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Empirical analysis of cycling distances in three of Europe's most bicycle-friendly regions within an accessibility framework

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ABSTRACT

In this paper, we study observed cycling distances within an accessibility framework, using data from the Netherlands, the Copenhagen Metropolitan Area and the Freiburg Region. As a scope, we look at outbound trips in home-based tours which include a single destination. We relate these observed cycling distances to a rich set of explanatory variables using both quantile and ordinary least square regression models. The results provide evidence that cycling distances are similarly distributed in all three regions. Most cycling distances are rather short, with a median of only two and a mean of three kilometers. These values vary depending on the type of activity at the destination, gender and age of the traveler and the type of bicycle that has been used. Moreover, a few remarkable differences have been found between the three regions, such as substantially different effects of age and e-bike use on observed cycling distances. Noteworthy is the missing effect of urban density. The findings of this research provide urban planners with differentiated information about how far people cycle to daily-life destinations. As shown for the example of the "15 minutes city," the outcomes can also be used to refine existing concepts of bicycle accessibility. Finally, this research offers valuable insights into three of Europe's most developed bicycle cultures.

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Accessibility; Copenhagen; cycling distances; Freiburg; the Netherlands

1. Introduction

People mainly travel to reach destinations where they perform activities such as working or shopping. While the mobility to reach the corresponding destinations is important for the functioning of modern society, the resulting traffic poses a problem to many urban areas. In particular motorized traffic is associated with serious environmental (e.g. air pollution, noise …) and societal issues (congestion, space consumption …) (Bilbao-Ubillos, 2008; Grahame & Schlesinger, 2010; McCahill & Garrick, 2012; Passchier-Vermeer & Passchier, 2000). One way to reduce these travel-related problems is a mode shift from car to bicycle. Cycling is known to have virtually no environmental impacts, to be affordable for the user and both space and cost efficient for the city (Haustein et al., 2019). Furthermore, cycling can improve health due to increased physical activity, resulting in external benefits for the society (Gössling et al., 2019; Rich et al., 2021). However, a prerequisite for the frequent use of the bicycle in daily life is that many destinations are within reach.

In the context of a mode shift from car to bicycle, empirical knowledge of the bicycle range is of interest in two respects. First, it can be used to analyze the bicycle substitution potential of car trips for an existing area and its trip distribution (Beckx et al., 2013; Delso et al., 2018). By applying a particular distance threshold as a filter on all trips, the maximum theoretically achievable bicycle use can be estimated. Such information can be used by urban planners to identify high potential corridors and prioritize bicycle infrastructure investments. Second, the idea of creating bicycle-friendly cities by developing diverse and dense urban neighborhoods with various destinations in proximity has recently gained new momentum. Especially the concept of the "15 minutes city," postulating basic urban amenities within a 15 minutes' walk or bicycle ride, has received wide attention and became the guiding principle of urban developments in cities like Paris (Moreno et al., 2021). A requirement for such bicycle-oriented neighborhoods is that frequently visited destinations are placed within the range of the bicycle (Li et al., 2020; McNeil, 2011; Saghapour et al., 2017). Against these backdrops, it is surprising how little differentiated our state of knowledge is regarding typical cycling distances to destinations.

To date, representative information on typical cycling distances can mostly be found in summary reports of (national) travel surveys (e.g. Christiansen & Baescu, 2021; de Haas & Hamersma, 2020; Nobis, 2019). The reports provide aggregated descriptive statistics of cycling distances

