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Abstract

Parking is often overlooked by urban researchers even though parking consumes large proportions of a city's physical footprint and imposes a significant impediment to more sustainable travel. Underpinning this lack of attention is suitable data and methods capable of capturing the complex dynamics of parking. Here we redress this gap by drawing on an emergent source of parking data and deploying empirical techniques to unpack this complexity. Data from 3542 on-street parking sensors observed over a 9-year period are used to delineate the first typology of parking routines before using a fixed-effects logistic regression model to explain how nearby land-use types and land-use mix shapes tempo and timing of parking utilisation. The benefit of our approach lies in its capacity to discriminate broad types of temporal rhythms associated with parking dynamics at particular places, how these change over time and how these rhythms are associated with different types and mixes of nearby land use. This knowledge is important to inform policies seeking to optimise the use of on-street parking and invoke more sustainable patterns of mobility.

Keywords

On-street parking, nearby land use, land-use change

Introduction

Estimates for American and Australian cities suggest that laying land dedicated to parking flat would create a surface covering at least 10% of urban areas (Chester et al., 2015; Kimpton et al.,

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2021; Scharnhorst, 2018). This is despite those private cars are estimated to be in motion for just five percent of the time (Button, 2006), and that at least three parking spaces exist for each car registered (Jakle and Sculle, 2004). As such, the merit of parking space is frequently a subject of public debate and within transport research given that it is the flows of people and goods that make cities productive rather than stationary private cars. Shoup's *High Cost of Free Parking* (2005) demonstrates that the entire public is paying for parking irrespective of whether individuals own a car given that land use and transport authorities embed the cost of public parking in land rates, and developers and landowners embed the cost of 'free' parking in goods and services. Public parking is a particularly contentious issue given that it is generally concentrated within high demand destinations and inner cities where land is most expensive, and on-street parking is located on public roads thus reducing road capacity and creating side-stream friction (Box, 2000; Cao et al., 2017; Edquist et al., 2012).

Overlooking parking is also overlooking the expanses of artificial surfaces that expand urban sprawl and contribute towards the urban heat island effect yet urban mobility research to date has sought to primarily focus on the brief daily peaks when cars are in motion – or at least locked within traffic congestion (Kimpton et al., 2021). As such, there is a shortage of research that focuses on the remainder of the time when private cars equate to a public burden and displace more productive land uses. Further, merchants consistently overestimate the proportion of their customers arriving by car and underestimate those arriving by walking, cycling or riding public transport (Yen et al., 2020). Of the various types of parking, on-street parking supply is especially overlooked in research with researchers instead drawing focus optimising vehicle assignment, pricing and timed restrictions (Najmi et al., 2021). This oversight is mirrored in policy for while the provision of off-street parking is typically governed by policy (e.g. parking minimums or parking maximums; Shoup, 1999), the provision of on-street parking is typically an ad hoc occurrence once kerb space becomes available, or as a band aid solution that temporarily appease voters frustrated by cruising for parking soon to discover that the parking is reducing road capacity and traffic speeds (Shoup, 2006). Further, while off-street parking policy may be calibrated to the associated land use (Shoup, 1999), on-street parking is a response to parking demand at a district level (Barter, 2015). Indeed, parking research and policy generally overlooks the land-use types and mix located within a walkable range and so an underlying assumption is that motorists have a single destination in mind and will locate parking onsite. As such, policy makers and practitioners have only a limited empirical evidence base when deciding where to provision on-street parking.

The growing number of parking studies is also increasingly exploring the temporal dimension(s) of parking utilisation through simulation and drawing on emergent source of parking data (i.e. electronic parking sensors and parking lot gates). This growing body of research explores the intensive margins of parking demand (Zakharenko, 2016), peak demand for paid parking (Yang and Qian, 2017), pricing equilibrium between paid off-street and on-street parking (Inci, 2015), optimal street segment on-street parking vacancy rates to minimise cruising (Arnott, 2014) but in general, these studies examine the temporal dimension(s) apart from associated land-use types and mix. Further, these studies examine the temporal dimension of parking using *linear* methodologies that require *segmenting* daily parking routines into arbitrary daily periods by introducing artificial break points such as midnight. Whilst this approach might present an empirical solution, it fails to capture when, motorists may park across this period and in doing so introduce empirical bias in the findings through creating floor and ceiling effects (Brunsdon, 2017). This empirical limitation has been addressed in a small number of applications in the social sciences through deploying circular statistics to better capture behavioural routines (Brunsdon, 2017; Corcoran et al., 2019; Kimpton et al., 2017). This approach is well suited to extend our current understandings of the temporality of on-street parking, and especially as temporality relates to nearby land use.

To this end, this study draws focus on the temporality and locality of on-street parking. More specifically, we employ circular statistics as part of an analytic strategy to develop the first typology of parking routines. Here we draw on an emergent source of big data, namely, data from 3542 on-street parking sensors observed over a 9-year period. Further, we employ a fixed-effects logistic regression model to determine the degree to which these types of parking routine are explained by change to nearby land-use types and land-use mix across the 9-year observation period. Through our novel analytic approach, we seek to ‘sense make’ (Klein and Moon, 2006) of a set of publicly available big data (i.e. 349,423,785 parking observations or 54 GB) and translate this large and complex resource into interpretable visual outputs that can contribute to policy.

