on public transport. Renters, particularly those in lower-income brackets, typically depend on affordable transport options like buses to access work and services. However, the low public transport usage rates in these areas suggest that bus services are currently insufficient to meet this demand.

4.3.4 Public transport usage and car dependency

Public transport usage across all four expanding suburbs is strikingly low, indicating a high level of car dependency. Casey and Melton exhibit the lowest rates of public transport usage, with only 3.3% and 3.7% of residents using public transport, respectively (Table 1). Hume (4.3%) and Whittlesea (4.8%) show slightly higher figures but are still below the state average. Wyndham has the highest public transport usage rate (5.9%), yet this remains insufficient given its rapid population growth. These low public transport usage rates suggest inefficiencies in the bus networks, such as infrequent services,

poorly connected routes, or a lack of integration with other transport modes. This is especially concerning Casey and Melton, where populations are set to increase significantly. The data shows that bus services are underutilized, which may indicate that they are not meeting the needs of the population, particularly in terms of access to employment hubs, education, and essential services.

4.3.5 Car ownership and transport equity

Car ownership rates are high across all four regions, further emphasizing the issue of car dependency. Casey and Melton have the highest car ownership rates, with an average of 2.1 vehicles per household. Hume and Whittlesea are slightly lower but still reflect high car dependency (Table 1). These figures indicate that most residents rely on private vehicles for their daily commutes, which is not sustainable as populations grow and congestion increases. While high car ownership rates may indicate affluence in some cases, they also reflect the inadequacy of public transport options. For low-income residents, particularly those in Hume and Whittlesea, owning a car may not be feasible. In these areas, 4.2% (Whittlesea) and 4.4% (Hume) of households have no access to a private vehicle, making them entirely dependent on public transport (Table 1).

These findings respond to Objective 2, examining the socioeconomic impacts of inadequate bus services, i.e., high car dependency, reduced access to employment, and increased exclusion among lower-income households.

4.4 Improving public transit connectivity

4.4.1 Southeastern growth corridor

The following data has been collected (Table 2) via the isochrones from TravelTime and the Public Transport Victoria Website (2024). Table 2 presents the Southeastern Growth Corridor results summary.

Table 2 Southeastern expanding suburbs results summary. (Source: Authors)

				Percentage % Suburb Coverage (Max 15min Walking time)		
Corridor	**Service**	**Time**	**Suburb**	**<30mins**	**<45mins**	**<60mins**
SE	Peak	9:00	Clyde	0%	25-50%	25-50%
SE	Peak	9:00	Clyde North	0%	25-50%	25-50%
SE	Peak	9:00	Cranbourne	50-75%	75-100%	75-100%
SE	Peak	9:00	Cranbourne North	0%	25-50%	75-100%
SE	Peak	9:00	Narre Warren South	0-25%	25-50%	75-100%
SE	Peak	9:00	Junction Village	0%	0%	25-50%
SE	Peak	9:00	Botanic Ridge	0%	25-50%	75-100%
SE	Weeknight	23:00	Clyde	0%	0%	0%
SE	Weeknight	23:00	Clyde North	0%	0%	0%
SE	Weeknight	23:00	Cranbourne	0-25%	0-25%	0-25%
SE	Weeknight	23:00	Cranbourne North	0%	0%	0%
SE	Weeknight	23:00	Narre Warren South	0%	0%	0%
SE	Weeknight	23:00	Junction Village	0%	0%	0%
SE	Weeknight	23:00	Botanic Ridge	0%	0%	0%
SE	Weekend	12:00	Clyde	0%	25-50%	25-50%
SE	Weekend	12:00	Clyde North	0-25%	25-50%	25-50%
SE	Weekend	12:00	Cranbourne	75-100%	75-100%	75-100%
SE	Weekend	12:00	Cranbourne North	25-50%	75-100%	75-100%
SE	Weekend	12:00	Narre Warren South	0-25%	50-75%	75-100%
SE	Weekend	12:00	Junction Village	0%	0%	0%
SE	Weekend	12:00	Botanic Ridge	0%	0%	0%

During peak hours, access to train stations varies widely. Cranbourne performs best due to its proximity to Cranbourne station, with 50–75% of the population able to reach a station within 30 minutes and 75–100% within 45 to 60 minutes. Other suburbs such as Clyde, Clyde North, and Botanic Ridge struggle with having no suburb coverage within 30 minutes and only partial coverage (25–50%) within 45 to 60 minutes. Junction Village has no suburb coverage within 45 minutes and only partial coverage within 60 minutes (25–50%). Cranbourne North and Narre Warren South only achieve 25–50% suburb coverage within 45 minutes, which is particularly concerning considering their central location in this corridor. For those who have access to a bus stop within a 15-minute walk during peak hours in Clyde and Clyde North, the 881 and 889 buses only operate approximately every 40 minutes, while the 897 bus runs more frequently, approximately every 20 minutes [72]. On weekends, travel patterns generally mirror those observed during peak weekday times. However, suburbs such as Junction Village and Botanic Ridge show no improvements, with zero access to stations throughout the weekend.

