Weather to scoot? How weather shapes shared e-scooter ridership patterns

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Weather to scoot? How weather shapes shared e-scooter ridership patterns

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Abstract

Weather, climate, and daily human mobility patterns are inextricably linked, and so quantifying and examining these patterns is essential for smarter urban policy and design that are tailored to support our daily mobility needs and foreground urban sustainability. This study provides an empirical approach to better understanding the interface between weather, climate, and daily human mobility on more than 800,000 shared e-Scooter trips across subtropical Brisbane, Australia. We find that the number of eScooter trips increases with heat and declines with rain. However, results reveal that the 'connectivities' between land use types remain stable irrespective of weather conditions while trip distance contracts during inclement weather. As such, weather influences the appeal and distance of eScooter trips but seemingly not trip purpose.

Keywords: weather, e-scooter, land use, rain, heat index

Introduction

Weather is intertwined in our daily mobility decisions. It influences *where*, *when*, and *how* we travel, which in turn has collective implications including congestion, pollution, and travel experiences (Liu et al., 2015; Tao et al., 2018; Wei et al., 2019). In an era characterised by shared mobility alternatives *and* a rapid transition to decarbonised transit, there is a need to understand how weather impacts daily travel patterns (Böcker, et al., 2013; Koetse & Rietveld, 2009). Among all transport modes, active transport and micromobility—including shared e-scooters, e-bikes, and bicycles—are known to be the most impacted by weather given the user's level of exposure (Helbich, et al., 2014), yet also present an important part of a solution for transport planners focussing on sustainability and rechargeable alternatives to the status quo.

E-scooters represent the newest addition to the shared micromobility space. Since the September 2017 launch of the first e-scooter scheme in Santa Monica, California, e-scooter schemes have spread to more than 200 cities worldwide, with growth expected to continue (VanderZanden 2020). Scholarship investigating this emerging micromobility technology and service is somewhat lagging as the data generated from these schemes has not been made widely available to the research community (Zou et al. 2020). What we do know from the shared e-scooter scholarship is that trip purpose is generally recreational (Caspi et al., 2020), users tend to be younger, more educated, and male (Christoforou et al. 2021), trips concentrate in city centre locales (Bai et al., 2020; Huo et al., 2021), most trips are short in duration (typically less than 15 minutes) and concentrated towards particular periods of the day and week (Mathew et al., 2019).

While there exists a deep body of scholarship examining the factors impacting other micromobility options such as bike-sharing schemes (Eren & Uz, 2020; Pojani et al. 2020; Fishman, 2016) and including the effect of weather and climate (Corcoran et al., 2014; Bean et al. 2021), their role on electric micromobility has been largely overlooked. An understanding of how weather impacts e-scooter usage remains limited, which is in part attributable to the newness of the technology and its initially slow adoption. At a time when sustainable urban transport is a priority, the need for an empirical measurement of the impacts of weather on daily mobility is important in shaping our understanding of the suite of factors that together condition our day-to-day micro-mobility decisions.

In the current study, we examine how weather shapes e-scooter usage dynamics in Brisbane, a subtropical city on the Australian east coast. More specifically, we aim to unveil the way in which local weather conditions shape the trip tempo, destination choice, and spatial patterns. To achieve this aim, we examine individual trip-level data collected by Neuron—an e-scooter sharing company—over the period March 2020 to February 2021, representing the company's first 12 months of operation in Brisbane. Prior to proceeding to the empirical study, we summarise the emerging literature on e-scooter transport and mobility, with a focus on weather impacts on e-scooter dynamics.

Background: e-scooters, weather, and land use

Table 1 summarises the findings from sixteen e-scooter studies that focus on the relationships between this mode and weather and climate. Most of these studies are set in the United States and/or examine case study contexts characterised by temperate climates. This small body of work employs a range of quantitative methods and a diversity of data sources, including user surveys, travel diaries, and e-scooter GPS-trails made available to the research community via vendors or open-data Application Programming Interfaces (APIs) and repositories. Studies ostensibly focus on the usage patterns of shared e-scooters rather than private e-scooters. A synthesis of these findings is summarised in Table 1.

Table 1. Summary of studies on e-scooters, weather, and land use.

Study authors	*Study location and climate**	*Key findings*
Studies set in the United States		
Bai et al. (2020)	Austin, TX, USA *Humid subtropical (Cf)* Minneapolis, MN, USA *Temperate continental (Dc)*	e-scooter usage is concentrated in downtown areas, city centres, and at university campuses and is associated with transit services, greater land-use mix in both cities, and commercial areas, and parks, specifically in Austin. Ridership also peaks in the afternoons and troughs at nights in Austin whereas the trough is in the morning for Minneapolis.
Caspi et al. (2020)	Austin, TX, USA *Humid subtropical (Cf)*	e-scooter trips are typically recreational and at the city centre, and predominantly start and end in residential, commercial, and industrial land use types, and near bus stop locations.
Noland (2021)	Austin, TX, USA *Humid subtropical (Cf)*	e-scooter usage is less sensitive to weather conditions than cycling. e-scooter use declines in colder, rainier, and windier weather, as well as extreme heat and high relative humidity. Public events spur e-scooter usage.
Noland (2019)	Louisville, KY, USA *Temperate continental (Dc)*	While rain and snow reduce e-scooter usage, changes in average temperature and wind speed have minimal effect on total daily trips. Travel distances decline in windy weather and increase during warmer temperatures. Speeds also increase with warmer temperatures.
Younes et al. (2020)	Washington, DC, USA *Temperate oceanic (Do)*	Dockless e-scooters ridership is less sensitive to weather than dockless bike-sharing ridership.
Sanders et al. (2020)	Tempe, AZ, USA *Dry arid (Bw)*	Survey results reveal that users prefer riding e-scooters to walking in hot weather.
Mathew et al. (2019)	Indianapolis, IN, USA *Temperate continental (Dc)*	e-scooter usage declines in the morning and just 15% of e-scooter trips exceed an hour in duration.
Huo et al. (2021)	Austin, TX, USA *Humid subtropical (Cf)* Minneapolis, MN, USA *Temperate continental (Dc)* Kansas City, MO, USA *Temperate continental (Dc)* Louisville, KY, USA *Temperate continental (Dc)* Portland, OR, USA *Temperate oceanic (Do)*	e-scooter ridership increases with population, employment, intersection density, and land-use mix, and decreases according to the median age of the nearby resident population and proximity to the city centre.
Hosseinzadeh et al. (2020)	Louisville, KY, USA *Temperate continental (Dc)*	e-scooter use peaks on Saturdays (1:00pm-5:00pm), and concentrates towards commercial land-use, away from industrial land-use both during on- and off-peak periods.
Ziedan et al. (2021)	Louisville, KY, USA *Temperate continental (Dc)*	e-scooter ridership is not associated with nearby bus ridership but is negatively associated with rain and snowfall.
Studies set outside the United States		
Reck et al. (2021, 2022)	Zurich, Switzerland *Temperate oceanic (Do)*	Rain is negatively associated with choosing e-scooters.
Hardt and Bogenberger (2019)	Munich, Germany *Temperate oceanic (Do)*	Users report that e-scooters are viable for most daily trips, and charging infrastructure is sufficient whereas subjective safety, adverse weather conditions, and baggage capacity are limiting factors.
Christoforou et al. (2021)	Paris, France *Temperate oceanic (Do)*	e-scooter users are typically male, aged 18-29, and highly educated, and the key motivations for using e-scooters are travel

