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Hotspots of change in use of public transport to work: A geospatial mixed method study

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ABSTRACT

Introduction: Several studies have supported the role of public transport in encouraging active transport through commuting. Investigating actual increases in public transport use within focussed local areas can help unravel what causes such increases.
Methods: In this study, we investigated factors related to the increase in public transport use in focussed local areas (hotspots) through a geospatial mixed-method approach using data from South Western Sydney, Australia, spatial cluster detection, and local stakeholder interviews. We also examined areas with low levels of public transport use.
Results: We found that while distance to train station is a significant predictor of usage, other important factors include the professional and socioeconomic profile of the neighbourhood around the train station, the train line's deemed attractiveness and parking availability.
Conclusions: Thus, researchers and planners must consider a range of built environment factors when planning for changes that encourage public transport use. In addition, focusing on small local areas utilising geospatial mixed methods can provide important insights into the local drivers of public transport use.

1. Introduction

A significant amount of literature supports the benefits of active commuting (Dinu et al., 2019). Active commuting involves commuting to work with some form of physical activity, such as walking or cycling (Bopp et al., 2012; de Bruijn and Gardner, 2011). Ideally, this would be a walking or cycling round trip from residence to work. However, more common are mixed-mode or mode share forms of active commuting where commuters may combine walking or cycling with public transport or even drive for a portion of their

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trip. Thus, for instance, in Brisbane, Australia, the median distance walked by people who use trains as public transport is 0.89 km (home to transport) and 0.62 km (train to the workplace) (Burke and Brown, 2007). Often convenience drives active commuting. Most commuters do not choose to use a specific mode with the motivation of adding to their hours of physical activity but generally choose what is most convenient to them. Thus, commuters' travel choices are primarily driven by convenience, cost, speed and reliability of the mode of travel (Jones et al., 2012).

Distance to public transport is a key measure of active commuting convenience. Commuters are less likely to walk or cycle to public transport if the public transport station/stop is located at a distance too inconvenient to walk or cycle (Kent et al., 2023). As the distance to public transport and work increases, the likelihood of active commuting decreases (Yang et al., 2017). Indeed, distance to public transport has filtered into the policy domain, with some policy documents now explicitly requiring that residences be within a specific walking distance of public transport (Greater Sydney Commission, 2018; Victoria State Government, 2019) in order to encourage transit-oriented developments (Cervero, 2007).

In addition to easy geographical access to public transport, various infrastructure factors can make an active commuting journey more convenient. For instance, direct routes to public transportation, traffic and personal safety, e.g. segregation from motor vehicles and improving the commuting experience, e.g. improving the route aesthetics (Panter et al., 2017) or increasing street lighting (Yang et al., 2017) of an area could encourage walking or cycling uptake. Since existing infrastructure may be easier to modify than the distance to public transport, local government stakeholders and policymakers are often interested to know what qualitative changes to existing infrastructure are most likely to result in increases in commuting patterns (Hirsch et al., 2017).

Various economic and sociodemographic factors can also affect the uptake of public transport. Car ownership is inversely associated with public transport use, and densely settled areas have greater usage of public transport (Mulalic and Rouwendal, 2020; Nigro et al., 2019; Saghapour et al., 2016). Immigrants and individuals with high Socioeconomic Status (SES) are more likely to use public transport (Chia et al., 2016; Heisz and Schellenberg, 2004). In Sydney, Australia, many individuals commute from the Western suburbs to the central business district for jobs in the professional and service industries (O'Neil, 2020).

While several factors have been found to be associated with public transport uptake, investigations on specific interventions that cause reductions in car usage or an increase in active commuting provide causal evidence in support of the specific intervention (Goodman and Phillips, 2005). Interventions may include anything from behavioural interventions, economic interventions (such as parking fees), legal interventions (such as no car zones), changes in the active transport environment (such as pathway beautification), or any combination of the above (Scheepers et al., 2014). An example of an intervention that produced effective change can be seen in a randomised control trial (RCT) in Finland, described by Aittasalo et al. (2017).

While the above research asks, "What interventions lead to more active commuting or active transport?" the question, "An increase in active commuting is associated with what factors?" may provide interesting insights. The critical difference is that while in the first question, the increase in active commuting is prospective, in the second question, the increase is being retrospectively examined. An essential advantage of the second approach is the opportunity to leverage existing, large secondary data sources such as the census and implement analyses in a time and cost-effective manner. For instance, a recent study in New Zealand has linked census data with mortality data to investigate mortality changes from active transport (Shaw et al., 2020). Alternatively, consider a study by Liu et al. (2019), where changes in commuting behaviours were associated with population density and accessibility.

One shortcoming of the current literature using either approach is the lack of "on the ground" feedback from stakeholders about their opinions on the drivers of increased active transport. Such opinions are important since many built environment interventions that could help support active commuting are specific to a local area and often implemented at the local government level (Kuss and Nicholas, 2022). Studies that do elicit such local stakeholder feedback generally address the question "What do you think *will increase* active transport" (Brüchert et al., 2021; Le Gouais et al., 2020) but lack a tie with empirical results at the local level that could answer the question "What do you think increased active transport in a specific locality in the last few years?" The second question provides more specific and practicable information for future active commuting-related interventions. Similar questions can be asked of areas with low uptake of active commuting.