On weeknights at 23:00, the situation worsens across all suburbs, with nearly zero coverage of train stations. Even Cranbourne, which shows relatively better performance during peak hours, has less than 25% of residents able to reach a station in under 60 minutes. Other areas, such as Clyde, Clyde North, and Narre Warren South, have no access to stations within the given time frames. This is because there are no bus services available after 11 PM on weekdays, leaving residents without access to public transport during late hours. The only night services in the Casey Council region operate at weekends.

4.4.2 Northern expanding suburbs

The following data (Fig. 6) has been collected via the isochrones from TravelTime, and the Public Transport Victoria Website (2024). Figure 6 presents the bus route 501/525 Sunday Timetable (PTV, 2024).

During peak hours, the accessibility of train stations varies widely across the Northern Expanding Suburbs. Suburbs such as Donnybrook and Mickleham have the highest coverage, with 75–100% of the suburban area being able to access a train station within 30, 45, and 60 minutes. However, these suburbs lie on the outer edge of the expanding suburbs and have yet to be populated and expand the way Clyde and Clyde North have. Roxburgh Park also performs well, with 75–100% of its area covered within the same timeframes. Craigieburn, however, shows a less optimal situation, with only 25–50% of the suburbs covered within 30 minutes, although this improves to 75–100% coverage within the 45 to 60-minute timeframes. This suggests that while the outer parts of Craigieburn may be less well-served, a significant portion of the suburb does have reasonable access to train stations. Epping, due to its proximity to its local station, provides 50–75% coverage within 30 minutes, which increases to 75–100% within 45 to 60 minutes. On the other hand, Wollert experiences the most limited access, with 0% coverage within 30 and 45 minutes, and only 75-100% of the area can access a station within 60 minutes.

Late at night, coverage drops significantly across the entire Northern corridor. For residents in Donnybrook, Mickleham, and Craigieburn, there are no bus services available after 11:00 pm on weeknights. Epping and Roxburgh Park residents have a limited late-night service available from their respective train stations. On weekends, Donnybrook and Mickleham maintain high levels of coverage, with 75–100% of the suburbs able to

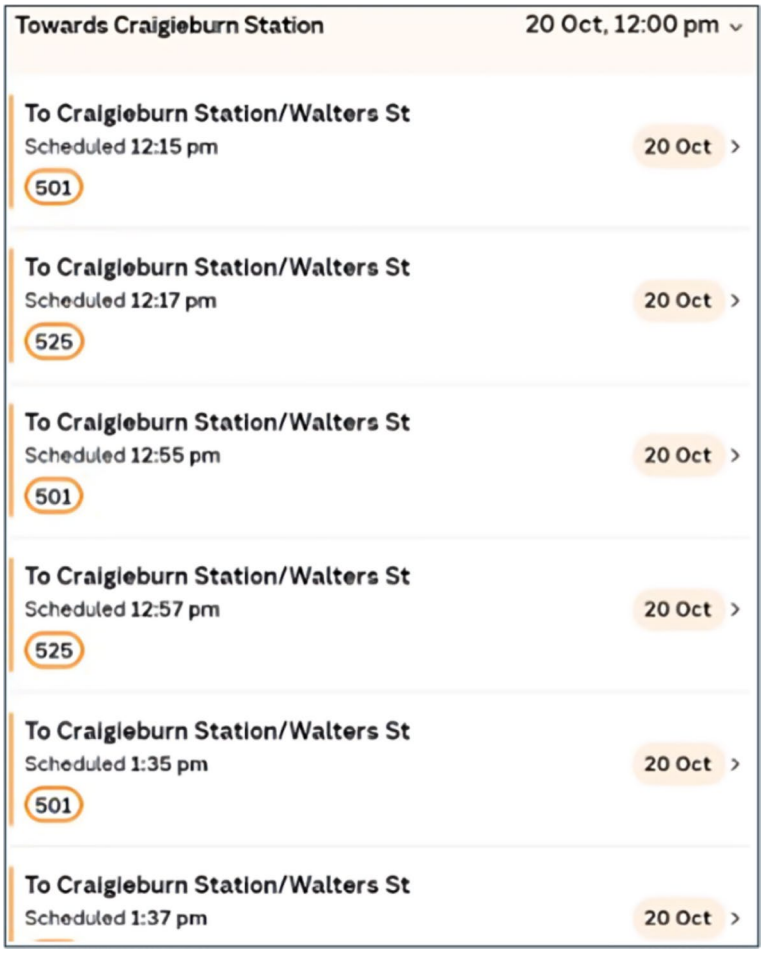

Fig. 6 The bus route 501/525 sunday timetable (PTV 2024)

access a train station within 30 minutes, mirroring peak time results. However, the two services, 501 (Donnybrook to Craigieburn direct) and 525 (Donnybrook to Craigieburn via Mickleham), operate less frequently every 40 minutes and do not operate in a staggered manner (See departing Donnybrook Station just two minutes apart. Roxburgh Park has 75–100% suburb coverage; however, Craigieburn and Epping continue to face challenges, with only 25–50% of their area covered within 30 minutes, which improves to 75-100% coverage within 45 minutes. Wollert continues to struggle, with 0% coverage within 30 and 45 minutes, and only 75–100% of the suburbs are covered within 60 minutes. Table 3 provides a summary of the Northern Expanding Suburbs results.

