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Understanding the determinants of bike-sharing demand in the context of a medium-sized car-oriented city: The case study of Milton Keynes, UK

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A R T I C L E I N F O

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A B S T R A C T

Emerging modes of shared mobility like bike-sharing may significantly contribute to increasing the share of sustainable travel in medium- and small-sized cities. However, research exploring the bike-sharing usage determinants specifically for them has been severely underrepresented in the literature. To address this gap, we conducted an analysis of bike-sharing rentals for over a one-year period in Milton Keynes, a medium-sized city of 288,000 residents. Being the largest of the planned settlements built under the UK government "New Towns" programme, Milton Keynes despite having the infrastructure to offer opportunities for modal shift has been repeatedly characterised as a car-centric city. The paper examines temporal variation by comparing the average number of bike rentals in different seasons and months. Analysis of peak rentals and travel directions suggests that throughout the year bikes are mainly used to travel to work. By contrast, recreational travel appears to happen mostly during the summer months. Regression analysis shows that the number of public transport stops, offices and schools are associated with a higher number of bike rentals, supporting the view that utilitarian travel is the main usage pattern. Our research also highlights the bike-sharing's potential to be adopted as a first/last-mile option that will complement and support public transit.

1. Introduction

Cities, in the era of rapid urbanisation, globalisation and technological progress, have become arguably the epicentre of human development (Morton, 2018; Nikitas et al., 2021a; Tsagkis et al., 2023) accommodating according to the World Bank approximately 56% of the world's population (i.e., close to 4.4 billion inhabitants). Cities, now therefore, more important than ever before for the fabric of our societies (Knowles et al., 2020; Mouratidis, 2019), are increasingly faced against unprecedented global challenges with potential paradigm-changing consequences that refer to climate change and necessitate efforts for more sustainable and resilient development (Nikitas et al., 2024; Nocera & Attard, 2021). Traffic congestion, a by-product of car-centric design (Tsigdinos et al., 2022), with its implications spanning from more road accidents and loss of productivity to additional Greenhouse Gas (GHG) emissions and noise nuisance (Liu et al., 2020; Zhang et al., 2023), is according to Zhao & Hu (2019) one of the key barriers obstructing sustainability and liveability in many cities. The promotion of urban cycling, in general, and bike-sharing, in particular, is widely regarded as a vital contribution to exiting this vicious cycle of automobility and excessive motor traffic (Radzimski & Dzięcielski, 2021) and establishing a more balanced and equitable modal share (Bartle et al., 2013).

A bike-sharing scheme (BSS) is a short-term bicycle rental service for a city catchment that provides locally customised bikes via subscription or 'pay-as-you-go' options for extending the reach of public transport to final destinations (Nikitas, 2018) and for normalising urban cycling (Goodman et al., 2014). It was introduced as early as 1965 through the unconventional experiment of the Amsterdam's free 'White Bikes' (Ploeger & Oldenziel, 2020) but became prominent only lately when automated credit card payment, smartcard integration, wireless tracking, SMS locking and geofencing became widely available (Bakogiannis et al., 2019). Bike-sharing, typically defined as a sustainable first- and last-mile travel mode for congested urban and metropolitan environments (Politis et al., 2020; Ricci, 2015) is now in the aftermath of the eye-opening Covid-19 pandemic that highlighted all that was wrong with motorised transport (Nikitas et al., 2021b), timelier and more meaningful than ever before (Christoforou et al., 2023). Also, the emergence of GPS-based, stationless and free-floating schemes

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where bikes do not need docking stations *per se* (Eren & Uz, 2020) expanded the BSS concept into a more dynamic mode with door-to-door travel capabilities.

Shaheen et al. (2010) and Nikitas (2019) summarised the potential benefits of bike-sharing as flexible mobility, emission reductions, physical activity benefits, reduced congestion and fuel use, individual financial savings and support for multimodal transport connections. More recently, Teixeira et al. (2021) noted that the biggest of these benefits are the increases in physical activity levels (triggering health gains) as well as travel time savings to the BSS users. On the other hand, Nikitas (2018) notes as possible BSS problems and barriers: their systematic underuse, vandalism and theft, complicated planning procedures, sluggish or over-ambitious scheme expansion tactics, inflexible business models, strict cycling regulations including compulsory helmet use for some countries, political friction when claiming back car parking space, road traffic safety concerns and lack of adequate complementary cycling infrastructure (e.g. bike lanes, cycle paths, parking racks).

Bike-sharing has been implemented and studied primarily within the context of larger cities and metropolitan environments (e.g., Achillen et al., 2016; Bustamante, et al., 2022; Chen et al., 2022; Dobruszkes & Dzięcielski, 2023; Fan and Zheng, 2020; Fishman et al., 2015; Li et al., 2019; Shen et al., 2018; Teixeira et al., 2022; Xing et al., 2020) but far more infrequently employed and researched for the context of smaller and medium-sized cities[1] with a few notable exceptions (e.g., smaller cities: Audikana et al., 2017; Bakogiannis et al., 2019; Nikitas, 2018 – medium cities: Böcker et al., 2020; Caulfield et al., 2017; Nikiforiadis & Basbas, 2019; Nikitas et al., 2016; Radzimski & Dzięcielski, 2021). This ‘big city’ dominated literature leaves a lot of unanswered questions about how BSSs work for smaller urban communities and how demand is derived for less populated built environments. Also, because of dockless bikes’ relatively recent development and turbulent brief history - i.e., rapid emergence but with stigmatising scheme closures as per Nikitas (2019) – the BSS literature is still incomplete and inconclusive. Studying these systems could yield different results than what is currently known for the more traditional dockbased systems (Sun et al., 2024) and also affect these latter programmes (since mobility provision does not operate in a vacuum and these systems many times co-exist and share the market) and the totality of the BSS paradigm. In fact, more research is necessary for cities providing both dockbased and dockless services to understand BSS better (Qian et al., 2020); even when data for the dockless systems may not be available due to the complexity of their nature and complications in collecting them.

This work means to address this complex research gap in an intriguing timeline when redefining and re-evaluating bike-sharing may be necessary. On the one hand we have many especially dockless systems seriously fading out including the previously ‘global’ mega-initiatives of Mobike and Ofo that have retreated back to China (Nikitas et al., 2019) and this has sparked loud criticism about BSS being a genuinely viable long-term investment (e.g., de Chardon, 2019). But on the other hand, we have as many as 2039 operating and 207 planned local BSS in the world with 9,076,632 bikes (as of July 2024 per The Meddin Bike-sharing World Map) which is a burgeoning number. In fact, the rising global warming pressures combined with the transformative Covid-19 experience (Teixeira et al., 2023) dictated the introduction of many strategic bike-centric investments to promote greener urban planning and support the heavily affected from the pandemic public transport systems (Buehler, 2021; Kyriakidis et al., 2023; Nikitas & Bakogiannis, 2024) with BSSs becoming increasingly an ‘easy win’ in these regards.

