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Determinants of zero-car and car-owning apartment households

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Abstract

While much research has explored the determinants of car ownership, there is little understanding of these factors in the context of apartment households, where off-street car parking provision is frequently stipulated by planning requirements and zero-car households are more evident. Drawing on a survey of apartment residents (n = 1316) in three Australian cities, this study aimed to understand the determinants of zero-car and car-owning apartment households. The data was analysed using binary and multinominal logistic regression, including random parameter modelling. A joint model of car ownership and off-street car parking supply was also developed to account for potential endogeneity between these two variables. The results highlight the significant association between car ownership and off-street car parking supply, alongside a range of socio-demographics, attitudes, perceptions, built environment and transport characteristics. An additional off-street car parking space, on average, was found to increase the odds of having 2+ cars, compared with zero cars, by around 10 times. The findings imply that reducing off-street residential car parking requirements can play a significant role in supporting lower car ownership levels among apartment households.

Keywords Car ownership · Zero car household · Parking · Apartment · Multi-family housing

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Introduction

High levels of car ownership in cities have been associated with a range of issues such as traffic congestion, air pollution, urban sprawl, road safety concerns, health impacts, and car parking problems (Gössling et al. 2022; Haustein 2021). Understanding the determinants of car ownership, including households who choose not to own a car, is therefore integral to addressing these issues. Previous research has found that car ownership is influenced by a range of socio-demographic, built environment and transport-related characteristics (Guo 2013; Li et al. 2010; Zegras 2010), yet there is little understanding of these characteristics in the context of apartment households, particularly among apartment households who do not own a car.

Understand the determinants of car ownership among apartment households is important as apartment housing tends to trigger requirements for off-street car parking in many cities. These requirements can stipulate how many car parking spaces need to be allocated to each apartment, often as a minimum amount, but in some cases as a maximum (De Gruyter et al. 2021; Mingardo et al. 2015). This typically varies based on the size of the apartment (e.g. number of bedrooms), but in limited cases is linked to transport characteristics such as distance to public transport (Barter 2011; De Gruyter et al. 2020; Kimpton et al. 2020). Various studies have shown that minimum off-street car parking requirements are often set too high, leading to a host of problems such as an oversupply of car parking and inefficient use of space, greater housing costs, along with increased car ownership and use (Gabbe et al. 2020; Manville 2013; Shoup 1999; Weinberger 2012).

The aim of the present study is to understand the determinants of zero-car and car-owning apartment households. Doing so can help to inform the development of more tailored off-street car parking requirements, alongside efforts to support reduced car ownership in cities, including the conditions needed to facilitate apartment households choosing to be 'car-free'. This research uses data from a survey of apartment residents (n = 1316) in three Australian cities: Perth, Melbourne and Sydney. The survey data is analysed using binary logistic regression modelling for zero-car households and multinominal logistic regression modelling for car-owning households. The potential for endogeneity between car ownership and off-street car parking supply—that is, the extent to which they may influence one another—is also considered through the development of a joint model of car ownership and off-street parking supply. In addition, random parameter modelling is employed to account for unobserved heterogeneity in independent variables.

The study contributes to an understanding of the determinants of zero-car and car-owning households, specifically those in residential apartment buildings where off-street car parking is typically allocated to individual households under planning requirements. In addition, this research accounts for potential endogeneity between car ownership and off-street car parking supply in the context of apartment households. The research also provides a multi-city comparison of the determinants of zero-car and car-owning apartment households in Australia, where considerable growth in apartment housing has occurred over the last decade, accounting for more than one-third (35%) of all residential building approvals in cities (ABS 2021b).

The term 'apartments' is used throughout this paper to describe multiple self-contained dwellings located within the same building, regardless of management structure or housing tenure. In other countries, terms such as apartments, flats, condominiums or multi-family housing may be used depending on housing tenure or management structure.

The remainder of this paper is organised as follows. The next section provides a literature review of car ownership studies, followed by context for the research through a description of each city. The method used to undertake the research is then detailed, including an overview of the resident survey and analysis techniques. The results of the analysis are then presented, followed by a discussion of the implications for car parking policy.

Literature review

This section provides a review of key studies that have investigated factors associated with car ownership at the household level. Model types used in previous studies are also covered, along with considerations for dealing with potential endogeneity. This section ends with the identification of research gaps that the present study seeks to address.

Table 1 provides a synthesis of factors that have been found across 20 published studies to be significantly associated with car ownership at the household level. The selection of these studies was based on key papers that are cited on the topic, with additional papers identified through backward and forward referencing. The studies are not intended by any means to be exhaustive, but rather serve to illustrate the range of factors associated with household car ownership. Collectively, the studies cover a range of geographies including North America (Blumenberg et al. 2020; Brown 2017; Chu 2002; Giuliano and Dargay 2006; Guo 2013; Potoglou and Kanaroglou 2008), South America (Zegras 2010), Europe (Clark 2007, 2009; Giuliano and Dargay 2006; Oakil et al. 2016) and various parts of Asia (Cho and Baek 2007; Dissanayake and Morikawa 2002; Sanko et al. 2014; Soltani 2017; Verma et al. 2016; Yagi and Managi 2016), particularly China (Li et al. 2010; Shao et al. 2022; Shen et al. 2016; Wu et al. 1999).

The factors in Table 1 have been classified into household/individual characteristics, built environment factors, and transport-related characteristics. Factors were only included where they were found to be statistically significant in more than one study. As can be seen, *income* was positively associated with household car ownership in almost all studies (18 out of 20), followed by *children in household* (positive association in 11 out of 20 studies). *Population and/or employment density* was generally found to be negatively associated with household car ownership (10 out of 20 studies). Other factors were less common, although the following variables were significant in at least 7 out of the 20 studies: *workers in household* (positive association), *age* (both negative and positive associations), *land use mix* (generally a negative association), and *distance to public transport stop/station* (positive association). Of relevance to the present study, but rarely incorporated in previous research, is *apartment housing* (generally a negative association based on 4 studies) and *parking provision/availability* (positive association based on 3 studies).

Attitudes and perceptions were captured in only 3 out of the 20 studies (Shen et al. 2016; Verma et al. 2016; Wu et al. 1999) but are not shown in Table 1 due to the diversity in attitudes/perceptions that were measured. Examples included the car seen as a status symbol (positive association), preferences for comfort and time savings (positive association), pro-sustainability and tax-conscious attitudes (negative association), and preferences for cost savings (negative association).