4.4.3 Western expanding suburbs

The following data (Table 4) has been collected via the isochrones from TravelTime and the Public Transport Victoria Website (2024). During peak hours, the accessibility to train stations in the Western Expanding Suburbs produced mixed results. Melton and Melton South have the highest levels of bus coverage, with 75–100% of both suburban areas being able to access a train station within 30 minutes, being near the Melton train station. In contrast, Melton North, Cobblebank, and Rockbank North/Aintree show more limited coverage, with 25-50% within 30 minutes and 75–100% coverage within 45 minutes. Cobblebank, however, is serviced by the FlexiRide service, which is an

Table 3 Summary of the northern expanding suburbs results (Source: Authors)

				Percentage % Suburb Coverage (Max 15min Walking time)		
Corridor	**Service**	**Time**	**Suburb**	**<30mins**	**<45mins**	**<60mins**
N	Peak	9:00	Donnybrook	75-100%	75-100%	75-100%
N	Peak	9:00	Mickleham	75-100%	75-100%	75-100%
N	Peak	9:00	Craigieburn	25-50%	75-100%	75-100%
N	Peak	9:00	Roxburgh	75-100%	75-100%	75-100%
N	Peak	9:00	Wollert	0%	0%	75-100%
N	Peak	9:00	Epping	50-75%	75-100%	75-100%
N	Weeknight	23:00	Donnybrook	0%	0%	0%
N	Weeknight	23:00	Mickleham	0%	0%	0%
N	Weeknight	23:00	Craigieburn	0%	0%	0%
N	Weeknight	23:00	Roxburgh	0-25%	0-25%	0-25%
N	Weeknight	23:00	Wollert	0%	0%	0%
N	Weeknight	23:00	Epping	0-25%	0-25%	0-25%
N	Weekend	12:00	Donnybrook	75-100%	75-100%	75-100%
N	Weekend	12:00	Mickleham	75-100%	75-100%	75-100%
N	Weekend	12:00	Craigieburn	25-50%	75-100%	75-100%
N	Weekend	12:00	Roxburgh	75-100%	75-100%	75-100%
N	Weekend	12:00	Wollert	0%	0%	75-100%
N	Weekend	12:00	Epping	25-50%	75-100%	75-100%

Table 4 Summary of western expanding suburbs results

				Percentage % Suburb Coverage (Max 15min Walking time)		
Corridor	**Service**	**Time**	**Suburb**	**<30mins**	**<45mins**	**<60mins**
W	Peak	9:00	Melton	75-100%	75-100%	75-100%
W	Peak	9:00	Melton North	25-50%	50-75%	50-75%
W	Peak	9:00	Melton South	75-100%	75-100%	75-100%
W	Peak	9:00	Cobblebank	25-50%	50-75%	50-75%
W	Peak	9:00	Rockbank North	25-50%	50-75%	50-75%
W	Peak	9:00	Rockbank South	75-100%	75-100%	75-100%
W	Weeknight	23:00	Melton	0-25%	0-25%	0-25%
W	Weeknight	23:00	Melton North	0%	0%	0%
W	Weeknight	23:00	Melton South	75-100%	75-100%	75-100%
W	Weeknight	23:00	Cobblebank	50-75%	50-75%	50-75%
W	Weeknight	23:00	Rockbank North	0%	0%	0%
W	Weeknight	23:00	Rockbank South	75-100%	75-100%	75-100%
W	Weekend	12:00	Melton	75-100%	75-100%	75-100%
W	Weekend	12:00	Melton North	25-50%	50-75%	50-75%
W	Weekend	12:00	Melton South	75-100%	75-100%	75-100%
W	Weekend	12:00	Cobblebank	50-75%	50-75%	50-75%
W	Weekend	12:00	Rockbank North	0%	0%	0-25%
W	Weekend	12:00	Rockbank South	75-100%	75-100%	75-100%

on-demand bus option intended as a transitional solution in low-density areas; although it offers coverage, it does not match the service frequency, integration, or scalability of fixed-route buses (Public Transport Victoria 2024b). Rockbank South, due to the locality of the suburban train station and premature growth, has 75–100% of its area covered within 30 minutes.

