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Bike sharing use in conjunction to public transport: Exploring spatiotemporal, age and gender dimensions in Oslo, Norway

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Abstract: Bike sharing could provide a key role in a transition towards a less car dependent and more sustainable, healthy and socially inclusive urban transport future. This paper investigates two important prerequisites for bike sharing to fulfil these premises: Does it synergise rather than compete with current alternatives to car-based urban mobility; and is it inclusively accessible across population and spatial segments? Drawing on complete 2016-2017 trip records of the Oslo (Norway) bike sharing system, this paper analyses the potential use of bike sharing for accessing, egressing and interchanging public transport and explores its age and gender dimensions. Bike sharing ridership is substantially higher on routes that either start or end with metro/rail connectivity, whilst controlling for other factors, such as route distance, elevation, urban form, time of day and bike dock capacities. However, our results also reveal that bike sharing – both as a stand-alone system and in conjunction with public transport – is less accessible to, suited to, and used by women and older age groups. Especially gender biases appear profound, multifaceted, and intersected by spatial inequalities favouring central male-dominated employment areas. These findings are discussed to derive policy and design directions regarding multimodal integration, dock expansion, rental limitations, and the introduction of e-bikes, to improve the performance, multimodal integration, gender equality and overall socio-spatial inclusiveness of bike sharing.

Key words: Bike Sharing, Public Transport, Access-Egress, Gender, Age, Oslo Norway

1 Introduction

A transition towards multimodal urban mobility systems dominated by public transport use, walking and cycling and where cars play only a minor role, could provide for drastic CO_2-emission, air pollution and road congestion reductions, freeing up of valuable urban space, promotion of active lifestyles, and more socially inclusive mobility. Around the world, bike sharing systems are increasingly put forward as an important stand-alone transport mode for less car-dependent urban mobility (e.g. Fishman, 2016; DeMaio, 2017; Meyer & Shaheen, 2017). Recently, studies have provided important critical knowledge on bike-sharing's social inclusiveness and environmental implications by identifying who do and do not use bike sharing, and how usage competes with other transport modes (e.g. Fishman et al., 2013, 2015; Martin & Shaheen, 2014; Noland et al., 2015; Raux et al., 2017; Campbell & Brakewood, 2017; Hosford & Winters, 2018). Studies conclude that bike sharing use is often biased towards privileged early adopters (e.g. men, Caucasian, younger age, higher education, higher income, inner-city dwellers), and that it does little in promoting cycling as a mass transport mode (De Chardon, 2019). It substitutes some private car and taxi use, but especially also the use of sustainable alternatives like walking, private bicycles and public transport. Despite the criticism bike sharing systems can be equitable if planned and managed correctly (Nikitas, 2019).

Moreover, bike sharing may be more than just a viable stand-alone mode in a future urban transport system. By providing fast, seamless and inexpensive access to public transport stations, cycling has the potential to vastly increase the competitiveness and social equity of public transportation system as a whole by reducing total travel times, waiting times at stations, travel costs, and enhancing flexibility, reliability and comfort, especially in disadvantaged areas where local access to public transport is suboptimal. These potential advantages are made visible by studies that model bike-and-ride accessibility as compared to traditional public transport models with just pedestrian access (e.g. Boarnet et. al., 2017; Pritchard et. al. 2019; Hamidi et. al., 2019). Compared to ordinary cycling, bike sharing could synergise with public transport even better by providing the same advantages not only for access, but also for egress and possibly even for interchanging between public transport stops. Yet, the empirical knowledge base for the use of bike sharing as an integrative part of multimodal public transport is currently limited to a couple of studies. Moreover, it is under investigated how spatiotemporal patterns of bike sharing generally, and of bike sharing as part of multimodal public transport particularly, differ between different population categories.

To address these shortcomings this paper has two objectives: (1) assessing the potential use of bike sharing for accessing, egressing and interchanging between public transport stops, and (2) exploring its age and gender dimensions. The paper draws on complete 2016-2017 records of 4.7 million trips of the third-generation dock-based bike sharing scheme in Oslo (Norway). It provides route- and trip-based multivariate analyses of bike sharing frequencies, age/gender profiles, and the use of bike sharing in proximity to metro/rail whilst controlling for route distance, elevation, temporalities and urban form at origins and destinations. The next section of this paper discusses existing literature on bike sharing in relation to sociodemographic profiles, spatiotemporal attributes and potential access-egress use. A third section introduces our case study area, data and methods. The fourth section maps the geographies of bike sharing and presents our multivariate results. The paper concludes with a discussion of the significance of our bike sharing findings for research and policy oriented towards a more environmentally sustainable and socially inclusive urban mobility future.

2 Existing findings

Bike sharing user profiles

Studies typically find that the majority of bike sharers are caucasian males under the age of 40, employed, highly educated and often in high-income groups (e.g. Martin & Shaheen, 2014; Campbell & Brakewood, 2017; Fishman et al., 2013; Fishman et. al., 2015, Hosford & Winters 2018). The overlap between these characteristics and those of early adopters are hard to miss (Shaheen et. al. 2011). While uneven technology adoption rates are often linked to preferences, skills or costs, uneven access in the case of bike sharing seems first and foremost related to geography. Two comparison studies from U.S. (Ursaki et al., 2015) and Canadian cities (Hosford & Winters, 2018) highlight the need for substantial efforts in geographical expansion of bike sharing services to disadvantaged areas.

Other point specifically at gender biases. Similar to more general typologies of cyclists (Ricci, 2015), Vogel and others (2014) developed a segmentation of bike sharing users in Lyon, France, ranging from ‘users of heart’ to ‘sporadic users’. Gender emerged as a significant category in defining these user typologies, as the intensity of cycling practice was strongly linked to being male. Adams and others (2017) argue that a lack of basic bicycle infrastructure can explain why some women avoid bike sharing, as women often have higher safety concerns. Gendered preferences for low-speed, safe cycling environments emerge in a survey conducted among members of Oslo bike sharing as well (Uteng et. al. 2019). Women, on average, had several issues differing sharply from what the male members quoted. For example, female members were critical towards the maximum allowed rental time of 45 minutes as trip-chaining and conducting leisure trips proved to be challenge in this timeframe. The fact that women were conducting other trips than access-egress also points towards the gendered variation of both the usage and expectations from the system. Similar results were found in New York where Citi Bike trip data revealed that male users were more inclined to end a trip by a bus stop or subway entrance (Wang & Akar, 2019).