In modelling household car ownership, many studies have used zero-car households as a reference category to compare car-owning households against. However, limited efforts have been made to explicitly understand factors associated with zero-car households. Studies undertaken by Blumenberg et al. (2020) and Brown (2017) in California found that

Table 1 Factors significantly associated with car ownership at the household level based on published studies

Variable	Published study (see list below table)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Household/individual characteristics																					
Income	+	+	+	+	+	+	+	+	+	+	+		+	+	+		+	+	+	+	18
Children in household		+	+	+			+		+	+	+		+	+					+	+	11
Workers in household							+			+	+	+	+				+	+	+		8
Age*	–		–						–			+	+		–				+		7
Occupation status*	+	+	+						+					+				–			6
Household size (people)				+					+						–			+		+	5
Housing ownership					+			+	+									+		+	5
Ethnicity (non-native)								–					–				–		+/–		4
Apartment housing				–	+					–								–			4
Education status*	–								+							+	+				4
Parking provision/availability	+				+						+										3
Single family/detached housing		+					+	+													3
Licensed drivers in household		+					+														2
Housing size					+			+													2
Built environment factors																					
Population and/or employment density		–		–	–	–			–	–	–		–		+/–					–	10
Land use mix		–			–		–			–								–	–	+	7
Distance to CBD			+						+	+										+	4
Intersection density										–										+/–	2
Transport-related characteristics																					
Distance to public transport stop/station	+			+			+		+	+	+									+	7
Regional accessibility					+					–		+									3
Commuting distance							+							–				+			3
Household bicycle/e-bike ownership									–											–	2

Table 1 (continued)

Variable	Published study (see list below table)																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Household motorcycle ownership									–											–	2

+ significant positive association, − significant negative association, * usually referring to the household head, variables only listed where significant in more than one study. *Source*: Authors' synthesis of the literature based on the following studies: 1. Wu et al. (1999), 2. Chu (2002), 3. Dissanayake and Morikawa (2002), 4. Giuliano and Dargay (2006), 5. Cho and Baek (2007), 6. Clark (2007), 7. Potoglou and Kanaroglou (2008), 8. Clark (2009), 9. Li et al. (2010), 10. Zegras (2010), 11. Guo (2013), 12. Sanko et al. (2014), 13. Oakil et al. (2016), 14. Shen et al. (2016), 15. Yagi and Managi (2016), 16. Verma et al. (2016), 17. Brown (2017), 18. Soltani (2017), 19. Blumenberg et al. (2020), 20. Shao et al. (2022)

zero-car households tend to have less children, lower employment rates, lower incomes, lower educational attainment, and are more likely to be non-white and live in more mixed-use, established areas. These findings are consistent with research undertaken by Chu (2002) in New York City, also finding that zero-car households tend to have less licensed drivers and are less likely to live in a single family home. Similar results have also been reported in Bangkok in Thailand (Dissanayake and Morikawa 2002) and Shiraz in Iran (Soltani 2017), with the addition of age (>50 years old), apartment living, and lack of home ownership being positively associated with zero-car ownership.

In terms of modelling household car ownership, discrete choice models are commonly used based on the underlying choice response mechanism (De Jong et al. 2004). Binary logit models have been used to predict households owning cars vs. no cars (Li et al. 2010; Oakil et al. 2016; Shen et al. 2016), while ordered logit (or probit) and multinominal logit (or probit) models have commonly been used to predict levels of household car ownership (e.g. 1, 2, 3+cars) relative to zero-car ownership (Blumenberg et al. 2020; Chu 2002; Giuliano and Dargay 2006; Potoglou and Kanaroglou 2008; Sanko et al. 2014; Wu et al. 1999; Zegras 2010). Nested logit models have also been used to model household car ownership (Dissanayake and Morikawa 2002; Guo 2013; Soltani 2017). Following a study by Bhat and Pulugurta (1998), which found unordered-response mechanisms, in this case the multinominal logit model, to be superior to the ordered logit model for predicting household car ownership, many studies have adopted an unordered-response mechanism. A key reason is that unordered-response mechanisms are consistent with the theory of global utility maximisation (De Jong et al. 2004), whereby households associate a utility value with each car ownership level and choose the level that maximises their utility (Potoglou and Kanaroglou 2008).

Despite the link between household car ownership and car parking provision (Weinberger et al. 2009), very few studies include parking supply as an explanatory variable when modelling car ownership, often due to a lack of available data (Guo 2013). Proxies for parking supply/availability have commonly been used instead, such as housing type, often based on a dummy variable for single family/detached housing (Chu 2002; Potoglou and Kanaroglou 2008). However, a key issue that arises when modelling household car ownership is the potential for endogeneity (Mannering 1986), particularly with car parking supply. Guo (2013) meticulously tackles this issue in the context of understanding how parking supply can affect household car ownership in New York City. While a range of approaches to dealing with endogeneity can be adopted, a common technique being the use of instrumental variables, Guo (2013) controls for endogeneity by dividing the sample into two homogeneous groups (households with and without off-street parking) who have similar unobservable attributes relating to car ownership preferences.

In addition, other studies have investigated residential self-selection effects in the context of car ownership and off-street car parking provision (Manville 2017; Millard-Ball et al. 2022). That is, households with access to off-street residential car parking may be more likely to own a car, and those who own cars may also choose housing with off-street car parking provision. In a study of San Francisco's housing affordability lotteries, Millard-Ball et al. (2022) found that increased off-street car parking provision causes higher car ownership and more car use, regardless of how accessible a neighbourhood is to public transport. Here, an increase in parking provision of 0.43 spaces per household was associated with a household being 14 percentage points more likely to own a car. In another causal analysis that used data from across nine U.S. cities over time, McCahill et al. (2016) found that an increase in car parking provision from 0.1 to 0.5 spaces per person was associated with an increase in the mode share for automobiles of approximately 30 percentage points. Furthermore, Manville (2017) found that households with bundled off-street car parking—where parking is included in the rental or purchase price of housing—were far more likely to own a car than households without bundled parking, even after controlling for residential self-selection. These findings highlight the strong relationship that exists between car ownership and off-street car parking provision, even when controlling for residential self-selection effects.

In summary, while a considerable body of research has provided insight into the determinants of household car ownership, there is little understanding of how these characteristics vary in the context of apartment households where off-street car parking is typically allocated to individual households under planning requirements. There is also a limited understanding of the determinants of zero-car households, particularly those based in apartment buildings. Finally, little research of this nature has been undertaken in Australia, a country that has seen considerable growth in apartment housing over the last decade, accounting for more than one-third (35%) of all residential building approvals in cities (ABS 2021b). The present study seeks to address these gaps.

Research context

This section provides context for the research through a description of the three cities that were surveyed: Perth, Melbourne, and Sydney. As shown in Fig. 1, each of the cities are located on the coast of the Australian mainland. Perth is located on the west coast, Melbourne in the south east and Sydney in the east.

Table 2 provides a summary of key characteristics of each city, compared with the whole of Australia. Of the three cities, Perth has the smallest population at 2.1 million people, followed by Melbourne (4.9 million) and Sydney (5.2 million). Collectively, these three cities account for almost half (48%) of Australia's total population (25.4 million). Population density is notably higher in Melbourne (492 people/sq. km) and Sydney (423 people/sq. km) than in Perth (330 people/sq. km).

In terms of housing, Sydney has a much greater number of apartments (approximately 562,000), than Melbourne (278,000) or Perth (59,000). Apartments account for almost one-third (31%) of all housing in Sydney, compared with only 16% in Melbourne and 8% in Perth. Across the three cities, average household sizes are smaller for apartments, with Sydney having a larger apartment household size on average (2.05 people/household) than Melbourne (1.72 people/household) and Perth (1.63 people/household). Household car ownership is also notably lower for apartments, with Perth having the highest rate of apartment household car ownership on average (1.18 cars/household), followed by Sydney (1.06 cars/household) and Melbourne (0.97 cars/household). The percentage of households with zero cars is also higher for apartments, with Melbourne having the highest rate (29.5%), followed by Sydney (24.5%) and Perth (17.6%).