Late-night accessibility presents a significant challenge across much of the Western Expanding Suburbs. Melton North and Rockbank North have no bus coverage after 11:00 pm, with 0% of these suburban areas connected to train stations within 60 minutes. This lack of late-night service completely isolates these suburbs from the public transport network during the evening hours. Melton South and Rockbank South have produced 75–100% coverage; however, this can be attributed to most of the suburbs

Table 5 Summary of southwestern expanding suburbs results (Source: Authors)

				Percentage % Suburb Coverage (Max 15min Walking time)		
Corridor	**Service**	**Time**	**Suburb**	**<30mins**	**<45mins**	**<60mins**
SW	Peak	9:00	Tarneit North/Truganina	0-25%	0-25%	0-25%
SW	Peak	9:00	Tarneit	75-100%	75-100%	75-100%
SW	Peak	9:00	Tarneit West	25-50%	50-75%	75-100%
SW	Peak	9:00	Wyndham Vale	75-100%	75-100%	75-100%
SW	Peak	9:00	Hoppers Crossing	50-75%	75-100%	75-100%
SW	Weeknight	23:00	Tarneit North/Truganina	0%	0%	0%
SW	Weeknight	23:00	Tarneit	0-25%	0-25%	0-25%
SW	Weeknight	23:00	Tarneit West	0%	0%	0%
SW	Weeknight	23:00	Wyndham Vale	50-75%	50-75%	50-75%
SW	Weeknight	23:00	Hoppers Crossing	0-25%	0-25%	0-25%
SW	Weekend	12:00	Tarneit North/Truganina	0-25%	0-25%	0-25%
SW	Weekend	12:00	Tarneit	75-100%	75-100%	75-100%
SW	Weekend	12:00	Tarneit West	25-50%	50-75%	75-100%
SW	Weekend	12:00	Wyndham Vale	75-100%	75-100%	75-100%
SW	Weekend	12:00	Hoppers Crossing	0-25%	75-100%	75-100%

being within a 15-minute walk of the train station. This lack of overnight services can create significant barriers for residents who work late shifts or require public transport during evening hours, further reducing the viability of public transport as a primary commuting option. On weekends, Melton North experiences limited accessibility, with only 25–50% of the area covered within 30 minutes and 50–75% coverage within the 45 to 60-minute timeframes. Similarly, Cobblebank sees 50–75% coverage within all timeframes, indicating moderate bus service provision but still leaving parts of the suburb without reliable access. Rockbank North faces the most significant accessibility issues on weekends, with 0% coverage within 30 and 45 minutes, and only 0–25% coverage within 60 minutes. This demonstrates a clear gap in bus services during weekends, severely limiting residents' ability to access train stations. Table 4 shows the summary of Western Expanding Suburbs results.

4.4.4 South western expanding suburbs

The following data (Table 5) has been collected via the isochrones from TravelTime and the Public Transport Victoria Website (2024). During peak hours, train station accessibility across the Southwest Expanding Suburbs shows significant variation between suburbs. Tarneit and Wyndham Vale perform well, with 75–100% of both suburbs covered within 30 minutes. Hoppers Crossing also fares reasonably well, with 50–75% of the suburbs covered within 30 minutes and 75–100% coverage within the 45 and 60-minute ranges, indicating satisfactory access for most of the suburbs. Tarneit West shows moderate coverage, with only 25–50% of the area covered within 30 minutes, though this increases to 50-75% and 75–100% coverage within the 45 and 60-minute timeframes, respectively. Tarneit North/Truganina, however, experiences the most significant challenges, with only 0–25% suburb coverage by a regular bus service within 60 minutes. The rapidly expanding region does have partial access to the FlexiRide service, which offers flexible coverage, yet remains limited in operational hours and capacity, especially during late-night and peak periods (Public Transport Victoria 2024b). Table 5 displays the summary of the Southwestern Expanding Suburbs' results.

Late-night accessibility is a significant issue in the Southwest corridor, with no bus services available after 11 PM on weekdays. The only exception is a limited service between

Wyndham Vale and Werribee. This lack of late-night services presents a major challenge for residents who work late shifts or engage in activities that require transport after regular service hours. This highlights the need to introduce such services to enhance transport equity. On weekends, Tarneit and Wyndham Vale maintain their strong performance, with 75–100% of both suburbs covered within 30, 45, and 60 minutes. Tarneit West has 25–50% of the suburb covered within 30 minutes, and this increases to 75–100% within 60 minutes. Hoppers Crossing provides 0–25% coverage within 30 minutes, increasing to 75–100% within 45 and 60 minutes. Truganina continues to experience limited coverage, with only 0-25% of the suburb covered within 30, 45, and 60 minutes.

This analysis directly addresses Objective 1, highlighting the gaps in bus service provision across Melbourne's outer expanding suburbs, which focuses on service frequency, travel times, and coverage within key accessibility thresholds.

4.5 Interpretation of findings: effective city planning

4.5.1 Accessibility and efficiency of bus services

The results of this study reveal deficiencies in the accessibility and efficiency of bus services across Melbourne's expanding suburbs. In particular, the data indicates that suburbs such as Clyde North, Tarneit West, and Tarneit North suffer from inadequate public transport coverage. For instance, less than 25% of residents in Clyde North and Tarneit North can access a train station within 45 minutes during peak hours, while some areas show zero coverage within this timeframe. This contrasts sharply with better-connected suburbs like Cranbourne and Wyndham Vale due to their proximity to a train station.