On-street parking

On-street parking is often a contentious land use given that it is located on public roads that are generally built by state transport authorities for improving traffic flow but later repurposed as on-street parking by local land-use authorities to provide ‘spot accessibility’ to adjacent land use (Barter, 2015). By provisioning on-street parking, local land-use authorities effectively narrow roads and in so doing, reduce road capacity and slow traffic speeds (Box, 2004; Cao et al., 2017; Edquist et al., 2012). Likewise, on-street parking provision can limit space for streetscape improvements such as parklets and street trees, and for sustainable transport such as potential cycleways and footpath widening (Moran, 2021). Further, on-street parking increases the visual complexity on the road which can increase motorists’ reaction times and reduce pedestrian safety (Loukaitou-Sideris et al., 2007). Perhaps ironically, on-street parking often functions as a protective buffer between cars, pedestrians and cyclists and goes some way to explain why pedestrians feel safer alongside on-street parking (De Cerreño, 2004; Marshall et al., 2008). State transport authorities often respond to on-street parking in turn by further expanding road capacity to restore former traffic speeds and ensure that motorists have road space for manoeuvring around other motorists that are either cruising while locating parking or manoeuvring once they have located a parking bay (Calthrop and Proost, 2006; Glazer and Niskanen, 1992; Inci, 2015; Inci and Lindsey, 2015). As such, a positive feedback loop can emerge between road widening and parking provision as elected officials attempt to appease voters frustrated by traffic congestion (McCahill and Garrick, 2014; Shoup, 2005; Weinberger, 2012; Yousif and Purnawan, 2004). Likewise, *policy inequalities* can emerge through poor coordination between the state transport and local land-use authorities that result in rising congestion or expanses of underutilised parking that reduce the appeal of alternatives such as active and public transport.

Where exactly the public responsibility for the private convenience of driving should sit is the subject of debate. Henderson (2013) argues that a ‘conservative’ discourse often pervades urban mobility policy, which is frequently as individualistic responsibility where motorists purchase road space through payments including vehicle registration and fuel excise taxes, leading to opinions among motorists that roads are strictly the domain of their automobiles while untaxed transport modes are an encroachment on this purchased space. Meanwhile, Barter (2015) recognises that a diversity of ‘mindsets’ regarding urban mobility policy can be found among government department and elected officials. These mindsets can be arranged along three dimensions depending on whether parking is: (1) regarded a *market good* where the user pays or *infrastructure* that is essential for minimising public conflict; (2) to planned for each individual *site* or for the *district*; and (3) made *abundant* to minimise cruising times and maximise the appeal of a location relative to alternatives reachable by car or *restricted* to reduce the appeal of private transport relative to the active and public alternatives. Indeed, multiple studies suggest that the abundancy mindset is positively reinforced given that local governments that increase parking supply are in effect expanding visitor and worker catchment areas from adjacent local governments while state transport authorities are left to address the externalities such as heightening traffic congestion and demand for road capacity (McCahill and Garrick, 2014; Young and Miles, 2015). Likewise, there is positive reinforcement for businesses to relocate to where parking is abundant since this enlarges their customer catchment area (Marsden, 2006), whereas reductions in parking can send customers to competitors (Box, 2000; Meyer and McShane, 1983). For this reason, parking is often framed as the 'life blood' of businesses (Box, 2000) yet local land-use authorities are left in a double bind since they wish to attract and retain productive businesses, yet roads cannot simultaneously move and store cars (Montgomery, 2013). Kimpton et al. (2021) likewise explores this continuum of planning approaches ranging from 'predict and provide' planning approaches whereby parking is made abundant to accommodate motorists (e.g. parking minimums policies) and 'demand management' planning approaches whereby parking is restricted (e.g. parking maximums) and land use is mixed to minimise the requirement for private cars. 'Unbundled parking' is a further demand management approach that effectively removes off-street parking from policy altogether and instead, developers can pass on the savings of not providing parking to land buyers and land buyer can purchase parking according to their household or commercial requirement rather than being burdened by needing to purchase unrequired parking (Guo and Ren, 2013; Martens, 2005). Further, Kimpton et al. (2021) 'multimodalism' planning approaches (e.g. park '*n*' rides and kiss '*n*' rides) are midway along this continuum whereby parking is made abundant along rapid public transport corridors so that residents from car dependent suburbs have alternatives to driving into the inner city. While 'multimodalism' could be the more pragmatic approach, it is not without its shortcomings given that overflow from park '*n*' rides will often spread into nearby streets and along rapid transport corridors that lack park '*n*' rides resulting in long-stay on-street parking functioning as informal park '*n*' rides to the frustration of nearby residents and businesses.