Study authors	Study location and climate*	Key findings
		time reductions and playfulness. Trips last 15 minutes on average.
Almannaa et al. (2021)	Riyadh, Saudi Arabia *Dry arid (Bw)*	Extremely hot summer weather (~45°C) is a major barrier to e-scooter use.
Zhu et al. (2020)	Singapore *Tropical wet (Ar)*	Rainfall and high temperatures at noon suppress e-scooter use. e-scooters are used 3.15 times per day on average; most are used for less than 20 min (hence most shared e-scooters are idle most of the time). e-scooters are redistributed by car, thus producing extra vehicular trips, GHG emissions, and high operational costs.
Heumann et al. (2021)	Berlin, Germany *Temperate oceanic (Do)*	e-scooter trips peak near transit around 8 am on weekdays suggesting these e-scooters are addressing the first and last mile of commuter trips.

*Based on the Trewartha climate classification.

E-scooter ridership is primarily recreational and to a lesser extent, e-scooters are used for work-related travel including commuting and first/last mile trips connecting transit stops to endpoints. Users report enjoying e-scooters' speed, reliability, fun, low cost, and convenience. As with cycling, most e-scooter users tend to be younger, male, and more educated. Most trips are shorter than 15 minutes, and take place within downtown locales, parks, and university campuses. Overall, shared e-scooters are in operation for a relatively small portion of the day.

Table 1 reveals that e-scooter trips are sensitive to the prevailing weather conditions. There appears to be some variability across cities and between different climatic contexts, but the extant studies are too limited, and their methodology too varied for a systematic comparison. There is some evidence to suggest that e-scooter ridership is less sensitive than bikeshare ridership to adverse weather—although travel distances and speeds are lower in cool, windy conditions, and ridership declines with precipitation, strong winds, and high temperatures. Conversely, travellers prefer e-scooters to walking in hot weather.

In relation to land use, studies attribute e-scooter usage to characteristics of the built environment in cities. Compact, mixed land uses, and commercial land uses were associated with increased e-scooter usage (Jiao & Bai, 2020; Tuli, et al. 2021) whereas industrial areas have been found to reduce trip densities (Hosseinzadeh, et al. 2021).

While the existing literature provides a broad foundation, the scholarly understanding of e-scooter usage remains incomplete. More case studies and eventually cross-national and cross-climatic studies and meta-analyses are required for developing a fuller understanding of the weather and climate impact on e-scooter ridership. This is important in the current era of climate crisis coupled with a rapidly progressing energy transition toward rechargeable vehicles—and their dedicated infrastructure. Studies predict that some cities will shift in their climate zone categorisation (Irfan et al. 2019), and this will likely affect most weather patterns in those cities. Moreover, climate change may manifest itself as an increase in extreme weather events—e.g., heatwaves, floods, and storms—rather than as a gradual increase in average temperatures. Hence the effect of weather on scooting—and micromobility more generally—remains an important focus for research.

Methodology

The case study context, datasets, and analytic approach are discussed next.

Case study context

Brisbane is the Queensland state capital city with 1.3 million inhabitants and the third-largest Australian city in terms of population. The population density is low by international standards at 845 inhabitants per square kilometre (ABS 2016), and it is primarily auto-centric suburban development that produces a strong tendency toward single-family living (Willing and Pojani 2017). The city is divided by a meandering river (i.e., the Brisbane River), and the Central Business District (CBD) is located in a river peninsula (Sigler et al. 2016). Given this monocentric urban form, the transit network tends to be inwardly oriented toward the CBD. The implication of this is that trips to and from the CBD are efficient by public transit but relatively inefficient when circling around the urban form. This may explain Brisbane's high car ownership and usage rates by global standards with more than 85 percent of households owning cars (ABS 2016), and more than 50 percent owning more than two cars (ABS 2016). However, car-free households generally concentrate within the higher density and more walkable suburbs in the inner city.

Overall, micromobility use in Brisbane is limited. While many people walk and cycle for recreation, fewer than 2 percent of commuting trips are by bicycle and fewer than 10 percent are on foot (ABS 2016). Some portions of Brisbane are hilly, and the summers can be hot and humid[1] —factors which are known to reduce the appeal of cycling on conventional bicycles. The Brisbane City Council reports that there are approximately 1,000 kilometres of bikeways but notably these are typically a painted line to delineate cycleways from cars rather than protected or dedicated cycleways. There are, however, a few high-quality cycling paths—currently shared with e-scooters—that are situated in the city centre and along the Brisbane River and adjacent suburbs. However, the 'motorised' nature of e-scooters means that some ambiguity remains as to whether e-scooters belong on footpaths, bikeways, or roadways. Regarding shared micromobility, CityCycle was a docked bike-sharing scheme launched in 2012 that led to a slight increase in cycling rates but this public service ceased in 2021 and has now been replaced with dockless public e-bikes.