In terms of travel behaviour, total annual public transport ridership is highest in Sydney (721 million trips), followed by Melbourne (559 million trips) and Perth (141 million trips). Collectively, these three cities account for 83% of all public transport trips in Australian capital cities (1,708 million). Public transport modes operating in the three cities include train (all three cities), tram/light rail (Melbourne and Sydney only), bus (all three cities) and ferry (Sydney and Perth only). Of the three cities, Sydney has the highest percentage of work trips undertaken by public transport (25%) and the lowest percentage

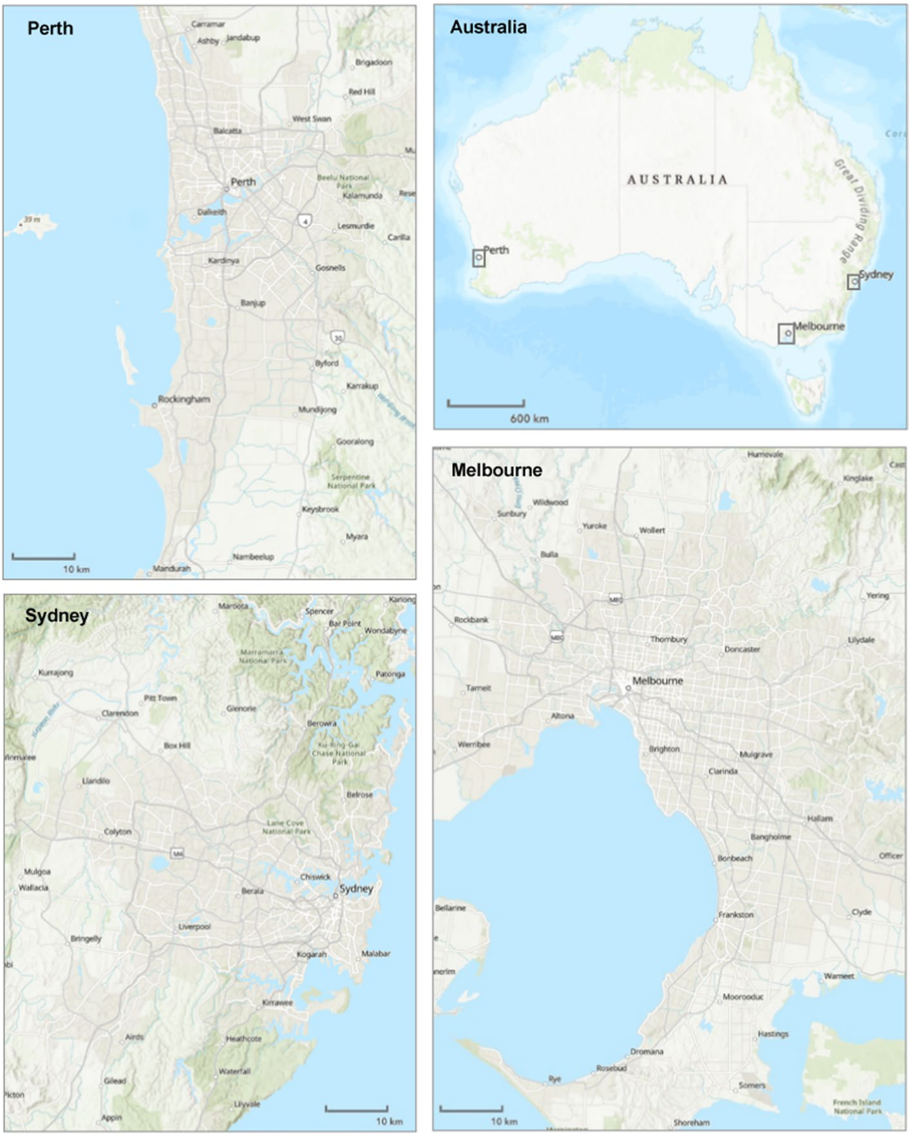

Fig. 1 Location of surveyed cities (Perth, Melbourne, Sydney) across Australia. *Note* Maps produced by authors using ABS Maps (ABS 2021a)

undertaken by car (63%). This contrasts with Perth where only 12% of work trips are undertaken by public transport and around 78% are by car.

In addition to the information presented in Table 2, it is worth noting that off-street car parking is generally 'bundled' with the purchase price or rental cost of apartment housing in Australian cites, and therefore allocated individually to households. This means that

Table 2 Characteristics of surveyed cities (Perth, Melbourne, Sydney) compared to whole of Australia

Characteristic	Perth	Melbourne	Sydney	Australia
Total population[a]	2,116,647	4,917,750	5,231,147	25,422,788
Total area (sq. km)[a]	6417	9993	12,369	7,688,095
Population density (people/sq. km)[a]	329.9	492.1	422.9	3.3
Total occupied households[a]	778,620	1,781,346	1,828,859	9,275,217
Total occupied apartment households[a]	59,492	277,512	561,988	1,319,095
% apartment households[a]	7.6%	15.6%	30.7%	14.2%
Average people per household[a]	2.52	2.60	2.70	2.54
Average people per apartment household[a]	1.63	1.72	2.05	1.86
Average cars per household[b]	1.92	1.73	1.65	1.78
Average cars per apartment household[b]	1.18	0.97	1.06	1.08
% zero-car households[b]	5.1%	9.2%	11.6%	7.9%
% zero-car apartment households[b]	17.6%	29.5%	24.5%	23.6%
Total annual public transport trips (millions)[c]	140.8	558.8	721.3	1,707.7[d]
% journey to work trips by public transport[b]	11.6%	17.3%	25.0%	12.8%
% journey to work trips by car[b]	77.7%	71.4%	62.5%	74.3%

[a]Based on 2021 Australian Census (ABS 2021c)

[b]Based on 2016 Australian Census (ABS 2016)

[c]Based on TTF & LEK (2018)

[d]Figure is for Australian capital cities only, based on TTF & LEK (2018)

residents have limited choice in how many car parking spaces they have, as this is generally dictated by planning requirements. Previous research has found that bundled car parking is associated with greater car use, less public transport use and reduced housing affordability (Gabbe and Pierce 2017; Manville and Pinski 2020).

In Australian cities, minimum off-street car parking requirements are widely used which stipulate a minimum number of car parking spaces that need to be provided per apartment dwelling, usually based on the number of bedrooms in the dwelling. However, variations to these requirements in the form of maximum rates and lower minimums are also used in some cases. For example, maximum car parking requirements are used in parts of Sydney (Kimpton et al. 2020), with lower minimums stipulated for apartment development within 800 m of a railway station or light rail stop (NSW Government 2015). In Melbourne, parking overlays are used in the CBD and other activity centres to specify a lower minimum and/or maximum requirement, with visitor car parking not required for apartment development within 400 m of high-quality public transport (De Gruyter et al. 2020). In Perth, reduced minimum requirements apply to apartment development located within 800 m of a train station, 250 m of a high frequency bus or light rail route, or within the defined boundaries of an activity centre (WAPC 2019).

Method

Resident survey and compilation of dataset

This research is informed by a survey of apartment residents that was administered across three Australian capital cities: Perth, Melbourne and Sydney. The survey is part of a broader study focused on apartment design guidelines (Foster et al. 2019).