Regarding age, most studies conclude that the age profile of bike share users is typically younger than the general population average (Fishman et al., 2013). In a study of the four North American cities Montreal (n= 3322), Minneapolis-Saint Paul (n=1238), Toronto (n=853) and Washington DC (n=5248), Shaheen and others (2012, 2013) highlight clear overrepresentation of younger people amongst bike sharing members. Despite this skewness, a fair share, about 40% of all respondents, were 35 years of age or older. In Melbourne and Brisbane, Australia, Fishman and others (2015), similarly found younger age (18-34), along with bike sharing access near the work location, to be among the more important predictors of bike share membership. Campbell & Brakewood (2017) found that in New York City, the median age for bikeshare trips taken by annual members was 35 years old, and only 1.19% of these bike trips were taken by persons age 65 or older. They further conclude that targeted expansion of bike docking stations, particularly around employment precincts and especially for those with large number of employees aged under 35 may provide a significant increase in membership. However, marking particular age groups as more probably prospective members might exclude other age groups who are equally willing to participate in the bike sharing schemes but simply lack information, confidence or/and availability of bike sharing schemes in their vicinity. Another New York study finds that age not only affects overall use, but also that generational cohorts have different spatial and temporal patterns of bike sharing usage (Wang et al., 2018). Despite these valuable contributions, conclusions regarding the role of age as a predictor of bike sharing frequencies, and especially its role as a mediator for patterns of use, need further examination in different contexts.

Topography, urban form and temporalities

While various studies discuss user profiles, the relationship of bike sharing to spatial and temporal aspects, such as topography, urban form, diurnal rhythms or seasonality, is less well explored. Especially integrated analyses of spatial and temporal factors for bike sharing as well as intersectionality with user profiles are understudied. Bike sharing, similarly to ordinary cycling, can be expected to be constrained by topography. However, what is distinctive for most bike sharing systems is that in contrast to private bicycle use, people can cycle one way downhill and use alternative transport modes when going uphill. Midgley (2011) identifies moderate and steep uphill slopes (>4% incline) and steep downhill slopes (>8%) to be an inhibiting factor for bike sharing, albeit without offering empirical evidence for this. A Brisbane, Australia, study (Mateo-Babiano et. al. 2016) confirms that on some routes, users avoid returning shared bicycles to stations located at higher elevations. The study finds for instance 1.9 times more downhill than uphill trips on routes with a 2.8% average gradient, although exceptions of higher uphill frequencies were also found, making it hard to draw robust conclusions. For Oslo, the context of this study, a national newspaper (Aftenposten) article observes that bike sharing trips in Oslo are predominantly downhill (Kirkebøyen, 2016). Whether this pattern is mainly a consequence of avoiding steep gradients or a spurious result of other factors, such as specific land uses at different elevation levels and peak/off-peak rhythms, needs further examination.

Other studies point at the effects of urban form and other spatial and temporal factors. A Montreal BIXI bike sharing scheme study (Faghih-Imani et. al. 2014) identifies higher ridership around the densely build urban core than in more peripheral locations of the study area. Ridership was also found significantly related to accessibility indicators and the presence of restaurants, commercial enterprises and universities in the vicinity of a bike docking station. An important finding emerging from the modelling exercise highlights that reallocating capacity by adding a further BIXI station had a stronger impact on bicycle flows compared to increasing one station's capacity. This means that dense bike sharing station networks may have a beneficial effect on usage levels. In line with other studies (e.g. Uteng 2019), this study also found population density and job density around bike sharing stations to influence demand and usage rates at different times of the day/week. The study reports on ridership reductions during weekends, but with the notable exception of Friday and Saturday nights. Multiple studies point at inequalities in the geographic coverage of bike sharing systems, as they tend to favour centrally located and often wealthy areas (e.g Duran et. al., 2018). A London study (Ogilvie & Goodman, 2012) finds strong underrepresentation of residents from deprived areas. Similarly, a case studies from Glasgow, UK, and Malmø, Sweden, demonstrate how bike- and car-sharing schemes are less likely to extend to areas where people live that are most at risk of transport-related social exclusion (Clark & Curl, 2016; Hamidi et al., 2019). With the gradual expansion of bike sharing systems over time, the spatial inclusiveness of bike sharing schemes may change. A later London study finds significant yet precarious increased usages for lower income groups, with the expansion of bike sharing services into poorer areas (Goodman & Cheshire, 2014).

A couple of studies highlight the intersectionality of spatiotemporal patterns of use with user characteristics. A London Barclays Cycle Hire (BCH) study (Lathia et. al., 2012) reports on a December 2010 policy change that allows casual users to access the scheme for spontaneous journeys without registering for an annual membership. Whilst the system continued to be primarily used for week-day commuting, the change generated greater weekend usage and a complete reversal of usage in a number of stations was noticed. Two other London studies (Beecham & Wood, 2014; Nickkar et al., 2019) find evidence for intersectionality of spatiotemporal bike sharing usages with gender. Women perform more touring and recreational bike sharing trips. They also avoid more than men routes involving large, multi-lane roads, even for utilitarian trip purposes, and rather prefer selecting areas of the city associated with slower traffic and more segregated cycle routes. A study from Nanjing, China (Zhao et. al. 2015) further reveals gender variation in bike sharing trip chaining behaviour. Compared to men, women are more likely to make multiple-circle bike sharing trips (i.e., with multiple destinations but same start and end point) especially on weekdays. Similarly, studies from Montreal, London and Dublin (Faghih-Imani et. al. 2014, Beecham & Wood 2014, Murphy & Usher, 2015) highlight that different trip purposes are influenced by gender and temporal variables, such as time of the day and day of the week, and should be considered as vital inputs in future designs of bike sharing systems.

Bike sharing and public transport

Studies indicate that bike sharing systems across the world have been better at substituting walking and public transport trips than replacing car trips (Ricci 2015, Fishman et. al., 2013). Interactions between bike sharing and public transport can be classified in two ways. First, there are bike sharing trips that exclusively supplement or substitute public transport trips as a stand-alone mode. Evidence of this substitution type is found for example in Melbourne, where the emergence of bike sharing docking stations in areas with relatively poor public transport triggers some to start bike sharing and no longer use public transport (Fishman et al. 2015).