Alongside dockless public e-bikes, Brisbane was the first Australian city to allow shared e-scooter services (Field and Jon 2021). Two schemes were launched in 2019 i.e. Neuron and Lime with the latter replaced by Beam in 2021. These are dockless, powered by a rechargeable battery with a range of 20-60 kilometres per charge and top speed of 25 kilometres per hour. As of 2021, Neuron and Beam's combined fleet comprised about 1,500 vehicles that serve about 5,000 trips per day (Dennien 2021). The proportion of the commute trips taking place by e-scooter is currently unknown since the most recent census was collected in 2016 and thus prior to e-scooters in Brisbane. The rate for these shared e-scooter services is AUD$1 to unlock and 30 to 45 cents per minute for casual users with discounted daily, weekly, and monthly passes available for regular users. Micromobility advocates claim that e-scooters will shift short-distance travellers away from cars—if they can avoid the usual complaints around speed, littering and safety (Sipe and Pojani 2018; Field and Jon 2021).

Data

This study draws on three datasets: (1) e-scooter trips; (2) land use; and (3) weather. These are described below.

[1] The average daily high was 29.7 degree Celsius during January 2022 according to the Bureau of Meteorology

E-scooter trip data

The e-scooter data was supplied by Neuron covering the period March 2020 to February 2021 and captures all scooter trips that begin or end within Brisbane's inner city[2]. The data includes in excess of 800,000 trips and for each trip contains the GPS trace of the path taken between the point of origin and destination.

Land-use data

Land use data at the mesh block level is used to differentiate between six types of primary land use. These data permitted us to capture differences between residential, commercial, education, hospital/medical, industrial, and transport settings. Mesh blocks are the smallest geographical census unit designed by the national statistical agency, the Australian Bureau of Statistics. The primary land use is determined by aggregating the individual land parcels that form the area covered by the mesh block, and residential mesh blocks typically include between 30 to 60 dwellings (ABS, 2021). See Appendix A for the spatial distribution of Mesh Blocks across the case study context.

Weather data

Brisbane is characterised by a humid subtropical (Cf) climate based on the Trewartha classification (Belda et al., 2014). Hourly data for rainfall and the heat index form the two weather parameters of interest given their established capacity to impact cycling (Bean et al., 2021). Hourly rainfall data were accessed from the "ERA5-Land" data set of the Copernicus Climate Data Store (CDS). Introduced in July 2019, these data provide historical weather data at a 0.1-degree resolution worldwide.

In addition, we also accessed data from the UTCI (Universal Thermal Climate Index) to capture a measurement of heat stress; an index specifically developed to measure thermal comfort for outdoor activities (Bröde et al. 2012) and is appropriate for the present study. The UTCI was created in 2009 to describe heat exchanges between the environment and the human body (Jendritzky et al., 2012). Recently, the index has been used to assess diverse health risks including heatwaves in Europe (Di Napoli et al., 2018) and to assess thermal comfort in outdoor recreational activities (Honjo et al., 2020). One of the four design requirements of the UTCI was that it is "appropriate for key applications in human biometeorology" as previous indices had proven inadequate for this e.g. by combining air temperature with one other parameter such as humidity or air speed.

The UTCI is deemed appropriate for our study based on Brisbane's historic climatic data[3]. These data are available as part of the "ERA5-HEAT" dataset (Di Napoli et al., 2021) at a 0.25-degree resolution and hourly worldwide. The gridded dataset can be accessed starting from 1979 and is available in near real-time.

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[2] Specifically, the bounding region for which eScooter trips begin and end is the Brisbane Inner City Statistical Area 4 (Australian Bureau of Statistics. 2020).

[3] UTCI is a multivariate parameter taking four input values i.e. 2 metre air temperature (Ta), 2 metre dew point temperature (or relative humidity, rH), 10 m wind speed (va) and mean radiant temperature (Tr). The technical details of the calculation may be found in Bröde et al. (2012), whereby a regression model or a look-up table is used. Bröde et al note that these two procedures are only valid within the bounds: $-50°C \leq Ta \leq +50°C$, $-30°C \leq Tr - Ta \leq +70°C$, $0.5\ m/s \leq va \leq 30.3\ m/s$, $5\% \leq rH \leq 100\%$ (with pa<50 hPa). Brisbane—this case study city—has not historically exceeded the temperature bounds—records: 2.3 to 43.2 °C from 1887 to 1986—and gusts seldom exceed 30.3 m/s (Bureau of Meteorology, 2022). No other limitations are known and so the use of this parameter is believed to be robust and appropriate for our purposes.

Analytic approach

Spatially integrating the three datasets described previously permits an exploration of the scooter-land use-weather relationship. As such for any scooter trip, we know the type of land use at the beginning and end of trips in addition to the prevailing weather conditions at these points in time. The analysis segments trips by rainfall—into two categories: dry and rain— and by the heat index—into three categories: low, medium, and high—for visual comparison. A "low" heat index is more than a standard deviation below the average heat index throughout this period, and a "high" heat index is more than a standard deviation above.

We used violin plots (Hintze & Nelson, 1998) for examining whether heat and rainfall influence the ridership of e-scooters, and smoothed LOESS (Local Polynomial Regression) plots (Sommer, et al., 2018) to examine whether further variation exists within the low/medium/high heat categories. We employed alluvial plots (Brunson, 2020) to reveal the extent to which travel between land use types changes according to weather and heat index. Finally, we used contagion mapping, also often termed "Comaps", to reveal the geography of the scooter-weather relationship (Corcoran et al., 2007). Comaps permit us to examine where e-scooter trips intensify geographically throughout Brisbane, and whether this intensification varies according to time of day, weather, or by heat index i.e. low, medium, and high. Time of day is categorised into four consecutive daily periods [6am-10am; 10am-2pm; 2pm-7pm; 7pm-11pm]. These times simply seek to segment the two traditional weekday peak hour periods alongside two-off peak periods, one morning/early afternoon and the second during the evening/nighttime.