These findings are significant as they demonstrate a clear geographic inequity in public transport services. Outer suburbs, especially those experiencing rapid population growth, tend to have fewer public transport options, leading to greater reliance on private vehicles. The inconsistent bus frequencies and limited connectivity to train stations in suburbs like Clyde North and Tarneit North reflect a broader issue of transport inequality, where outer suburban residents are at a distinct disadvantage. Moreover, the significant drop in service coverage during late-night hours is alarming. For instance, in the Northern corridor, suburbs like Donnybrook, Mickleham, and Craigieburn have no bus services operating after 11:00 pm on weeknights. This lack of late-night services poses a major barrier for residents who work evening shifts or require transport for social and recreational activities, further limiting their mobility. Moreover, this can have serious implications that extend beyond transport inconvenience; For shift workers in healthcare, hospitality, logistics, and emergency services, this creates a significant barrier to employment, reliability, and personal safety. The infrequency of bus services at night in expanding suburbs exacerbates the socio-economic exclusion of vulnerable populations, such as low-income households and individuals without access to private vehicles. In areas like Clyde and Botanic Ridge, where bus frequencies are limited to every 40 minutes, residents face substantial delays, which further reduces the attractiveness of public transport as a viable commuting option. These service inefficiencies create a cascading effect on social inclusion, reducing access to essential services like education, employment, and healthcare. Although the analysis focuses on travel times to train stations, these were used as proxies for broader accessibility, considering their role as key nodes connecting residents to employment, education, and services across

greater Melbourne. Direct access to other critical destinations is also useful; Future analyses could build on this framework by mapping accessibility to a wider set of destination types, yet this remained out of scope of our analyses.

This analysis continues to align with Objective 2, highlighting how geographic disparities in bus connectivity translate into socioeconomic inequalities across expanding suburbs. These results also inform Objective 3, focusing on the evidence base for recommending service enhancements aimed at improving efficiency, expanding coverage, and supporting Melbourne's sustainable transport goals.

5 Discussion

The differences in the accessibility of bus services highlighted in this study reflect larger theoretical frameworks related to public transport equity. As discussed in Sect. 2.2, Geurs and van Wee (2004) [35] define accessibility as a function of spatial proximity, travel time, and cost. These results underscore the urgent necessity to improve spatial accessibility in the outer suburbs of Melbourne. They also correspond with the notion of "transport deserts" as examined by Jiao and Dillivan [52], which refers to regions where the demand for public transport greatly surpasses the available supply. Suburbs such as Clyde North, Tarneit North, and significant areas of Cobblebank, as well as newly developing communities to the south, illustrate this phenomenon. In these regions, infrequent and unreliable bus services leave numerous residents isolated from economic opportunities and vital services, with some depending solely on limited alternatives like FlexiRide to fulfill their mobility requirements.

Although a detailed cost-benefit analysis is beyond the scope of this study, preliminary evidence from existing FlexiRide pilots demonstrates both operational feasibility and positive community response [29]. These services have been funded through targeted state transport budgets and local council partnerships, often with lower per-user infrastructure costs compared to fixed-route buses in low-density areas. FlexiRide offers interim coverage where conventional services are not yet viable, helping to reduce access gaps for vulnerable populations. However, its limitations, e.g., restricted hours and limited integration with other modes, highlight that it should be seen as a complementary measure rather than a long-term substitute for high-frequency services.

Additionally, the results echo the concerns raised by Guzman et al. [47] who argue that transport inequity disproportionately affects low-income and vulnerable populations. Suburbs like Hume and Melton, which have some of the highest unemployment rates in Melbourne's expanding suburbs, rely heavily on public transport to access employment. However, low public transport usage in these regions - just 3.3% in Casey and 3.7% in Melton - indicates that the bus services currently available are insufficient to meet the demands of the population. This creates a vicious cycle of car dependency, wherein those without access to private vehicles are disproportionately disadvantaged. As the literature suggests, public transport equity must go beyond providing access to transport; it must also ensure that transport systems are designed to meet the needs of marginalized populations. The inadequate bus service coverage found in this study aligns with Pereira, Schwanen, and Banister's [70] argument that transportation policies often fail to address the unique needs of low-income or underserved communities, further deepening socio-economic divides.