A geospatial population health qualitative mixed method approach can address such a question. The geospatial analysis leverages the power of hotspots/coldspots or discrete local geographic areas with statistically significant excess (or lower for coldspots) probability of a specific phenomenon occurring. Examining these hot/coldspots further, from a local stakeholder as well as a quantitative population health perspective could provide insights into the drivers of what caused these hot/cold spots in the first place and thus provide insights about the phenomenon being examined (Mazumdar et al., 2020a). This is precisely the aim of this study. In addition to examining local stakeholder feedback, we also examine the hotspots/coldspots from a quantitative population health socio-ecological perspective (Aittasalo et al., 2017).

Our study aims to examine areas associated with an increase in the use of public transport (hotspots) and also coldspots or areas with statistically significant low levels of public transport use. Note that while we are seeking to identify hotspots with *an increase* in public transport use, we are identifying coldspots that are areas with low public transport use (and *not a decrease* in public transport use). This is because, in most practical scenarios, actual decreases in public transport use are rare (Zander et al., 2014); Conversely, investigating coldspots can provide important insights into areas with low levels of active commuting, which some commentators have termed as active commuting "deserts"(Jiao and Dillivan, 2013).

While mixed-mode travel or combining car travel with walking or cycling is possible, we use the term "active commuting" with public transport in mind. Finally, commuting in this paper implies going to work, and as such, it excludes students going to educational institutions. We describe the study area and expand on the research questions and methods in further detail in the sections that follow:

1.1. Study area and research questions

Our study area comprised the South Western Sydney Local Health District (SWSLHD), a large and diverse local health district in the Sydney metropolitan area, Australia, consisting of seven Local Government Areas (LGAs). SWSLHD is one of the fastest-growing regions of Sydney (George et al., 2011). The district transitions from very urbanised areas in the east to peri-urban and rural areas in the west. The less urbanised fringes are the target of greenfield residential developments. It also has large pockets of economic, social and health disadvantage (Mazumdar et al., 2020c). There is significant commuting from the area to the eastern suburbs and the Sydney central business district for employment (ABS, 2018a). While some SWSLHD residents use public transport, others may drive to work (Merom et al., 2015). The most common form of public transport is the Sydney metro or trains, a relatively efficient mass rapid transit electrified heavy rail network (ABS, 2017). As such, we use the terms "public transport" and "train" interchangeably for the remainder of the manuscript. We also refer to the train transit system as the "train" for the remainder of this manuscript to align with the official name of the network, - "Sydney Trains". For instance, in the LGA of Liverpool, in SWSLHD in 2016, while 12% of commuters used the train as the primary mode of commuting to work, only 1.9% used the bus to commute (ABS, 2018a). However, the electrified train network only covers some of SWSLHD. Two of the Southern LGAs (Wingecarribee and Wollondilly) in SWSLHD are covered by a much slower and infrequent diesel train service, even though these LGAs are home to many commuters to the Sydney CBD. The diversity of transportation geographies, the fast-growing demographics, along with the economic and health-related disadvantaged nature of the district makes SWSLHD an ideal locale for investigating patterns associated with public transport use (Mazumdar et al., 2020b, 2020c; Shuvo et al., 2021).

Our research questions are as follows:

i) Where have there been significant increases in public transport use over five years in public transport (hotspots) in SWSLHD?
ii) What areas of SWSLHD have significantly low public transport (coldspots)?
iii) What factors are associated with the presence of spatial clusters of increased (hotspots) and low levels (coldspots) of public transport use, and what are the opinions of local government stakeholders about what is causing the hotspots and coldspots?

2. Methodology

2.1. Overview

As indicated earlier, this study follows a mixed-method design (Biesta, 2010). The design comprised a sequential explanatory design with triangulation (Creswell and Clark, 2017). As such, a quantitative hotspot analysis was followed by a qualitative investigation, a separate quantitative (regression) analysis in parallel, and the results were reconciled in the end. Hotspots and coldspots of public transport were identified using the Spatial Scan Statistic (Kulldorff, 1997). Next, a qualitative analysis comprising of in-depth semi-structured interviews with relevant local government stakeholders in some of the key hotspot areas was implemented, followed by a thematic analysis. Using linear regression, the quantitative analysis explored key sociodemographic and other factors associated with hotspots. We describe these methods in detail next.

2.2. Data

2.2.1. Quantitative data

Census data for SWSLHD were obtained for the years 2011 and 2016. The data were at the Statistical Area Level 1(SA1) geography. SA1s are the smallest geography at which census data are available in Australia with a population of between 200 and 800 people, and an average of around 400 people. While most SA1s were unmodified between 2011 and 2016, the ABS modified around 9% of SA1s and ABS crossover weighting tables were used to reassign the 2011 data in these modified SA1s to conform with 2016 SA1 boundaries (ABS, 2020).

