Natural barriers facing female cyclists and how to overcome them

Abstract

Worldwide, the gender gap in urban cycling is staggering, with most cyclists being young to middle-aged men. In the current study we first seek to capture the suite of cycling barriers facing women before empirically investigating whether and the extent to which three natural barriers (inclement weather, hilliness, and darkness) impact female users of bikesharing systems. For the analysis, we spatially integrate gender for more than 200 million bikesharing trips with fine-grained weather, gradient, and sunset/sunrise data. Computing a suite of the generalized additive models for ten cities worldwide covering a period of 14 years, we find that wind and precipitation disincentivise cycling, and more so for women than for men. Similarly, steeper gradients are a significant barrier for female bikeshare users for many cities. In every city, women make fewer trips in the dark (i.e., before sunrise and after sunset) compared to men. Regardless of natural barriers, in higher-cycling cities, cycling declines less with age for women compared to other cities. To overcome the barriers presented by inclement weather, hilliness, and darkness we recommend (a) partial electrification of bikesharing fleets, (b) reduced exposure along bicycle paths (through manufactured shelters or tree canopies), and (c) adequate nighttime lighting along cycling paths.

Introduction

The gender gap in urban cycling is staggering. While many women would like to embrace cycling due to environmental or health concerns (Ravensbergen et al. 2019; Prati et al. 2019), in most countries, the majority of cyclists are young to middle-aged men. This skew in the cycling population is especially pronounced among commuter cyclists (Goel et al. 2022). In the Anglosphere (e.g., Australia, United States, Canada, New Zealand and the United Kingdom), women constitute just one-third of recreational cyclists and one-quarter of commuter cyclists (Garrard 2021). Further, in most European countries, there are more women than men who have never used a bicycle (see Prati 2018).

In high-cycling geographies (i.e., contexts whose cycling mode share is higher than 7 percent) women use bicycles as much as men (Goel et al. 2022). However, those settings are the exception rather than the rule and tend to be concentrated in north-western Europe (Germany, Netherlands and Denmark) and north-eastern Asia (China and Japan). According to a study of 17 countries across 6 continents (Goel et al. 2022), for women to be equally represented across all age groups, cities need to have a cycling share greater than 13%. Otherwise, cycling is the province of working-age women, with young girls and older women excluded (Goel et al. 2022). Some cities in low-and-middle-income countries, such as New Delhi (India), Kisumu (Kenya), and Bogota (Colombia), are more gender-imbalanced than could be expected from their overall cycling rates (Goel et al. 2022). Possibly, this owes to the fact that these countries are unequal and masculine in terms of culture (Hofstede Insights 2022).

Why should we care about the cycling gender gap? In fact, why should we care whether women cycle or not? While cycling is beneficial for all genders, women may stand to gain more from it because, according to the World Health Organisation, they tend to exercise less than men (WHO 2021). Meanwhile, women may need more of the type of exercise like cycling that builds bone density, strengthens muscles, helps manage weight, and ameliorates mood, as they are at higher risk of osteoporosis, arthritis, anxiety, depression, and a variety of autoimmune diseases (NLM 2018). Women generally prefer physical activity that is non-strenuous, incidental, and seamlessly incorporated into daily routines, and cycling meets that need (Garrard 2021).

A more implicit benefit of adequate cycling conditions is that children and older adults can travel independently by bicycle, saving mothers and other female caregivers much escorting time (Garrard 2021). Conversely, where cycling conditions are adequate, many women may want to cycle alongside their children as a way to perform 'good mothering' and role-model a healthy behaviour (Ravensbergen et al. 2019). Finally, cycling may even help women to feel more empowered, free, and confident in their bodies and abilities. For these benefits to be accrued, we need to gain a better understanding of the relationship between gender and urban cycling.

In the current article we first present the suite of barriers to female cycling grouped under six broad domains: *Psychology & Identity; Culture & Society; Income & Poverty; Built Environment; Health & Physiology;* and *Policies & Institutions*. This provides a framework through which to begin examining the underpinning causes and effects. Then we focus on the role of three natural barriers: inclement weather (precipitation, wind, and temperature), hilliness, and darkness. These factors fall within several of the domains we have identified and are known to affect cyclists in general (see Bean et al. 2021). However, up to now, few empirical studies have sought to examine differences between men and women (see Le et al. 2019). With discussions advancing around the climate crisis and its impact on cities and sustainability, some natural cycling barriers may increase or decrease among women (and other genders) depending on one's geographic location alongside culture, health, income, and other variables.

Research has already established the various ways in which weather impacts bikesharing usage dynamics (Lepage and Morency 2021; Bean et al. 2021; Tu et al. 2019; El-Assi et al. 2019; Heaney et al. 2019; An et al. 2019; Kim 2018; Lu et al. 2017; de Chardon et al. 2017; Rudloff and Lackner 2014; Gebhart and Noland 2014; Corcoran et al. 2014; Wygonik et al. 2014) but most studies do not report findings by gender. The effect of hilliness on bikesharing rates is also well researched (Cervero et al. 2009; Iseki and Tingstrom 2014; Parkin 2016; Braun et al. 2016; Mateo-Babiano et al. 2017; de Chardon et al. 2017; Le et al. 2019; Eren and Uz 2020; Scott et al. 2021; Tyndall 2022; Cubells et al. 2023), the consensus being that steep gradients lead to less cycling.[1] However, gender differences are not well known. The role of darkness in relation to bikesharing use remains nearly unexamined (see Noordzij 1976; Cubells et al. 2023 for a few exceptions). Therefore, this study helps expand our understanding of bikesharing operations, in addition to exploring gendered travel patterns (Pojani et al. 2022).

We chose to focus on bikesharing rather than cycling in general for two reasons. First, scrutinising gender gaps in bikesharing is necessary because this activity is known to attract more men than women, but the reasons for this disparity are poorly understood (Pojani et al. 2020). Second, there are major advantages in employing data harvested from digital bikesharing systems rather than relying on surveys or observations of cyclists. Gathering longitudinal and representative survey data is excessively costly and time-consuming. Population censuses are only run once every five to ten years, and only report data on commute travel during a single workday of the year. Other useful information, such as on weekend and recreational travel, is not collected. Travel surveys run by transport agencies often rely on panels which may not be representative of the general population. Also, surveys tend suffer from inaccurate completions. In contrast, some bikesharing schemes make data available on trip characteristics, users' age, vehicle type, and, until recently, users' gender.

The fact that most bikesharing systems no longer provide gender data makes this study particularly timely. We analyse more than 200 million bikesharing trips in ten cities worldwide over the course of 14 years. These are matched with fine-grained weather, gradient, and sunset/sunrise data, which are available through various public agencies. Before proceeding to the empirical portion of the article, we provide some background on the cycling barriers facing women.

Background: Barriers for women and cycling

Ideally, transport geographers of a feminist persuasion should consider both sides of the coin: how gender shapes mobility and how mobility shapes gender (Ravensbergen et al. 2019; Hanson 2010; Low 1999). With this mind, we have summarised the gender-specific barriers to cycling in Table 1. We expect most of these barriers to apply to bikesharing as well. The table has been developed based on foundational work by Loukaitou-Sideris (2020) on the transport-related barriers faced by women. To compile the table, we have relied on literature reviews (Hanson 2010; Garrard et al. 2012; Ravensbergen et al. 2019; Garrard 2021) or empirical studies that cover more than one country (Totaro Garcia et al. 2022; Le et al. 2019; Prati et al. 2019; Prati 2018) or city (Aldred et al. 2016; Butterworth and Pojani 2018), rather than attempting to account for every case study in this space.