As already noted, this research is to evaluate how gaps in bus service provision affect socio-economic outcomes in Melbourne's expanding suburbs. The findings directly address this objective by illustrating the clear link between inadequate bus services and increased socio-economic inequality. Residents in poorly connected suburbs face not only longer travel times but also increased financial burdens due to car dependency. This, in turn, restricts their access to employment, education, and social services, factors that are critical for upward social mobility. The significant population growth projected for Melton (92.7% by 2036) and Wyndham (59.3% by 2036) will only exacerbate the strain on existing transport infrastructure. Without significant improvements to bus services, these regions will face heightened levels of social exclusion and economic immobility, particularly for residents without access to private vehicles. The research findings demonstrate that a lack of efficient and frequent bus services is not merely an inconvenience but a structural barrier that limits socio-economic opportunities for residents in expanding suburbs. Moreover, the findings highlight the environmental implications of this issue. As Melbourne's outer suburbs become increasingly car-dependent due to inadequate bus services, the city's sustainability goals, such as reducing carbon emissions and traffic congestion, are undermined. The reliance on private vehicles increases greenhouse gas emissions and contributes to urban sprawl, which runs counter to Melbourne's broader urban planning objectives, as outlined in Plan Melbourne 2017–2050 [27]. This study did not quantify potential emissions reductions associated with improved bus services. However, previous research suggests that even modest modal shifts from cars to public transport can lead to significant decreases in transport emissions (e.g., [51]).

This study offers a novel integration of travel time isochrones with demographic data to assess bus service gaps in Melbourne's expanding suburbs. Its spatial-demographic approach provides policy-relevant insights that support equity-focused transport planning aligned with Plan Melbourne 2017–2050. Although the findings of this study are focused on the context of Melbourne's expanding suburbs, similar transit challenges are evident in other high-growth cities. For instance, Sydney faces comparable issues in its outer suburbs with fragmented bus networks and high car dependency [74]. Vancouver has also struggled to extend frequent, reliable bus services into rapidly developing outer municipalities [80]. In Shanghai, high population growth has led to efforts to integrate bus-rail systems into peri-urban zones to maintain accessibility and reduce inequality [45]. These instances highlight the broader relevance of the findings and the need for scalable, equitable solutions across fast-growing metropolitan regions.

6 Conclusion and recommendations

This research provides a critical analysis of Melbourne's bus network through the framework of intelligent urban planning, assessing the connectivity of public transit throughout the city's swiftly growing outer suburban regions. Emphasizing the North, Southeast, West, and Southwest growth zones, the study utilizes spatial and demographic information sourced from the Victorian Planning Authority and the Australian Bureau of Statistics to evaluate the accessibility and effectiveness of current bus services. The results indicate significant disparities in service coverage, especially in developing suburbs like Clyde North, Tarneit North, and Truganina, which are witnessing considerable population increases but lack adequate transit infrastructure. These deficiencies

in service hinder the fundamental goals of intelligent urban planning by restricting fair access to employment, education, healthcare, and civic engagement. The ensuing spatial inequalities intensify socio-economic disparities, perpetuating cycles of disadvantage in communities that are already underserved. Although the study is mainly descriptive, it thoughtfully examines the connection between transport accessibility and socio-economic results, providing insights relevant to policy without making causal assertions. The section wraps up with a series of strategic recommendations aimed at directing future investments in the expansion of the bus network, optimization of service frequency, and the design of inclusive services, which are essential for fostering a more interconnected, sustainable, and equitable metropolitan Melbourne.

These findings align with the concept of "transport deserts" [52], where transport demand exceeds supply. In areas such as Clyde North, Tarneit North, and Cobblebank, limited bus services restrict access to essential services, employment, and public mobility, particularly for those without private vehicles. Specifically, Clyde North and Tarneit North experience less than 25% of bus service availability during peak hours, with no public transport options available after 11:00 pm. This situation reflects the perspective of Geurs and van Wee (2004) [35], who assert that accessibility is contingent upon factors such as proximity, travel duration, and cost—elements that remain inadequately addressed in Melbourne's outer suburbs. The socio-economic ramifications of these transportation deficiencies are particularly evident in regions characterized by elevated unemployment rates and lower income levels, such as Melton and Hume. In these areas, where unemployment rates surpass the Victorian average, residents are disproportionately impacted by the shortcomings of public transport services. Insufficient bus connections and extended commuting times hinder access to employment, education, and healthcare, exacerbating social exclusion for individuals lacking private vehicles. Guzman et al. [47] contend that inadequate public transport exacerbates socio-economic disparities, particularly among vulnerable groups, a trend observed in Melbourne's outer expanding suburbs. In regions like Casey, where merely 3.3% of the population utilizes public transport, and Melton, with a usage rate of 3.7%, the evidence suggests that the existing bus networks fail to meet community demands, thereby reinforcing reliance on private transportation.

Moreover, the environmental impacts associated with insufficient public transportation must be considered. In Melbourne's outer suburbs, the predominant use of automobiles leads to elevated greenhouse gas emissions, exacerbated traffic congestion, and increased environmental harm, thereby jeopardizing the sustainability objectives outlined in Plan Melbourne 2017–2050. If substantial enhancements to bus services are not implemented, these regions may become increasingly reliant on cars, contradicting the City's aims to lower emissions and promote sustainable transportation alternatives. Therefore, it is essential to expand bus networks and enhance service frequency, especially during peak and late-night periods, to mitigate car dependency and achieve sustainability goals. Further, the results of this study underscore the critical necessity for strategic enhancements to the bus services in Melbourne's outer expanding suburbs. It is imperative to tackle these transportation shortcomings to facilitate better access to employment, education, and healthcare, while also decreasing reliance on automobiles and supporting Melbourne's overarching sustainability goals. To achieve equitable public transport access for all residents, particularly in underserved regions such as Clyde

North and Tarneit North, it will be essential to expand bus services and increase the frequency of these services.