The three cities were selected to reflect varying levels of apartment design policy. The sampled apartment buildings in Sydney were developed under the most comprehensive policy in Australia—State Environmental Planning Policy 65 (SEPP65)—compared with relatively limited guidance available at the time in Perth and Melbourne (Foster et al. 2019). To be eligible for inclusion, buildings were required to have at least 40 apartments and three or more storeys, with endorsed architectural or development plans available, to ensure sufficient scale for surveying purposes. In addition, buildings were required to have been built between the years of 2006 and 2016. As the broader study was focused on apartment design guidelines, this building date range was chosen to align with buildings developed under SEPP65 in Sydney, which until recently was the most comprehensive planning policy for apartment development in Australia (Foster et al. 2019). Apartment buildings were also randomly selected from areas of high, mid and low disadvantage to ensure diversity in area socioeconomic status (ABS 2018).

Administration of the survey involved posting an information pack to each apartment household inviting the adult (18+ years old) with the next birthday to participate in an online version or hardcopy of the survey. Those who completed the survey were entered into a prize draw to win a retail voucher.

Survey questions covered a range of topics relating to apartment design, health and well-being, lifestyle, and socio-demographics. Within these topics, residents were asked how many cars are in their household, with response options including 0, 1, 2, 3, and 4 or more cars. They were also asked "How many car parking spaces are allocated to your apartment?" which residents would interpret as their bundled off-street parking allocation. As noted earlier in the Section "Research context", off-street car parking is generally 'bundled' with the purchase price or rental cost of apartment housing in Australian cites, and therefore allocated individually to households. Indeed, examples of apartment buildings that provide unbundled parking remain rare in the Australian context. Other questions asked in the survey that were relevant to the analysis included housing tenure, number of bedrooms, household size, number of children who live in the household, annual household income, the extent to which residents agree that they are able store their bicycle/s in a convenient storage area, importance of car parking in the choice of dwelling, whether car parking problems had been experienced in the last 12 months, and the extent to which residents agree that enough visitor and resident car parking is provided at their apartment building.

The survey was conducted from 2017 to 2019. A total of 10,560 households were invited to participate, with 1316 valid survey responses received across the three cities, corresponding to a response rate of 13.2% after accounting for a 5% rental vacancy rate. This response rate is within the range of response rates of 11–20% achieved in similar surveys (De Gruyter et al. 2016; Sinclair et al. 2012). A similar number of survey responses were received in Perth (n = 577) and Melbourne (n = 448), with fewer received in Sydney (n = 291).

In addition, various built environment and transport-related characteristics were created in GIS for each apartment building location, including dwelling density, street connectivity, social infrastructure mix, effective transit service headway, distance to public transport stops/stations, presence of car sharing, and travel time to the CBD by car and public transport. These variables were chosen based on the literature review reported earlier and their established relationships with travel behaviour more generally (Aston et al. 2021; De Gruyter et al. 2020; Ewing and Cervero 2010; Guo 2013; Holmgren 2020; Jain et al. 2022; Kitamura 1989; Li et al. 2010; Potoglou and Kanaroglou 2008; Weinberger et al. 2009; Zegras 2010; Zhou et al. 2020).

All variables included in the analysis are listed in Table 3, including their source, units, sample size range, mean and median values. The dependent variables included in the analysis were zero-car household (1 = no, 2 = yes) and household car ownership (0 = 0 cars, through to 4 = 4+ cars). A total of 25 independent variables were considered, categorised into household characteristics (total of 6 variables), attitudes and perceptions (5 variables), built environment factors (4 variables), and transport-related characteristics (10 variables).

Sample characteristics and comparison to population

A comparison of sample characteristics against the apartment household population (based on the Australian Census) across each city is provided in Table 4. Here, the apartment household population was limited to occupied apartment households in buildings with 3+ storeys to be consistent with the survey sample. While the sample was also limited to apartments built between 2006 and 2016, building age was not available for the apartment household population (from the Australian Census), so the population also includes apartment households in buildings constructed earlier than 2006. Therefore, differences between the sample and population are to be expected.

The comparison in Table 4 shows that a much higher proportion of apartment households were surveyed in Perth (43.8%) compared to its population (5.6%), while a much lower proportion were surveyed in Sydney (22.1% vs. 67.0%). A relatively similar proportion were surveyed in Melbourne (34.0%) compared to the population (27.4%). Table 4 also shows that the resident sample had a higher proportion of apartment owners compared to the population (48.8% vs. 34.4% overall), particularly in Perth (56.0% vs. 33.3%). In addition, the resident sample had a moderately higher proportion of 1-bedroom apartments (35.3% vs. 25.0% overall) and a lower proportion of 3+ bedroom apartments (7.6% vs. 13.6%), translating to smaller household sizes (88.2% had 2 people or less compared to 74.5% from the population). The proportion of households with 1 car was slightly higher among the resident sample (64.8% vs. 52.9%) compared to those with zero cars (14.1% vs. 26.9%). These differences therefore need to be considered when interpreting the findings from the analysis.

Data analysis

A comparison of household car ownership levels against off-street car parking supply was undertaken first to identify any patterns between car ownership and parking provision, given the potential for endogeneity between these variables. This was followed by regression modelling to determine which independent variables were significantly correlated with zero-car households and household car ownership levels. Here, a binary logistic regression model (binary logit model) was developed for each city and in total for zero-car

Table 3 Variables included in the analysis

Variables	Source	Units/coding	n	Range	Mean	Median
Dependent variables						
Zero-car household	Resident survey	1 = No, 2 = Yes	1259	1.00–2.00	1.14	1.00
Household car ownership	Resident survey	0 = 0 cars, 1 = 1 car, 2 = 2 cars, 3 = 3 cars, 4 = 4+ cars	1259	0.00–4.00	1.10	1.00
Independent variables						
Household characteristics						
Number of allocated off-street car parking spaces	Resident survey	Number of spaces	1293	0.00–3.00	1.17	1.00
Housing tenure	Resident survey	1 = Own, 2 = Rent	1312	1.00–2.00	1.51	2.00
Number of bedrooms in apartment	Resident survey	1 = studio or 1 bedroom, 2 = 2 bedrooms, 3 = 3+ bedrooms	981	1.00–3.00	1.71	2.00
Household size	Resident survey	Number of people	1265	1.00–6.00	1.77	2.00
Children in household	Resident survey	1 = No, 2 = Yes	1267	1.00–2.00	1.11	1.00
Household income	Resident survey	1 = under \$30,000, 2 = \$30,001–\$60,000, 3 = \$60,001–\$100,000, 4 = \$100,001–\$150,000, 5 = over \$150,000	1205	1.00–5.00	3.40	3.00
Attitudes and perceptions						
Importance of car parking in choice of dwelling	Resident survey	1 = Not at all important/unimportant, 2 = Neither unimportant nor important, 3 = Important/very important	1299	1.00–3.00	2.68	3.00
Parking problems with residents in last 12 months	Resident survey	1 = No, 2 = Yes	1286	1.00–2.00	1.22	1.00
Enough visitor car parking at my building	Resident survey	1 = Strongly disagree/disagree, 2 = Neither agree/disagree, 3 = Agree/strongly agree	1284	1.00–3.00	1.92	2.00
Enough resident car parking at my building	Resident survey	1 = Strongly disagree/disagree, 2 = Neither agree/disagree, 3 = Agree/strongly agree	1285	1.00–3.00	2.30	3.00
Able to store bicycle/s in convenient storage area	Resident survey	1 = Strongly disagree/disagree, 2 = Neither agree/disagree, 3 = Agree/strongly agree	1016	1.00–3.00	2.65	3.00
Built environment factors						
City	Resident survey	1 = Perth, 2 = Melbourne, 3 = Sydney	1316	1.00–3.00	1.78	2.00
Local dwelling density within 1600 m	OSM, ABS (2016)	Dwellings/hectare	1314	7.90–65.75	23.22	21.13