Folk legalities

Notably, these resident and business frustrations are not always justified given that on-street parking is typically public space. Despite this fact, residents and traders frequently make false ownership claims (i.e. folk legalities) for on-street and public parking (Christiansen et al., 2017; Taylor, 2014). For instance, homeowners may threaten to vacate if 'their' on-street parking becomes time restricted or is removed (Jacks, 2018) and in Brisbane, Australia and despite months of public consultation, a single household delayed the completion of a cycleway and endangered cyclists for several months by ensuring their cars were continuously parked on-street to prevent the re-painting of the road surface (Elliot, 2016). It is notable that these cars were parked on-street legally and so the local government was powerless to intervene and yet culpable for an incomplete cycleway that endangers cyclists by forcing them to momentarily enter traffic to navigate around the cars parked on-street. Likewise, on-street parking often becomes de facto parking space for households that: (1) have repurposed the garage for storage or accommodation; (2) own more vehicles than off-street parking bays; or (3) have relocated to areas where off-street parking supply is restricted (e.g. multi-unit dwellings where parking maximums policies are in place to encourage public transport patronage; see Taylor (2014)). Drawing on a further example from Brisbane Australia, one household frustrated their neighbours and endangered motorists, cyclists and pedestrians for months by having six registered cars, a campervan, a caravan, two boats and a jet ski legally parked on-street and again this local government was powerless to intervene given that parking on-street was legal, and all the vehicles were registered with the state transport authority (Lim, 2014).

Restrictions on parking utilisation

Rather than remove the on-street parking altogether, councils will often introduce parking restrictions such as parking permits, timed restrictions and parking sensors to discourage misuse of on-street parking (Barter, 2015; Litman, 2006) although this can also be a controversial planning approach. For instance, paid parking and parking fines are often framed by the media as 'government revenue raising' even though the government in question could be attempting to increase parking turnover for nearby residents and merchants (Fuller, 2018; O'Sullivan and Gladstone, 2019) or the fact that the 'revenue raised' is unlikely to make up the shortfall lost purchasing space for public parking and especially within high demand areas and inner cities. Shoup's (2005) collaborations with San Francisco land-use authorities reveal that the public finds paid parking more palatable when the authorities signal to the public how this 'revenue raising' is spent uplifting the adjacent area, for example, pavement maintenance, plants, street furniture, lighting, cleaning, building renovations and further parking space. Likewise, parking permits are generally implemented at locations where residents lack off-street parking alternatives and Speck (2012) notes that this can be made more palatable by initially pricing parking permits below the true cost of public parking and gradually increase price once nearby residents and traders have come to appreciate having dedicated on-street parking. Notably, parking rates can also be calibrated to cheapen for longer stays to reduce traffic-delaying parking turnover (Glazer and Niskanen, 1992), cheapen away from high demand areas to disperse parking demand (Arnott & Rowse, 1999), or to dynamically adjust until a market equilibrium is reached, ensuring there are a few empty bays on each road segment to minimise cruising for parking (Pierce and Shoup, 2013). Notably, the hunt for cheaper or free parking also highlights how motorists often under-value their time when searching for parking and while walking from more distant parking bays (Glazer and Niskanen, 1992; Kobus et al., 2013). Lastly, the enforcement of paid on-street parking can be a heavy administrative burden for local authorities since motorists may choose to gamble the occasional fine unless there is near perfect enforcement (Inci, 2015). As such, the provision of on-street parking is challenging in ways that set it apart from the provision of off-street parking which has a stronger empirical base and governing policies although this evidence base weakens when nearby land use is considered.

Smarter cities, smarter parking

Cities have historically adapted gradually to new problems and technologies but with the rise of 'the Internet of Things' (i.e. embedded sensor networks) and digital control systems that respond to this Internet of Things, cities are becoming more dynamic but less predictable in potentially disruptive ways (Batty, 2020). These opportunities fall under the broad umbrella of 'smart cities'; however, the concept is still in its infancy and so the officials, practitioners and policy makers responsible for planning and shaping cities typically lack the requisite training to recognise or leverage the public value of these emerging data streams. As such, vast volumes of urban data are constantly discarded rather than archived or left forgotten on institutional hard drives. Indeed, live data streams from intersection counts, public transport smart cards, and parking sensor arrivals and departures have immense public value for examining and explaining actual urban mobility patterns in high spatial and temporal resolution. Further, these data provide opportunities to capture naturally occurring experiments such as how travellers along a public transport corridor respond to service disruptions or motorists respond to parking price changes. For example, the SFpark demand-responsive project in San Francisco monitors parking occupancy and demand (i.e. market rate upon arrival) in real time from administrative data streams, and then dynamically adjusts the cost for the remaining parking bays with the aim of maintaining an 80% occupancy equilibrium (Pierce and Shoup, 2013). Advantages of this approach include a new datastream that reveals the true market value of parking space in real time, minimisation of cruising for parking given that 20% of parking spaces on street segments remain vacant and that motorists are generally spending less on average for on-street parking. As more data streams become publicly available and are archived, it will become possible to develop more comprehensive and dynamic models of urban systems, make informed and incremental changes that improve rather than reduce urban quality of life, and to generate unimagined urban opportunities rather than merely reduce administrative overheads such as charging at the parking metre and capturing parking infringements as this relates to on-street parking. With this idea in mind, the current study overlays 9 years of accumulated parking sensor readings and nearby floorspace surveys for a novel examination of how on-street parking utilisation is linked with nearby land use.