6.1 Recommendations

The following are the proposed recommendations from this research. The recommendations are loosely prioritized and numbered to support staged implementation. Expanding DRT is identified as the most immediate action due to its lower cost and quick rollout, followed by increasing service frequency and late-night coverage. Larger-scale improvements to connectivity and infrastructure should follow as part of longer-term planning:

1. The introduction of DRT systems, such as FlexiRide, is proposed as a temporary solution for underserved regions while permanent bus networks are being established. These DRT systems offer adaptable and economical transportation options for areas characterized by low population density or newly developed neighborhoods. Studies conducted by Nelson et al. (2010) [68] and Mulley et al. (2020) [67] indicate that DRT systems serve as an effective short-term strategy to mitigate transportation disparities and enhance connectivity to essential transport nodes. Furthermore, Rye and Wretstrand [76] highlight the significance of DRT systems for marginalized communities, as they provide flexible and responsive services that cater to fluctuating public transport demand. The objective is to deploy DRT services in 80% of underserved suburbs within the next two years, thereby ensuring that residents have access to public transportation until more permanent solutions are established. This approach distinguishes short-term adaptive measures from long-term infrastructure planning needed to support sustained growth.
2. The enhancement of late-night and off-peak transportation services is essential, particularly in rapidly developing areas such as Donnybrook and Clyde North, where the absence of such services after 11:00 pm significantly restricts transportation access. Addressing this gap is vital for mitigating transportation disparities and ensuring mobility for shift workers, economically disadvantaged individuals, and those lacking private vehicle access [34, 58]. Research indicates that extending operational hours, particularly in areas that are currently underserved, can facilitate economic advancement by allowing residents greater access to employment opportunities, educational institutions, and social engagements [15, 47]. By the year 2027, all suburbs within expanding suburbs must have bus services that operate beyond 11:00 pm on both weekdays and weekends. Additionally, where service coverage is enhanced, the implementation of overnight FlexiRide services should be considered to cater to the unique requirements of these communities.
3. Enhancing the Frequency of Bus Services. Evidence suggests that a more frequent and dependable bus service is crucial for diminishing car reliance and encouraging the adoption of public transportation [3, 50]. In the expanding regions of Melbourne, the existing bus services are insufficiently frequent to satisfy the growing demand, especially in areas such as Clyde North and Truganina. Research has demonstrated that increasing the frequency of bus services can lead to shorter waiting times, thereby making public transport a more appealing option for commuters [26, 46]. By aiming to provide bus services every 20 minutes during peak periods by 2026, the attractiveness of public transport as a viable alternative to car travel will be significantly improved,

which is likely to result in decreased traffic congestion and lower greenhouse gas emissions [51].

4. Enhancing Bus Accessibility in Transport Deserts. The phenomenon of "transport deserts", as articulated by Jiao and Dillivan [52], reveals that certain suburbs within Melbourne's expanding corridors, such as Clyde North, Tarneit North, and Truganina, are significantly underserved by public transportation. This inadequacy leads to higher car reliance and restricts residents' access to employment opportunities and essential services. It is imperative to broaden bus service coverage in these areas to promote equitable public transport access, especially for lower-income populations who depend heavily on bus services for their daily needs (Martens 2017, [16]). Research indicates that enhanced bus networks contribute to greater social inclusion by facilitating improved access to job markets and educational institutions [24]. The objective is to augment bus service coverage in these transport deserts by 10% over the next five years, ensuring that 90% of all suburbs within the expanding suburbs are located within a 15-minute walking distance to a bus stop during peak hours.
5. Enhancing Connectivity with Train Stations. Numerous outer suburbs, especially those located in the Northern and Western expanding suburbs, experience significant challenges related to inadequate connectivity between bus services and train stations. This deficiency restricts access to the CBD and various employment centers. The seamless integration of bus and train services is crucial for improving the efficiency of public transport systems and encouraging multimodal travel [43, 65]. Research underscores the necessity of enhancing connectivity to minimize travel durations and to make public transport a more viable alternative to private vehicle usage [31, 73]. The objective is to ensure that by 2030, 95% of suburbs within the expanding suburbs are served by bus routes that connect to a major train station within a 30-minute timeframe, thereby fostering increased public transport utilization and decreasing reliance on cars. To support this goal, a phased implementation approach is recommended, as this would enhance feasibility and allow for resource alignment over time.

This study outlines clear opportunities to improve bus service equity and accessibility. However, several practical challenges to implementation must be acknowledged. These include funding limitations for new routes, infrastructural barriers, political (and potential social) resistance to reallocation of road space or transport budgets, and coordination across multiple jurisdictions and agencies. As past infrastructure efforts have shown, even well-supported proposals can face delays due to shifting political priorities or resource constraints. Acknowledging these barriers is critical to ensuring that recommendations are idealistic and grounded in the realities of policy and planning.