All analysis was conducted using R (R Core Team 2019) version 4.1.1 and the pre-processing and analysis scripts are available to the research community upon request.

Study limitations

There are some notable limitations of the current study. The first relates to a lack of user information, which did not allow us to measure how weather impacts different types of users i.e., women, older adults, commuters, tourists, and so on. What we do know from the weather and cycling research is that user characteristics do matter (Nahal and Mitra 2018)—so there is opportunity for studies with access to user characteristic data to investigate variation within user groups. A second limitation is that we did not categorise routes nor unpack the effect of route characteristics on ridership. Understanding the level of protection from, and/or exposure to, prevailing weather conditions experienced on a given route would form an interesting follow up study. In the future, it would be useful to establish the way in which physical structures and vegetation on certain routes offer enhanced protection from inclement conditions and in doing so extend scooting.

Results

The results are presented in three parts: (1) heat and rainfall; (2) land use; and (3) spatial patterns. Table 2 summarises e-scooter trips by weather—i.e., heat and rain—and time —i.e., hour of day. Visualisations are provided in Figures 1, 2 and 3.

Table 2: e-scooter Trips by weather (rain and heat) and time period

Weather	Heat [Index]	Time [Period]	Observation [%]	Trip Kilometres [median]	Trip Minutes [median]
dry	low	6am-10am	1.3%	0.78	9.18
dry	low	10am-2pm	0.1%	0.86	13.43
dry	low	2pm-7pm	0.5%	0.81	12.59
dry	low	7pm-11pm	5.0%	0.9	16.14
dry	medium	6am-10am	4.0%	0.79	9.84
dry	medium	10am-2pm	5.3%	0.87	13.71
dry	medium	2pm-7pm	15.4%	0.85	12.61
dry	medium	7pm-11pm	17.8%	0.85	14.78
dry	high	6am-10am	1.5%	0.78	10.44
dry	high	10am-2pm	7.2%	0.81	12.62
dry	high	2pm-7pm	9.8%	0.82	12.11
dry	high	7pm-11pm	0.3%	0.79	13.24
rain	low	6am-10am	0.2%	0.8	9.28
rain	low	10am-2pm	0.0%	0.65	13.09
rain	low	2pm-7pm	0.1%	0.67	11.46
rain	low	7pm-11pm	0.5%	0.89	15.8
rain	medium	6am-10am	3.2%	0.78	9.9
rain	medium	10am-2pm	5.0%	0.83	13.21
rain	medium	2pm-7pm	7.7%	0.82	12.22
rain	medium	7pm-11pm	4.5%	0.84	14.38
rain	high	6am-10am	0.9%	0.78	11.04
rain	high	10am-2pm	4.8%	0.81	13.11
rain	high	2pm-7pm	4.8%	0.8	12.48
rain	high	7pm-11pm	0.2%	0.79	13.26

Violin plots (Figure 1) reveal the relationship between the number of e-scooter trips by heat and rain. Each of the three violin plots depict the number of trips taken in dry (red) and wet (blue) conditions. The left-hand plot captures trips taking place when the heat index is low and the right hand graphic when the heat index is high. In sum, the plots reveal that more trips are taken as the heat index increases, and that dry conditions produce more trips than wet ones. Rain appears to be less of a deterrent in warmer conditions.

Starting with the effect of rainfall, some subtle differences are visually discernible in the distribution of trips in wet and dry conditions. Of the total trips, 31.8 percent take place in wet weather and 68.2 percent in dry conditions. Following Corcoran et al., (2014), we computed a two-sample Poisson test to examine whether particular weather conditions—i.e., rain—are related to the number of trips taken. Consistent with the hypothesis that rain does not significantly affect the number of trips taken, the estimated ratio is 1.9 with the 0.95 confidence interval falling in the range [1.81, 2.00]. See Appendix B for more details of this test.

In terms of the heat index, there also exists a positive association between heat index and scooter trips per hour—as depicted by the peaks of each of the violin plots allied with the average displayed by the diamond symbols. This relationship is consistent for both wet and dry conditions, but with a higher number of trips per hour in dry conditions.

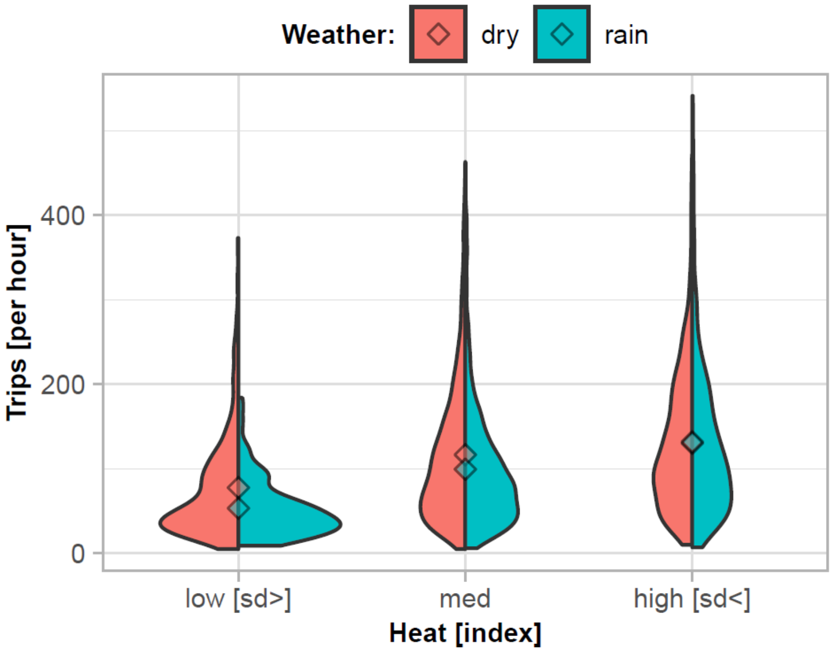

Figure 1: Hourly e-scooter trips by heat index (low/medium/high) and rainfall (wet/dry) for the start and end of a trip.