[1] We assumed OECD criteria, according to which cities are considered to be medium sized if their population is between 200 000 and 500 000; and, small urban areas if their population is between 50 000 and 200 000. Source: https://www.oecd-ilibrary.org/urban-rural-and-regional-development/urban-population-by-city-size/indicator/english_b4332f92-en

Our work concentrates on Milton Keynes, one of England’s newest mid-sized cities, atypically smart in its urban design, with a 270 km segregated network of cycle and pedestrian routes that on paper provides an exceptional potential for modal shift. However, according to Marum & Patterson (2017) it is still disproportionally car-centric; i.e., the percentage of journeys to work by bicycle was according to these authors just 3.02% compared to 72.73% by private motor vehicles. We study the local demand of the main BSS of the city for a whole year and try to develop an understanding of the determinants reflecting and affecting demand and real usage to contribute to understanding better the under-investigated landscape of the medium-sized car-centric city environment.

Henceforward, the paper provides in Section 2 a description of Milton Keynes focusing on its transport service provision and BSS offer. Section 3 describes the methodology employed, Section 4 presents our analysis and results, and Section 5 provides a thorough discussion benchmarking our results against the related literature and offering policy and industry-relevant recommendations. Finally, Section 6 concludes this work by summarising our key results, main contribution, reflections and future research recommendations.

2. Case study description

Milton Keynes, a city of 288,201 residents, is one of the youngest urban centres in the UK. Situated 80 kilometres north-west of London, it originates from the "New Towns" programme, which aimed to alleviate congestion and overcrowding affecting cities in the postwar period. When the construction of Milton Keynes started in 1967, the programme already had more than two decades of history and had been receiving somewhat mixed reviews. Thus, it became one of the planners’ primary tasks to address the "new town blues", including problems such as lack of social amenities and failure to mix social classes (Barkham, 2016). Melvin Webber’s idea of ’communities without propinquity’, which emphasised novel forms of communication such as radio and television over face-to-face human interaction, influenced early plans for the new city (Luck, 2022). Nevertheless, original plans had foreseen an essential role of walking accessibility to neighbourhood-scale local centres. As it often happens, the plans later changed in several key aspects (Edwards, 2001).

In particular, the transport concept became increasingly focused on facilitating vehicular traffic at the expense of public transport, walking and cycling. The grid layout of the road network was updated to accommodate higher driving speeds. Pedestrian underpasses, already present in the original plans, became a widely adopted solution due to safety concerns. Milton Keynes is also known for the widespread use of roundabouts, substituting traffic lights included in original plans, and for its many publicly available parking spaces. The overall design of the transport system gave the new town a rather car-centric leaning, which is reflected in the modal share, as roughly two of every three work trips are made by car (Table 1).

In recent years, reducing car travel has become a policy objective as the city seeks various ways of promoting low-carbon mobility (Haarstad et al., 2022). However, Milton Keynes’ public transport system consisting of only buses faces several problems, also due to the city’s increasing population. A 2016 survey found 84% of bus passengers in Milton Keynes to be satisfied with the services, the fourth lowest score

Table 1
Milton Keynes basic data. Sources: Office for National Statistics, Milton Keynes Council.

Population 2011	Population 2021	Population 2050 (projected)	% car travel 2011	% car travel 2030 (target)	% car travel 2050 (target)
248,800	287,100	400,000	65	60	50

among 21 surveyed cities, with the value-for-money score as low as 60% (Milton Keynes Council, 2018). Actions aimed at increasing public transport usage include smart city solutions (Cook & Valdez, 2021) and demand-responsive public transport (Potter et al., 2022). At the same time, many transport policy objectives aim to encourage cycling and other modes of active travel as a second pillar of sustainable mobility alongside public transport and as a first/last mile solution (Milton Keynes City Council, 2023).

The network of cycling infrastructure in Milton Keynes extends for over 500 kilometres (Fig. 1). The redway system - a network of shared use paths for cyclists and pedestrians, which owes its name to red tarmac typically used as surface material, makes up about two-thirds of it. Expanded continuously since the 1970s, the redways constitute the backbone of the city's cycling network. The remaining one-third consists primarily of informal cycling infrastructure, such as trails in green areas (Fig. 1). Accessibility of cycling infrastructure in most neighbourhoods is acceptable, but its quality often needs improvement. Barriers discouraging cycling include poor surface quality, inconsistent signage and a shortage of parking facilities. Apart from eliminating these barriers, there are also plans to expand the already existing network of "super redways", i.e., high-quality cycleways along frequently used corridors, and to promote cycle hire schemes (Milton Keynes Council, 2023).

According to the Meddin Bike-sharing World Map, two bike-sharing schemes are available in Milton Keynes as of July 2024. The first has been operated since 2015 by Nextbike (currently TIER) under the brand Santander Cycles. Starting from 300 docked bicycles in 40 stations, the scheme has been expanded in 2020 to 500 bicycles in 60 stations. A further expansion followed in July 2023 with the introduction of 92 dockless pedelecs. The standard fee for a 20-minute ride is 1£, with monthly and annual passes available at 12£ and 78£, respectively. The other scheme consists of about 100 dockless e-bicycles provided by Lime, which also offers other shared mobility services such as e-scooters. The Lime bikes can be unlocked for £1 and ridden for 15p per minute.