We obtained data on the number of people utilising various modes to commute to work in SWSLHD at the SA1 level from the ABS. The modes include walking, bicycling, car, bus, train, ferry, or any combination of these modes. In the 2016 census, the question that informed these data was: "How did the person get to work Tuesday, 9th August 2016?" (ABS, 2018b), with a corresponding question in the 2011 census. Various other data obtained from the ABS were further processed into the following variables: number of people in specific age groups (less than 15, 15 to 64, older than 64 years) by SA1s, average number of cars per person in the SA1, percent Australian born in the SA1, percentage of SA1 devoted to high or medium density dwellings, and percent of people in SA1 who work in professional industries which included (following ABS categories) professional, scientific, technical, accommodation, food, financial, insurance, health care, social assistance, education and training services.

We also obtained the Index of Relative Socioeconomic Disadvantage (IRSD) by SA1s. The IRSD is an area-level index of disadvantage published by ABS. It is a composite index of disadvantage including many area-level census variables, including the percentage of low-income households and people with low education levels (ABS, 2018a). We also calculated the road network distance from the centroid of each SA1 to the nearest Sydney rapid mass transit system train station using location data from Transport NSW (Open Data, 2019) and the Quantum Geographic Information System's (QGIS) Network Analyst tool (QGIS.org, 2022).

3. Methods

3.1. Quantitative methods

We were interested in areas with significant increases in public transport use between 2011 and 2016 (hotspots). To identify these areas, we first calculated the number of people in a given SA1 who would be expected to be utilising public transport in 2016 if they were utilising public transport in the SA1 at the same rates as in 2011. Next, we used these SA1 level expected rates of public transport use in 2016, the actual rates of use in the SA1 in 2016, and the Spatial Scan Statistic to search for hotspots or areas with significantly greater than expected increases in public transport use. For detecting coldspots, we calculated the number of people expected to be utilising public transport in 2016 in an SA1, given the overall rates of public transport use in SWSLHD. The Spatial Scan Statistic, realised through the SaTScan software, is a validated and widely utilised method of detecting hot and coldspots or spatial clusters (Kulldorff, 1997). The method draws multiple circles over the study area, centred in turn on each SA1, that grow until a certain population threshold is reached (Fig. 1). Likelihoods are calculated within each circle, and a Monte Carlo hypothesis test is implemented to find the most likely circle/cluster. This method has multiple advantages over other methods of cluster detection, including the bypassing of the multiple testing problem, adjustment of underlying inhomogeneous populations, management of unstable rates by utilising adaptive filters, and a relatively flexible approach to defining cluster geometries (Kulldorff, 1997; Mazumdar et al., 2010). We used a Poisson model, one percent of the population as the maximum filter size, a circular expected cluster shape and 999 Monte Carlo replications to generate reference likelihood ratio distributions. A Poisson model is appropriate since count data are being analysed. Also, the relatively small size of the SA1s and the small population threshold (1%) means that a circular filter will be able to detect most clusters (Mazumdar et al., 2010). The filter size is an important parameter that decides the upper threshold size for a detected hotspot or coldspot (Mazumdar et al., 2020a). We utilised a one percent population filter size because we were interested in detecting small, localised clusters. ArcMap Version 10.7 (ESRI 2018, 2018) was used to map hotspots and coldspots.

We investigated the odds of an SA1 being a hotspot (1/0) as a function of change in SA1s between 2011 and 2016 in the percentage of car ownership density, percent aged 15 to 64, percent born abroad, percent over 64, and percent in professional employment (all variables as defined earlier). Other variables were distance to the nearest train station (road network distance) and IRSD quintiles. No distinction was made between the diesel and electric train systems. These (age, distance to train station, etc) were the independent variables in a logistic regression model predicting the odds of an SA1 being an active transport hotspot (or coldspot). Also, commuting data are known to be spatially correlated, thus, for instance, allowing the creation of commuting regions (Davidson et al., 2021). To manage the issue of spatial autocorrelation, we bootstrapped confidence intervals of the odds ratio estimates (Mazumdar et al., 2019). The method consisted of drawing a random 50% sample of the data, running the regression, storing the parameter estimates, and repeating the procedure for 10,000 replications. The stored parameter estimates were then used to generate 95% confidence intervals. To denote statistical significance, p values were reported, and $p < 0.05$ was considered significant. Separate regressions were implemented for coldspots using the same predictors and inferential procedure as hotspots, with the dependent variable being an SA1's coldspot status (1/0).