Second, bike sharing may synergise with, rather than cannibalise on, public transport, by facilitating its often problematic first- (access) and last-mile (egress) segments. Assuming access-egress by foot, a maximum of 400m is often identified as a range that people are willing to travel to get to a station before demand tapers off (Iacobucci, et al., 2017). Others problematise this absolute range, indicating that people are willing to walk further for high efficiency transportation modes like trains and metros than for trams and busses, for instance in the Oslo region (Ellis et.al., 2018). Either way, adding bike sharing as an access-egress mode to public transportation instead of walking can prove to be beneficial for both transportation modes (Ji et.al., 2018). Studies find higher bike sharing ridership numbers for docks that are connected to train stations in London (Goodman & Cheshire, 2014) and Washington DC (Shaheen et al., 2014), and to metro stations in Paris (Shaheen et al., 2014). In Montreal, bike sharing integration has reportedly led to a 10% increased rail usage (Martin & Shaheen, 2014).

Survey-based studies point out that people do indeed integrate bike sharing and public transport. In Beijing and Hangzhou, over half of the respondents of the bike sharing programs were reportedly combining these transportation modes (Fishman et.al, 2013). Mobike Global estimated that majority of their shared bike trips were undertaken to link with buses and trains (Ding et. al. 2018). A Vienna study (Leth et. al., 2017) on travel time ratios, route-base heat maps, detour factors and cumulative frequencies of trip distances and travel times, conclude that users do indeed combine bike sharing with public transport and that the two systems are supplementing rather than competing with each other. Adding to this Jäppinen and others (2013) modelled potential benefits of bike sharing on public transport travel times in Helsinki. Their findings showed that bike sharing combined with public transport reduced travel times on average by more than 10%. However, research on whether and how bike sharing for public transport access-egress intersects with user characteristics like age and gender and place of residence is currently lacking.

3 Methods

Study area

This study draws on data from the “Oslo CityBike” bike sharing scheme operated by Urban Infrastructure Partner (currently known as Urban Sharing). The rationale for choosing Oslo, Norway, to study bike sharing use and its integration to public transport is fourfold: First, current literature on bike sharing is mostly focussed on only a select number of countries/regions (e.g. USA, UK, France, Australia and China) (Fishman, 2016). Empirical bike sharing evidence from Northern Europe is limited to only a handful of studies (e.g Caulfield et.al., 2017; Hamidi et. al., 2019; Jäppinen et.al., 2013; Nikitas et.al., 2016), and only few of which addressing spatial inclusiveness (e.g. Hamidi et.al., 2019). The unique and potentially favourable conditions for bike sharing, including relatively compact urban designs, well-functioning public transportation systems, low car dependences in the bigger cities, and high and increasing shares of active transport modes despite strong seasonal variations in climate conditions, make Nordic cities interesting cases to study. Second, Oslo forms a unique case with ambitious environmental targets aiming at reducing greenhouse gas emissions by 50% within 2030 (Plansamarbeidet, 2015). With the Norwegian land-based power sector being 100% renewable, emission reduction efforts are more than in other countries focused on the transport sector, with Oslo – where half its total emissions originate from transport – being no exception. Several of these efforts are focused on shifting car use to other transport modes, including strategies on decoupling growth in car traffic from population growth, establishing car free zones, spending parts of road toll incomes on public transport and bicycle infrastructures (Norwegian Ministry of Transport and Communications, 2017). Third, Oslo has had a bike sharing scheme since 2002 (Alsvik, 2009), but which gained particular strong traction in recent years: from 950,000 trips by 29,000 users in 2015 to 2,7 Million trips by 77,000 users in 2017 (UIP, 2018). Moreover, the bike sharing business model applied in Oslo is particularly well-suited to be used for public transport access and egress. Being *dock-based*, it allows for the controlled clustering of bikes at docks in the vicinity of public transport stations. Being *one-way* it can be used for both access and egress, linking up station to non-station locations. By applying continuous redistributive freighting of bikes, the scheme has some options to actively rebalance spatiotemporal matching of supply and demand, although docks do run full and empty despite these efforts. Fourth, Oslo's regional public transport authority Ruter recently pinpointed the importance of bike sharing for better integrated Mobility as a Service-inspired travel solutions for the Oslo region (Aarhaug, 2017).

Data

The empirical basis for this study is formed by the complete 2016-2017 records (4.4 million trips) of population data of the Oslo bike sharing scheme. The data consists of unique bicycle trips and includes geolocated trip origins and destinations, bike dock capacities, time, date, and unique personal information of users (i.e. birth year, gender and postal code of residence). The latter information has only been available to us for the selected years. With only moderate expansions to the network after since, the 2016-2017 data is nevertheless still representative for Oslo's bike sharing patterns today, although it is important to note that there has been a change to the competitive landscape with the introduction of shared electric scooters. As parts of the record are anonymous, some of our analyses are limited to data on 2.1 million trips made by 36,230 unique users who registered their personal information. In comparison the Oslo bike sharing scheme had 46,000 and 77,000 unique users in 2016 and 2017 respectively. The rest of the record consists of trips by unknown users and is only used for our analysis of total bike sharing frequencies. For parts of our analyses, trip data were aggregated to a route level. Total 2016-2017 bike sharing frequencies were summed up for each unique one-way origin-destination pair were in operation for at least 3 months (n=23,214), including non-travelled zero frequency routes. For routes between stations that were in operation more than 3 months but less than the full two years, frequencies were adjusted to its two-year equivalent. In addition, the variables *mean age* and *female share* were calculated for each route with a frequency higher than 25 (n=16,953). This minimum frequency was set to avoid inaccurate aggregations based on minimal information, to avoid strong outliers, and to secure normal distributions.

In a next step, both trip and route datasets were linked in *ArcGIS Pro* to population and employment densities[1], building use diversity[2], share of surface area covered by centre zones[3], and women's population and employment shares[4]. These were summarised over 250x250m grid cells intersected by a 250m buffer around each geocoded trip/route origin and destination. To test the effects of public transport proximity on bike sharing use, additional

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[1] Data source: Statistics Norway. https://www.ssb.no/natur-og-miljo/geodata

[2] Based on a Shannon Entropy Index (Shannon, 1948), ranging from minimal value when all buildings have the same function to maximum value when dwellings, stores, offices and/or industry are equally present.