Materials

Study area

The City of Melbourne local government area is the study area. This includes Melbourne's central business district which in 2016 – the most recent available Australian Census of Population and Housing – was home to 135,964 residents and the workplace for 436,752 workers (Australian Bureau of Statistics, 2021). Notably, this 45% increase on 2006 residents and a 47% increase on 2006 workers occurred while curb space has remained relatively static and so it is plausible that there is heightening demand for on-street parking (Australian Bureau of Statistics, 2021).

Parking transaction and sensor data

The City of Melbourne is a relatively unique among Australian local governments in that it archives on-street *parking transactions* data (Figure 1), which in turn is uploaded annually to an open data portal (City of Melbourne, 2022b). As such, these 349,423,785 recorded arrivals and departures collected at 3542 parking sensors from 2011 to 2019 affords the rare opportunity to examine how weekly routines of on-street parking utilisation change across 9 years both at a high temporal and spatial resolution (Figure S1 & S2 in the Supplementary Material).

Multistory land-use data

The City of Melbourne is also relatively unique among Australian local governments in that it conducts an annual Census of Land Use and Employment (CLUE) and uploads these data to an open data portal (City of Melbourne, 2022a). The 2011 through to 2019 CLUE data are available from

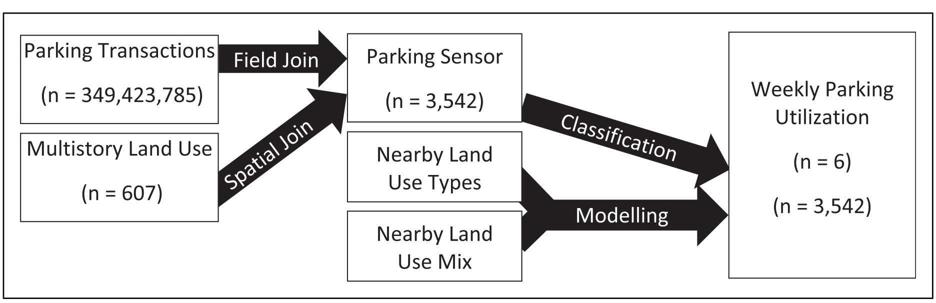

Figure 1. Methodological approach for determining whether nearby land-use types and mix influences weekly parking utilisation patterns.

this portal which covers 607 discrete City of Melbourne inner-city blocks and distinguishes 65 discrete land-use types when measuring both floorspace area and counts (e.g. dwellings, parking bays, restaurant seating or premises). As such, this *multistory land-use* data are suitable for overlaying with the parking utilisation data and provides a novel opportunity explain change to on-street parking utilisation according to nearby land-use types and mix across the 9-year period (2011–2019).

Methods

Spatial metrics

A 250-m buffer around each parking bay is used for operationalizing Dovey and Pafka's (2017) 'experiential mix' and all CLUE blocks are weighted according to the proportion of the block that intersects the 250-m buffer before floorspaces and counts are summed (Figure 1; Figure S3 in the Supplementary Material). As such, *multistory land-use* types are operationalised from theoretically relevant counts (i.e. commercial off-street parking bays, dining capacity, dwellings, retailers, services and residential parking bays), whereas land-use mix is operationalised from floorspace by type using the most common entropy index

$$entropy = 1 - \sum_{t=1}^{k} p_i^2$$

where k is the number of land-use types and p is the proportional area of each land-use type.

Classification

Weekly parking utilisation is classified using the Partitioning Around Medoids (PAM) cluster method that is the most common k-medoid cluster method. Notably, the k-medoid cluster method is distinct from the more common k-means cluster methods via the way in which it identifies the most representative value of a given cluster rather than the average for a given cluster thus this is a more robust method especially when observations align poorly with the clusters available (Kaufman and Rousseeuw, 1990). Further, we transform the counts using Isometric Log Transform Ratio so that all values range between 0 and 1 since we are comparing how parking utilisation varies throughout the week between parking bays rather than occurrence at a specific moment within this week (Figure S4 in the Supplementary Material). The medoids for the k number of clusters is visualised using polar plots to reveal the kernel-smoothed weekly parking utilisation pattern for parking sensors belonging to a given cluster, and an alluvial plot is used to visualise how the 3542 parking sensors transition between cluster memberships from 2011 through to 2019.