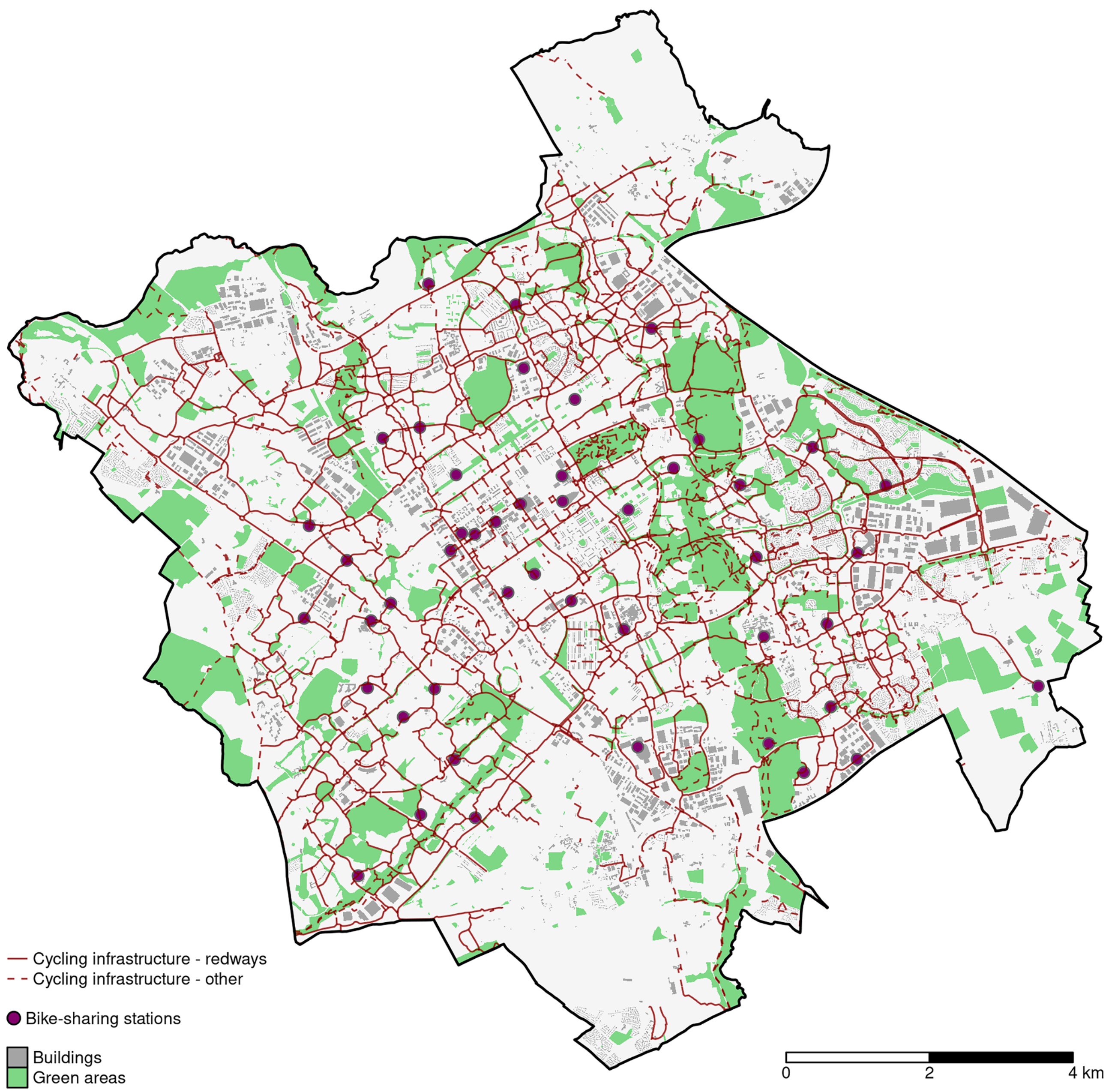

Fig. 1. Cycling infrastructure in Milton Keynes urban area. Source: Openstreetmap.

3. Data

The main data used in this study consists of GPS-recoded bicycle positions and the usage of bike-sharing stations obtained from the web API of the system operator, Nextbike (currently part of the TIER company). Data related to bikes and stations (identifier, name, location, the current number of bikes, and time) was downloaded using a script written in Python and saved to CSV files. There were separate files containing information about stations and bikes. Data was downloaded for a one-year period from June 2022 to May 2023 every 2 minutes, 24 hours a day, 7 days a week.

Data preparation included the cleaning of outliers, i.e., observations of bikes/stations with geographical coordinates that did not match the area of the city. Based on the locations database, a database of bicycle movements was generated by creating trajectories of bicycle movements with the same bicycle ID, and then splitting the trajectories to segments connecting individual stations. Only those bicycles that changed their geographic location within the city limits were selected for further analysis. Displacements associated with the relocation of bicycles by the operator (so-called rebalancing) have been filtered out. We also removed trips meeting one of the following criteria: average speed was greater than 30 km/h (around 19 mph) or equal to 0, trip duration was more than 4 hours, or the distance travelled was less than 50 m, as these were likely erroneous observations. The movements database was then used to obtain the geographic coordinates of stations in the system. The resulting table containing the coordinates, name, unique ID and number of bicycle racks at each station was exported to QGIS as a CSV text layer to visualise a bike-sharing journey. A layer containing station data extended with station coordinates and a layer containing route data was exported to a CSV file for loading into R language to identify bike rental peaks and to conduct regression analysis. By having these operations processed it was possible to obtain information about the distribution of bike rentals by hour and day of the week. It was also possible to check the usage of each station and get information about the average number of bike rentals. After all these operations we observed 25,410 bike rentals in Milton Keynes from June 2022 to May 2023. Data of the free-floating system (Lime) were not available and therefore were not included in the analysis. The meteorological data for the examined area in the selected period have been downloaded using the climate package written in R language (Czernecki et al., 2020).

4. Methodology

Estimating the relationships that occur between phenomena and the factors that shape these phenomena can be achieved using regression analysis. The basic form of the regression model, which makes it possible to determine a linear statistical relationship between the dependent variable and a number of independent variables, is the linear regression model, whose structural form can be written with the formula:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \varepsilon \quad (1)$$

where: y is the dependent variable, x_1, x_2, ..., x_k are independent variables, β_0,β_1,β_2, ..., β_k are regression coefficients and ε is an error term.

One of the assumptions of regression analysis is that there is no collinearity. A parameter that may be used for assessing collinearity between independent variables is the variance inflation factor (VIF). This indicator shows how many times the variance of the predictor is greater than the value undistorted by collinearity. In analytical practice, when the VIF parameter is above 10 indicates the disturbing effect of collinearity on the model parameter.

Location and distance can affect the degree of dependence between phenomena in space (spatial autoregression). If spatial dependence is not taken into account, the estimation of model parameters may be biased. The use of spatial regression models makes it possible to eliminate the negative influence of spatial effects. The basis for model selection is spatial autocorrelation analysis, which measures the correlation between the values of a variable at different points in space. An assessment of the level of spatial autocorrelation can be made based on the Moran's I coefficient. Taking into account the specific relationships between observation units, resulting from their location, is made possible through the construction and use of spatial weighting matrices.

In this research, we use point-based observations of trip counts at bike-sharing stations. Distances between observations differ significantly in this research, so a contingency-based matrix with a queen-type neighbourhood was adopted. First, we created Voronoi polygons associated with bike-sharing stations. Then, we calculated a weights matrix by assuming that two observations were neighbours if they shared either a common boundary or a common point.

Two types of spatial regression models may be used when spatial effects are detected in empirical data. Spatial lag models are used when the dependent variable has spatial dependence, whereas spatial error models allow the spatial dependence on random error to be taken into account. Lagrange Multiplier test diagnoses spatial autocorrelation and allows to choose the proper model form.

Our research hypothesis is that the number of bike-sharing rentals is dependent upon the population and opportunities present in the catchment area of bike-sharing stations. Milton Keynes is a medium-sized city, and the bike stations are located densely, especially in the city centre, hence we assumed catchment areas based on a walking distance of 200 metres. The isochrones were calculated with the QGIS plugin ORS Tools, which uses the free Openrouteservice API. Explanatory variables representing possible destinations such as: public transport stops, parks, tourist attractions, offices, schools, universities and malls were downloaded from the Openstreetmap. A complete list of our explanatory variables is given in Table 2.

5. Results

The average number of rentals per day by hour throughout year recorded in Fig. 2 showcase the morning and evening peaks. Furthermore, noticeable is a third peak at around 13:00. This suggests that bikes are used more often for utilitarian purposes, for example to go to work, rather than for recreation.

Fig. 3 presents the average number of bike rentals per day by hour during the different seasons of the year. For every season we observe a morning peak at around 08:00 and an evening peak at around 17:00. This finding suggests that a significant part of bike-sharing rentals is related to work commutes. Interestingly, we also found a third daily

Table 2
List of explanatory variables with summary statistics.