[3] Share of surface area covered by central zones defined by diverse economic activities, the presence of retail and public services (Statistics Norway, undated) https://www.ssb.no/a/metadata/conceptvariable/vardok/2598/en

[4] The gendered division of employment between different sectors is based on the national statistics available from The Norwegian Directorate for Children, Youth and Family Affairs, available at:
https://www.bufdir.no/Statistikk_og_analyse/Kjonnslikestilling/Arbeidsliv_og_kjonn/Kjonnsfordeling_sektorer/
The national averages of employment in the different sectors were applied to the jobs available in the different sectors in the different city wards of Oslo to plot the tentative concertation of female employment in the different wards of Oslo.

information was added on whether or not origins and destinations are within a 200m range of a metro or railway station. From earlier research we know that bike sharing plays an especially important role in access/egress trips to and from metro- and railway stations (Lansell, 2011; Ji et. al., 2018). Sensitivity analyses were also run for other buffer sizes (100m, 300m and 500m) as well as for access to tram and bus stops, but were ultimately excluded due to weaker parameter effects and poorer overall model fit. Next, an origin-destination cost matrix network analysis was run based on the Open Street Map network to estimate trip/route distances based on shortest paths on cyclable infrastructures. These were intersected with a digital elevation model to calculate elevation difference between start and end points. Finally, correlation matrices were run to test for multicollinearity. One problematic correlation was identified and confirmed by a VIF test (Field, 2018) between building use diversity and employment density. These two variables have therefore been added only separately and never together in our final models. Table 1 provides an overview of all variables in this study and their respective descriptive statistics.

Table 1: Descriptive statistics

	min	max	mean	sd
User attributes *(n=36,230 users)*				
age	15	85	30.49	10.44
male	0	1	.58	.49
user from inner-Oslo	0	1	.59	.49
user from outer-Oslo	0	1	.14	.35
user from outside Oslo	0	1	.25	.43
Bike dock attributes *(n=185 docking stations)*				
bike dock capacity (# locks)	6	60	22.16	9.74
population density (inh. / km^2)	0	15318	6501	4421
employment density (jobs / km^2)	140	47213	12574	13045
building use diversity (Shannon Index)	.15	1.45	.76	.31
centreness (% surface area covered by centre zone)	0	100	62.23	34.39
% women in population	38	55	48.43	3.39
% women's employment	38	65	48.81	5.22
yes or no rail/metro access within 200m	0	1	.11	.31
Bike route attributes *(n=23,241 routes)*				
frequency of use (daily avg.)	.00	23.62	.36	.76
route distance in km	.00	9.74	2.71	1.46
Δ elevation	-130	130	.00	43.07
Bike trip attributes *(n=2,069,287 trips)*				
morning peak	0	1	.21	.41
afternoon peak	0	1	.09	.28
weekend	0	1	.14	.35

Statistical modelling techniques

This paper makes use of three types of multivariate modelling techniques run in the statistical software package Stata. First a Negative Binomial model was applied to estimate the effect of public transport connectivity on *total bike sharing route frequencies*, whilst controlling for urban form and route characteristics. The negative binomial model is preferred over a Poisson regression, because it handles better the overdispersed bike sharing frequency count data (Lee et.al, 2012). Despite an excessive number of zero-frequency routes, the Negative Binomial model is also preferred over a Zero-Inflated Negative Binomial model, because there is no theoretical foundation for separate processes that lead to zero or non-zero outcomes. Second, two OLS regression models were run to investigate the determinants of *route mean age* and *route female share*, both of which appear normally distributed dependent variables upon visual inspection. Finally, a Multinomial Logit model was run on the trip level to investigate under which circumstances bike sharing trips are more likely to be made in proximity to metro/rail at start of a trip, at the end, at both start and end, or at neither start or end. This a discrete outcome with four alternatives, where no metro/rail access is set as the reference category. In this final model large numbers of trips are made by the same unique users over the course of two years. This raises a challenge of dealing with non-independent observations. To relax the usual requirement that all observations should be independent, this final model was performed with the Stata's "vce-cluster" command. This command estimates robust standard errors for all observations (trips) clustered within each unique user, thus correcting for intragroup correlation (Wooldridge, 2002).

4 Results

This section first outlines the geographic descriptions and multivariate investigations of bike sharing frequencies and age/gender profiles on a route level. Subsequently, it presents a multivariate investigation of user, trip and spatiotemporal characteristics on bike sharing system use in proximity and possible connection to metro and train stations on a trip level.

Bike sharing route frequencies

Figure 1 shows a map of total bike sharing frequencies for each route segment over the course of our 2-year data period (2016-2017) visualised on a simplified Gabriel network (O'Sullivan & Unwin, 2014), that connects all bike sharing docks. These total frequencies represent the aggregated sum of all unique route frequencies that run through each route segment, based on a shortest path network analysis. Explorative examination of the map reveals three patterns. First, as expected based on its higher work and residential densities, and in line with earlier research from Montreal (Faghih-Imani et. al. 2014), bike sharing use is highest in the most central parts of the bike sharing network and lower towards the network's fringes that are located outside the city centre, but still within the larger Oslo centre circumnavigated by the Oslo motorway ring. Second, bike sharing frequencies seem to be larger on *radial* routes into and out of the city centre (mainly north-south oriented) than on routes across or around the city centre (mainly east-west oriented). This pattern can be explained from its overlap with commute routes connecting employment-heavy areas in the downtown area to dense residential neighbourhoods adjacing the downtown area especially to the north. Third, bike sharing frequencies seem larger on routes perpendicular to and away from metro/rail infrastructure than on routes parallel to these main public transport infrastructures. This might indicate that bike sharing is used less on routes that compete directly with metro/rail, and that it has a higher competitive edge in areas without metro/rail infrastructures and especially on routes that connect such areas to metro and railway stations.

Table 2 presents the negative binomial regression results of distance, topography, urban form and metro/rail connectivity on the one-directional frequencies of use of all unique bike sharing routes between docks that were in operation for at least three months in the period 2016-2017, including zero-frequency routes. Due to over-dispersion of the count data, the negative binomial model is strongly preferred over a Poisson model, as confirmed by the high (4.0E+6) and strongly significant chibar^2 statistic in a likelihood ratio test whether or not alpha equals zero. The parameter coefficients of all continuous independent variables have been standardised to ease comparison of their relative impacts independent of unit of analysis, while z-scores are presented to compare the relative magnitudes of statistical significance. Bike dock capacities (i.e. the number of bicycle locks) at the start and end stations have been included as a control variable, revealing unsurprisingly strong positive correlations with frequency of use.

As expected, the most important determinant of bike route frequency is distance - i.e. measured as shortest path across cyclable infrastructure network. Routes of shorter distance are more frequently used than longer distance routes, but the distance decay appears more linear than expected after revealing a higher parameter estimate and model fit compared to sensitivity analyses with transformed logarithmic, squared and square-rooted distance functions. Topography is another important factor. Routes with a lower absolute elevation difference between start and end location have higher frequencies than hillier routes. Congruent to existing research (e.g. Mateo-Babiano et. al. 2016), an additional positive “downhill” effect is observed where routes that have a net elevation loss are being favoured over routes with a net elevation gain. This is possible in the Oslo bike sharing scheme since routes are essentially one-way and bicycles are continuously being freighted between docking stations to balance demand.