Figure 2 helps to build on the understanding depicted in Figure 1 by examining how weather—i.e., rain and heat—impact scooter ridership on a continuum. The increase in the number of trips per hour and increasing heat index is clear with the largest number taking place when the heat index is high. This same relationship also holds for trips taking place in wet conditions. Further, Figure 2 reveals an interesting peak in trip frequency when the heat index is ~38 (dry trips) and ~33 (wet trips) suggesting the weather conditions beyond these values begin to deter users. Another interesting observation is that when the heat index is high, the difference between the number of trips per hour in wet and dry conditions appears to be negligible. This relationship is also confirmed in Figure 1 wherein the means for the number of trips per hour are very similar indicated by the single diamond symbol in the violin plot.

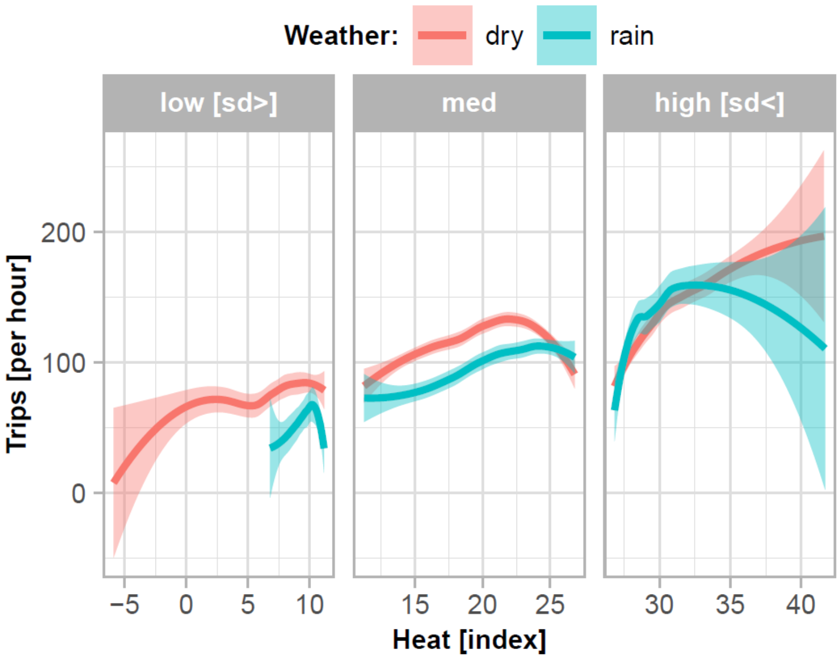

Figure 2: Hourly e-scooter trips by heat index (low/medium/high) and rainfall (wet/dry).

Figure 3 examines the relationship between the number of e-scooter trips by heat and rain and land use and by trip origin (start) and trip destination (end). Each individual alluvial plot captures the distribution of the two land uses comprising all trips for a given level of heat and rain. Thus the matrix of the six alluvial plots in Figure 3 collectively depict variations in land use, heat and rain. A visual inspection of the results in Figure 3 reveal remarkable stability in the land use types at the beginning and end of e-scooter trips irrespective of weather conditions.

There are several takeaway findings: Commercial, Parkland and Residential land uses comprise the majority of both the origins (95.5%) and destinations (95.0%) of all trips. The most frequent origin-destination land use combination is Residential to Residential comprising 20.9% of all trips, followed by Commercial to Commercial (15.1%), Residential to Commercial (12.6%) and Parkland to Parkland (8.1%). Notably, 7.7% of trips start during an hour with a low heat index and 16.2% of all observed hours had this low heat index whereas 29.5% of trips began in an hour with a low heat index and 17.1% of all observed hours had this high index. Likewise, 68.2% of trips start in an hour with dry conditions and 68.3% of all observed hours had these dry conditions; however, just 32.5% of days remained dry throughout an entire 24-hour period. These findings suggest that e-Scooters gain appeal during hot conditions and lose appeal during damp conditions.