Variable	Definition	Mean	Standard deviation
Public transport	Number of public transport stops in catchment area	2.021	2.489
University	Number of universities in catchment area	0.043	0.204
Tourism	Number of tourist attractions in catchment area	0.404	1.096
Park	1 if park within catchment area, 0 otherwise	0.574	0.499
Office	Number of office blocks in catchment area	0.149	0.416
Industrial area	1 if park within catchment area, 0 otherwise	0.106	0.312
School	Number of schools (primary and secondary) in catchment area	0.447	0.502
Mall	Number of malls in catchment area	0.069	0.247
Cinema	Number of cinemas in catchment area	0.043	0.204
Population density	Number of residents aged 15 or more per hectare divided by 1000	0.501	0.369
Cycleway	Length of cycleway (in km) in catchment area	0.562	0.342

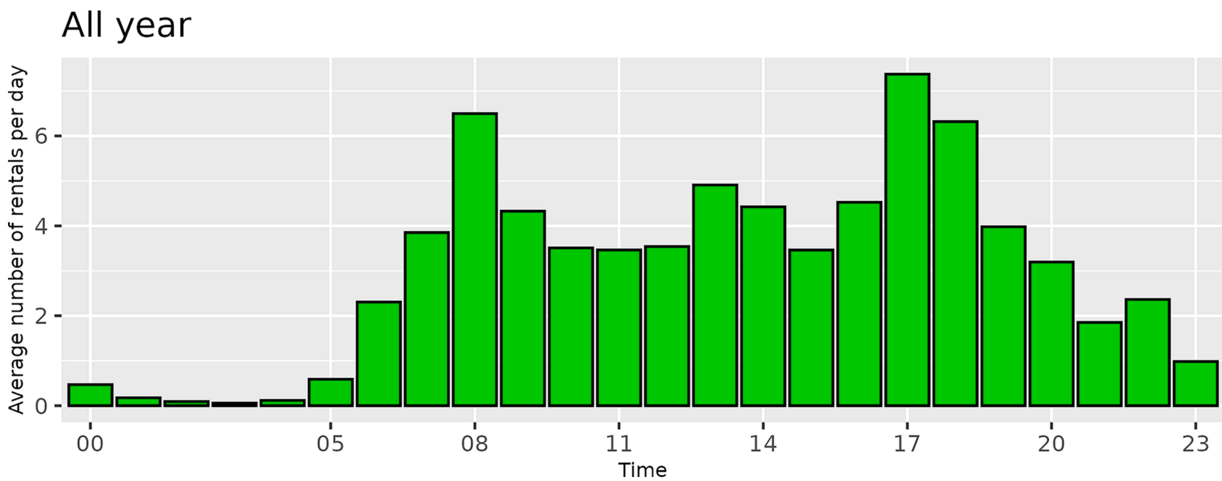

Fig. 2. Average number of rentals per day by hour throughout year.

peak around 13:00. We observed it for every season, but most prominently in the winter. This is also the season when we found the lowest overall number of rentals, whereas the highest number of rentals was found in the summer, especially in the evening hours.

The average number of rentals per hour by month is presented in Fig. 4. The highest number of rentals was found in the summer months (June, July and August), and the lowest average number of rentals is seen during winter months (December, January and February). This indicates that weather has a high impact on bike-sharing rentals in Milton Keynes. Again, for the winter months three peaks are seen clearly. However, for April, May and September this third peak is invisible. Interestingly, in November and December the morning peak is larger than the afternoon peak. For a period from April to August, it can be seen that the afternoon peak is higher than in other months, which may suggest that due to warmer weather, bikes are also used for recreation.

We picked August and December, for further analysis, as examples of a summer and a winter month. The average number of rentals per day on workdays and weekends in August and December is presented in Fig. 5. The average number of rentals in the summer month is over 3 times as high as for the winter month, suggesting that bike-sharing users in Milton Keynes are highly sensitive to weather conditions. In the case of workdays, the typical three peaks in the morning, the afternoon and the evening are observed. We found interesting differences with regard to the number of rentals on weekends. In August the number of rentals increases from 05:00 to 17:00, while in December bikes are rented mainly from 07:00 to 14:00. Interestingly, bikes are rarely rented on weekend evenings in December, possibly due to poor weather (i.e., low temperatures, rain or snow) and early sunset, which maybe a reason to use car or public transport instead.

The average number of bike rentals per month and average temperature, wind speed and sum of precipitation in every month are presented in Fig. 6. To detect correlation between variables we calculated the Pearson correlation coefficient (r). It is seen that a higher number of bike rentals is observed when average temperature is higher ($r = 0.98$). However, wind speed is negatively correlated with a number of bike rentals ($r = -0.7$). It seems that precipitation is weakly negatively correlated with usage of shared bikes ($r = -0.4$).

We calculated the average shared bikes riding distance and duration during weekdays, weekends, morning and evening peaks and off peaks (Table 3). It is clearly seen that the shortest and fastest trips are during the morning peak, and the longest and slowest trips are on the weekends.

We also looked at the spatial distribution of trips before and after 15:00 in a one-year perspective from June 2022 to May 2023 (Fig. 7). This hour was selected because by that time travels are distributed almost evenly between morning and afternoon. We observe two major spatial clusters of trips: the primary one around the city centre with the train station as a strong focal point, and the secondary one to the east of the centre, in an area including the campus of the Open University and the retail/industrial areas of Kingston. Also, a noticeable pattern is the daily cycle of travels between the train station and a business park situated in the north-eastern part of the city (i.e., the Linford Wood Business Park).

5.1. Regression analysis

To examine the relationship between the number of bike rentals and the variables shown in the Table 2, we conducted a regression analysis. Distances between bike stations differ significantly in Milton Keynes. We did not consider distance-based or k-nearest neighbours-based matrices. Voronoi polygons were generated for each station (in QGIS), and the spatial weights were calculated based on their geometry (spdep package in R). We adopted a contingency-based matrix with a queen-type neighbourhood. Two bike stations (in the form of polygons) were regarded as neighbours if they shared a common boundary. Next, we tested if there was spatial autocorrelation in the bike rentals database. Global Moran's I test shows that p-value was greater than 0.01, so there is no global autocorrelation. The summary of global autocorrelation test is presented in Table 4.

Results of the OLS regression show that the number of public transport stops, offices and schools are associated with a higher number of bike rentals in the full year perspective and in selected months. Interestingly, for primary and secondary schools the effect was negative, but we found a positive effect for universities. This may suggest that university students use shared bikes to go to school when primary and secondary school students and their parents and guardians do not.

It is seen that: parks, places of interest to tourists, industrial areas, malls, cinemas and population density are not associated with bike rentals. Interestingly, for the case of shopping malls we observe a positive coefficient in August, while for the full year and December the coefficient was negative. As restaurants and entertainment sites are often located in shopping malls, the result may suggest that in the summer shared bikes might be used for entertainment purposes too. A similar phenomenon is seen in the case of parks. The summary of the regression results by time span are shown in Table 5.