In addition to the effects of distance and topography, bike sharing route frequencies appear strongly influenced by urban form attributes observed in a 250-500m radius[5] around both start and end locations. Congruent to literature on cycling generally (Saelens et. al. 2003a, 2003b; Christiansen et. al. 2016; Yang et. al. 2019), but rarely studied in the context of bike-sharing, urban density and diversity have strong positive effects on bike sharing frequencies. In order of magnitude of effect, routes boast higher frequencies when having higher population density, higher building use diversity[6] and higher centreness[7] in the vicinities of start and end locations. Although present at both ends, the effects of these urban form attributes appear somewhat larger in magnitude at the end compared to start locations, indicating that more trips are heading towards the most urbanised areas than originating from, again made possible by redistributive freighting of bikes. The effects of employment densities at start and end locations were also tested, but ultimately omitted for multicollinearity reasons (Pearson’s r = .77 with building use diversity).

Besides being related to distance, topography, dock capacity and the various urban form characteristics discussed above, bike sharing route frequencies are also clearly affected by the proximity of both route ends to metro or rail stations, congruent to findings from Washington DC, London and Paris (e.g. Goodman & Cheshire, 2014; Shaheen et al., 2014). Even though we have no direct information on whether bike sharing trips have been made in connection to the use of metro or rail services, our results whilst controlling for all other demand-affecting factors discussed above, give a strong indication that the Oslo bike sharing system is significantly used for public transport access and egress purposes. Routes that *either* start from a bike dock within a 200m buffer[8] of a metro or train station exit, *or* that end at one, but importantly not routes that do *both*, have clearly higher frequencies of use than the reference category of stand-alone routes without connectivity to public transport. A logical explanation is that the bike sharing system is specifically used by some to extend the metro/rail network to locations that are otherwise not directly connected to train and metro stations. That routes connected to metro/rail at both ends have lower frequencies may be related to the competitive advantage that the high-frequency metro and rail services themselves already have on these routes.

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[5] The radius is variable as information is retrieved from 250x250m grid cells intersected by a 250m buffer around the bike station, see section 3.

[6] Based on a Shannon Entropy Index, ranging from minimal diversity when all buildings have the same function to maximum diversity when dwellings, stores, offices and/or industry are equally present.

[7] Share of surface area covered by central zones defined by diverse economic activities and the presence of shops/services.

[8] Sensitivity analyses were also run for other buffer sizes (100m, 300m and 500m) as well as for access to tram and bus stops, but were ultimately omitted due to lower parameter estimates and inferior overall model fit.

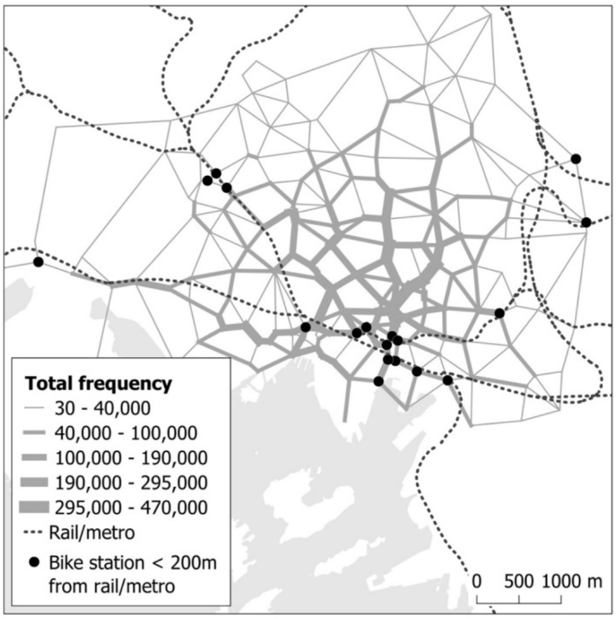

Figure 1: Aggregated 2016-2017 bike sharing frequencies

Table 2: Bike sharing route frequency

	bike route freq. 2016-2017 (neg. binomial., n=23,214)	
	coef.	z
route distance	-.857	-119.58***
Δ elevation (abs)	-.306	-38.64***
Δ elevation	-.272	-40.04***
origin dock capacity	.213	34.21***
pop. density at origin	.157	17.98***
building diversity at origin	.099	11.94***
centreness at origin	.062	7.32***
destination dock capacity	.217	35.22***
pop. density at end	.162	18.83***
building diversity at end	.112	13.45***
centreness at end	.079	9.42***
metro/rail <200m at start	.279	13.52***
metro/rail <200m at end	.220	10.74***
metro/rail <200m at both	-.014	-0.27
(ref. no metro/rail prox.)		
constant	4,739	696.56***
*model fit: LR Chi^2=21,335*** Pseudo R^2 (McFadden)=.072*		

Bike sharing route age and gender profiles

To examine whether and how bike sharing patterns differ with regard to age and gender, we will first geographically explore how average age (Figure 2) and the share of female bike sharers (Figure 3) differ for bike sharing route segments across our study area. Besides a colour scheme to reveal the respective age and gender profiles, both figures also show the total bike sharing frequencies by line width similar to Figure 1, this to examine the respective flows of male, female, younger and older bike sharers in both relative and absolute terms. When looked at age, it appears that there is a clear north-south divide, even though the age of bike sharers overall is quite young – e.g. even routes with the oldest bike sharers have an average age under forty. Bike sharing route segments with the highest average age are located downtown (centrally to the south in the study area) and westwards from there. These are routes connecting the most employment-dense downtown areas with some of the most affluent Oslo neighbourhoods westwards (e.g. the city districts of Frogner and Ullern). In contrast, areas north of the study area have much lower age shares. Possible explanations are that this is where Oslo's main university campuses are located (towards the northwest, as well as some of its trendiest gentrified and gentrifying neighbourhoods (towards the north east).