Table 3 (continued)

Variables	Source	Units/coding	n	Range	Mean	Median
Local street connectivity within 1600 m	OSM	3+ way intersections/sq.km	1314	63.48–226.27	123.96	131.41
Average social infrastructure mix score[a]	OSM, Victorian Government (2016)	Score out of 16	1314	2.01–14.19	9.77	10.61
Transport-related characteristics						
Effective weekday transit service headway (7am-9am) within 800 m	GTFS	Minutes	1297	0.04–7.50	0.76	0.42
Effective weekday transit service headway (7am-7 pm) within 800 m	GTFS	Minutes	1301	0.00–7.50	0.90	0.48
Distance to closest bus stop < 400 m	GIS, GTFS	1 = No, 2 = Yes	1286	1.00–2.00	1.87	2.00
Distance to closest bus stop with high frequency service[b] < 400 m	GIS, GTFS	1 = No, 2 = Yes	1254	1.00–2.00	1.78	2.00
Distance to closest train station < 800 m	GIS, GTFS	1 = No, 2 = Yes	1316	1.00–2.00	1.40	1.00
Distance to closest tram stop < 800 m	GIS, GTFS	1 = No, 2 = Yes	1316	1.00–2.00	1.29	1.00
Car sharing service < 800 m	Car sharing websites	1 = No, 2 = Yes	1314	1.00–2.00	1.47	1.00
Travel time to CBD by car[c]	Google Maps	Minutes	1314	3.00–105.00	22.21	18.00
Travel time to CBD by public transport[c]	Google Maps	Minutes	1314	6.00–178.00	29.85	25.00
Ratio of travel time to CBD by car to public transport[c]	Google Maps	–	1314	0.25–1.77	0.71	0.73

[a]Score reflecting local access to 16 different types of social infrastructure destinations (Davern et al. 2017)

[b]Defined as a bus service operating at least every 30 min between 7am to 7 pm on weekdays

[c]Measured using Google Maps in October 2019 based on departure times ranging from 7:45am to 8:30am

OSM Open Street Map, *GTFS* General Transit Feed Specification, *GIS* Geographic Information System

Table 4 Sample characteristics and comparison to population

Variable	Perth		Melbourne		Sydney		Total	
	Sample	Population	Sample	Population	Sample	Population	Sample	Population
No. apartment households	577	33,293	448	161,982	291	396,823	1316	592,098
% apartment households	43.8%	5.6%	34.0%	27.4%	22.1%	67.0%	100.0%	100.0%
Housing tenure								
Own	56.0%	33.3%	37.5%	28.4%	51.9%	36.9%	48.8%	34.4%
Rent	44.0%	66.7%	62.5%	71.6%	48.1%	63.1%	51.2%	65.6%
Apartment size								
0 bedrooms	0.4%	1.2%	1.6%	2.5%	1.4%	2.2%	1.2%	2.2%
1 bedroom	27.5%	28.6%	41.8%	34.2%	32.1%	21.1%	35.3%	25.0%
2 bedrooms	64.5%	54.3%	53.3%	53.6%	52.3%	61.7%	55.9%	59.1%
3+ bedrooms	7.6%	15.9%	3.4%	9.8%	14.3%	15.0%	7.6%	13.6%
Household size								
1 person	41.8%	47.1%	43.8%	43.3%	24.1%	32.8%	38.6%	36.4%
2 people	47.4%	39.2%	47.0%	40.9%	57.9%	37.0%	49.6%	38.1%
3 people	8.3%	9.4%	6.7%	10.6%	11.9%	16.8%	8.5%	14.8%
4+ people	2.5%	4.4%	2.5%	5.2%	6.1%	13.4%	3.3%	10.7%
Household car ownership								
0 cars	4.5%	17.3%	22.0%	35.4%	20.7%	24.3%	14.1%	26.9%
1 car	67.9%	58.7%	63.7%	49.4%	60.5%	53.8%	64.8%	52.9%
2 cars	24.7%	20.6%	12.5%	13.2%	17.4%	18.8%	18.9%	17.4%
3+ cars	2.9%	3.5%	1.9%	1.9%	1.4%	3.0%	2.2%	2.8%

Population source is the Australian Census (ABS 2016), with the comparison limited to occupied apartment households in buildings with 3+ storeys to be consistent with the survey sample

households (zero-car vs. having at least one car). Next, a multinominal logistic regression model (multinomial logit model) was developed for each city and in total for household car ownership levels (1 car and 2+ cars[1] vs. 0 cars). Ordered logistic regression (ordered logit model) was also tested given the ordered nature of car ownership levels; however, the parallel line assumption was rejected by the Brant test, leading to the adoption of more generic multinomial logistic regression.

Potential multicollinearity was checked using the Variance Inflation Factor (VIF), whereby a VIF value of less than 4 was conservatively chosen as not presenting any significant concerns (O'Brien 2007). The final models were found to not exhibit any significant multicollinearity (VIF values < 4). The VIF analysis was performed using R. Model fit for logistic regression was assessed using the McFadden's adjusted R-squared.

Potential endogeneity between car ownership levels and off-street car parking supply was considered by developing a joint multinominal logistic regression model of car ownership and parking supply. Here, rather than parking supply being included as an independent

[1] The number of households in the sample with 3 cars (n = 24 or 1.9%) or 4+ cars (n = 4 or 0.9%) was relatively small so a category of 2+ cars was adopted for the analysis.

variable and therefore assumed to be exogenous, as with the previous models, it was entered as a dependent variable in combination with car ownership, so that it could be treated as endogenous. Each combination of car ownership (0, 1, 2+ cars) and parking supply (0, 1, 2+ spaces) was modelled, with 0 cars and 0 parking spaces acting as the reference category. No households in the sample had 2+ cars and 0 spaces, so a total of seven possible combinations (e.g. categories) were modelled: (1) 0 cars and 1 space, (2) 0 cars and 2+ spaces, (3) 1 car and 0 spaces, (4) 1 car and 1 space, (5) 1 car and 2+ spaces, (6) 2+ cars and 1 space, and (7) 2+ cars and 2+ spaces. The results of the joint multinominal logistic regression are provided in the Appendix. These results were found to be largely consistent with the previous models where parking supply was included as an independent variable (and therefore treated exogenously).[2] Therefore, when parking supply was explicitly treated as an endogenous variable, the same variables associated with car ownership were found to remain significant, albeit to varying degrees, suggesting that endogeneity between car ownership and parking supply is not a key concern. The findings also echo those of other studies (Manville 2017; McCahill et al. 2016; Millard-Ball et al. 2022) that show a strong relationship between car ownership and off-street car parking provision, even after accounting for other effects such as residential self-selection.