6. Discussion

Increasing the share of cycling, especially utilitarian cycling (i.e., trips made by bicycle for practical transport purposes such as commuting to and from work) has been recognised as a necessary

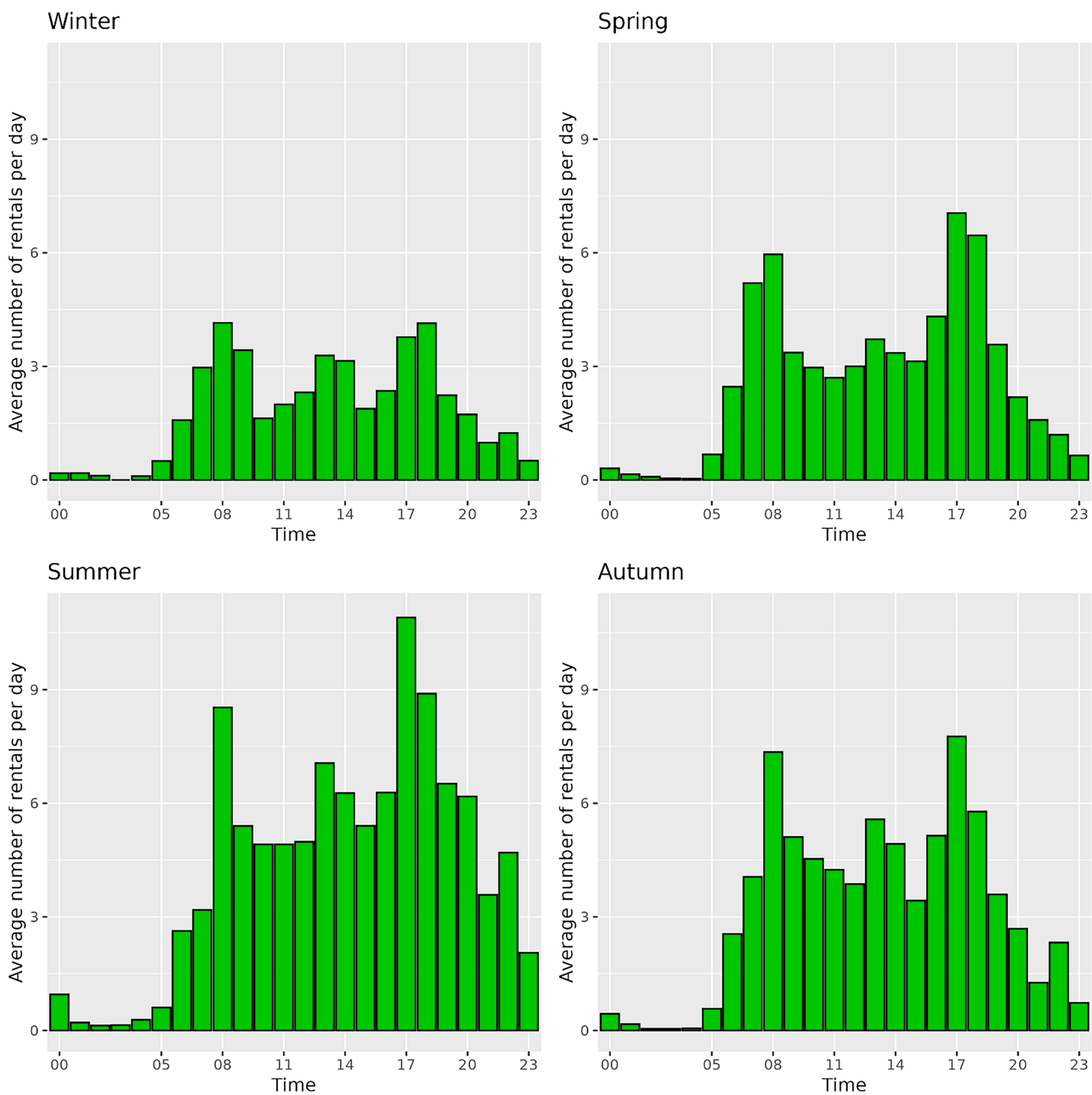

Fig. 3. Average number of rentals per day by hour and by season.

requirement when planning for more sustainable urban transport futures (Nikitas et al., 2021b; Pucher & Buehler, 2017) that is a particularly dynamic and difficult-to-tackle policy challenge in car-oriented cities (Adam et al., 2020; Goel et al., 2022). This modal shift needs to be actively encouraged by pro-cycling policies to increase the attractiveness of cycling and the construction of new cycling infrastructure (Caulfield, 2014) with the utilisation of bike-sharing schemes being a potential key for these plans (Nixon & Schwanen, 2019). Interestingly, despite having an extensive network of cycling infrastructure, the modal share of cycling in Milton Keynes has been historically low. Our results showing relatively consistent usage patterns throughout the year illustrate that by lowering the entry costs, bike-sharing may facilitate the transition to everyday cycling, and thus help overcome the path of car dependence.

Our results may improve our understanding about the bike-sharing usage determinants in small and medium-sized cities. In contrast to major cities where most bike-sharing systems are deployed, sustaining viable ridership levels is more difficult without a significant share of non-local users. To address this issue, some bike-sharing systems in small and medium-sized cities have been tailored specifically to address the needs of visitors (He et al., 2019) or university students (Mattson & Godavarthy, 2017). However, in many small and medium-sized cities there is no significant tourism sector and therefore the bike-sharing systems are more dependent upon local demand (Scott & Ciuro, 2019). With an economy primarily relying on the services and office jobs, Milton Keynes may offer some insights into the functioning of