Table 1. Cycling barriers facing women. Mentions of natural barriers are in bold font.

Barriers	*Causes*	*Patterns and/or effects*
Psychology & Identity	Fear of mugging and victimization	Avoidance of bicycles / Cycling only during **daytime** / only in certain places / only accompanied by others
	Fear of bicycle theft	Avoidance of bicycles, especially where secure bicycle parking is missing
	Parental fear of stranger-danger	Children not allowed to travel independently by bicycle / Children (esp. girls) escorted everywhere mostly by mothers
	Concerns over traffic safety / high sensitivity to risk (fatality/injury/near misses)	Avoidance of cycling in mixed traffic / cycling slowly and carefully (increasing trip length) / Avoidance of cycling along paths with potholes, gravel, debris
	Women may not see themselves as 'sporty' / have low confidence in their physical abilities	Avoidance of fast-paced on-road cycling
	Some cycling contexts are hypermasculine / cycling is used to perform masculinity	Women are uncomfortable cycling in public / girls fear being labelled a 'tom boy'
	Feminine body comportment is marked by restraint / hesitation	Women are reluctant to cycle
	Harassment/aggression from drivers and other male cyclists (e.g., for being too slow or clumsy)	Avoidance of cycling in mixed traffic
	Women have higher wayfinding anxiety / prefer different wayfinding strategies	Avoidance of cycling if infrastructure is confusing / lacks clear wayfinding signs

Barriers	*Causes*	*Patterns and/or effects*
Culture & Society	Women receive less encouragement to cycle throughout their lives	Avoidance of cycling, especially in adolescence and old age
	Some religious norms / practices around women's presence in public space	Banning women from bicycle ridership
	Fears that cycling causes virginity loss in girls	Banning women from bicycle ridership
	Women are primary caregivers for children / parents / domestic chores	Trip chaining / travelling with others / hypermobility / time poverty / carrying large items during travel
	Social ideals of appropriate female behaviour and appearance	Women avoid 'putting their body on show'
	Dress codes in workplaces / women expected to wear skirts/heels/makeup	Avoidance of bicycle for commuting, especially in **rainy / cold / humid weather** or where showers are missing at work
Income & Poverty	Lack of economic resources for bicycle ownership / modal affordability	Lack of access to bicycles / shift to walking
	Lack of economic resources for expensive equipment / accessories / clothing / repairs	Avoidance of bicycles / shift to public transport
	Lack of economic resources for bikeshare scheme membership / cycling club membership	Avoidance of bikeshare / cycling clubs, reduced opportunities for socialising
	Bicycle use as a symbol of poverty / low class	Middle-class women avoid cycling
Built Environment	Automobile-oriented urban form / sprawl / large distances between destinations	Overreliance on faster and/or less strenuous modes such as private automobiles
	Segregated land-uses / large distances between destinations	Overreliance on faster and/or less strenuous modes such as private automobiles
	Lack of adequate infrastructure for cycling	Avoidance of bicycles
	Concentric-radial urban patterns with jobs concentrated in CBDs	Avoidance of long cycling commutes from middle/outer suburbs to the CBD
	Preference for shorter cycling distances	Avoidance of long cycling commutes
	Cycling infrastructure often located in flood plains (along water bodies)	Avoidance of cycling in **wet weather** due to fear of floods
Health & Physiology	Preference for moderate-intensity physical activity / less vigorous travel	Avoidance of bicycles in **hilly topography / inclement weather**
	Less strength on average	Avoidance of bicycles if they need to be lifted to a storage space
	Pre-menstrual/menstrual symptoms / low energy and energy surges during those periods	Avoidance of cycling during part of the month
	Female low-centre anatomy / different cycling style	Avoidance of bicycles built for a male anatomy
	Women as primary caregivers for children & parents	Avoidance of bicycles because carrying others (i.e., children) on a bicycle is more strenuous
	Women are more health-conscious / bear more responsibility for their family's heath	Avoidance of cycling in polluted air / along **uncovered paths (sun exposure)**
	Pregnancy and longer life-spans for women	Physical ability to cycle may vary substantially over the life course
Policies & Institutions	Requirement to wear helmets while cycling interferes with hair coiffure	Avoidance of cycling to work
	Excessive focus on cycling infrastructure with low separation from cars along major roads	Avoidance of cycling on main roads
	Women are excluded from cycling sports	Perception that cycling is not for women
	Slow response to increasing flooding events (due to climate change)	Avoidance of cycling
	Male-dominated cycling services (shops/repair points)	Avoidance of cycling services that do not understand women's needs
	Male-dominated planning/engineering institutions	Gender issues in cycling given short shrift / Women uninvolved in planning processes

Note that some of the causes and effects in Table 1, especially in the *Health & Physiology* and *Psychology & Identity* domains, are speculative or based on anecdotal evidence and will need stronger empirical research evidence to substantiate. Also, some barriers are universal whereas others pertain to particular geographies, age brackets, ethnicities, and socio-economic groups (Ravensbergen et al. 2019). One of the strongest and ubiquitous barriers appears to be women's heightened perception of risk while cycling (Prati et al. 2019; Halefom et al. 2022) – although the actual risks of cycling are generally higher for men (Prati et al. 2019). Many women will only cycle on fully segregated bicycle paths (Le et al. 2019). This means that low-cost solutions such as sharrows or bike lanes involving a simple line painted on the asphalt are ineffective in attracting women (Teschke et al 2017, Garrard et al 2008). Drawing on the extant scholarship, we hypothesise that natural barriers such as inclement weather, a hilly topography, and darkness are another cause of the observed gender imbalance in cycling.

Methods

We examine data from 229,413,658 individual bikesharing trips undertaken across ten cities worldwide, recorded between February 2010 and January 2023 inclusive (Table 2). Six of the cities are in the United States (New York City, Chicago, Columbus, San Francisco Bay Area, Boston, Minneapolis), with the remaining schemes located in Australia (Brisbane), Finland (Helsinki), and Mexico (Mexico City and Guadalajara). By far the largest two bikesharing systems are in New York City and Mexico City, representing 78% of the total number of trips. Gender data is provided in all ten cities, but it is possibly skewed by cultural factors.[2] For this study, we consider only self-identified male and female users as there is insufficient information to distinguish between other possibilities (such as no answer, non-binary, intersex).

Table 2. List of cities studied, sorted by share of female users.

City Name	*Start Month*	*End Month*	*Total male trips*	*Total female trips*	*Female trips %*	*Link to data***
Columbus	Mar 2018	Mar 2020	30,131	5,524	15.5	CoGo
San Francisco Bay Area*	Jun 2017	Apr 2019	1,902,810	637,069	25.1	Bay Wheels
Chicago	Jun 2013	Dec 2019	12,235,830	4,112,553	25.2	Divvy
Boston	Jul 2011	Apr 2020	6,843,613	2,334,078	25.4	Bluebikes
Guadalajara	Dec 2014	Jan 2023	16,232,629	5,658,999	25.9	Mibici
New York City	Jun 2013	Jan 2021	74,574,098	26,339,265	26.1	Citi Bike
Mexico City	Feb 2010	Jul 2022	56,371,073	20,002,605	26.2	Ecobici
Brisbane*	Oct 2010	Mar 2015	423,938	185,073	30.4	CityCycle
Minneapolis*	Apr 2011/18	Nov 2012/19	380,283	196,815	34.1	Nice Ride
Helsinki*	May 2017	Oct 2017	568,686	378,586	40.0	City Bikes
Total			169,563,091	59,850,567	26.1	

*The Minneapolis system is open only April-November. The Helsinki system is only open May-October. For Brisbane, until 1 December 2013, bike hire was only available between the hours of 5am and 10pm. The San Francisco Bay Area includes San Francisco, East Bay (Oakland and Berkeley), and San Jose.