Modelling

A mixed-effects logistic regression model is used to explain weekly parking utilisation according to nearby land-use types and mix. Specifically, this model is used to estimate the likelihood of cluster membership (i.e. t) according to land-use type and mix, and the fixed-effects component ensures that the repeated measures (i.e. i) across the 9 years for a given parking bay (i.e. j) are not assumed statistically independent (Chamberlain, 1980). The formula (Vermunt, 2005) is

$$Pr\left(x_{ij} = t \middle| w_{ij}, z_{ij}\ , \beta_j\right) = \frac{exp\left(\eta_{ijt}\right)}{\sum_{t=1}^{T} exp\left(\eta_{ijt}\right)}$$

with

$$\eta_{ijt} = w_{ij}^{l}\alpha_t + z_{ij}^{l}\beta_{jt}$$

where *t* is cluster membership as a binary outcome, *i* is each annually repeated measure and *j* is each unique parking bay. Further, *xij* is matrix of land-use independent variables weighted according to proportional intersection within a 250 m buffer surrounding the parking bay j, wij and zij are design vectors for the fixed and random effects, respectively. Lastly, *α* is unknown fixed effects for cluster membership *t*, and *βjt* the unknown random effects for parking bay *j*.[1]

Results

Classifying weekly on-street parking turnover

The PAM classification method identified six distinct temporal patterns of weekly on-street parking turnover across the 9-year study period (Figure 2). Figure 3 reveals how cluster membership changes throughout the 9 years, and Figure 4 shows the physical locations of these cluster types. Each of the on-street parking turnover types is now described:

1. **Office Hours and Dining:** Relatively uncommon at the beginning of the study period and almost completely absent by 2015, this generally concentrated towards the CBD along East-West aligned roads. Here parking bays were generally occupied throughout the workday, with a consistent drop off after work, and a return to occupancy in the evening. These parking bays were generally unoccupied late at night and early in the morning and for the entirety of Sundays.
2. **Not Saturday Afternoons:** Prominent at the beginning of the study period and almost completely absent by 2016, they are particularly concentrated towards the north near the popular Queen Victoria Markets that are open Saturday mornings.
3. **Daytime:** Prominent at the beginning of the study period and almost completely absent by 2015 they are typically concentrated towards the centre and along parallel streets. This cluster is distinct from the previous two given that the parking bays are similarly occupied throughout both weekdays and weekends.
4. **Long Days:** Prominent in 2014 and remain to the end of the study period they are concentrated towards the north where the Queen Victoria Markets are located. These parking bays had similar occupancy patterns to the previous cluster however occupancy extended later into the evening.
5. **Intensive Turnover:** Emerged to prominence in 2014 and by 2015 became the main cluster throughout the remainder of the study period. Except for a slight drop in the early hours of the morning, occupancy is almost constant.
6. **All Remaining**: This type lacks any discernible pattern and forms the smallest of the six clusters.

Cluster membership change explained by nearby land-use changes

Models 1, 3 and 5 (Table 1) were null models for calculating the Intra-class Correlation Coefficient (ICC) that reveals the proportion of variation explained according to the grouping variable (i.e. unique parking bay identifier). Further, these null models function as baseline models when iterating through potential models to identify which explanatory variables improve model fit using an analysis of variance (ANOVA), and by comparing Log-likelihoods, Akaike Information Criterion (AIC) and