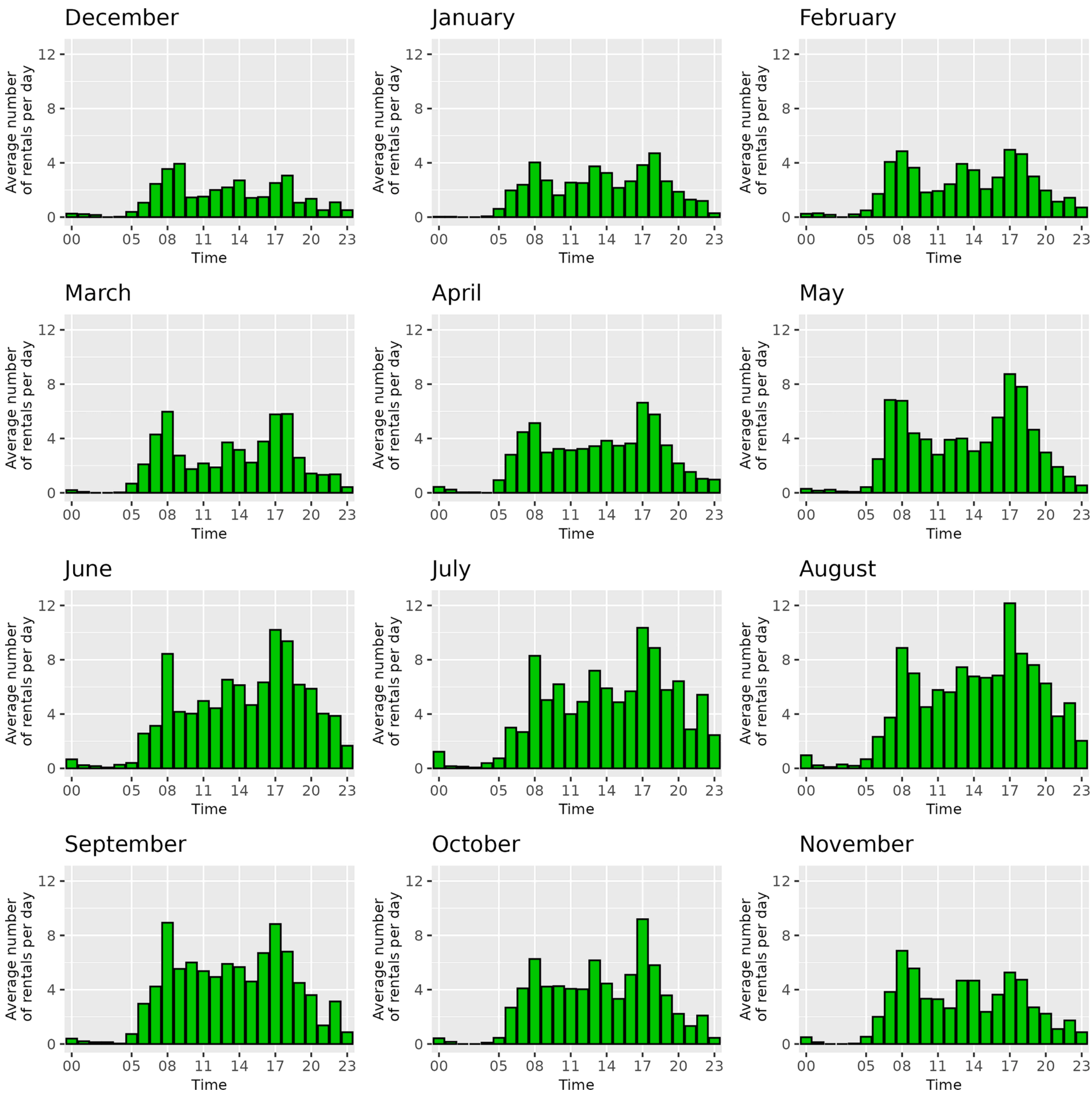

Fig. 4. Average number of rentals per day by hour and by month.

bike-sharing systems in this category of cities.

Our findings are aligned with results observed in the city Cork, Ireland (population of around 224,000), where bike-sharing trips were made mainly on weekdays and shared bikes were used mostly for commuting reasons (Caulfield et al., 2017). Another similarity between Milton Keynes and Cork is the existence of morning and afternoon rental peaks, as well as of a third peak between 13:00 and 14:00. Weather conditions were found to have an impact on bike-sharing usage in both cities.

By contrast, research in medium-sized cities with a large tourist sector has tended to identify recreational opportunities as relevant to bike-sharing demand. For instance, in the city of Limassol, Cyprus (100,000 residents) land use factors such as residential, commercial and park land use, as well as the presence of the beach and cycling paths positively influence the frequency of bike-sharing use (Maas et al., 2021). However, there is a similarity in higher afternoon peaks for summer months in both Milton Keynes and Limassol, suggesting that favourable weather conditions tend to increase recreational use among local populations and visitors. Another case where a higher number of bike rentals during summer was observed was that of Boulder, Colorado, USA with a population around 100,000 (Hu et al., 2019). Our results also match well with findings from some major cities, such as Nanjing, China (9.4 million residents), where entertainment opportunities were found to increase dockless bike-sharing usage, but impede docked bike-sharing usage (Ma et al., 2020).

Employment opportunities were found to be a relevant determinant

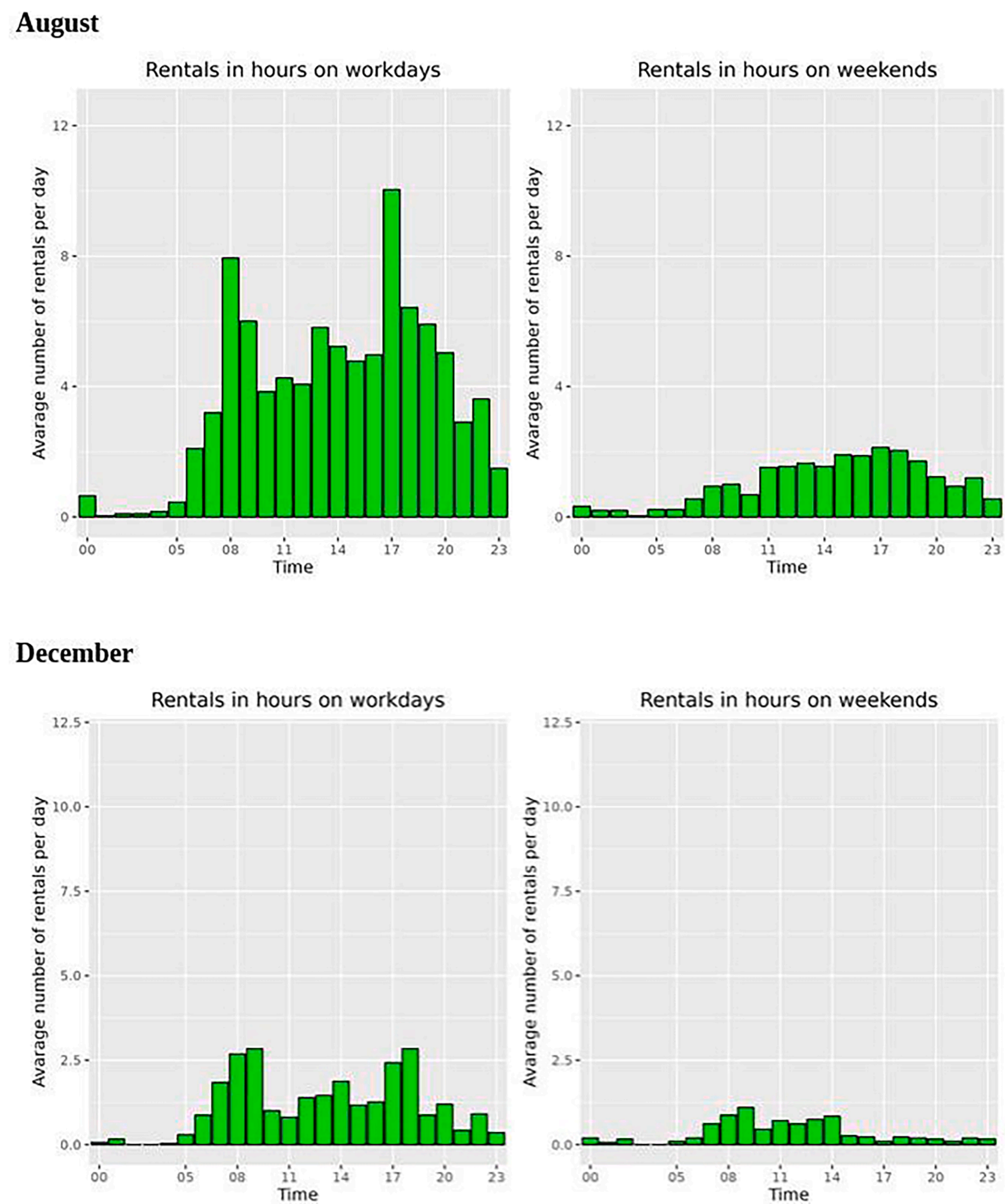

Fig. 5. Average rentals per day in workdays and weekends in August and December.