**We only provide a link where the data are publicly available.

The outbreak of the Covid-19 pandemic in January 2020 presents a challenge in terms of data comparability. More specifically, we do not know how lockdowns affected male mobility compared to female mobility in the cities studied. In five cities (New York City, Boston, Guadalajara, Columbus, and Mexico City), a portion of the bikesharing data was recorded in 2020 and after. In the other five cities, the data records stop by the end of 2019 at the latest. Other confounding factors, including system expansions, station closures, and price changes for bikesharing or public transport may have affected different categories of users in different ways (see Bean et al. 2021).[3] To counter these effects, we have performed the analyses on a yearly or monthly basis. The effects of wind and rain on gender are more easily detectable on a yearly basis, whereas monthly effects are seen in the gradient and time-of-day analyses.

The Brisbane data are limited by time-of-day while Minneapolis and Helsinki data are limited by month. If we apply the same restrictions to the rest of the data - that is, limiting trips to 5am to 10pm, April to November, and May to October - we find that the female ratio never differs by more than 2% from the female ratio calculated without the restrictions. Given this finding, we can divide the ten cities into three distinct groups with respect to the ratio of trips made by women: (1) Columbus with 15.5%; (2) New York City, Boston, Chicago, Guadalajara, Mexico City, and the San Francisco Bay Area with 25.1-26.2%; and (3) Brisbane, Minneapolis, and Helsinki with 30.4-40.0%.

The City of Helsinki conducts a large bi-annual survey of adult residents concerning cycling in the city. In 2020, the percentage of self-reported female cyclists was 51% (City of Helsinki, 2020), which is even higher than Helsinki's female ratio in bikesharing. In three other cities, we observed a strong *annual* growth trend in the percentage of female cyclists was observed in three cities: New York City (from 22.6% in 2014 to 32.0% in 2020), Brisbane (from 24.0% in 2011 to 34.2% in 2015), and Guadalajara (from 22.6% in 2015 to 27.2% in 2021). For New York City, this growth may be related to improvements in segregated cycling infrastructure (AitBihiOuali and Klingen 2021).

Some scholars (e.g., Totaro Garcia et al. 2022) have identified a significant link between the percentage of female cyclists and the modal share of cycling overall. Also, they have noted that bicycle use among women declines with age in low-cycling cities but not in high-cycling cities. For a more intersectional analysis, we plotted bikesharing users' gender and age for each city (Figure 1).[4] As seen in the figure, adolescents of both genders are only minimally represented. Most bikesharing users tend to be younger adults, with use nearly halving after age 35. While women cyclists tend to outnumber men in the 18-35 age bracket, men dominate the older age brackets. Helsinki and Minneapolis, which are high-cycling cities, are notably different from the others. Here, older women (46-75) cycle more than men.

To calculate the effect of weather (precipitation, wind, and temperature), hilliness, and darkness on female riders, we matched hourly bikesharing trip data with (a) hourly weather data, obtained through the European Centre for Medium-Range Weather Forecasts (ECMWF);[5] (b) digital elevation data, obtained from Japan Aerospace Exploration Agency's Advanced Land Observing Satellite (ALOS);[6] and (c) sunset/sunrise data, calculated using the *suncalc* package in R.

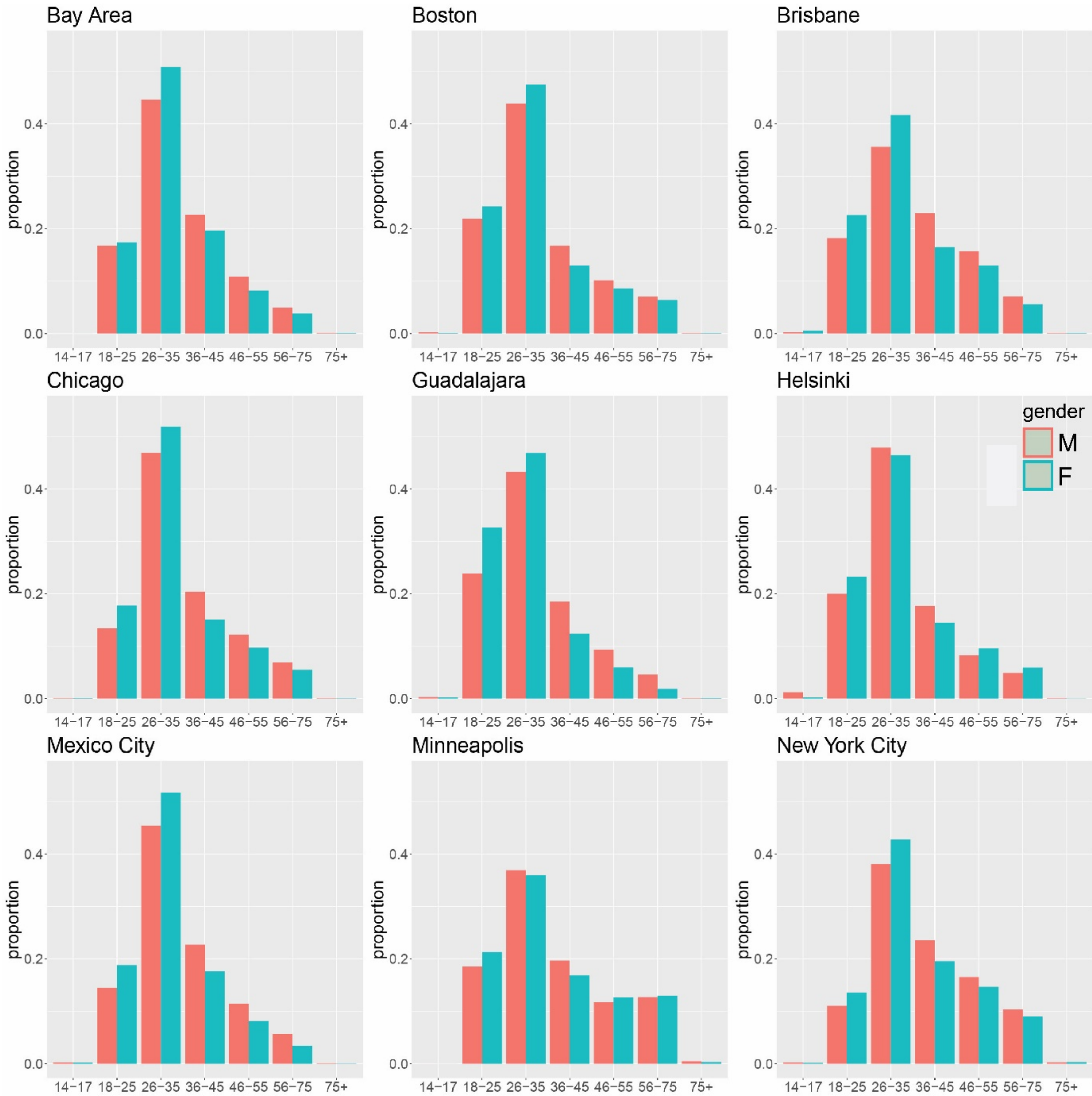

Figure 1. Gender versus age in nine cities. The male and female cyclist numbers are standardised (the sum of each age is adjusted to be 1). Columbus is excluded due to low cyclist numbers in each bin.