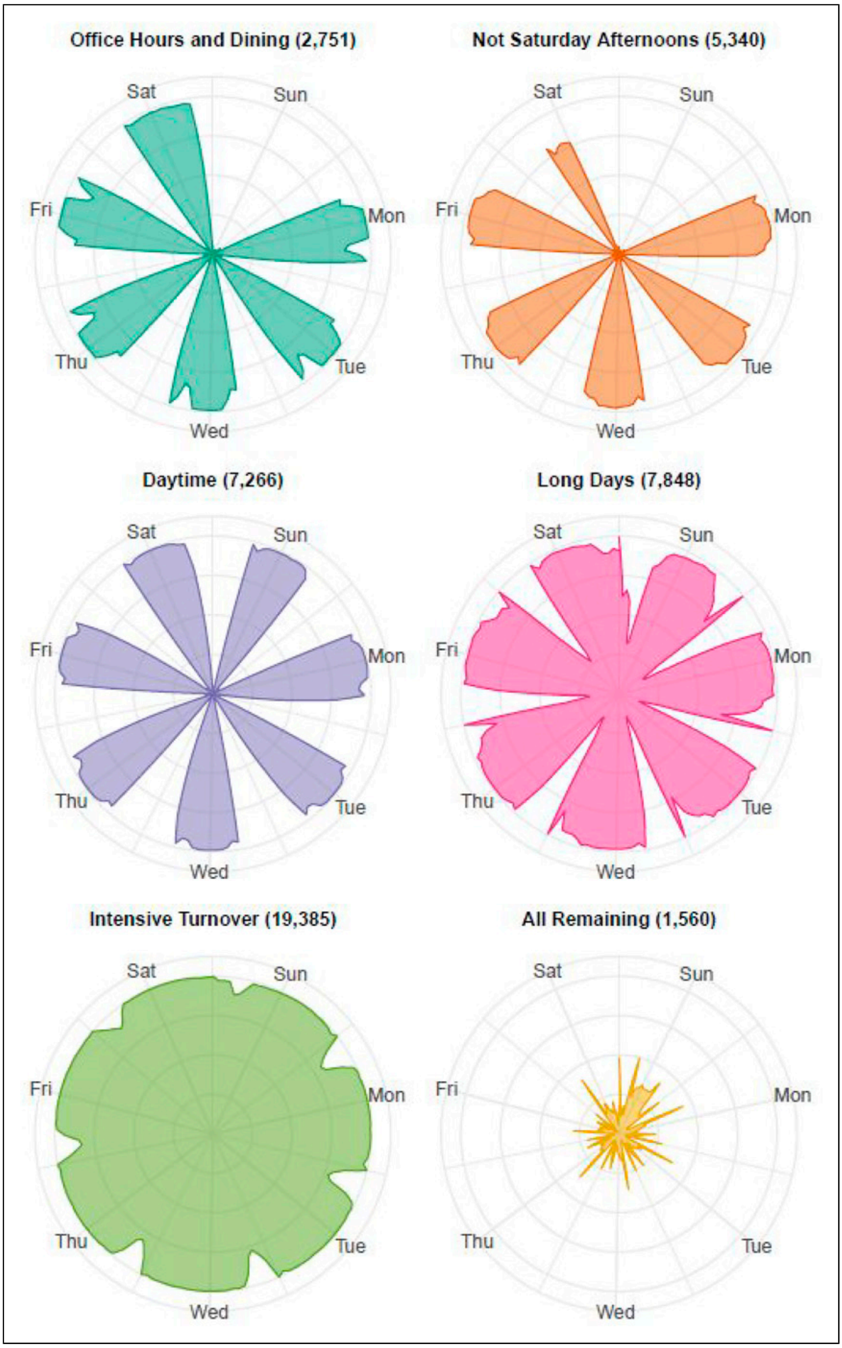

Figure 2. Six distinct types of parking utilisation by day and hour where 0° aligns with midnight.

Bayesian Information Criterion (BIC). By adopting this systematic approach, it was possible to empirically minimise the sets of theoretically informed explanatory variables while maximising explanatory power to arrive at a parsimonious model. As such, only the explanatory variables that passed this systematic approach are present in models 2, 4 and 6 that will now be interpreted.

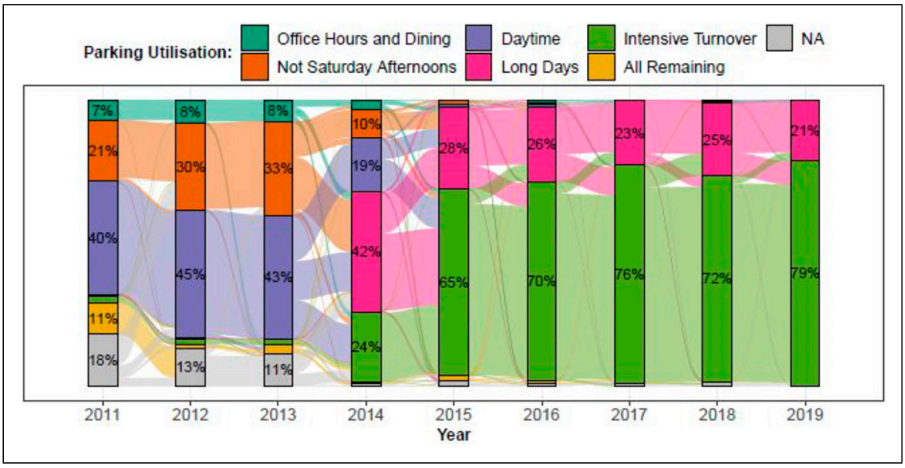

Figure 3. Change to parking bay cluster membership.

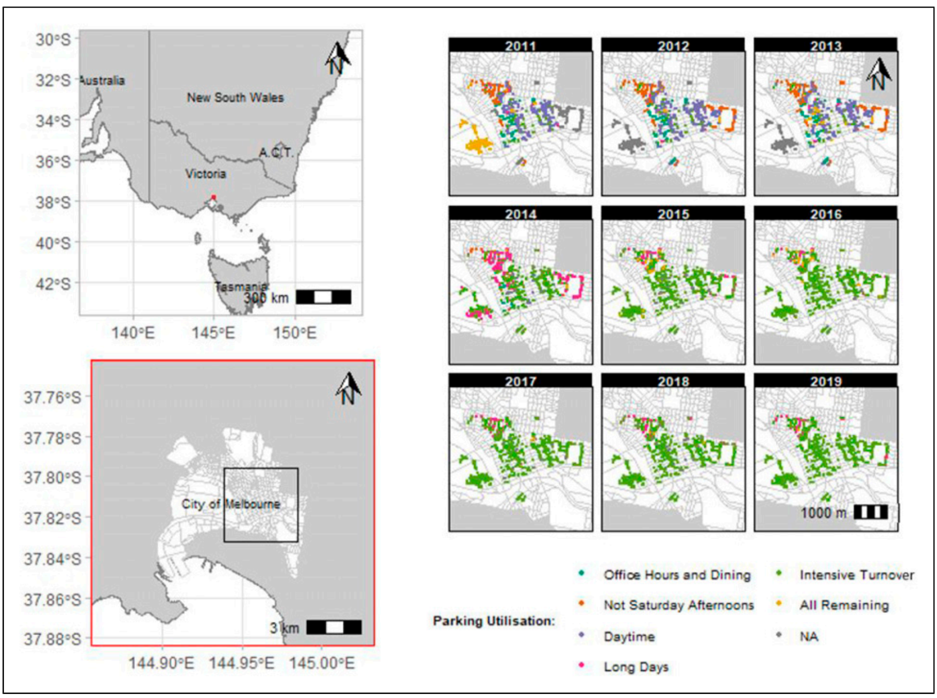

Figure 4. Parking bay and census of land-use and employment block by year.