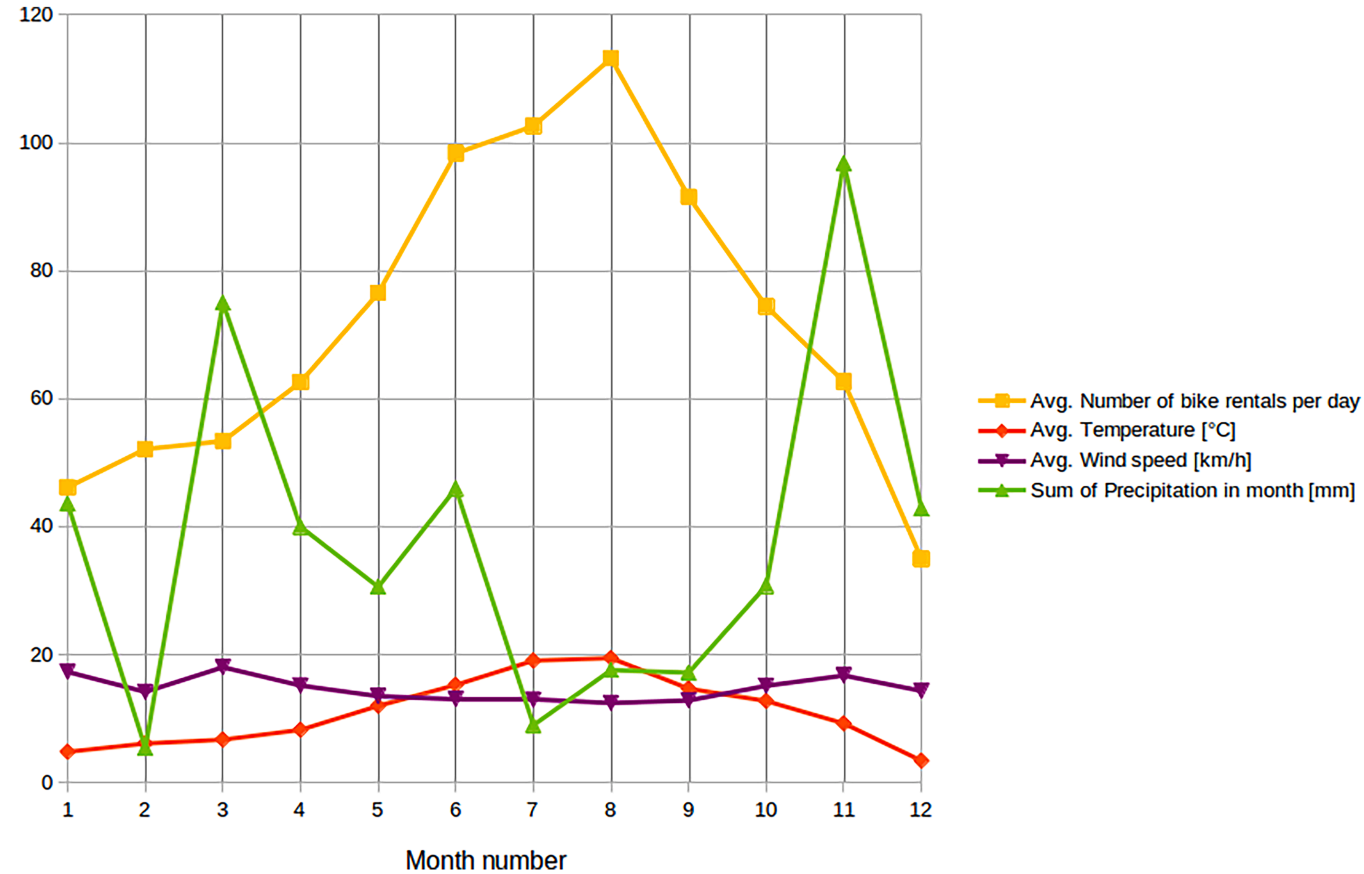

Fig. 6. Average number of bike rentals per month and average temperature, wind speed and sum of precipitation in every month.

Table 3
Average shared bikes riding distance and duration during weekdays, weekends, morning and evening peaks and off peaks.

Period	Avg. duration of bike rental (minutes)	Standard deviation of duration	Avg. distance of shared bike trip (km)	Standard deviation of distance
All year	24.15	22.86	3.06	1.94
Weekday	23.12	21.99	3.02	1.88
Weekend	27.39	25.14	3.21	2.12
Morning peak (7-9 a.m.)	18.59	13.61	2.89	1.53
Evening peak (5-6 p.m.)	21.31	18.47	3.13	1.95
Off peaks	25.42	24.45	3.08	1.99

of bike-sharing demand in some larger cities, such as Hamilton, Canada (569,000 residents; Scott & Ciuro, 2019). The study also confirmed the significant impact of weather-related variables. However, the role of proximity to public transport, which was found to be significant in Milton Keynes, had not been considered. Another study of seven US metropolitan areas found a positive effect of employment opportunities in one case (Nasri et al., 2020). One of the few studies to have looked at the linkages between bike-sharing and public transport in small or medium-sized cities was a study in Ithaca, New York (30,000 residents), where bike-sharing was found to positively contribute to first- and last mile trips.

We did not find a significant effect of the density of cycling infrastructure on bike-sharing use. However, this finding should not be taken as a recommendation against investments aimed at cycling network expansion. As pointed out by El-Assi et al. (2017), most bike-sharing systems are implemented in major cities where the possibility of cycling in many areas is severely limited by heavy traffic and lack of suitable infrastructure. Milton Keynes may be characterised as a car-centric city in several aspects, but somewhat paradoxically it also has an extended cycling network coverage.

As far as we know there is only one paper which examined the relation between bike-sharing and public transport in a medium-sized city (Hui et al., 2023). This research about Reno and Sparks, Nevada, USA (combined population of around 300,000) indicates that repeat bike users' trips that begin or end near the same bus stop are more strongly linked with proximity to bicycle lanes but tend to be further from recreational spaces like parks and casino resorts. There are few papers that show positive statistical association between bike-sharing rentals and public transport for cities larger than Milton Keynes, such as Poznań, Poland (Radzimski and Dzięcielski, 2021) or Tel Aviv (Levy et al., 2019) with the populations around 500,000, Las Palmas de Gran Canaria, Spain (Maas e al., 2020) with population of over 600,000 or Brussels, Belgium with population of around 1,200,000 residents (Dobruszkes and Dziecielski, 2023).

7. Conclusions

Despite being once considered a showcase of innovative urban planning practice, nowadays Milton Keynes is confronted with several challenges, which are also experienced by other cities around the world. Given the urgent need for action in the face of human-induced climate change, reducing car dependence by increasing the use of low-emission travel modes is undoubtedly a genuine challenge. At the same time, empirical evidence on the impacts of emerging low-emission solutions such as bike-sharing has been much scarcer in medium-sized cities compared to large cities and megacities.