In addition to the above, omitted variables can be another source of bias. To account for this potential unobserved heterogeneity, the logistic regression models with random parameters were estimated. The regression analysis was performed using NLOGIT 6.

Results

The results of the analysis are presented in three parts. First, a descriptive analysis of household car ownership and off-street car parking supply among the resident sample is provided. This is followed by the results of the binary logistic regression models to help understand factors that are associated with zero-car households. Results of the multinominal logistic regression models are then provided to identify factors associated with car-owning households.

Household car ownership and off-street car parking supply

Table 5 provides a classification of household car ownership vs. off-street car parking supply among the resident sample, by city and in total. This shows that higher rates of household car ownership tend to be associated with greater levels of car parking supply. On average, across all cities, household car ownership increases from 0.27 cars per household for those with zero car parking to 1.51 cars per households for those with 2+ car parking spaces. A similar pattern is found in each city, noting that Perth has no households in the sample with zero car parking. The findings suggest that off-street car parking supply is likely to be associated with household car ownership. However, this association is best assessed through regression modelling, as reported later in the paper.

[2] It is also noted that the coefficients for some variables (e.g. distance to closest bus stop < 400 m, ratio of travel time to CBD by car to public transport) may initially appear counterintuitive for the zero car alternatives, but need to be interpreted relative to the reference category of 0 cars and 0 parking spaces.

Table 5 Household car ownership vs. off-street car parking supply among the resident sample

Off-street car parking supply	Household car ownership								
	0 cars		1 car		2+ cars		Total		Average cars/household
	n	%	n	%	n	%	n	%	
Perth									
0 spaces	0	0.0	0	0.0	0	0.0	0	0.0	–
1 space	22	88.0	279	74.6	65	42.8	366	66.4	1.14
2+ spaces	3	12.0	95	25.4	87	57.2	185	33.6	1.52
Total	25	100.0	374	100.0	152	100.0	551	100.0	1.27
Melbourne									
0 spaces	32	36.8	13	4.8	0	0.0	45	10.8	0.29
1 space	51	58.6	240	89.2	45	72.6	336	80.4	1.00
2+ spaces	4	4.6	16	5.9	17	27.4	37	8.9	1.43
Total	87	100.0	269	100.0	62	100.0	418	100.0	0.96
Sydney									
0 spaces	26	47.3	8	4.8	0	0.0	34	12.4	0.24
1 space	26	47.3	134	80.2	25	48.1	185	67.5	1.00
2+ spaces	3	5.5	25	15.0	27	51.9	55	20.1	1.49
Total	55	100.0	167	100.0	52	100.0	274	100.0	1.00
Total									
0 spaces	58	34.7	21	2.6	0	0.0	79	6.4	0.27
1 space	99	59.3	653	80.6	135	50.8	887	71.4	1.06
2+ spaces	10	6.0	136	16.8	131	49.2	277	22.3	1.51
Total	167	100.0	810	100.0	266	100.0	1243	100.0	1.11

Table 5 also shows that Perth has the highest average rate of household car ownership at 1.27 cars per household, compared with 0.96 cars per household in Melbourne and 1.00 cars per household in Sydney. This pattern is broadly consistent with the average household car ownership rates reported for all apartment households in each city in the Section "Research context", noting that the resident sample is based on apartment dwellings built between 2006 and 2016 only.

In addition, Table 5 shows that across all cities, the highest number of observations are for households with one car and one car parking space (total of 653 out of 1,243 households). However, there are also households in the sample who have more car parking spaces available than the number of cars owned (245 households), indicating an oversupply of car parking, particularly among zero-car households (accounting for 109 of the 245 households). Conversely, there are households who have less car parking spaces available than the number of cars owned (156 households), indicating an undersupply of car parking, particularly among 2+car households (135 of the 156 households). While the survey did not ask respondents about their parking locations, particularly for those with an undersupply of off-street parking, previous research has shown that apartment residents in Australia have been reported to also use on-street parking where it is available, albeit at a lower rate than those in detached housing (Taylor 2020).

Table 6 Results of the random parameter binary logistic regression model for zero-car households (all cities)

Variables	Coefficient	Std. error	OR
Intercept	−2.464***	0.587	
Housing tenure (renting vs. own)	0.693***	0.180	2.000
Number of allocated off-street car parking spaces	−1.738***	0.201	0.176
standard deviation of random parameters	1.427***	0.137	
Household size	−0.610***	0.135	0.544
Household income (reference = $60,000 or below)			
$60,001–$100,000	−0.567**	0.219	0.568
$100,001–$150,000	−0.951***	0.246	0.386
Over $150,000	−0.666**	0.223	0.514
Local dwelling density within 1600 m	0.022*	0.010	1.023
Car sharing service < 800 m (yes vs. no)	0.827***	0.244	2.287
Ratio of travel time to CBD by car to public transport	1.032**	0.340	2.807
Log likelihood	−339.436		
Log likelihood (intercept only)	−466.610		
Akaike's Information Criteria	700.9		
McFadden Pseudo Adjusted R-squared	0.249		
Number of observations	1181		

Reference having at least one car, *Std.* standard, *OR* adjusted odds ratio, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

Factors associated with zero-car households

Table 6 presents the results of the random parameter binary logistic regression model for zero cars in all cities. This model was statistically significant at $p < 0.001$ and included a random parameter (normally distributed) for the number of allocated off-street car parking spaces ($p < 0.001$). This suggests the effect of off-street car parking varied across the samples with an overall odds ratio of 0.176, indicating that an additional parking space would reduce the likelihood of having zero cars by a factor of 0.176 on average. Results also show that renting households were twice as likely to have zero cars, while higher income or larger households were less likely to have zero cars. Additionally, households were more likely to have zero cars if located in areas with higher dwelling densities, where travel to the CBD is quicker by car than public transport, or if located within 800 m of car sharing.

Table 7 shows the results of the random parameter binary logistic regression models for each city. All models were significant at $p < 0.001$ and included one random parameter. In Perth and Sydney, households with more off-street car parking spaces, on average, were less likely to have zero cars although the effect varied across the samples. However, in Melbourne, the association between off-street car parking supply and owning zero cars was not significant. In all cities, those who felt that car parking was important or very important in the choice of their dwelling were less likely to live in a zero-car household. In Melbourne and Sydney, households with higher incomes were less likely to have zero cars although this effect in Sydney was weaker ($p < 0.1$). In Perth, households located within 800 m of car sharing were more likely to have zero cars. In

Table 7 Results of the random parameter binary logistic regression models for zero-car households by city