Models were computed using the "mgcv" package in R ("mixed GAM computational vehicle") to implement the Generalized Additive Model (GAM) (Wood 2012). This model is very useful for studying the effect of multiple predictor variables on a response variable. In this case, our response variables are measured hourly (male and female cyclists per hour) while the predictor variables are modelled non-parametrically (hour of day, day of year, temperature, precipitation, and wind) using splines or linear functions as necessary. To explore how gender interacts with the predictor variables, self-reported gender is considered as a categorical variable. Where possible, we split the gender data by weekend and weekday classifications because weekday and weekend bikesharing use is notably different (Todd et al 2021).[7] We have 53 years of data in total (Table 2). Given that weekdays and weekends needed to be considered separately, we have built a total of 106 models.

Table 2. List of complete years of data.

City	Complete years of data	Number of years
NYC	2014-2020	7
Boston	2012-2019	8
Chicago	2014-2019	6
Minneapolis	2011-2012, 2018-2019	4
Guadalajara	2015-2022	8
Mexico City	2011-2021	11
Brisbane	2011-2014	4
Columbus	2019	1
Helsinki	2017	1
San Francisco Bay Area	2018	3

Some cities provide information on the types of bicycles used in the system (classic vs electric, docked vs undocked).[8] Presuming that some of the barriers discussed here (such as steepness) may be removed using e-bikes, we also examined trip data by bicycle type. Future research could account for the weights of the shared bicycles and model the effect of headwinds, which have been shown to be a barrier. Prevailing trip directions in weekday mornings with a compass rose versus the prevailing wind would be an interesting visualisation. In some cities, the bikeways with the highest quality infrastructure may be undermined by the direction of the prevailing winds during peak commute times. Examining the effect of tailwinds is probably less important.

Results

Modelling results are presented to draw attention to significant gender differences in the ridership profiles for: (a) precipitation; (b) wind; (c) temperature; (d) gradient; and, (4) the proportion trips taken before sunrise or after sunset.

Inclement weather

The effect of the two weather factors – precipitation, wind, and temperature - are examined through a visual examination of GAM models.[9] We also checked the effect of temperature. For the analysis, we aggregated the data from 2014 to 2020 and built a Generalized Additive Model (GAM) for usage as follows:[10]

$$\text{Usage} = \text{gender} + s(\text{JulianDate}) + s(\text{Hour}) + te(\text{Hour}, \text{JulianDate}) + s(\text{temp}) + s(\text{rain}) + s(\text{wind}) + \varepsilon$$

ε: error term

We found that for the weekday model, all terms were significant with p-values less than 2e-16. Next, using the *gratia* package in R, we plotted the partial effect of rain by gender for a range of values of rainfall, with associated confidence intervals. Partial plots permit visualization of how a particular variable affects usage over the range of observed values. In the partial plots for New York (Figure 2), we display the 95% confidence intervals and where these are non-overlapping, this indicates a statistically significant difference for the relative interval. The "partial effect" values shown here refer to the log of the count data as we consider only hours with non-zero male and female usage.

The partial effect of precipitation for male versus female riders in New York is shown in Figure 2a. Note that the model was built from approximately 6,200 hours of data from weekdays in 2019, and of these only 14 hours have rain values greater than 5 mm. This makes it difficult to draw any clear inference for values of rain greater than 5 mm per hour. (In fact, adding in the term for rain without gender effects, the curve changes direction for values greater than 5 mm per hour, which suggests possible overfitting of the model.) However, the effect of rain is clearly different for male and female riders for rainfall between 1mm and 5 mm per hour. This accounts for 253 hours (or4% of the data coverage) of weekday riding in 2019.

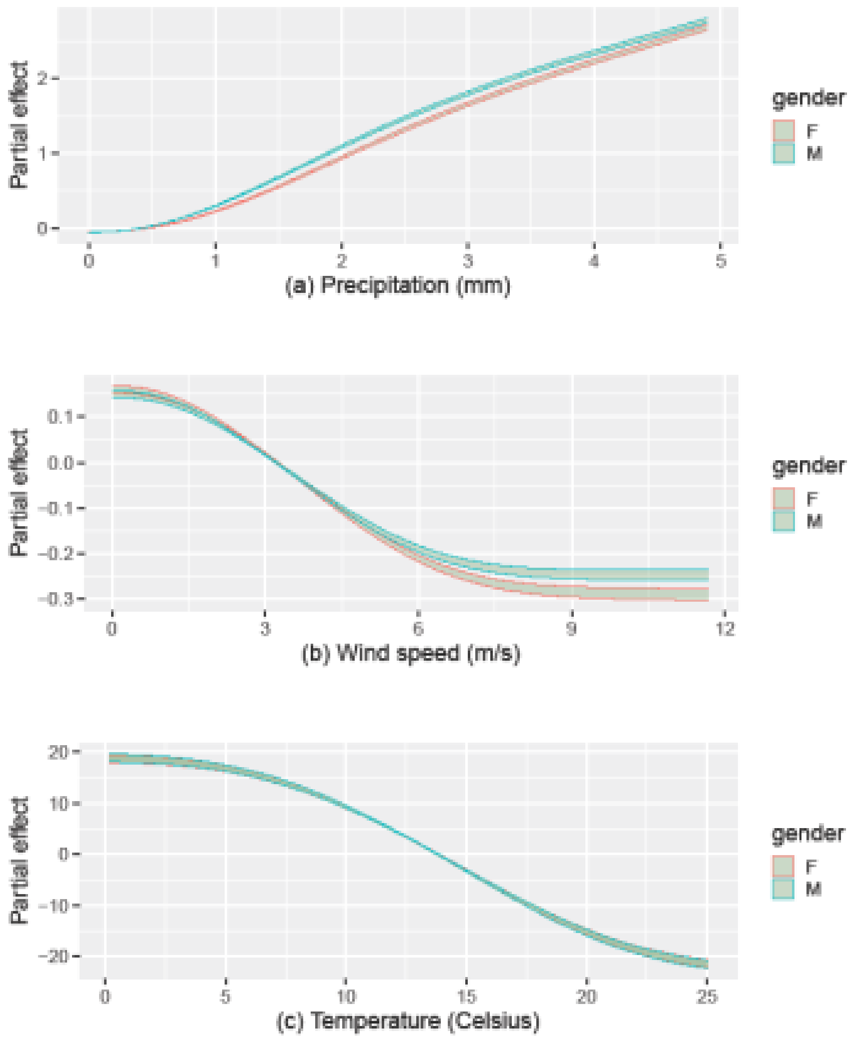

Figure 2. Partial effect of precipitation, wind, and temperature for male versus female riders, New York City, 2019, weekdays model.

We apply the same technique for wind. We have 924 hours with wind greater than 5 m/s. Above this value, there is a significant difference between male and female ridership (see Figure 2b). For temperature, the cross-over point is about 11°C, but the difference is not significant between men and women. Generally, below 11°C, the partial effect is greater for men; that is, women ride less below this temperature; however, the differences are very minor (Figure 2c).