Set against that background, in this paper we looked at the spatial

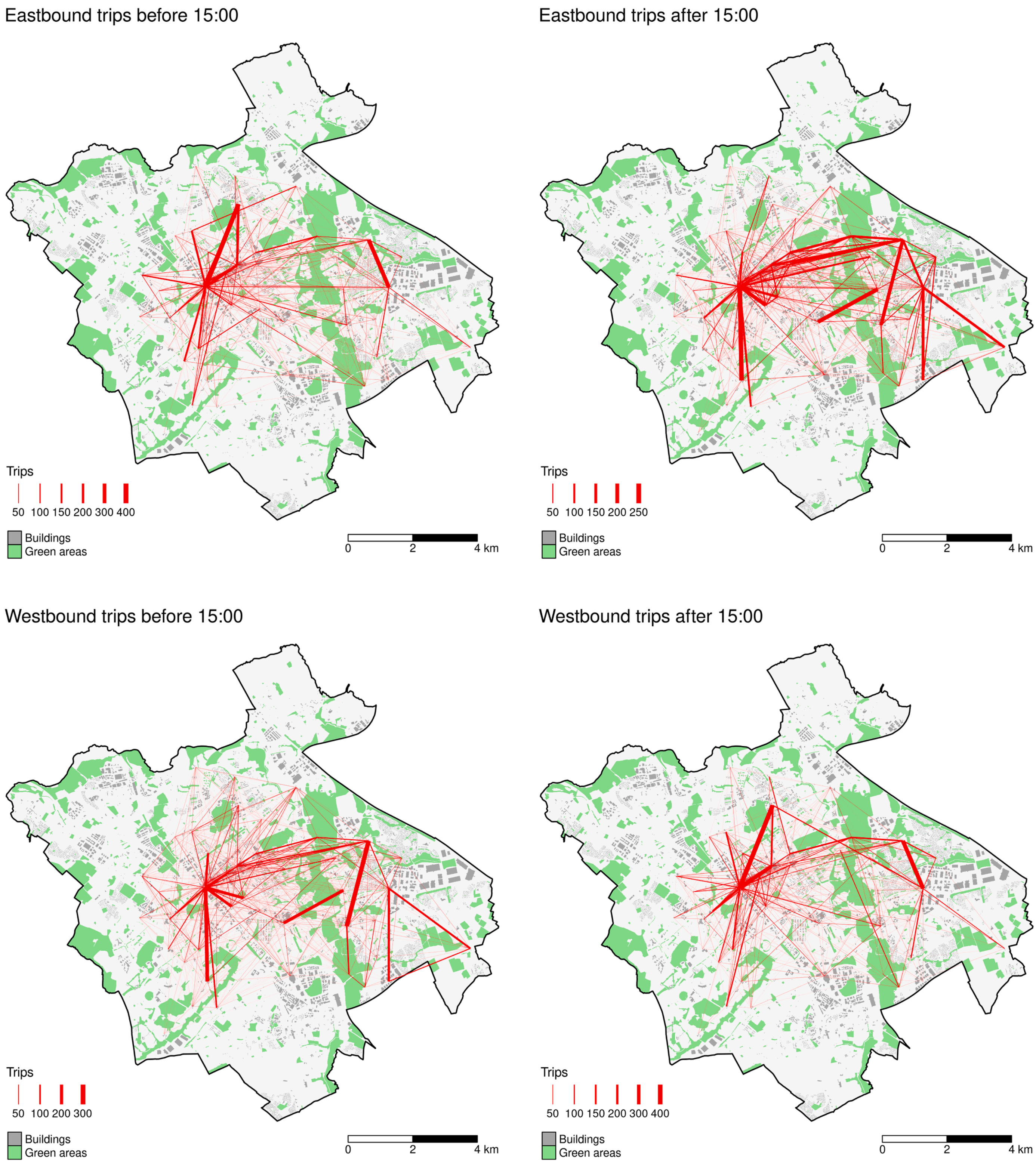

Fig. 7. Eastbound and westbound travels before and after 15:00 (3PM).

Table 4
Summary of global autocorrelation test.

Period	Moran's I statistics	p-value
Year	0.054820	0.13
August	0.098117	0.06
December	0.013488	0.29

and temporal distributions of bike-sharing trips in Milton Keynes, observed over the period of one year (June 2022 to May 2023). Using disaggregated data, we compared the hourly, monthly and seasonal distributions of trips as well as developed a spatial regression model with the purpose of identifying factors relevant to bike-sharing usage patterns in Milton Keynes. Our results suggest that the popularity of bike-sharing in this city is strongly dependent on the weather, as the

Table 5
Summary of regression results by time span.

	Model			
	Year Estimate	August Estimate	December Estimate	
(Intercept)	1.1069 **	1.5115 *	0.3673	**VIF**
	[0.3997]	[0.6856]	[0.2215]	
Public transport	0.2882 ***	0.3703 **	0.1431 ***	1.671161
	[0.0689]	[0.1183]	[0.0382]	
Tourism	-0.1584	-0.1341	-0.0552	1.878223
	[0.1659]	[0.2846]	[0.0920]	
Park	-0.0379	0.5961	-0.0238	1.630020
	[0.3392]	[0.5819]	[0.1880]	
Office	2.1194 ***	3.1042 ***	1.2266 ***	1.539131
	[0.3961]	[0.6794]	[0.2196]	
Industrial area	-0.1219	0.4548	0.1291	1.175671
	[0.4620]	[0.7924]	[0.2561]	
School	-0.8838 **	-1.5183 **	-0.4355 *	1.403321
	[0.3130]	[0.5369]	[0.1735]	
Mall	-0.7392	0.5887	-0.6347	1.627917
	[0.6857]	[1.1762]	[0.3801]	
Cinema	0.6909	1.1095	0.6894	1.407834
	[0.7722]	[1.3246]	[0.4281]	
University	1.8184	2.3658	0.8009	1.953273
	[0.8973]	[1.5603]	[0.5043]	
Popultion density	-0.4154	-0.7682	-0.0733	1.421114
	[0.4286]	[0.7353]	[0.2376]	
Cycleway	0.21059	0.4044	0.24060	1.186886
	[0.42259]	[0.7249]	[0.23428]	
Multiple R-squared	0.7803	0.7221	0.7652	
Adjusted R-squared	0.7112	0.6347	0.6913	

Signif. Codes: 0
*** ’ 0.001
** ’ 0.01
* ’ 0.05 ‘.’ 0.1 ‘ ’ 1

number of rentals during the summer months was significantly higher than those during the winter months. A second important finding was that bike-sharing was used much more frequently on weekdays than on weekends. Thirdly, by investigating hourly usage we found two distinguished peaks in the morning and evening hours. This leads us to a conclusion that the temporal patterns of bike-sharing usage in Milton Keynes correspond with commuting use more than recreational use.

The findings are corroborated by regression analysis, which allowed us to identify public transport stops and office buildings as key explanatory variables of bike-sharing trips. By contrast, we did not find tourist places or recreational spots such as parks or cinemas to be significant, and the results for universities were ambiguous. We also found some evidence of recreational trips, such as a strong afternoon/evening peak observed during the summer. Yet, in Milton Keynes the use for commuting appears to predominate. Due to the significance of proximity to public transport stops, we also find some evidence for the use of bike-sharing as a first/last mile travel mode. Our results demonstrate that in cities where a car-oriented approach has become entrenched in the planning practice, as it happened in Milton Keynes, bike-sharing may be a travel mode used on a regular basis.

Considering policy recommendations, our findings indicate that bike-sharing may be a viable option for medium-sized and car-oriented cities, in which the demand primarily depends upon local user base. It seems therefore that the characteristics of the bike-sharing system itself, such as affordability, maintenance and integration with public transport, may be more relevant to success than the characteristics of the city.

Our study has certain limitations. Firstly, the data sources we looked into only contain information about physical movements in space but lack any indication of motivations of bike-sharing users or their socio-economic characteristics. Further research may seek to combine both sources in an attempt to better understand the causal factors of bike-sharing use. Secondly, the geographical limitation of a case study, which is a medium-sized European city, may limit the transferability and generalisability of findings. Yet, due to relative under representation of cities of that size in the literature, we believe that the findings offer useful insights to both researchers and practitioners interested in understanding the determinants of bike-sharing usage.

CRediT authorship contribution statement

Michał Dzięcielski: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Alexandros Nikitas:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Adam Radzimski:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Brian Caulfield:** Writing – review & editing, Writing – original draft, Validation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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