6.2 Further research

Future research pathways include:

- This study emphasizes the immediate effects of insufficient bus services on employment opportunities, educational access, and social integration. However, subsequent research could delve into the wider socioeconomic ramifications. For example, limited public transportation access might lead to a rise in mental health challenges, increased feelings of social isolation, and persistent economic

stagnation. Examining these aspects would yield a more thorough understanding of how transportation inequities intensify social inequalities, thereby equipping policymakers with the insights necessary to implement more effective and focused policy interventions.

- A significant avenue for future investigation lies in comprehending the experiences and preferences of individuals who utilize public transportation. Although this study is grounded in quantitative metrics related to the frequency and coverage of bus services, the incorporation of qualitative data through methods such as surveys or interviews could elucidate the reasons behind residents' choices to favor private vehicles over public transit options. Research that emphasizes user satisfaction, safety issues, and perceptions of service reliability would provide planners with a deeper understanding of the obstacles that hinder increased public transport utilization. This understanding could subsequently guide the development of user-centered policies aimed at boosting ridership and improving the overall effectiveness of public transportation systems.
- Future research should consider conducting a comparative analysis of bus services concerning other transportation modes, including trains, trams, and ridesharing options. By examining the interconnections among these various modes and identifying existing gaps within the transport network, researchers can gain critical insights that may enhance the overall efficiency of the public transport system. A thorough understanding of the advantages and disadvantages associated with each mode could facilitate the development of more integrated transport solutions, thereby decreasing dependence on private vehicles and enhancing accessibility for users. Such efforts could lead to more cohesive and effective transportation strategies that cater to the needs of expanding outer suburban areas.
- Future investigations should delve into additional elements that hinder public transport accessibility, extending beyond the conventional metrics of service coverage and frequency. Critical considerations include the issue of affordability, as high fare prices can dissuade low-income individuals from utilizing public transport. Furthermore, concerns regarding personal safety, particularly during off-peak hours, significantly influence ridership decisions. The challenges of accessibility for vulnerable groups remain pronounced; even with the 15-minute walking distance criterion applied in this study, individuals with mobility impairments may still find it excessively challenging to access services. Additionally, the reliability of public transport, characterized by delays and irregular service intervals, serves as a deterrent to potential users. Lastly, the societal perception of car ownership as a symbol of status warrants further examination, as it may play a substantial role in shaping attitudes towards public transport usage.
- Future research can expand on this study through the application of statistical techniques such as correlation or regression analysis to examine causal relationships between bus service quality and socioeconomic outcomes such as employment access, income inequality, or car dependency.
- Additionally, future research could focus on the quantification of potential reductions in greenhouse gas emissions from increased bus ridership, to support the environmental case for expanding public transport in Melbourne's outer suburbs.

- Future research could benefit from working with real-time and semi-real-time data. Such data could be derived using different technologies such as digital twinning, grounded in Internet of Things and Wireless Sensory Networks (WSN) [33].

6.3 Limitations of research

This study provides insights into the accessibility and effectiveness of bus services in Melbourne's outer expanding suburbs. The research relies on static data sources, such as official schedules and route maps, which do not capture real-time fluctuations in service quality, including delays, overcrowding, or disruptions. As a result, the assessment may not fully reflect actual user experiences. This study relies on secondary data sources; As such, it may not capture real-time service reliability or actual user behavior, which could influence accessibility outcomes and transport mode choices. Additionally, the study primarily measures bus service efficiency based on travel times to train stations, which may overlook other critical factors such as passenger comfort, safety, and reliability. Although the research examines how gaps in bus services affect access to employment, education, and social inclusion, it does not explore broader socioeconomic impacts, such as mental health, community cohesion, or long-term economic mobility, due to the complexity of these issues and the constraints of the study. Environmental benefits, such as reduced carbon emissions and traffic congestion, are acknowledged; however, not the central focus, as the study prioritizes accessibility and socioeconomic implications. Furthermore, the findings are specific to selected expanding suburbs and may not directly apply to other Melbourne or Australian areas. The study also does not account for future infrastructure projects or anticipated improvements to public transportation, which could significantly alter the current network. Thus, although the recommendations offer valuable insights, they may require adaptation as new services are introduced.

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Authors contributions
Jonathon Tiralosi, Koorosh Gharehbaghi, Amin Hosseinian-Far, and Chris Eves contributed equally to the following: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing-original draft preparation, writing-review and editing, visualization, supervision, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Data Availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate
This work does not report research involving human or animal subjects, their data, and/or biological materials. Thus, not applicable/not required.

Consent to publication
No participants were used. Thus, not applicable/not required.

Competing interests
The authors declare no conflict of interest.

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Koorosh Gharehbaghi and Amin Hosseinian Far declare they are an Editorial Board Member of Discover Cities and confirm that they were not involved in the handling or decision-making of their own submission.

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