The effect of hour-of-day (i.e., darkness) is clear (Figure 3). The confidence intervals are too small to be visible, and the cross-over points are around 4:20 am and 6:30 pm. Before this and after this, women ride less. However, this plot does not capture the interaction term with day-of-year; therefore, it is more informative to examine the female and male riding percentage before sunrise and after sunset in each city.

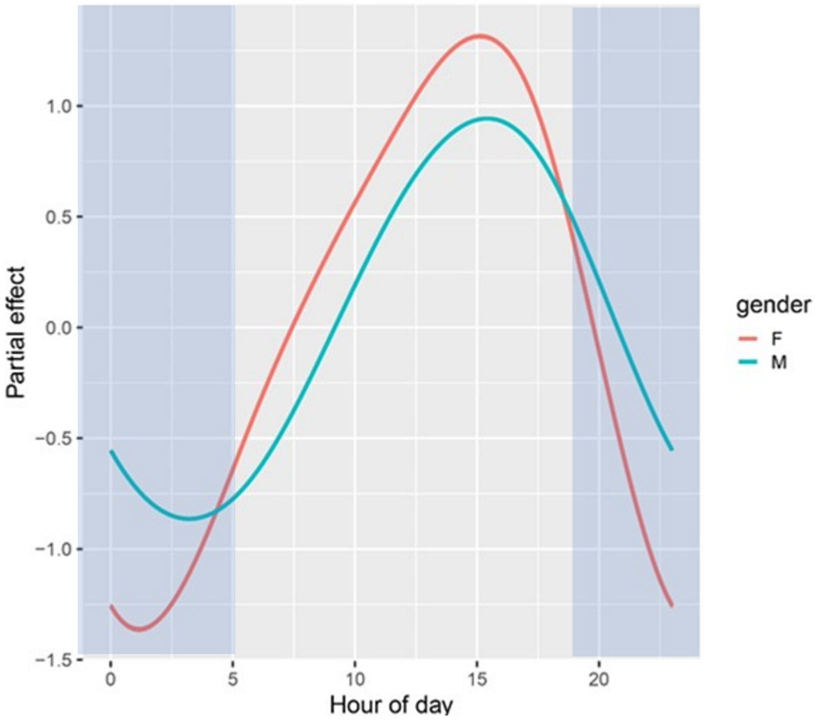

Figure 3. Partial effect of hour-of-day for male versus female riders, New York City, 2014 to 2020 (blue shaded areas indicated periods of darkness).

To test the difference in male and female cycling rates while considering the effects of wind and rain, we also fitted a parsimonious model with linear terms for wind and rain as follows:

$$\text{Usage} = \text{gender} + s(\text{JulianDate}) + s(\text{Hour}) + te(\text{Hour, JulianDate}) + s(\text{temp}) + \text{rain} + \text{wind} + \varepsilon$$

where the "rain" and "wind" are linear terms, and every term also considers the interaction of "gender" (only trips with self-identified male and female riders are used); ε represents an error term. This model also has the advantage of avoiding possible overfitting of the rain and wind terms using smooth functions. We fitted this model for whole calendar years of trips for each city. This gave us parametric coefficients for the intercept, gender, rain, wind, rain interacting with gender (gender:rain) and wind interacting with gender (gender:wind).

Generally, the rain and wind coefficients are negative.[11] Note that these coefficients relate to female riders and can be adjusted by the "genderM:rain" and "genderM:wind" coefficients for male riders. Thus, it is possible, although unlikely, that a wind coefficient for a particular city / year / day-of-week model could be negative for female riders, but positive for male riders.

If the "genderM:rain" coefficient is positive, then the slope of the rain line is higher for male cyclists, which indicates they ride more during rain. This coefficient is positive in 82 of 106 models and the results are statistically significant in 66 of those.[12] Among the 24 models where the coefficient is negative, only 8 return statistically significant results.[13] Similarly, if the "genderM:wind" coefficient is positive then the slope of the wind line is higher for male cyclists, which indicates they ride more in windier weather. This coefficient is positive for 72 of 106 models, of which 54 have statistically significant results.[14] Of the 34 models where the "genderM:rain" coefficient is negative, the results are statistically significant in 13.[15]

To summarise, wind and rain are generally a greater barrier for female cyclists than for male cyclists. The exceptions to this rule are in Guadalajara and Mexico City during several years where the reverse was found. New York City, each of the 14 models had a positive and statistically significant coefficient for wind and rain for male cyclists (p<0.05 for all). Similarly in Chicago each of 12 models had positive coefficients (p<0.05 for 23 of 24). Boston also has 16 models with positive coefficients (p<0.05 for 16 of 32 coefficients). The plots of the model outputs for the other cities look quite similar to New York's and, therefore, are not shown here.

Hilliness

The concept of hilliness was operationalised as digital elevation. For each trip, we calculated the average gradient using the difference in elevation and the great circle distance calculated using the "distGeo" function in R from the *geosphere* package in R. We were interested in finding out whether uphill gradients are a bigger barrier for female cyclists than male cyclists. For this purpose, we studied trips where the estimated "great circle" average gradient exceeded 1%. The gender difference can be most clearly seen by plotting the number of trips which exceed this value. Below we present the findings for five large cities. Due to space constraints, we only show the plot for New York City in the text. All the other plots are shown in Appendix 1.

In New York City, the gender difference is very clear (Figure 4). For the 92 months examined (June 2013 to January 2021), in 91 months the percentage of male trips with an average gradient greater than 1% was greater than the percentage of corresponding female trips (although the difference is never more than a few percentage points).[16] The general upward trend in cycling possibly reflects the expansion of the system to areas outside the original core. The annual seasonal effect is also clear and may be explained by several factors, including a different mix of recreational versus commuter trips, or the possible avoidance of hills in warmer months.

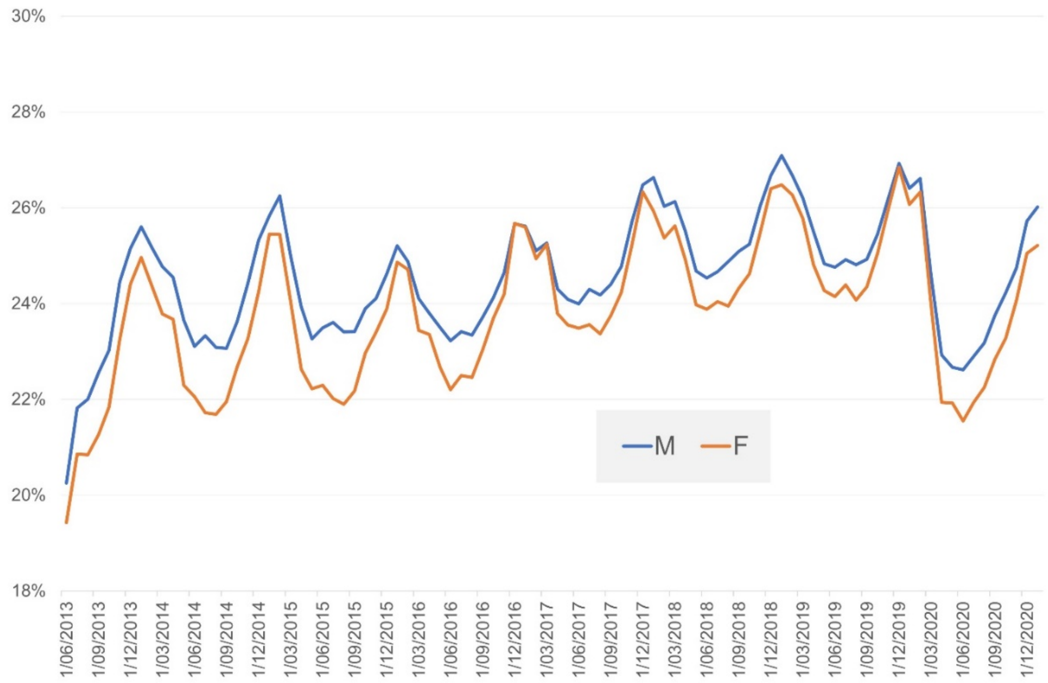

Figure 4. New York City, June 2013 to January 2021: plot for male and female, percentage of trips with average gradient greater than 1%.