The system is also gender-biased. While 58% of users is male (Table 1), the share of trips by men are even higher (68%). Especially downtown areas are highly male dominated, with almost all route segments here having less than 32% female cyclists (Figure 4). Route segments further away from the city centre feature somewhat more balanced gender shares, although even here most routes still have a higher share of men. An explanation could be related to the geographic and gender differences in employment sectors. Downtown Oslo features large shares of employment sectors (e.g. private sectors of commerce, finance and insurance), which nationally feature much high shares of male employment. In contrast, the more gender-balanced bike sharing routes outside the city centre appear to coincide with areas that host more female-dominated employment sectors (see dotted areas in Figure 3). Another gendered pattern that can be recognised is the male dominance on route segments with proximity to metro and train stations, indicated by the black dots in Figure 3. This may indicate that men use shared bikes more as public transport access or egress modes, which is in line with previous findings from New York that bus stops and the number of subway entrances have a larger effect on male than on female bike sharing trips (Wang & Akar, 2019). This and other gender and age patterns explored above will be multivariately examined next.

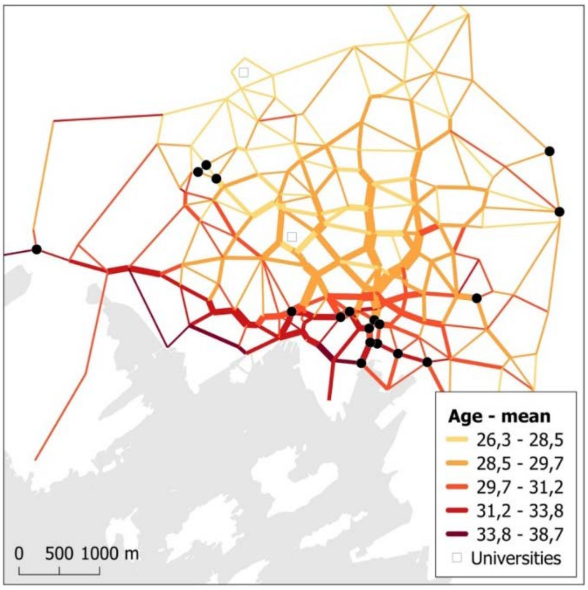

Figure 2: Spatial distribution of bike sharers' age

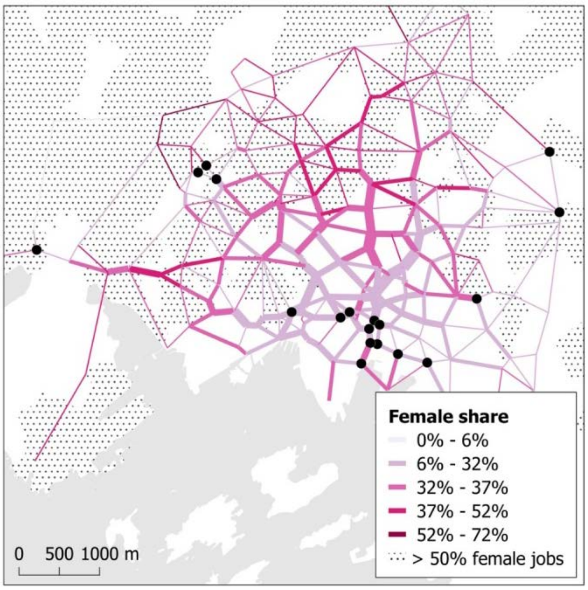

Figure 3: Spatial distribution of bike sharers' gender
Source: Based on and expanding upon Uteng et al. 2019

Table 3 presents the multivariate regression results of how bike sharing route age and gender profiles are affected by route distance, topography, urban form and metro/rail connectivity. The gender profile analysis is based on and expands upon a previous study by the authours (Uteng et al., 2019). To minimise unreliable and/or extreme values on the dependent variables of mean age and gender share, all routes with frequencies below 25 were omitted from the analysis. From this frequency of 25 and up, a visual check revealed that both dependent variables were more or less normally distributed. Again, standardised coefficients are presented for all continuous independent variables, while t-scores show the relative magnitudes of statistical significance. Regarding age, besides a model with *mean age* as the dependent variable, additional models were estimated on the *share of younger* (<30 years old) and *older adults* (≥60 years old), but these were ultimately omitted as they revealed little additional information and had poorer overall model fits. The few instances where these alternative age models did reveal non-linearities will be discussed.

Longer route distance positively affects the average age of users. A logarithmic distance function has a better fit than a linear one, indicating that distance effects on age mainly manifest themselves on shorter routes. Alternative younger and older-adult share models reveal that this distance-age relationship should mainly be attributed to the higher under-30 shares on shorter distance routes, while 60+ shares were not significantly affected. Additionally, uphill routes reveal older average age profiles, while downhill routes are more frequented by younger age groups. Although this may seem somewhat counterintuitive, one possible explanation could be that several major education centres are located on higher elevated parts of the study area and that the bike sharing network in those vicinities is possibly frequently used one-way (i.e. downhill) by younger age groups. Urban form effects on bike sharing route age profiles are somewhat mixed. Routes with higher population densities at both starts and ends have younger age profiles. Also, bike sharing routes linking up areas covered by centre functions have younger overall are age profiles, although this effect is only half as strong as that of population density. On the other hand, routes linking up areas with higher building use diversity, especially at the destination side of a bike sharing route, have older age profiles. When testing the alternative younger and older adult share models, urban form effects on age profiles seem to be mainly related to distinct route shares for those under 30, while over-60 shares are not significantly affected. Finally, metro/rail access at the end of routes has a negative effect on average age, mainly as a result of such routes being used significantly less by people aged 60 and older. However, this potential access/egress effect on age profiles is only minor in comparison to other factors.

Regarding gender, route distance (again a better fit with a logarithmic function) has a positive effect on women's shares. It appears that especially men can be found on the shortest distance routes. Overall, uphill bike sharing routes are slightly more used by women than by men, however an additional square-transformed[9] elevation effect shows that it is male shares that are higher on routes with the elevation gains or losses. Nearly all previously discussed urban form attributes have clear negative effects on women's route shares, indicating that men use the system relatively more in the most central, trafficked, densest and urbanised parts of the study area. This is in line with findings from New York that female riders prefer areas with less traffic (Wang & Akar 2019). However, a more complete picture arises when supplementing these classic urban form variables with attributes describing the gendering of urban structures. Women's route shares are clearly positively affected by the population share of women and, even more so, the employment share of women, with regard to both the destinations and especially the origins of routes. These insights are in line with the geographic pattern of gendered bike-sharing observed in Figure 3 and findings of the aforementioned gender-investigation of Oslo bike sharing (Uteng et al., 2019). Finally, women's shares are significantly lower on routes that have metro/rail access at start, end or both start and end location. This gives a strong indication that men are more likely to use the bike sharing scheme for access, egress purposes, while women seem to use bike sharing more as a stand-alone mode.