Variables	Perth			Melbourne			Sydney		
	Coefficient	Std. error	OR	Coefficient	Std. error	OR	Coefficient	Std. error	OR
Intercept	−0.990	0.792		2.285*	1.157		2.954***	0.786	
Housing tenure (renting vs. own)				0.902*	0.384	2.466			
Number of allocated off-street car parking spaces	−0.998*	0.492	0.369				−1.192**	0.434	0.303
Standard deviation of random parameters	0.439*	0.187					1.292***	0.297	
Importance of car parking in choice of dwelling (reference = neither unimportant nor important)									
Not at all important/unimportant				1.495***	0.394	4.458	2.699***	0.686	14.872
Important/very important	−1.265***	0.305	0.282	−2.307***	0.374	0.100	−1.550**	0.520	0.212
Household size				−0.982***	0.253	0.375	−1.194***	0.295	0.303
Household income (reference = $60,000 or below)									
$60,001–$100,000				−0.916*	0.436	0.400			
$100,001–$150,000				−1.047**	0.373	0.351	−0.923+	0.514	0.397
Over $150,000				−1.353**	0.495	0.258	−1.130+	0.587	0.323
Car sharing service < 800 m (yes vs. no)	0.718*	0.350	2.051						
Travel time to CBD by public transport				−0.068**	0.021	0.934			
Standard deviation of random parameters				0.049***	0.009				
Log likelihood	−87.667			−108.549			−64.217		
Log likelihood (intercept only)	−101.512			−213.695			−131.479		
Akaike's Information Criteria	185.3			237.1			144.4		
McFadden Pseudo Adjusted R-squared	0.087			0.445			0.451		
Number of observations	546			412			260		

Reference = having at least one car, Std. = standard, OR = adjusted odds ratio, + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

Melbourne, while the effect of travel time to the CBD by public transport was random, on average, households located in areas with higher travel times to the CBD by public transport were less likely to have zero cars. Overall, the model results for each city generally aligned well with those of the model results for all cities.

Factors associated with car-owning households

The results of the random parameter multinomial logistic regression model for household car ownership levels in all cities are presented in Table 8. The model was significant at $p < 0.001$ and included a random parameter (normally distributed) for the number of allocated off-street car parking spaces for households with 2+ cars. Results show that an additional car parking space, on average, would increase the odds of having 2+ cars, compared with zero cars, by 10 times (OR = 10.072). Renting households were less likely to have cars. Those who felt that car parking was important or very important in the choice of their dwelling were more likely to live in a one-car household (OR = 7.747) and much more likely to live in a household with 2+ cars (OR = 12.380). In addition, those who disagreed or strongly disagreed that there was enough resident car parking at their building were more likely to live in a household with 2+ cars (OR = 7.804). As expected, larger and higher income households were more likely to have more cars. Households located within 400 m of a bus stop, in areas with higher dwelling densities, or with greater ratios of travel times to the CBD by car to public transport were less likely to have one car and much less likely to have 2+ cars.

Table 9 shows the results of the multinomial logistic regression models for each city. All models were significant at $p < 0.001$ whereby no random parameters were found (the standard deviation was not significant). As with the model for all cities, the effects of off-street car parking provision, perceived importance of car parking in choice of dwelling, perceived adequacy of residential car parking, household size, income, and local dwelling densities were significant, especially influencing the odds of having 2+ cars over zero cars. In Melbourne, it was found that households located in areas with longer travel times to the CBD by public transport were more likely to have one car and much more likely to have 2+ cars.

Discussion and conclusions

Drawing on a survey of apartment residents in three Australian cities, this research has provided insight into the determinants of zero-car and car-owning apartment households. Results showed that the determinants of zero-car households were mostly the same as those of car-owning households yet tended to act in the opposite direction of one another. For example, off-street car parking supply was found to be *negatively* associated with zero-car households (OR = 0.176) but *positively* associated with car-owning households (OR = 1.248 for 1 car, and OR = 10.072 for 2+ cars). In other words, what was found to be positively correlated with zero-car households tended to be negatively correlated with car-owning households, and vice versa.

There were also differences observed in the magnitude of coefficients (and odds ratios) of each determinant *between* the three cities. For example, the negative association of off-street car parking supply with zero-car households was slightly larger in Sydney

Table 8 Results of the random parameter multinomial logistic regression model for car ownership (all cities)

Variables	1 car			2+ cars		
	Coefficient	Std. error	OR	Coefficient	Std. error	OR
Intercept	3.931**	1.217		−3.145+	1.894	
Housing tenure (renting vs. own)	−0.620*	0.261	0.538	−0.412	0.350	0.663
Number of allocated off-street car parking spaces	0.222	0.313	1.248	2.310***	0.487	10.072
Standard deviation of random parameters				1.716*	0.836	
Importance of car parking in choice of dwelling (reference = neither unimportant nor important)						
Not at all important/unimportant	−1.611***	0.345	0.200	−4.272**	1.319	0.014
Important/very important	2.047***	0.304	7.747	2.516***	0.477	12.380
Enough resident car parking at my building						
Strongly disagree/disagree	0.009	0.303	1.010	2.055***	0.488	7.804
Household size	0.747***	0.202	2.111	2.118***	0.338	8.313
Household income (reference = $60,000 or below)						
$60,001–$100,000	0.601+	0.315	1.825	0.720	0.457	2.055
$100,001–$150,000	1.293***	0.370	3.645	1.811***	0.507	6.115
Over $150,000	0.880*	0.363	2.410	1.477**	0.489	4.379
Local dwelling density within 1600 m	−0.044***	0.012	0.957	−0.060***	0.017	0.942
Distance to closest bus stop < 400 m (yes vs. no)	−0.837+	0.429	0.433	−1.195*	0.530	0.303
Ratio of travel time to CBD by car to public transport	−1.889***	0.466	0.151	−2.453***	0.636	0.086
Log likelihood	−645.927					
Log likelihood (intercept only)	−993.572					
Akaike's Information Criteria	1345.9					
McFadden Pseudo Adjusted R-squared	0.323					
Number of observations	1139					

Reference no cars, *Std.* standard, *OR* adjusted odds ratio, + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

Table 9 Results of the multinomial logistic regression models for car ownership by city

Variables	Perth		Melbourne		Sydney	
	1 car	2+ cars	1 car	2+ cars	1 car	2+ cars
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Intercept	2.086+	−3.158*	−3.735**	−12.232***	−3.076**	−9.044***
Number of allocated off-street car parking spaces	0.683	1.722**	−0.122	1.777**	0.782	2.562***
Importance of car parking in choice of dwelling (reference = neither unimportant nor important)						
Not at all important/unimportant	−1.113	−5.659***	−1.080*		−3.163***	−1.467
Important/very important	1.282	1.783**	2.949***	3.248***	1.849**	3.396***
Enough resident car parking at my building						
Strongly disagree/disagree			−0.518	1.218*		
Household size	0.106	1.874***	0.871**	2.121***	1.347***	1.715***
Household income (reference = $60,000 or below)						
$60,001–$100,000			0.949+	1.338+		
$100,001–$150,000			0.971+	2.147**	1.080+	1.635*
Over $150,000			1.327*	2.222**	1.162+	1.217+
Local dwelling density within 1600 m	−0.062	−0.112*				
Travel time to CBD by public transport			0.063**	0.092***		
Log likelihood	−314.496		−217.305		−156.991	
Log likelihood (intercept only)	−412.957		−348.491		−242.367	
Akaike's Information Criteria	653		472.6		342	
McFadden Pseudo Adjusted R-squared	0.209		0.322		0.294	
Number of observations	545		392		260	

Reference no cars, *Std.* standard, *OR* adjusted odds ratio, + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

(OR = 0.303) than in Perth (OR = 0.369), yet not significant in Melbourne. This implies that the provision of off-street car parking is likely to have the greatest effect in Sydney on reducing the chance of an apartment household having zero cars, compared to Perth, with Melbourne not expected to be significantly affected. Similarly, the positive association of off-street car parking supply with 2+ car households was much stronger in Sydney (OR = 12.962) compared to Melbourne (OR = 5.912) and Perth (OR = 5.596). These results imply that car ownership among apartment households in Sydney is likely to be more sensitive to off-street car parking provision than it is in Melbourne or Perth, suggesting that changes to parking provision, including off-street residential car parking requirements, are likely to have the greatest effect on car ownership in Sydney. While the reasons for these differences are not entirely clear, they may be partly attributed to higher apartment household sizes in Sydney (2.05 people/household compared to 1.72 in Melbourne and 1.63 in Perth), resulting in higher demand for car ownership where off-street car parking is available.