In Boston, the percentage of uphill trips is somewhat lower, but the same annual pattern is observed despite the Digital Elevation Model resolution being much lower. In 63 of 64 months the percentage of uphill trips is lower for women than men.[17] In other large cities in our sample, we see a more nuanced pattern. In Guadalajara, for example, in 91 months examined, the percentage of uphill trips for men exceeds of women's in only 65 months.[18] A seasonal effect, if present, is not readily apparent. Note, however, that Guadalajara's elevation data has a relatively coarse resolution.[19]

Mexico City presents a similar pattern to Guadalajara. In only 67 out of the 149 months examined did the share of uphill male trips surpass the share of uphill female trips. Also, the trips taken seemed noticeably flatter than for New York City and Guadalajara. The steep drop in the total number of trips in 2012 may be due to reductions in service or the introduction of lighter bicycles. The analysis for Brisbane was based on much less trip data but the same fine-grained elevation model as in New York City. Of the 53 months studied, the percentage of uphill trips made by men exceeded percentage of uphill trips made by women in 43 months.[20]

The effect of fleet electrification could be investigated in some places as significant numbers of trips were taken with both classic and e-bikes. The San Francisco Bay Area and New York City schemes are illustrative (Figure 5). In the San Francisco Bay Area, which is known for being hilly, e-bikes were clearly used to overcome gradient issues. Overall, the percentage of steeper trips was 21% for men, 19% for women. However, classic push bicycles were used in only 19% of the steeper trips compared to 23% for e-bikes. In New York City, which is relatively flat, the opposite pattern was observed, with e-bikes used less than classic bicycles. However, men were still slightly more likely to cycle along steeper routes than women.

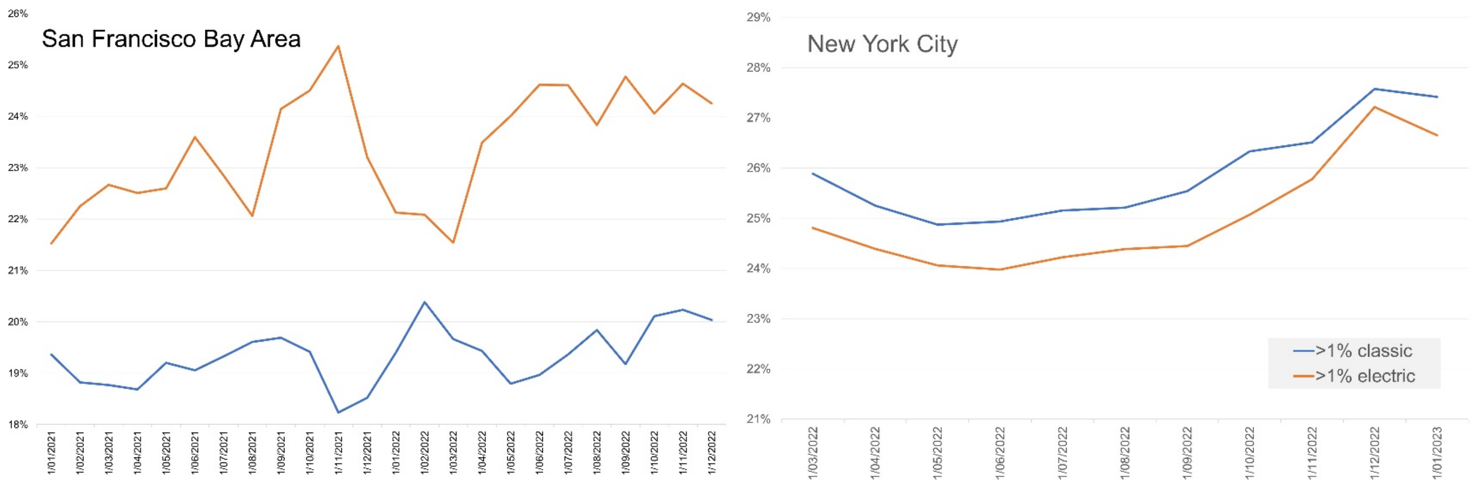

Figure 5. Steeper trips in the San Francisco Bay Area and New York City, electric vs classic bicycles.

Comparing the effect of hilliness in different cities is very difficult without knowing more about the bicycles used in each bikesharing system (i.e., their weights and gears). One study used standard deviation of station altitudes as a measure of scheme "hilliness" (de Chardon et al. 2017). As shown in Table 3, the "hilliness" of some schemes has changed considerably over time as each scheme expands beyond its original urban core. For example, New York City's scheme has increased from a value of 19.6 m in 2013 to 38.1 m in 2022; in a sense, the scheme can now be considered twice as "hilly". This helps to explain the upward trend over time seen in Figure 4.

Table 3. Hilliness measure for each scheme over time (standard deviation of station elevations in metres).

Year/City	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*
New York City				19.6	19.7	21.9	28.1	30.3	33.8	30.9	34.7	37.7	38.1	
Boston		15.1	12.8	11.8	11.5	11.9	11.3	11.0	12.2	12.3				
Chicago				6.0	6.0	11.1	16.7	16.7	18.3	17.5				
Minneapolis	13.2	12.8	16.1	15.4	15.2	14.7	14.3	14.5	15.8	16.2				
Guadalajara					10.1	15.6	19.8	20.0	20.9	21.0	21.0	21.6	21.6	21.6
Mexico City	10.9	10.9	12.9	12.9	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	
Brisbane	6.1	6.5	7.2	7.2	7.2	7.2								
Columbus									6.8	6.9				
Helsinki								8.7						
Bay Area (San Francisco)								21.4	22.2	28.0	27.2	26.1	26.8	27.0
Bay Area (East Bay)								22.8	24.8	30.6	24.1	27.4	26.0	27.4
Bay Area (San Jose)								9.9	12.3	9.2	8.5	7.7	7.3	7.4

Note: Minneapolis 2012-2017 data from station lists.

Darkness

The concept of darkness is operationalised as sunrise and sunset. In all ten cities, there is a strong pattern concerning trips before sunrise and after sunset: fewer women than men cycle before sunrise and after sunset (i.e., in the dark). To illustrate, we show the graph from New York City, the largest in the sample (Figure 6); the plots for all ten cities are shown in Appendix 2. These findings are in line with previously reported safety concerns (Cubells et al. 2023) but may also be due to the gendered patterns of most labour markets (for example, men may be more often engaged in shift-work, which requires late-night commuting).