Table 3: Multivariate outputs of bike sharing route age and gender profiles

	bike route mean age (OLS regression, n=16,473)		bike route female share (OLS regression, n=16,947)	
	coef.	t	coef.	t
route distance (log)	.284	11.95 ***	1.644	13.96 ***
Δ elevation	.458	12.86 ***	.475	2.52 *
Δ elevation (squared)	|	|	-.985	-8.40 ***
pop. density at origin	-.433	-12.94 ***	-.591	-3.85 ***
building diversity at origin	.268	8.01 ***	-1.079	-6.17 ***
centreness at origin	-.183	-5.64 ***	-.456	-3.00 **
% female pop. at origin	|	|	.779	5.48 ***
% female jobs at origin	|	|	1.610	14.19 ***
pop. density at end	-.401	-12.25 ***	-.135	-.90
building diversity at end	.438	13.21 ***	-.471	-2.70 **
centreness at end	-.205	-6.37 ***	-.556	-3.71 ***
% female pop. at end	|	|	.442	3.10 **
% female jobs at end	|	|	1.133	10.01 ***
metro/rail prox. at start	.039	.49	-1.256	-3.42 ***
metro/rail prox. at end	-.215	-2.77 **	-1.597	-4.39 ***
metro/rail prox. at both (ref. no metro/rail prox.)	.317	1.50	-2.631	-2.55 *
constant	29.770	1121.24 ***	33.513	270.76 ***
model fit: F(df) / RMSE / R^2	*213.14(11)*** / 2.891 / .122*		*96.27(16)*** / 13.035 / .086*	

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[9] Similar to the absolute elevation transformation in Table 2, this square-transformed elevation only returns positive values, but with the difference that this square transformation highlights more the effect of routes with highest elevation difference.

Bike-sharing trips in proximity to metro/rail further examined

This final analysis section provides a further trip-based investigation of the potential use of bike-sharing as an access and/or egress mode to public transport. Table 4 presents multinomial logistic regression results with regard to which types of trips have metro/rail connectivity at the start, at the end, and at both the start and end (in reference to trips on routes without such metro/rail access) and which users are most likely to make such trips. Again, standardised coefficients are presented for all continuous independent variables. Z-scores indicate the magnitude of statistical significance, while drawing on robust clustered standard errors that take into account the non-independence of trips made by the same users. However, before we can investigate the issues above, it is important to control for a number of urban form attributes that correlate with our dependent variable trip proximity to metro/rail. Trips that have metro/rail proximity at origin correlate very highly with job density around the metro/rail-linked start bike dock and highly with lower job and population densities around the unconnected end location. Reversed correlations with urban form apply to bike sharing trips with metro/rail proximity at the destination end. These findings are logical, but of little further interest for this paper as they say little about bike sharing and more about the location of metro/rail stations.

So, what characterises bike sharing trips with metro/rail access – i.e. the potential access-egress trips – in terms of spatiotemporal aspects and users? As expected, trips with metro/rail access at origin, destination or both are often of shorter distance. If indeed used for access-egress, these bike sharing trips are after all only first and last mile extensions from the nearest metro/rail station. However, the logarithmic distance effect despite being statistically significant is relatively minor compared to some of the other factors. Elevation for example has a more prominent effect, with a larger share of downhill rides on routes with metro/rail proximity at the start, but a larger share of uphill rides on routes with metro/rail proximity at its end. This pattern may be topographically unique to the Oslo city centre, where many work and other destination locations are on the lowest elevation areas and thus require downhill egress rides from the metro/rail stations and uphill rides back. The former downhill effect is larger than the latter uphill effect, which suggests indeed an overall preference for downhill rides and a partial substituting of uphill bike sharing access-egress rides by other transport modes, such as walking, bus or tram. With regard to trip timing, morning peak has the highest bike sharing ridership on access-egress routes, particularly in the direction from metro/rail to non-metro/rail locations (egress routes). Compared to the morning peak, both afternoon-peak and weekday off-peak periods have lower ridership shares on access and especially egress routes. Bike sharing trips on access-egress routes are fewest in weekends. In this period there are relatively more bike sharing trips on routes without metro/rail proximity (the reference category).

Regarding the characteristics of those using bike sharing in proximity to metro and railway stations, Table 4 confirms the earlier discussed age and gender dimensions. Men and younger age groups are more likely to use bike sharing in metro/rail proximity, although a strong positive squared age effect indicates that it is not the oldest, but rather the middle-aged groups in our study that use bike sharing less in proximity to metro and train stations. But the strongest effect on whether bike sharing is used in proximity to metro and railway stations (even stronger than that of distance and topography) is found with regard to the geographic background of users. Users that live outside the municipality of Oslo and especially those living in Oslo neighbourhoods outside the city centre, use the Oslo bike sharing scheme more in proximity to metro/rail. Inner-Oslo residents – i.e. who in contrast to the former two groups live inside the area serviced by the Oslo bike sharing scheme – use bike sharing more on routes without metro/rail access.

Table 4: Trip-based investigation of bike sharing in proximity to metro/rail

	bike trip metro/rail proximity (*ref. no metro/rail proximity)* (multinomial logit model, n=2,005,386 trips, clustered by 35,151 users)					
	proximity at origin (egress routes)		proximity at end (access routes)		proximity at both (interchange routes)	
	coef.	z	coef.	z	coef.	z
Locational correlates						
pop. density at origin	.093	2.75 **	-.219	-14.24 ***	.177	3.22 ***
job density at origin	1.266	43.38 ***	-.345	-20.81 ***	1.354	24.65 ***
centreness at origin	-.324	-11.79 ***	-.014	-1.07	-.708	-11.97 ***
pop. density at end	-.192	-11.89 ***	.247	6.18 ***	.535	4.21 ***
job density at end	-.410	-23.51 ***	1.534	41.01 ***	1.852	14.27 ***
centreness at end	-.030	-2.32 *	-.639	-20.26 ***	-1.226	-1.35 ***
Spatio-temporal aspects						
trip distance (log)	-.039	-3.47 ***	-.024	-2.28 *	-.199	-5.90 ***
Δ elevation	-.151	-12.07 ***	.081	7.92 ***	-.343	-7.68 ***
morning peak *(ref weekend)*	.287	8.72 ***	.100	3.39 ***	.041	.48
afternoon peak *(ref weekend)*	.015	.81	.039	2.69 **	.103	2,56 **
weekday off-peak (*ref weekend*)	.018	1.71	.028	2.63 **	-.022	-.70
User characteristics						
age	-.323	-5.94 ***	-.368	-6.91 ***	-.620	-5.98 ***
age (squared)	.314	5.75 ***	.329	6.05 ***	.600	5.75 ***
female *(ref male)*	-.083	-3.60 ***	-.097	-4.35 ***	-.249	-4.22 ***
outer-Oslo user *(ref inner-Oslo)*	.541	15.19 ***	.413	12.67 ***	.726	9.20 ***
outside Oslo user *(ref inner-Oslo)*	.320	8.15 ***	.326	8.66 ***	.272	2.67 **
constant	-2.576	-123.99 ***	-2.542	-118.23 ***	-6.008	-9.35 ***
*model fit: Wald Chi²(df) = 26,090.13(48)***, Pseudo R² (McFadden) = .222*						