Looking at other significant determinants, and consistent with previous research (Blumenberg et al. 2020; Jain et al. 2022; Soltani 2017), it was found that zero-car households were positively associated with renting, dwelling density, and access to car sharing. Zero-car households were also more likely to be located where travel times to the CBD were more competitive (shorter) by public transport than car. The findings for car-owning households were generally the opposite, where a negative association was found with these variables (except car sharing which was not significant), also consistent with previous research (Clark 2009; Giuliano and Dargay 2006; Li et al. 2010; Shao et al. 2022; Zegras 2010). Car-owning households, particularly those with 2+ cars, were also found to be positively associated with household size and income, again consistent with previous research (Dissanayake and Morikawa 2002; Oakil et al. 2016; Potoglou and Kanaroglou 2008).

In addition, two attitude/perception-based variables were found to be significant in this study that were not included in previous research. The first variable, car parking seen as important in the choice of dwelling, was negatively associated with zero-car households in each city, but positively associated with car-owning households, particularly those with 2+ cars (OR = 12.380). The second variable, whether enough resident parking is provided, was negatively associated with car-owning households, again particularly those with 2+ cars (OR = 7.804). Together these factors illustrate the different ways that car ownership impacts the experience of apartment living. Zero-car households tended to place little value on the provision of car parking when selecting an apartment, yet ~ 65% of zero-car households in the sample had allocated car parking that they did not need. On the other hand, car-owning households tended to prioritise car parking provision yet still perceived it as inadequate. These findings reiterate the need to de-couple car parking from the purchase price or rental cost of apartments (Gabbe and Pierce 2017; Manville 2017).

The potential for endogeneity between car ownership and off-street car parking supply was also considered in this research through the development of a joint multinominal logistic regression model and the use of random parameter modelling. A strong relationship between car ownership and parking supply was still found, even after accounting for endogeneity, consistent with previous car ownership studies (Manville 2017; McCahill et al. 2016; Millard-Ball et al. 2022) that have controlled for residential self-selection effects.

The findings from this study have important implications for policy and practice. First, the positive association between off-street car parking supply and household car ownership levels suggest that reducing residential car parking requirements can play a significant role in supporting lower car ownership levels among apartment households, including zero car ownership. However, these requirements should of course be tailored to the local context given differences that can be observed between and within cities (Barter 2011; De Gruyter et al. 2021). Second, significant determinants of zero-car households, such as higher dwelling densities, access to car sharing, and public transport services that are time-competitive to the car, should be planned for where possible in cities to support reduced (and potentially zero) car ownership. The findings validate the application (and appropriateness) of car parking policies and overlays that stipulate fewer off-street car parking spaces in apartment buildings in close proximity to public transport (De Gruyter et al. 2021). Third, the significance of attitudes and perceptions, particularly as they relate to off-street car parking facilities, is an important consideration in setting the conditions needed to facilitate apartment households to be car-free.

This study has contributed to the literature through providing an understanding of the determinants of zero-car and car-owning apartment households, while accounting for potential endogeneity and unobserved heterogeneity. In doing so, it has highlighted the significant role of off-street car parking supply, alongside a range of socio-demographics, attitudes/perceptions, built environment and transport characteristics. However, this study is also subject to some limitations. First, the dataset is cross-sectional in nature and so cannot be used to explore changes in car ownership levels over time, nor can it be used to infer causation. Second, the study was limited to three Australian cities so it is not clear how the results may vary elsewhere, including in other countries. Third, the study focused on contemporary apartments only, built between 2006 and 2016. While there were differences between the study sample and the broader population of apartment households, the findings are highly relevant to the apartment 'product' being developed across much of Australia. Future research that seeks to address these limitations would help to further improve our understanding of the determinants of zero-car and car-owning apartment households.

Appendix

See Table 10.

Table 10 Results of the joint multinominal logistic regression model for car ownership and off-street car parking supply (all cities)

Variables	0 car, 1 space		0 car, 2+ spaces		1 car, 0 space		1 car, 1 space		1 car, 2+ spaces		2+ cars, 1 space		2+ cars, 2+ spaces	
	Coef	SE	Coef	SE	Coef	SE	Coef	SE	Coef	SE	Coef	SE	Coef	SE
Intercept	10.320***	2.497	6.206*	2.421	−3.998*	1.778	13.431***	2.466	14.714***	2.562	9.697***	2.578	11.233***	2.621
Housing tenure (renting vs. Own)	−0.946+	0.538	−1.994*	0.877	0.390	0.767	−1.706**	0.533	−2.804***	0.575	−1.542**	0.567	−2.813***	0.580
Importance of car parking in choice of dwelling														
Important/very important	2.041***	0.572	2.775**	0.909	1.734*	0.694	4.875***	0.571	5.300***	0.653	5.179***	0.643	6.752***	0.768
Enough resident car parking at my building														
Strongly disagree/disagree	−1.936***	0.457	−2.398*	1.162	1.793*	0.726	−2.177***	0.460	−2.880***	0.541	−0.251	0.498	−2.287***	0.526
Household size	0.165	0.349	0.591	0.676	0.689	0.433	1.096**	0.341	1.472***	0.370	2.189***	0.364	2.350***	0.366
Household income (ref = $60,000 or below)														
$60,001–$100,000	−0.018	0.527	0.869	1.112	−0.928	0.820	1.145*	0.525	1.376*	0.600	1.152+	0.601	1.674**	0.640
$100,001–$150,000	1.116+	0.618			0.813	0.793	2.432***	0.620	2.956***	0.685	2.727***	0.687	3.499***	0.715
Over $150,000	0.734	0.610	2.442*	1.070	0.688	0.835	1.794**	0.615	2.404***	0.683	2.173**	0.678	3.096***	0.701
Local dwelling density within 1600 m	−0.089***	0.019	−0.097*	0.041	−0.017	0.020	−0.137***	0.020	−0.195***	0.024	−0.159***	0.023	−0.186***	0.024
Distance to closest bus stop < 400 m (yes vs. no)	−1.788*	0.884					−2.594**	0.875	−2.697**	0.916	−2.990**	0.915	−2.692**	0.925
Ratio of travel time to CBD by car to public transport	−2.487**	0.847	−4.532*	1.763			−4.152***	0.822	−6.078***	0.932	−4.525***	0.900	−6.635***	0.945
Log likelihood	−1248.11													
Log likelihood (intercept only)	−1740.49													
Akaike's Information Criteria	2642.2													
McFadden Pseudo Adjusted R-squared	0.241													
Number of observations	1153													

Reference = no cars and no parking spaces; the category for 2+ cars and no parking spaces had no data (see Table 5) and thus was excluded

Coef. coefficient, *SE* standard error, + = $p < 0.1$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$

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Declarations

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