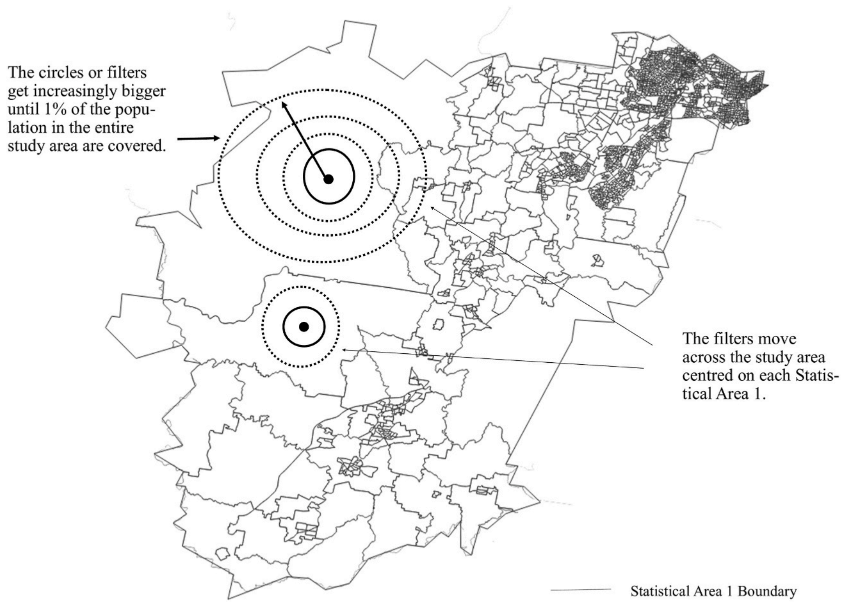

Fig. 1. SaTScan Geographic scanning procedure.

Qualitative methods

A semi-structured interview approach was utilised to collect qualitative data from key stakeholders. Participants were selected by allocation of geographic region to cover the diversity within the SWSLHD and hot/coldspot location; invitations were sent to; one rural, two peri-urban, and two urban LGAs. Interviews were conducted with two participants from three LGAs. One interview was conducted as a two-participant focus group from a fourth LGA and one participant from a fifth LGA. Two additional interviews were held with other stakeholders involved in planning for metropolitan Sydney in general, resulting in a total of 11 participants in nine interviews and one focus group.

A recruitment email was sent to the general manager of each LGA council with guidance for certain positions that may be the best interview candidates. This email was then forwarded to the relevant department. Also, snowball sampling was used for some interviews, with suggestions on who would be best to interview. Participants were primarily from a planning background, including strategic planning, landscape design, infrastructure, transport, and employment planning.

Interviews were conducted by the second author over two months, between February to April 2021, over Microsoft Teams meetings (video conferencing) and were audio-recorded and transcribed. Participants were provided with the hotspot and coldspot map described earlier and the semi-structured interview questions before the interview. As with any qualitative study, we must expand on the positionality (Biesta, 2010) of the interviewer who is the second author, a research officer at a university-based research centre with a Master of Public Health degree and, who has extensive experience conducting interviews and focus groups. The interviewer had several years of experience working in health partnerships with local governments and had working relationships with a few participants.

The qualitative interview data were entered into Nvivo 12 software (QSR International Pty Ltd, 2020) and analysed thematically using an open coding approach (Clarke et al., 2015). Data were anonymised; thus, participants, places, suburbs, and LGAs were not identified to avoid any unnecessary naming and shaming of places. While LGA and suburb names were anonymised with an 'X', their peri-urban, urban, or rural status was mentioned. Emerging themes were organised as either drivers or barriers to using public transport and synthesised with the findings from the quantitative analyses. Ethics approval for this project was obtained from the SWSLHD Human Research Ethics Executive Committee (2021/ETH01816).

4. Results

4.1. Hotspots and coldspots

Hotspots were more likely in urban and peri-urban areas, while coldspots were more likely in rural areas (Fig. 2). Eighteen percent of the population in 2011 and 25% in 2016 used active commuting means in the hotspots. In the coldspots, 9% of the population used active commuting in 2016. The median distance of train stations from hotspot SA1 centroids was 1.36 km compared to 2.09 km from coldspot SA1 centroids. All SA1s had an ageing population, with the proportion of those over 64's growing faster than other age groups between 2011 and 2016. While we are not investigating the relationship between the change in characteristics of the coldspots and changes in active commuting, we provide change statistics for coldspots in Table 1 to contrast them with hotspots. Compared to the

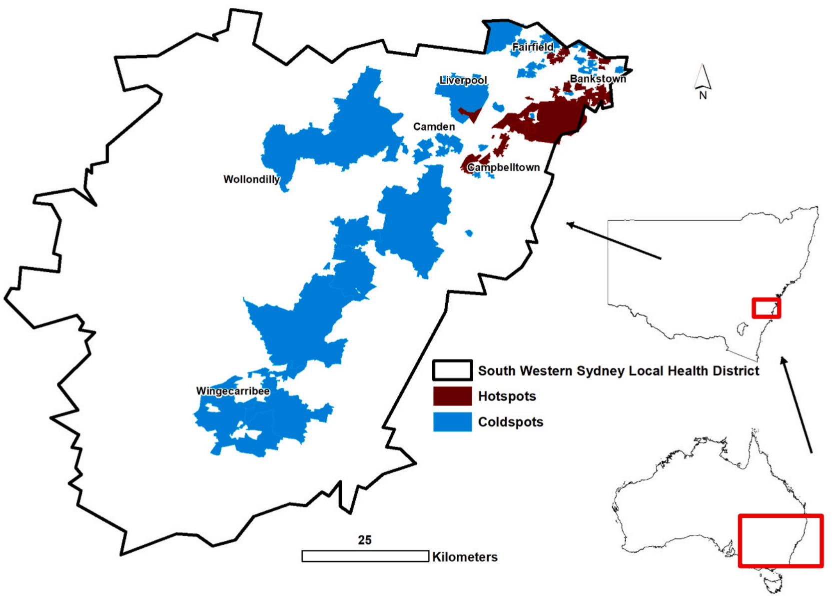

Fig. 2. Hotspots and coldspots-coldspots visible in rural areas.