The 'Weekends' models predicted the likelihood of belonging to a cluster group characterised by high weekend turnover (i.e. 'Daytime' and 'Long Days') rather than a cluster group characterised by minimal weekend turnover (i.e. 'Office Hours and Dining' and 'Not Saturday Afternoons'). The ICC for null model (Model 1) revealed that 57% of variation is explained by the parking bay that improved to 86% for the explanatory model (Model 2) and improvement of model fit using the explanatory variables was confirmed by the ANOVA ($p < 0.01$), and reduction in AIC and BIC.

Table 1. Nearby land use explaining on-street parking utilisation.

	Weekends		Longer days		Night time	
Dependent variable	1	2	3	4	5	6
Commercial parking [log(n + 1)]		0.37*** (0.03)		0.44*** (0.001)		0.12*** (0.02)
Private parking [log(n + 1)]				0.36*** (0.001)		−0.39*** (0.05)
Residential parking [log(n + 1)]		−2.55*** (0.19)		0.61*** (0.001)		−0.61*** (0.06)
Retailers [log(n + 1)]		1.35*** (0.13)		0.08*** (0.001)		
Services [log(n + 1)]						−0.11 (0.07)
Dining and bar seating [log(n + 1)]		−2.35*** (0.13)		−1.08*** (0.001)		−0.68*** (0.07)
Residential dwellings [log(n + 1)]		3.89*** (0.24)		−0.24*** (0.001)		1.5*** (0.08)
Land-use mix [x/|x|]				0.68*** (0.001)		0.09*** (0.03)
Constant	1.74*** (0.07)	6.02*** (0.55)	0.43*** (0.08)	2.85*** (0.001)	0.28*** (0.03)	1.59*** (0.25)
ICC	0.57	0.86	0.75	0.63	0.34	0.57
ANOVA	Pr(>chi sq)	df[2,7] ***	Pr(>chi sq)	df[2,9]***	Pr(>chi sq)	df[2,9]***
Observations	12,229	12,229	8,774	8,774	19,672	19,672
Log likelihood	−6593.00	−5944.00	−4888.00	−4462.00	−12652.00	−12199.00
Akaike Inf. Crit	13190.00	11902.00	9779.00	8943.00	25308.00	24416.00
Bayesian Inf. Crit	13205.00	11954.00	9793.00	9006.00	25323.00	24487.00

Note: ICC: Intra-class correlation coefficient; ANOVA: analysis of variance.
Note: *p < 0.1; **p < 0.05; ***p < 0.01.

Specifically, nearby commercial (b = 0.37; p < 0.1) parking increases weekend on-street parking turnover and wheras residential parking (b = −2.55; p < 0.01) reduces the likelihood of weekend on-street parking turnover. Likewise, nearby retailers (b = 1.35; p < 0.01) and residential dwellings (b = 3.89; p < 0.01) increase the likelihood of weekend on-street parking turnover, whereas nearby dining and bar capacity (b = -2.35; p < 0.01) reduces this likelihood. Cumulatively, these findings suggest nearby shopping increases on-street parking turnover on weekends. Further, the seemingly contradictory findings between residential off-street parking and dwelling counts could be explained by the introduction of 'parking maximums' policies that restrict the supply of parking in new residential development and so the weekend on-street parking turnover can at least in part be attributed to the spillover of additional household cars and visitors.

The 'Longer Days' models predicted the likelihood of belonging to the 'Long Days' rather than 'Daytime' cluster. The ICC for the null model (Model 3) revealed that 75% of variation is explained by the parking bay and this explanatory power reduced to 63% for the explanatory model (Model 4) although these explanatory variables improved the model fit as revealed by the ANOVA (p < 0.01), AIC and BIC. Specifically, commercial (b = 0.44; p < 0.01), private (b = 0.36; p < 0.01) and residential parking (b = 0.61; p < 0.01) all increase the likelihood of parking turnover continuing into the evening, and so too did the number of nearby retailers (b = 0.08; p < 0.01) and land use mix (b = 0.68; p < 0.01). In contrast, nearby dining and bar capacity (b = -1.08; p < 0.01) and residential dwellings (b = -0.24; $p < 0.01$) reduce this likelihood. Cumulatively, these findings suggest that nearby off-street parking increases on-street turnover in the evenings most likely aligned with the introduction of off-peak parking rates as it relates to paid parking. The turnover increase near retailers could be explained by the retailer types such as grocery shopping where the converse observed near dining and bars could lengthening stays reflecting the evening dining peak. Like the 'Weekends' set of models, residential parking and dwelling counts have a contradictory association that again could point towards the introduction of parking maximums policies resulting parking over-spill. The positive association between on-street parking and land-use mix is a particularly interesting finding when examined alongside the remaining explanatory variables since it suggests that on-street parking is providing the brief 'spot accessibility' as intended it is possible that motorists are selecting these locations that fulfil multiple trip purposes before moving on.