Conclusion and discussion

Bike sharing could provide a key role in a transition towards a less car dependent and more sustainable, healthy and socially inclusive urban transport future. Yet, whilst Mobility as a Service-initiatives advocate that successful multimodal public transport systems hinge on common platforms, smart technologies, uniform ticketing systems, and seamless connections between public and shared transport modes, this paper highlights that, such factors alone are not enough. For an integrated bike sharing-public transport system to successfully outcompete urban car mobility, it is crucial for bike sharing to (i) *synergise rather than compete* with current alternatives to car-based urban mobility (e.g. Fishman et al., 2013), and (ii) *be inclusively accessible* to different population segments. Drawing on complete 2016-2017 trip records of the one-way, dock-based Oslo (Norway) bike sharing system, this paper investigates the potential use of bike sharing for accessing, egressing and interchanging public transport and explores its age and gender dimensions.

Our cross-sectional findings indicate that ridership on bike sharing routes is strongly related to the connectivity to public transport, while controlling for other factors, such as route distance, elevation, urban form, time of day and bike dock capacities. Bike sharing ridership is higher on routes that have either their origin or destination bike sharing dock (but specifically not both) within a 200m range of metro/rail stations, especially during weekday morning peaks and least so during weekends. Rather than competing with public transport, bike sharing appears to fill a specific market share on commute routes perpendicular to the metro/rail network that provide access-egress to job or residential locations less accessible by public transport. A similar effect was not found for connectivity to bus or tram stops, indicating that bike sharing synergises best with higher-speed/capacity urban transport systems that on their own offer lower door-to-door access.

However, our results also reveal that bike sharing, both as a stand-alone system and in interconnection to public transport, is used differently by, and suited unevenly to different population segments in different parts of the study area. First, the system is confined to the larger inner-city area, with the finer-grained network privileged to the very city centre. Restrictions on rental duration and the inflexibility of not being able to park outside designated docks, effectively prevent use outside the confined areas. This excludes usage in the majority of high density lower-income residential areas and industrial/logistical employment centres. Second, gender differences are particularly striking: (i) despite recent incremental increases in use amongst women (Uteng et. al. 2019), the current system is still predominantly used by men (58% male users; 68% of trips by men); (ii) it offers poorer access to female- compared to male-dominated employment centres; (iii) it is utilised less by women to access-egress public transport; and (iv) its rental restrictions, such as on maximum rental duration and inflexibility of dock parking, are ill-suited to women's preferences (ibid) and spatiotemporally-complex everyday activities (e.g. Schwanen et al., 2008). Third, complementing on typical early adopter biases for bike sharing found in the literature (e.g. Fishman et. al., 2015, Campbell & Brakewood 2017, Hosford & Winters 2018), users are often young (mean age: 30), especially on routes in university areas and away from downtown employment centres. Access-egress bike sharing routes are used more by younger people and less by middle-aged groups.

So how are these findings relevant for attractiveness, inclusiveness, health and sustainability in cities? The knowledge provided by this study has particular significance for public and private actors who want to strategically use bike sharing to achieve such greater goals, rather than simply ticking the box of having a (growing) bike sharing system. To advance the performance, multimodal integration, and inclusiveness of bike sharing, policy makers, public transport authorities and bike sharing providers are advised to consider improvements targeting (i) multimodal integration, (ii) dock expansion, (iii) rental limitations, and (iv) e-bikes. First, public transport and bike sharing networks should be better integrated by installing bike sharing docks within the tested 200m range of a larger and more geographically distributed selection of train and metro stations. Integration could be further enhanced by trialling uniform ticketing for bike sharing and public transport; walkability improvements of interchange environments; and higher bike dock capacities to mitigate interchange connectivity uncertainties related to the risk of full or empty bike docks. Second, incentives should be given to trial dock expansion outside the city centre, particularly focussing on bike dock pairs connecting metro/rail stations to non-station locations of high residential or employment density, including lower income neighbourhoods and female-oriented employment centres. Third, trials should be incentivised to lift rental restrictions to better suit the mobility needs of women and other marginalised groups, including longer rental durations, opportunities to lock bicycles outside designated docks. Fourth, to lift range, time and bodily constraints in a hilly city context like Oslo, trials with shared electric bicycles should be incentivised. This could also enhance the hard competitiveness of bike sharing over the less physically active and arguably less durable free-floating systems of shared electric scooters.

To support the knowledge base for policy towards bike sharing and the multimodal integration of this fast-growing transport mode, further research is recommended along three lines of inquiry to expand on the limitations and findings of this study. First, with today's wide (public) availability of big data on bike sharing, studies could replicate our research design to assess and cross-compare the effects of metro-rail proximity on bike sharing ridership in a wider range of contexts, including smaller and larger cities, high and low public transport or cycling contexts, different topographies and climates, non-western contexts, and other types of bike sharing business models (e.g. one-way/two-way/free-floating, private or publicly-funded, advertised or non-advertised). Second, a limitation of our data is that we do not know whether bike sharing trips are actually used access-egress. We account for this limitation by controlling for other known determinants of bike sharing demand, but future studies could use other data collection methodologies to acquire actual revealed bike sharing access-egress behaviours, including data on integrated ticketing systems or GPS-tracking of bike sharing users. Third, studies should investigate the rapidly changing competitive landscape and possibly intertwined usages of bike sharing and other existing or new transport modes, including car sharing and aforementioned shared electric scooters for access-egress. Finally, hegemonic quantitative approaches in studying bike sharing, should be supplemented with qualitative approaches to better grasp the barriers, recruitment/retainment motivations and everyday life interdependencies that shape bike sharing practices.

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