Table 1
The table below summarises the change in different metrics, in all SA1s, SA1s that were hotspots and coldspots, in SWSLHD that happened between 2011 and 2016.

Change in all SA1s	Median Hotspots	Median Coldspots	Median All SA1s
Change in % younger than 15	−0.76	−1.235	−1.06
Change in % 15 to 64	−0.31	−0.94	−0.80
Change in % over 64	1.23	1.99	1.78
Change in % born abroad	2.78	2.31	1.94
Change car ownership density[a]	0.02	0.01	0.02
Change in % professionals	1.0	0.00	1.00
Change in % of medium to high density dwellings	0.03	0.00	0.01
Summary statistics for other metrics			
	Hotspots	**Coldspots**	**All SA1s**
% SA1s in IRSD quintile 3 to 5[+]	69.69	60.33	59.85
Distance to nearest train station in kilometres	1.36	2.09	1.72

Abbreviations: SA1- Statistical Area 1, IRSD – Index of Relative Social Disadvantage.
[a] Car ownership density is the fraction of cars per person in an SA1, +2016 IRSD Value.

average SA1, coldspots had greater growth in the proportion of over 64s from 2011 to 2016, while hotpots had less than average growth (Table 1). One reason for this could be immigration since hotspots had greater increases in percent born abroad between 2011 and 2016 than other areas. Hotspots also had greater increases in percent professionals and somewhat greater increases in medium to high-density dwellings. The change in car ownership density in hotspots was the same as in the average SA1, while coldspots showed no change in car ownership density (Table 1).

4.2. Modelling results

Table 2 and Fig. 3 show the results of the regression models. SA1s in more advantaged areas with IRSD (2016 IRSD) quintiles three to five are 2.49 (95% CI: 1.93, 3.31) times more likely than SA1s in disadvantaged areas with IRSD quintiles one or two to be a hotspot of public transport. Everything else remaining constant, a one km increase in distance travelled by road decreases the odds of an SA1 being a public transport hotspot by 36% (30%, 42%). The following observations can also be made: *ceteris paribus*, a one-unit increase in the percent of people engaged in professional services (professional scientific and technical services, accommodation and food services, financial and insurance services, health care and social assistance, education and training) in an SA1 between 2011 and 2016 leads to a 7% (2%, 12%) increase in odds of the SA1 being a public transport hotspot; a one unit increase in the percent of people born abroad in an SA1 leads to a slight increase: 3% (1%, 6%) in the odds of an SA1 being a hotspot, a one unit increase in the percent of people older than 64 in an SA1, leads to a 7% (3%, 11%) decrease in the odds of the SA1 being a public transport hotspot. Changes in the percent of high/medium density and the density of cars were not significant since these variables were not that different in the hotspot SA1s relative to the average SA1. When predicting coldspots, only one predictor was significant, - distance to the train station, which was positively associated with the likelihood of an SA1 being a coldspot with an odds ratio of 1.04 (1.02.1.09, $p < 0.05$). For the sake of brevity, the coldspot regression table is not shown.

4.3. Interviews

The most frequently mentioned factor that is believed to impact active commuting is the ‘attractiveness’ of public transport, with specific train routes being seen as more attractive than others. To be attractive and to increase uptake, respondents suggested that public transport must be reliable, cost-effective, convenient (in terms of time and mode changes) and visible. It was also mentioned

Table 2
Factors associated with hotspots of active transport increase.

Predictors of an SA1 being a hotspot	Odds Ratio (95% CI)	*p* value
Distance to train station	0.64 (0.58,0.7)	<0.05
IRSD quintile one and two	2.49 (1.93,3.31)	<0.05
Change between 2011 and 2016 in:		
Percent age 15–64 years	1 (0.96,1.03)	0.99
Percent age 64+	0.93 (0.89,0.97)	<0.05
Percent born abroad	1.03 (1.01,1.06)	<0.05
Percent of SA1 with high or medium dwelling density	2.31 (0.98,6.56)	0.08
Percent working in professional trades	1.07 (1.02,1.12)	<0.05
Total cars per household	0.53 (0.06,5.06)	0.59

Abbreviations: SA1- Statistical Area 1, IRSD – Index of Relative Social Disadvantage.