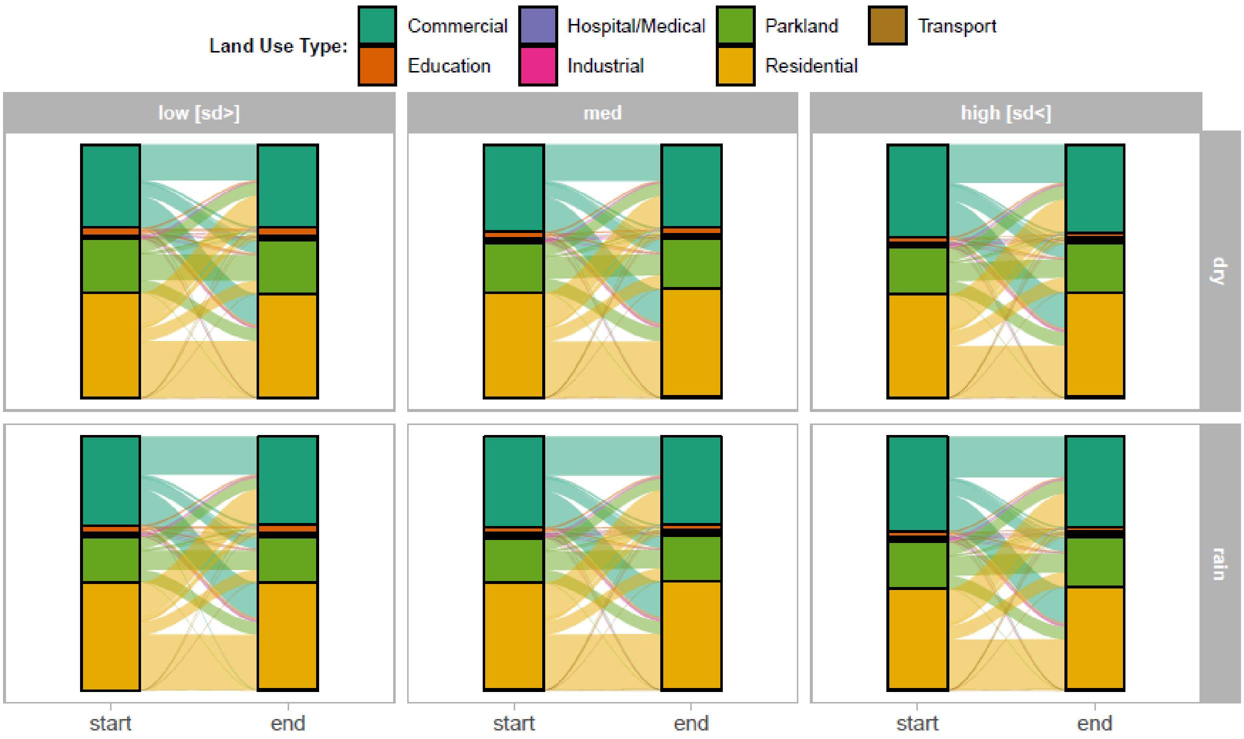

Figure 3: Land use at the start and end of a trip by heat index (low, medium, and high) and rainfall (wet/dry).

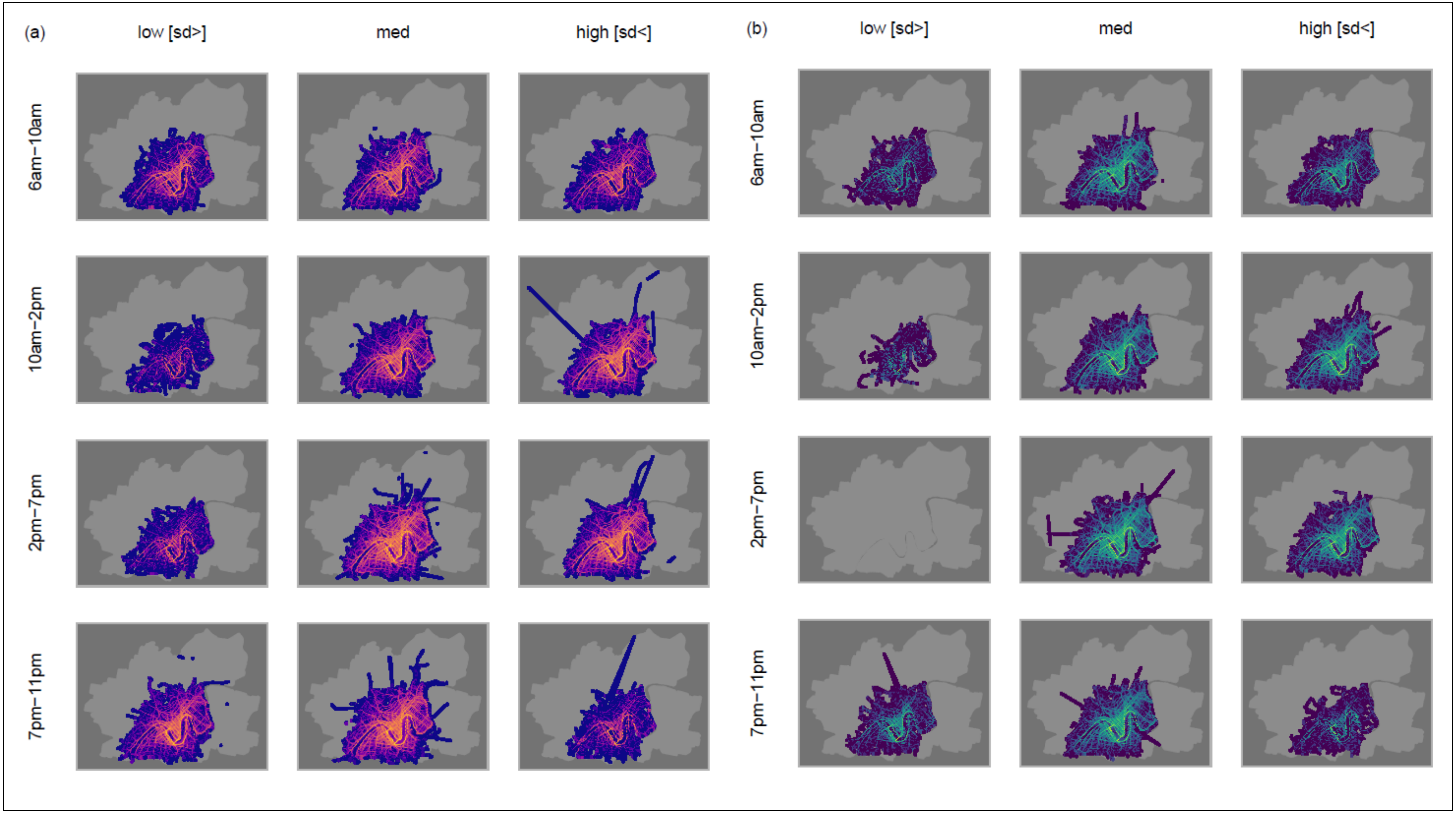

Figure 4: E-scooter trips during dry (a) and wet (b) weather by heat index (low/medium/high)[4].

[4] No scooter trips took place from 2pm to 7pm during wet conditions when the heat index was low.

Using two comaps, Figure 4 unpacks the geography of the weather-e-scooter relationship. Each individual plot captures the density of e-scooter trips within Brisbane for a given level of heat and time period. Lighter colours are used to represent higher densities of scooter trips and darker colours locales subject to fewer scooter trips. One comap captures this relationship for all scooter trips taking place during dry conditions (Figure 4a) and the other during wet conditions (Figure 4b). Thus, taken together Figure 4 depicts spatial variations in scooter trips by heat, time, and rain.