The final 'Night-time' models predicted the likelihood of belonging to the 'Intensive Turnover' cluster rather than the 'Daytime' or 'Long Days' clusters. The ICC for the null model (Model 5) revealed that just 34% of variation is attributable to parking bay however the introduction of the explanatory variables for the explanatory model (Model 6) increased this figure considerably to 57%. Likewise, these explanatory variables improved the model fit considerably as revealed by the ANOVA ($p < 0.01$), AIC, and BIC thus highlighting the role of nearby land use in explaining parking turnover throughout the night including weekends. Specifically, commercial ($b = 0.12$; $p < 0.01$) increases the liklihood of parking turnover whereas residential parking ($b = -0.39$; $p < 0.01$), private parking such as business and residential visitor bays were associated with reducing turnover throughout the night (b = -0.61; $p < 0.01$). Nearby services ($b = -0.11$; $p < 0.01$), dining and bars ($b = -0.68$; $p < 0.01$) also reduced the likelihood of turnover throughout the night, whereas this increased near high dwelling counts ($b = 1.5$; $p < 0.01$). Lastly, land-use mix again increased the likelihood of turnover throughout the night again suggesting that on-street parking is providing 'spot accessibility' to fulfil multiple trip purposes.

Discussion and conclusion

This study set out to examine the temporality and locality of on-street parking and develop the first typology of parking routines. Drawing on an emergent source of big data on parking and deploying a clustering technique employing circular statistics we reveal the presence of six distinct temporal patterns of parking that evolved across the 9-year study period. Modelling the membership of each of these six broad types showed the importance nearby land-use mix on parking utilisation which hold several important implications for policy and planning.

Car parking not only occupies a substantial amount of land in cities, it also has a significant influence on rates of car ownership and use. As such, the organisation of parking is a key challenge to achieving more sustainable patterns of mobility in cities (Kirschner and Lanzendorf, 2020). There are currently many opportunities for cities to use parking supply as a tool to promote more sustainable travel behaviour, which can simultaneously address issues of transport-related energy consumption and carbon emissions, urban land consumption, and the overall costs of transport infrastructure (Pojani et al., 2019). A range of parking policies, including temporally dynamic pricing and the reclamation and repurposing of underutilised parking space, can also be used to create more attractive, accessible and walkable environments in cities.

Using car parking more efficiently in cities is central to achieving many of the above aims. Amongst other things, the efficient use of car-paring space implies:

- Reducing the overall demand for parking and its supply.
- Minimising the size of individual parking spaces.
- Developing innovative ways of better utilising existing capacity.

Findings from this study highlight the way in which specific combinations of land-use types influence daily and weekly patterns of parking utilisation, and provide the empirical foundations for policies that connect on-street parking provision with adjacent land-use types. This new empirical understanding has the potential to be employed to maximise parking utilisation and the public return on this expensive public land-use type. These specific combinations of land-use types primarily affect parking turnover due to the times when different premises/land uses are used (that are closely related to opening and closing times), and on-street parking within drinking and dining precincts are especially associated with extended periods of underutilisation of on-street parking utilisation especially during weekday daytime. Urban planning, and land-use control more specifically, can be used to influence car parking use and occupancy. As such, increasing land-use mix can increase on-street parking utilisation throughout the day and week.

The temporal dynamics of parking are complex. Unpacking this complexity to reveal the tempo and timing of parking utilisation is an important first step in creating smarter empirically informed policies that maximise the use of on-street parking. A major impediment to understanding this complexity is both data availability alongside deploying suitable empirical methods. In the current study we place a focus on on-street parking and drew upon a novel data resource that offers the capacity to observe arrivals and departures of vehicles from individual parking bays at a fine temporal granularity and over a 9-year period. Through adopting a data fusion approach these parking data were joined with high resolution land-use data through which the relationship between parking dynamics and nearby land use (and change in land use) could be empirically explored.

There is no doubt that parking (including delivery/drop-off space for passenger and goods vehicles) will remain a contentious topic even with the possible future widespread use of automated vehicles in cities in whatever form they take, and the topic is only likely to be further heightened as cities wrestle with how best to transition to more sustainable, healthy and liveable futures (González-González et al., 2020; Papa and Ferreira, 2018). Understanding the temporality of parking and the way in which nearby land use and changes in land-use impact dynamics are a cornerstone to help inform future policy.

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Supplemental Material

Supplemental material for this article is available online.

Note

1. Count explanatory variables are transformed by adding one to eliminate zeros and then log transformed to resemble a normal distribution, whereas land-use mix was normalised (Figure S4 in the Supplementary Material).

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