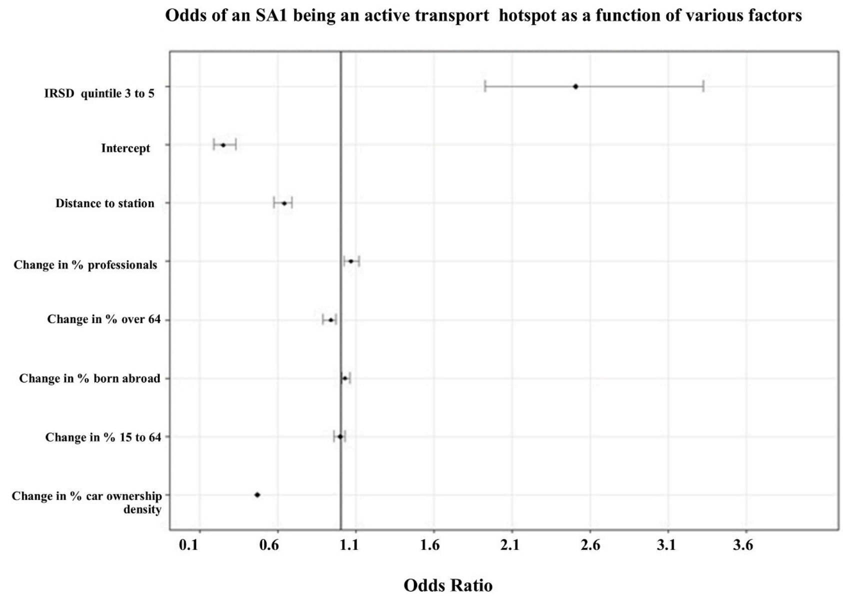

Fig. 3. Modelling results. Confidence interval of change in % car ownership density not shown (variable not significant)

that attractiveness is also influenced by where the person is commuting to, with some areas within and beyond the SWSLHD being more convenient to drive to rather than to utilise public transport. Private car ownership was also considered necessary by respondents. It was acknowledged that some LGAs within the SWSLHD have very high private car ownership and multiple private cars per household. The belief was that high car ownership usually resulted in decreased active commuting as habitual driving becomes convenient, and that this supported the trend of increased total number of cars per household.

SWSLHD is a rapidly growing area, with new development areas filled with housing (often low density) and rapidly populated. There was conflicting information about the uptake of active commuting in these new housing areas. It was suggested that low-density housing doesn't support or encourage active commuting (many areas of no-change and coldspots) due to poor access to public transport in terms of proximity to a train line. However, there were some areas where this was not the case.

> "In my mind, there is not a whole lot of access to any form of public transport anywhere in X (peri-urban LGA) except for places like X, which is the only train station."

> "Attractiveness and viability of public transport, it's the nature of the development we have quite sprawling we don't have the population density to get a lot of people living to the key areas where they work etc. it won't be well serviced in an area where density isn't so high."

In addition to low density, other specific reasons for private vehicle commuting were provided.

> "*a lot of new houses that have gone in there, and people there would be educated workers going to the CBD or X (Urban LGA outside of SWSLHD) to work, not tradespeople* (Tradesmen) … *If you are a tradesperson, you need to drive as you need your ute tools etc. so in some ways … using public transport could be a luxury of white-collar workers in a way."*

> "… … … …., people are moving here with the expectation that they are moving to the 'country' and they are going to drive everywhere ('two car garage and white picket fence ideology')"

Conversely, for newly developed/developing areas identified as hotspots, it was suggested that demographic changes in those areas may have led to increased uptake of active commuting.

> "It could be demographic changes; new types of people are moving into X (peri-urban LGA), especially to the northern part of the LGA, and with that might bring different attitudes and expectations of public transport, people might not be moving here thinking they are going to drive everywhere."

The qualitative evidence regarding the early delivery of public transport infrastructure and increased active commuting was mixed. While it was believed that some areas where early delivery of frequent bus services occurred saw an increase in active commuting, there were also cases where the delivery of such services resulted in no change to active commuting. It was acknowledged that within new development areas and notably higher density developments (i.e., those that include townhouse and apartment dwellings), there was an opportunity for development contributions (construction levies paid by developers to councils for new developments) to contribute to funding local infrastructure projects that support and encourage active commuting, e.g., footpaths and bus stops. Such development was, however, seen as complex within 'existing/older suburbs' where development contributions are unlikely to occur.

There were conflicting views about parking infrastructure at train stations where the train stations are either too far to walk for local residents or need more convenient feeder bus services. Since driving to a station to alight a train is considered active commuting, active commuting growth in some hotspots was attributed to substantial parking infrastructure at the station. This growth was particularly the case in areas where the train line was seen as ’attractive’ (which in addition to other factors include direct, express options to stations near the workplace), which were always in older/existing suburbs.

> “People do drive to X (peri-urban train stations) to get the train- if driving, finding parking and walking to train station takes too much time, it’s more convenient to just drive to the destination"

> “Stations without commuter parking, given these areas are quite low density … It might be found that lower car parking might discourage people to drive and catching the train. Most designers want to reduce the amount of parking, but in the shorter term, it might mean that you need commuter parking until density goes up and there is more walkability around the station. How do we have a transitional parking strategy, we are struggling with that."

> “State government built multi-deck parking stations at X and X and they have invested in the upgrades of X and X (urban train stations), making those more attractive places to drive to. X (urban suburb) is not walkable to any transport by any means, but they would all be driving to use that line because it has become attractive. The convenience of X and X (urban train stations) quickly get into the city, attractive choice in that period."