A visual examination of Figure 4 reveals three interesting yet subtle effects imposed by heat and rainfall. Firstly, areas proximate to the river are the locales where most scooter trips take place, a relationship consistent across all weather conditions i.e., heat and rain—these are areas that enjoy a high density of dedicated cycling infrastructure and home to the CBD, alongside a high concentration of restaurants and entertainment precincts. Secondly, the 2pm to 7pm window represents the period when scooter trips cover the largest physical area with more trips extending away from the river to the outer extremities of the e-scooter operating region —i.e., detailed by the light grey polygon. Thirdly, trips made in wet weather appear to be more spatially concentrated around the central business district and river locales than those in dry weather.

Discussion and conclusion

This study set out to explore how local weather conditions act to shape shared e-scooter usage dynamics. Through a descriptive analysis of 12 months of e-scooter trips in a subtropical city —Brisbane, Australia—we have determined that weather conditions do impose a series of subtle impacts on trip dynamics. Importantly, around 32 percent of e-scooter trips take place in wet weather—compared to ~28 percent[5] of bikesharing trips (Bean, et al., 2021). Also, a higher heat index leads to more e-scooter trips. Commercial, parkland and residential land uses comprise the majority of both the origins and destinations of all trips, regardless of prevailing weather. Most e-scooter trips take place in areas with dedicated cycling infrastructure, and wet weather leads riders to concentrate in those areas even more; possibly to avoid accidents on slippery roads. Unlike bike-sharing trips, which have a tri-modal distribution—i.e., morning and afternoon commute peak and lunchtime— e-scooters are more heavily used in the afternoon and evening. This suggests a larger recreational use.

The current study makes an empirical contribution to a small but emerging body of scholarship by providing evidence on e-scooter dynamics outside of the United States and in a warm climate. Our empirical approach is also useful to extend existing studies which examine micromobility changes in response to the Covid-19 pandemic (e.g., Li et al. 2021). Our data covers COVID-19, and the results do not reveal any substantive impact of the pandemic on ridership dynamics. Comparing our findings to two other studies from similar climatic settings—i.e., Austin and Singapore—we similarly find that rain suppresses scooter usage. In Singapore, high temperatures at noon tend to suppress e-scooter usage but this finding is inconclusive (Zhu et al., 2020). In Austin, lower temperatures and wind also reduce e-scooter usage but this reduction is less than that observed for bicycles i.e., e-bikes and docked bike-

[5] This figure relates to CityCycle trips that took place in 2014 when bicycles when 24-hour hiring was in place. In 2014 ~70 percent of days were dry days. A dry day is any 24-hour period that records less than 0.2mm precipitation.
In our e-scooter data, a dry day is also considered as any 24-hour period that records less than 0.2mm precipitation. Around 34 percent of days were dry days.

sharing. Clearly in the tropics and subtropics, people are more accustomed to year-round warm weather and do not tolerate temperature levels that might be considered as more typical in temperate climes. There is some evidence to suggest that in Brisbane there is a potentially greater tolerance for rain, acknowledging the need to ground this finding more formally via a cross-city comparison.

Given that most trips connect commercial and residential land uses, our study suggests that in addition to recreation, e-scooters are playing an important role in supporting Brisbane's inner urban mobility. With hot weather known to act as a deterrent to cycling, e-scooters may be an appealing and viable micromobility alternative in a city characterised by muggy summer days, and particularly for commuters wishing to avoid physical exertion and perspiration in business attire. Comparing the current findings to an earlier study of bikesharing in Brisbane (Corcoran et al., 2014), there is some preliminary evidence to suggest that weather might matter less for e-scooters. The lessened physical exertion required to use an e-scooter alongside the possibility of wearing more protective all-weather equipment might improve the e-scooter rider experience and therefore increase usage over bike-sharing in more inclement conditions (Noland, 2021). However, primary data is needed to unpack the extent to which the empirical evidence presented here accords with people's perceptions and behaviours.

Our findings hold practical implications for policy and planning. They contribute to an evidence base which is needed to inform smart urban design that is better tailored to our daily mobility needs. E-scooters form a small, but growing and potentially fruitful, addition to the range of micromobility and shared mobility options in contemporary cities. Bike-sharing programs have demonstrated potential to enhance active transport by providing valuable links between places lacking mass transit connectivity. Furthermore, they offer a potential solution to the vexatious first-mile/last-mile problem encountered by transport planners. E-scooters may serve much the same purposes.

E-scooters as micromobility solutions are certainly not a panacea. More specifically, it is unlikely that many shopping trips can be completed by e-scooter due to the lack of storage space for heavy items. The male-dominated nature of e-scooter users (Aman et al., 2021) suggests that women may be less inclined to use them as a transport mode, along with older and younger riders for whom speeds may be deemed unsafe. However, as a form of shared micromobility, e-scooters provide a viable and sustainable alternative to carbon-emitting vehicles; as their electric motors can be charged off-peak—e.g., at night—and from renewable energy sources. Thus, e-scooters can be considered as an individualistic expression of mobility. Considered alongside other shared mobility alternatives they form a component of our transition to decarbonised transit.

Our findings suggest that e-scooter riders (using a shared e-scooter service), like cyclists, prefer high quality, dedicated infrastructure. The micromobility paths of the future will need to be designed—and scaled —to accommodate multiple modes rather than solely bicycles. Cities could shift from the current design approach that segregates each mode into a dedicated space —e.g., a bus lane, footpath, bicycle path—into a simpler model segregating micromobility—e.g., e-scooters, bicycles, skateboards, mono-wheels, and so forth—and "macromobility"—e.g., cars, buses, trams, and eventually automated vehicles—into dedicated spaces to protect micromobility users and increase the appeal of choosing more sustainable transport modalities.