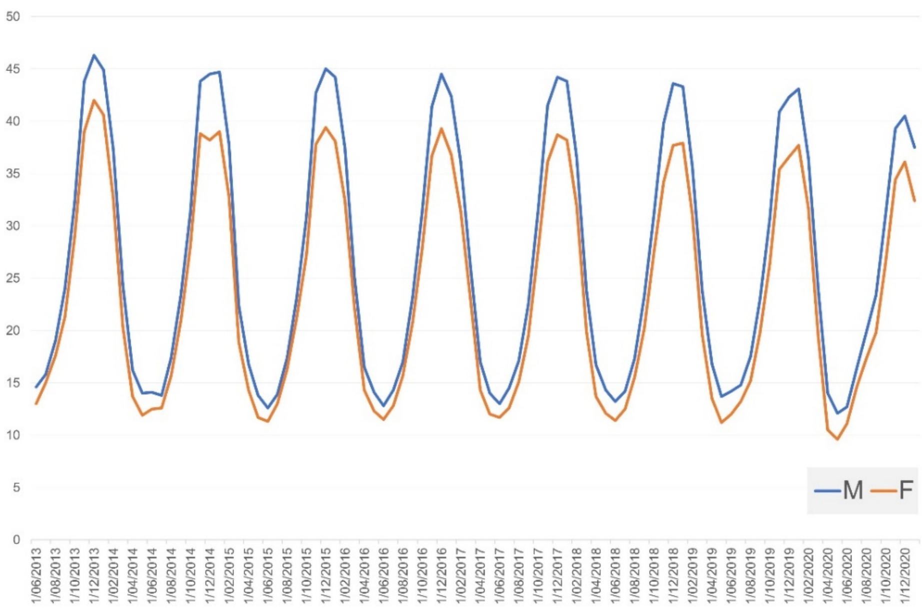

Figure 6. New York City, trips by gender made before sunrise and after sunset.

Conclusion

In this study, we set out to investigate whether and how much three natural factors (inclement weather, hilliness, and darkness) act as barriers to cycling for women. We started by integrating gender and other data from more than 200 million bikesharing trips with fine-grained weather, gradient, and sunset/sunrise data. Then we built models for ten cities worldwide covering a period of 14 years.

We found that, in many cities, wind and precipitation disincentive cycling, and more so for women than for men. Similarly, in many cities, steeper gradients are a significant barrier for female bikeshare users. In every city, women make fewer trips in the dark (i.e., before sunrise and after sunset) compared to men. Regardless of natural barriers, there is evidence that in higher-cycling cities (such as Helsinki and Minneapolis), cycling declines less with age for women compared to other cities. Due to data limitations, we could not explore intersectionality in further detail. However, the combined effects of gender, age, race, income, and sexuality on cycling in general and bikesharing in particular deserve more research attention.

Given these findings, what ought to be done to overcome the gender gap in urban cycling? We argue that measures should be gender-specific rather than general (Lam 2019) because increasing the overall share of bicycle trips does not automatically translate to improvements in female representation. While high-cycling countries have sustained a roughly equal representation of women over time (Garrard 2021), a number of cities - in the UK and Canada - have managed to increase cycling rates without any change in gender equity (Aldred et al. 2016; Winters and Zanotto 2017). Conversely, in Australia, declines in cycling rates have been associated with reduced proportions of female cyclists (Munro 2019). With decreasing levels of cycling, the representation of women deteriorates in every age group (Goel et al. 2022). Places such as Portland and Seville, which have increased cycling rates while also closing the gender gap (Garrard 2021), are outliers.

A set of recommendations to increase cycling participation among women has been provided by Garrard (2021). A summary follows:

- Along main roads: create cycling infrastructure that provides maximum separation from motor vehicles;
- Along neighbourhood streets: apply traffic calming devices such as speed limits, chicanes, and speed tables;
- Improve off-road recreational trails and multi-purpose paths which appeal to women and families;
- Raise awareness among all road users so that any interactions among drivers and cyclists are cooperative and respectful;
- Modify road engineering and planning processes to prioritise bicycle travel over car flow;
- Change traffic laws to presume driver liability in case of collisions with bicycles and generally protect cyclists;
- Design and market sit-up bicycles with women's comfort in mind.

To this list, we add three recommendations designed to specifically help eliminate the three barriers discussed in this article (inclement weather, hilliness, and darkness). Electric bikes offer much potential here. They require much less effort to ride than conventional bicycles thus enabling longer trips, more comfortable trips in hilly and/or windy places, and faster trips in the dark and/or rain. As seen in the analysis, e-bikes are already being used in the San Francisco Bay Area to overcome the gradient factor.

However, e-bikes come with some risks and challenges. They are not lightweight due to heavy batteries; this may not be an issue while riding but it does make it harder to lift the vehicle (for example, upstairs to a storage space). While costs are dropping, e-bikes remain relatively expensive and users need to factor in the cost of recharging the batteries. Because starts and stops are more abrupt and dangerous than conventional bicycles, users may need some training to safely use an e-bike.

Under these circumstances, planners must carefully balance the costs and benefits of replacing all, or some of, a classic pushbike fleet with e-bikes. For example, depending on the average gradients, prevailing wind directions, and precipitation patterns present in a city (de Chardon et al. 2015), a 50:50 mix of classic and electric bikes might provide the largest benefits by removing barriers for some segments of the population while keeping the costs low. Cities need to figure out what the correct ratio of e-bikes to classic bicycles is to help *women* overcome barriers. This type of calculation should factor in the safety advantage of e-bikes compared to e-scooters (Cox 2016).

Another desirable strategy is to minimise the exposure of bicycle paths, thus reducing the effect of heat, solar radiation, wind, and rain. Paths can be covered by manufactured shelters or tree canopies, and even artificially cooled by fans. Some good practice examples or ideas come from tropical or desert climes, such as Singapore and Dubai, rather than from temperate settings (see Lee and Pojani 2019; Macmichael 2023).

To deal with (actual or perceived) safety and security issues in the dark, cities need to provide better lighting along cycling routes. While the cost of energy may be an issue, and the effect of streetlights on crime per se may be unknown, research has established that better lighting alleviates the fear of crime, especially among women (Boomsma and Steg 2014). Women are in fact more likely to notice local improvements in street lighting compared to men (Painter 1996).

More broadly, a cyclable urban form should become the goal of planning. Beyond cycling-specific hardware, software, and orgware (Kong and Pojani 2022), that involves compact development and mixed land-uses (Mateo-Babiano et al. 2017). In a sense, women may be considered as the ‘canary in the coalmine’: cities are truly cycling-friendly when cyclists’ gender ratios are nearly equal (Baker 2009).