Respondents mentioned various contextual factors as drivers or barriers to active commuting during the 2011–2016 period. The introduction of the Opal Card, a contactless fare collection smart card, by NSW transport to replace paper tickets in 2012–2014 was suggested as a driver for active commuting as it created ease of use, encouraging multi-modal and frequent travel for users.

> “Opal card- incredibly significant reform, seeing transport as a network, transports focus on not the mode of transport but the network … Opal card was 2012–2014, so in the middle of that period. It was responsible for the significant growth, for several years on an already busy network, well above population growth. Road congestion encourages people to use public transport."

The rural areas of SWSLHD were perceived to have inferior access to attractive public transport options. There was also a belief that many SWSLHD residents travelled out of the district for employment which was associated with private car use.

> “Car use up to a point in less urban environments tends to correlate with socioeconomic status, and X (peri-urban LGA) is a slightly higher socioeconomic status (SES) area than others in SWSLHD, that is a macro level driver."

> “X (Rural town), more subdivisions, low-density development might increase the number of people driving. Demographics need to be considered too; many older people live there."

> "Growth and density will increase public transport use, but there is a threshold where that doesn’t work. Typical greenfield development, on car-based development (or more density in a rural area) that isn’t goes to produce public transport use and public transport use or walking cycling.”

> “Roads built potentially; you build roads you get car use. If you make space for cars make it easier to drive, you will get more driving; if you make more space for public transport, you’ll get more public transport usage. It may be that as roads and development have made Sydney artificially closer you are getting more people deciding to travel those distances (rural southern suburbs)."

Local amenity options and mixed land use were seen to be important drivers of active commuting and the use of public transport. Areas such as some suburbs in an urban LGA (which were identified as hotspots) were identified as having good amenities (e.g., shops, feeder bus stops and mixed land use), along with other urban design aspects (flat land, pedestrian infrastructure, grid-like roads) making it conducive to active commuting.

> “X (suburb in urban LGA) actually has a really good street network, fine grain grid, light topography down to the station, retail and services and not craters of parking, bus line that heads down to the station … mixed-use, medium density development, pedestrian crossings."

This was contrasted with a peri-urban suburb (identified as a coldspot) being an area of little to no amenity other than the relatively new train station, surrounded by a low-density residential area.

> “Why X (peri-urban suburb) above is cold, there isn’t infrastructure other than the train station.”

> "X (peri-urban suburb), interesting example … … … … mainly due to the fragmentation of land … as well as a lack of infrastructure, so the market wasn’t there. It hasn’t taken off, so X’s Train station functions as a commuter car park a lot of people travel from out of the area (nearby suburbs named). People park there and on the side of the road to get on a train."

> *“The blue parts* (coldspots) *are interesting, they are all parts of the city with pretty poor rail access … one of the blue spots, it’s a very walkable area with shared paths and river tracks but you aren’t near any train station or big centre”*

Some suburbs were identified as ‘walkable’ in terms of recreational and social activity (walkable distance to night-time economy, e.g., restaurants or recreational walking). One urban LGA was highlighted as an LGA with areas with excellent walking and cycling paths; however, these need to be integrated or directly linked to public transport. The climate was also raised as a contextual issue within SWSLHD. Respondents noted that heat, in particular, is a barrier to active commuting, particularly for those with longer trips, especially from the rural LGAs.

> “that area has lots of walking amenities but only for recreation; good parks, river, bush, but it doesn’t take you anywhere. It’s got all the right things going for it, but there’s nothing to go to. Its recreation"

> “Not surprised to see car use growing I would also say it’s getting hotter, climate is warming. The number of very hot days in 2010’s grew, and in Western Sydney is much hotter than places close to the coast. So that induces car use."

5. Discussion

Our study is one of the first to explore local spatial variations in increases in active commuting and low commuting levels using a mixed geospatial, qualitative, and quantitative approach. The study found that while the distance to a train station results in greater-than-expected increases in train use, several aesthetic and other factors were important. The literature has extensively explored the drivers of active commuting separately from quantitative and qualitative perspectives (Aittasalo et al., 2017; Brüchert et al., 2021; Goodman and Phillips, 2005; Kuss and Nicholas, 2022; Le Gouais et al., 2020; Scheepers et al., 2014), an examination of local areas concerning active commuting, from a quantitative and a stakeholder-qualitative standpoint has until now been missing.

Our study found that, agreeing with the existing literature increases in commuting in a local area can be affected by changes in the demographic composition of an area (Chia et al., 2016). Also, higher SES areas are more likely to see greater increases, as are areas with increases in the percentage of professionals or those born abroad. Conversely, an increase in retirees leads to decreased public transport use. Our qualitative interviews exposed that some of the new inhabitants of the hotspots may have "different attitudes and expectations" and feel more comfortable using public transport. These attitudes and expectations could be because of people with pre-existing motivation to utilise public transport self-selecting into such transit-oriented developments (Cervero, 2007).