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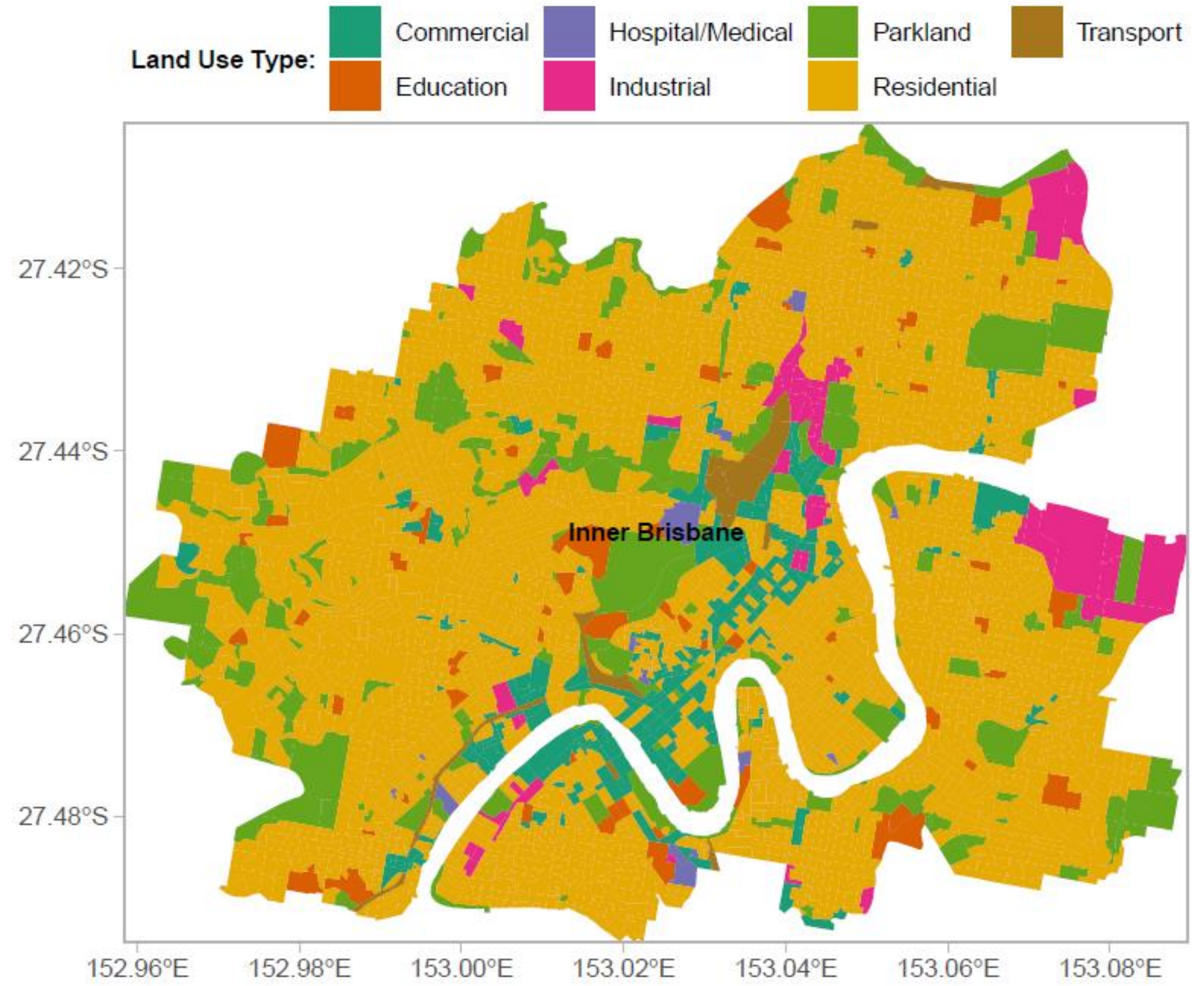
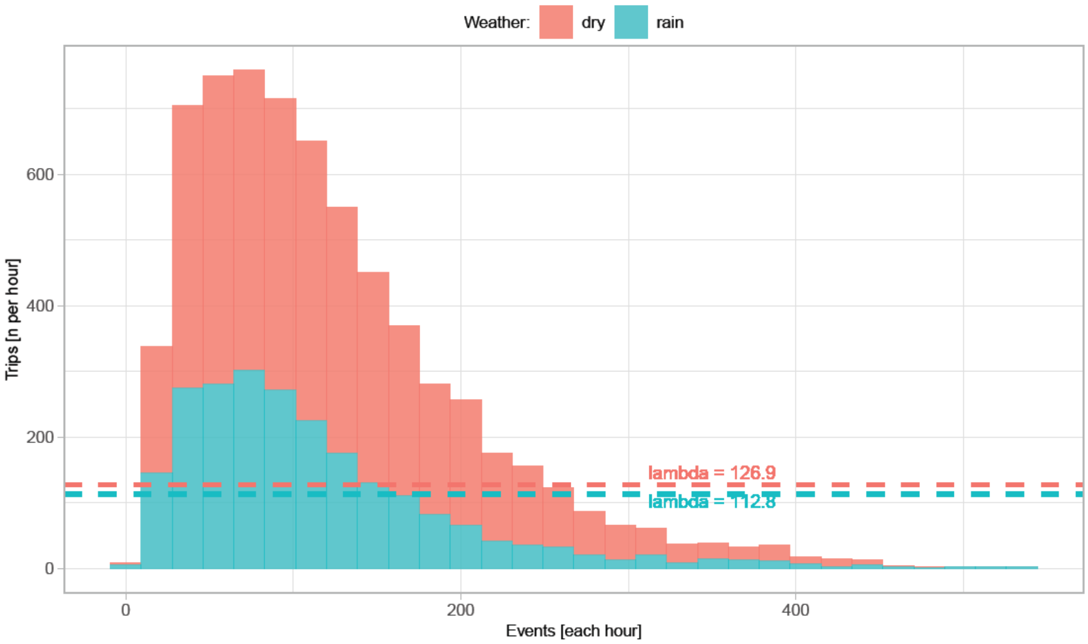
Appendix A

<u>Land use (by mesh block) across the case study context, Brisbane City, Queensland, Australia.</u>



Appendix B

Comparison of e-scooter trips taken in dry and wet conditions (Poisson two sample test).



Poisson two sample test results.

	Wet	Dry
Number of days	125	240
Number of trips	260,222	557,428

p-value for a two-sampled Poisson test assuming equal parameters 2e-16