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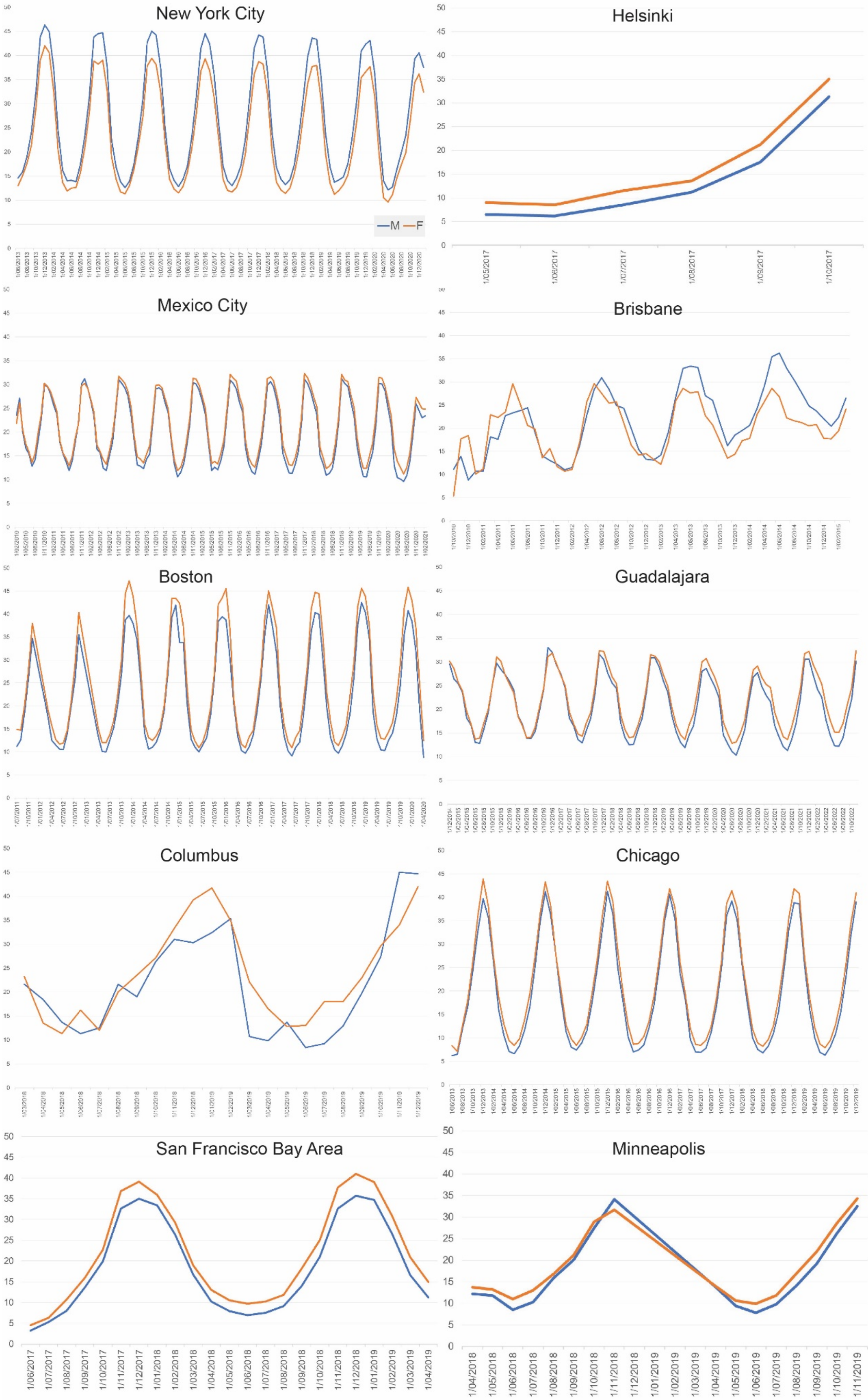
Appendices

Appendix 1. Plot for male and female, percentage of trips with average gradient greater than 1%.



Appendix 2. All cities, trips by gender made before sunrise and after sunset (i.e., in the dark).

Notes

[1] Gentle slopes may be tolerated as they provide an opportunity for exercise or if they allow users to take a safer route (Halefom et al. 2022; Stinson and Bhat 2003).

[2] For example, the "Citi Bike Trip Histories" page describes the data format for the "Gender" field as "Zero=unknown, 1=male, 2=female". A similar format is used across all the US cities studied; for example, the Boston data before 2015 used "Male", "Female" and a blank field, changing to the numeric format from January 2015. In the Guadalajara data in 2015, there are 469,871 trips made by 5,191 unique users, but only 236 trips where gender was not provided, which were made by two unique users.

[3] For example, in New York City, the price of a CitiBike annual subscription increased from $95 to $149 in October 2014.

[4] For the Brisbane long-term subscribers, age data was available in a binned form, with bins of ages: 14-17, 18-25, 26-35, 36-45, 46-55, 56-75 and 75+. In the other cities, age data was available as a continuous variable. To standardise, we applied the Brisbane bins to all the cities.

[5] Since 1950, the Copernicus Climate Change Service (C3S) at the European Centre for Medium-ranger Weather Forecasts (ECMWF) has produced a reanalysis of the global climate, called ERA5. This service contains hourly estimates of climate variables useful for our purposes, such as two-metre temperature, total precipitation, and wind speed.

[6] The ALOS project has a Global Digital Surface Model (DSM) at 30 metre resolution with freely available data. For two cities, we have finer resolution data: New York City with 1 foot (30 cm) resolution and Brisbane with 1 m resolution. We obtained those data from the following sources:

1) https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc
2) https://qldspatial.information.qld.gov.au/catalogue/custom/viewMetadataDetails.page?uuid=%7B5471036F-0ED8-41EE-BDBE-14EA846FC81E%7D

[7] Everywhere outside of mainland China.

[8] Data on classic vs electric bicycles: New York City (April 2021 on), Chicago (July 2020 on), and Minneapolis (May 2020 on). Data on docked vs undocked bicycles: San Francisco Bay Area, New York City, Columbus, Chicago, and Minneapolis, from as early as April 2020.

[9] Some studies (e.g., Bean et al. 2021) have summarised weather variables into one variable, such as the UTCI (Universal Thermal Comfort Index). This effectively captures the effect of wind, humidity, solar insolation, and temperature into one variable. In this study, we consider wind separately.

[10] We used cyclic cubic splines for hour and day of year to avoid discontinuities between the beginning of end of days and years. This was based on advice from Simpson (2012, 2019) who builds a similar model with hour and day of year. See:

1) https://stats.stackexchange.com/questions/308244/confidence-interval-for-the-slope-of-a-gam;
2) https://stats.stackexchange.com/questions/32730/how-to-include-an-interaction-term-in-gam
3) https://stats.stackexchange.com/questions/340387/gam-selection-when-both-smooth-and-parametric-terms-are-present
4) https://stats.stackexchange.com/questions/403772/different-ways-of-modelling-interactions-between-continuous-and-categorical-pred
5) https://stats.stackexchange.com/questions/413955/should-i-use-poisson-or-gaussian-family-in-gam

[11] In 101 of 106 models and 82 of 106 models respectively.

[12] $p < 2e\text{-}16$ in 51 models, $p < 0.01$ in 5 models, $p < 0.05$ in 8 models, and $p < 0.1$ in 2 models.

[13] $p < 2e\text{-}16$ in 3 models, $p < 0.01$ in 1 model, $p < 0.05$ in 3 models, and $p < 0.1$ in 1 model.

[14] $p < 2e\text{-}16$ in 35 models, $p < 0.01$ in 4 models, $p < 0.05$ in 5 models, and $p < 0.1$ in 10 models.

[15] $p < 2e\text{-}16$ in 3 models, $p < 0.01$ in 4 models, $p < 0.05$ in 5 models, and $p < 0.1$ in 1 model.

[16] Assuming a hypothesis of no difference for each month (that is, a probability of 0.5 for male/female ratio being higher), and independent observations, the estimated p-value for these observations is less than 2e-16 (two-sided binomial test). For the New York City figures, the differences range from -0.002% to 1.60% with an average of 0.74%.

[17] $p < 2e-16$.

[18] $p = 5e-5$.

[19] The resolution is 100 times lower than for New York City (30 metres vs 30 centimetres).

[20] $p=6e-6$.