Various factors were associated with public transport use. Some new inhabitants are likely immigrants, and an increase in those born abroad could mean that new immigrants without access to, or who do not wish to utilise, private vehicles, are utilising trains as a commuting mode (Amar and Teelucksingh, 2015). Also, the lack of professional job opportunities in Western and South Western Sydney (ABS, 2018b; Fagan, 2015) with such jobs being a train ride away to the East, could be the reason for the association between higher SES, more professionals and train commuting hotspots (Lee et al., 2018). In contrast, tradespeople carrying heavy equipment may choose to drive to work in their customised trade vehicle or operate locally, and hence not consider proximity to public transport important. Also, according to our study, some people may expect that moving into a new low-density development is part of a lifestyle choice that entails extensive car use, independent of proximity to public transport.

Attractiveness and viability of public transport were important factors. If a train line was found to be slower than desirable, then commuters preferred driving instead. As documented in the published literature, the interviewees considered that introducing the contactless pay system, “Opal card”, in 2012–2014, had significantly improving the ease of public transport use (Ellison et al., 2017). Also, increases in commuting in higher SES areas may be related to these areas having safer and more aesthetic routes to the train station. These results reiterate findings from a UK-based study, indicating that the main drivers of active commuting are convenience, cost, speed and reliability (Jones et al., 2012). Similarly, a recent randomised control trial reported increased active commuting after improving walking and cycling paths (Aittasalo et al., 2017). Issues such as general walkability in the route to the train station, how integrated such pathways were with the neighbourhood walking network, and weather conditions were also considered germane by stakeholders.

Distance was also a significant predictor of an area being a train use coldspot. Rural areas were identified as being lightly populated and very car-dependent; this was similar to findings in Yang et al. (2017), with those living further from work in lower-density areas being less likely to take up active commuting. However, the qualitative analysis also opens the debate on providing and expanding commuter parking or park-and-ride facilities. New developments may also lack amenities, necessitating vehicle trips to other neighbourhoods. Thus, for example, a lack access to schools within walkable distances in a neighbourhood may require that parents schedule dropping and picking up of children within their daily itinerary, necessitating the use of a vehicle (Chia et al., 2016).

It is acknowledged that driving to the train station (and back) is a better option than driving all the way to work and which forms the basis of the “park and ride” facilities in many cities (Scheepers et al., 2014). Nevertheless, there remains the option of active commuting by walking or cycling to and from the station. It was suggested that planners consider ‘transitional parking’ (Thumm and Perl, 2020) strategies for new development areas and future planning. In such a scenario, some parking is provided relative to demand and cognizant of density around the train station. As the density around the train station increases and commuters start walking to the train station, changes in parking facilities should accommodate the changed commuting patterns (Thumm and Perl, 2020). Also, while overall neighbourhood-level walkability is vital to encourage walking to public transport, the existing walking networks need to be integrated with paths to public transport hubs, which raises issues about holistic walkability planning for these neighbourhoods.

This study has several strengths. It investigates the factors associated with hotspots of change in the use of public transport. It achieves this by utilising standard statistical tools and extracting additional ‘depth’ information on the hot and coldspots by interviewing key stakeholders from local governments and transport agencies. This triangulation allows us to draw more informed conclusions about the drivers of public transport use in South Western Sydney. The geographic locale of this study is a fast-growing, geographically and demographically diverse area of a large metropolitan city, making it very relevant to many other areas with similar characteristics globally. The study has some limitations. Many factors associated with greater public transport use to work, such as walkability to public transport stops, aesthetics of the route, and crime, could not be quantitatively analysed. While our qualitative interviews engaged the opinions of essential local government stakeholders, the actual residents' opinions were beyond the scope and resources of this study. We recommend that future researcher in this domain focus on the "local" utilising geospatial tools such as ours. We also suggest that they extend the scope of the qualitative engagement to include residents (in addition to stakeholders) and, if possible, expand the range of quantitative predictors in the analysis. Finally, the data that this study engages are for the years 2011 and 2016, and future research could extend these analyses to more recent census data.

6. Conclusion

Extensive literature has grown around the drivers of active commuting. Nevertheless, there needs to be more engagement with the issue at a local geospatial level. Utilising a unique mixed geospatial approach, we explored the local drivers of active commuting in South Western Sydney. Our research found that while distance to train stations is an important factor in active commuting, the perceived attractiveness of both the public transportation mode as well as the feeder walking, or bicycling infrastructure are also important. We also found that increased active transport may be driven by demographic changes in an area. In addition, future researchers can leverage these methods to draw specific insights on local geographical areas of their choice.

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CRediT authorship contribution statement

Soumya Mazumdar: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Preparation, Visualization, Supervision, Project administration. **Karla Jaques:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Preparation. **Stephen Conaty:** Writing – review & editing, Preparation, Supervision. **Evelyne De Leeuw:** Writing – review & editing, Preparation, Supervision. **Ori Gudes:** Writing – review & editing, Preparation, Supervision. **Jinwoo (Brian) Lee:** Writing – review & editing, Supervision. **Jason Prior:** Writing – review & editing, Preparation, Supervision. **Bin Jalaludin:** Writing – review & editing, Preparation, Visualization, Supervision, Resources, Project administration. **Patrick Harris:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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