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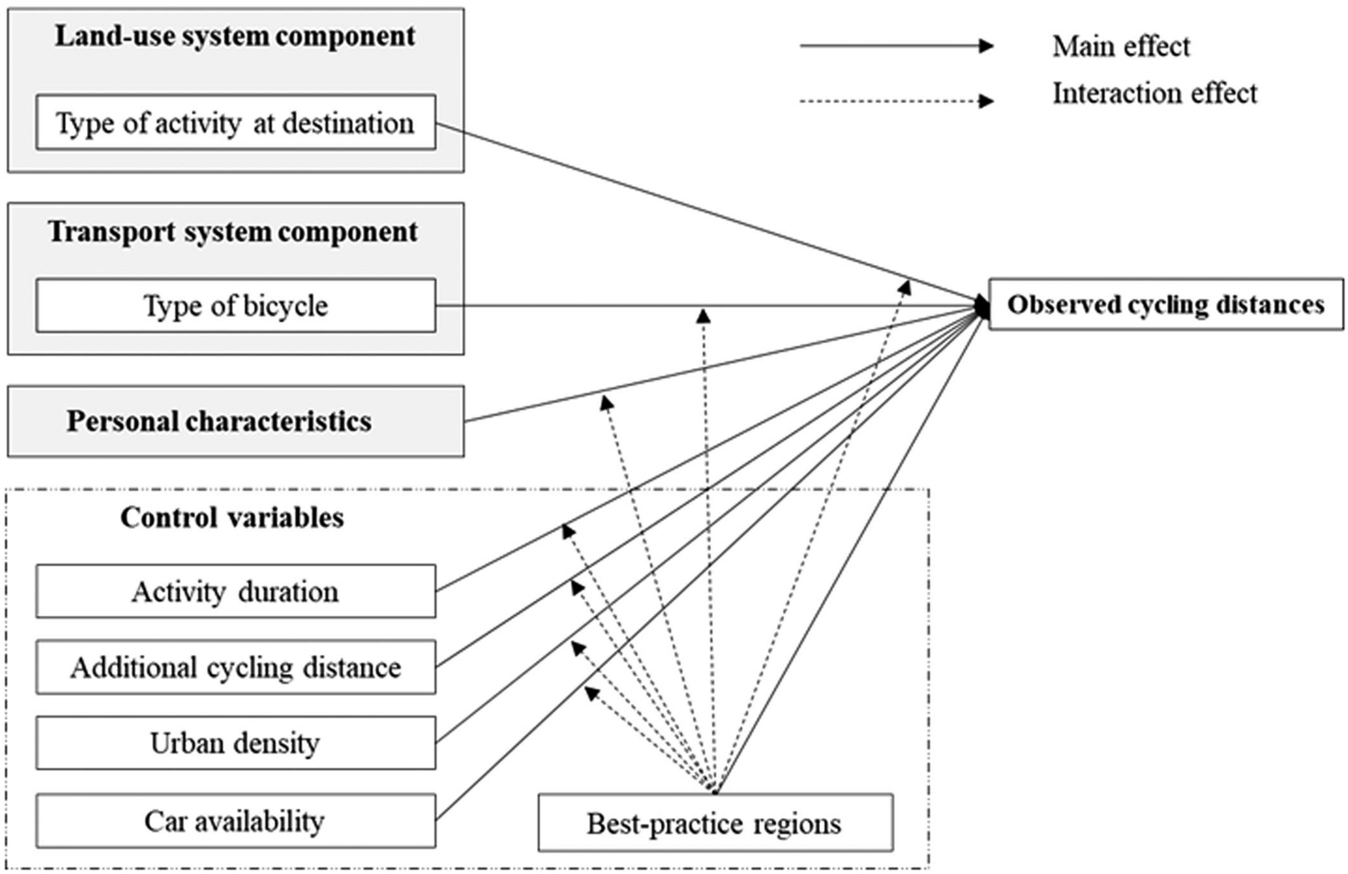

Figure 1. Conceptual model of the analysis of observed cycling distances.

such as the means for the whole sample or for different groupings of trips (e.g. age classes or trip purposes). Similarly, research on revealed bicycle travel behavior, such as route choice behavior (Hood et al., 2011; Ton et al., 2017), often includes summary statistics on travel distances. While former research relied on such fixed values to define distance thresholds for potential bicycle trips (Beckx et al., 2013), the use of context-independent cutoff points is debatable. In fact, we know from these reports that a variety of factors seem to affect cycling distances, for example the type of activity performed at a destination. As a consequence, accessibility assessments should consider the respective type of destination and the characteristics of the target group. To our knowledge, however, a systematic analysis disentangling the different effects (e.g. a girl cycling to school) on cycling distances is still lacking.

Another issue arises from the degree to which different types of cyclists are represented by the data. A typology proposed by Dill and McNeil (2013) distinguishes “the strong and fearless,” “the enthused and confident,” “the interested but concerned,” and those that are not open to cycling. It is obvious that the first three groups constitute the potential cycling population whose travel behavior should underlie any bicycle range definition. However, depending on the respective cycling conditions, the actual cycling population can be considerably smaller. Since travel surveys only capture the cycling trips of those who cycle already, there is a risk to overestimate the bicycle range for the potential cycling population.

In this research, we address the presented research gaps by extending the empirical knowledge of cycling distances. Within an accessibility framework, we relate a rich set of contextual variables to observed cycling distances using both quantile and ordinary least square (OLS) regression techniques. For this purpose, we create a unique data set combining travel diary data from three of Europe’s most bicycle-friendly regions, namely the Netherlands, the Copenhagen Metropolitan area in Denmark and the Freiburg Region in south-west Germany (Buehler & Pucher, 2011; Nielsen et al., 2013b; Pucher & Buehler, 2008). By looking at best-practice environments, we can expect that large parts of the potential cycling population are represented by the data. As a consequence, our results provide meaningful input for defining context-dependent bicycle ranges.

In the remainder of this paper, we first outline how we investigate cycling distances within an accessibility framework. Subsequently, we present the study areas and the data used in the analysis in Sec. 3. Next, we describe the statistical analyses performed in Sec. 4. Finally the results are presented and put into perspective in Secs. 5 and 6 before providing some concluding comments in Sec. 7.

2. Study approach: Bicycle accessibility framework

The goal of this study is to provide differentiated empirical insights into cycling distances that can be used for bicycle accessibility assessments. In the following, we define bicycle accessibility, shortly discuss cycling distances as an indicator

	Population	Urban density [inh./km²]
The Netherlands	17.1 millions	411
Copenhagen Metropolitan Area	2.6 millions	266
Freiburg Region	0.7 millions	295

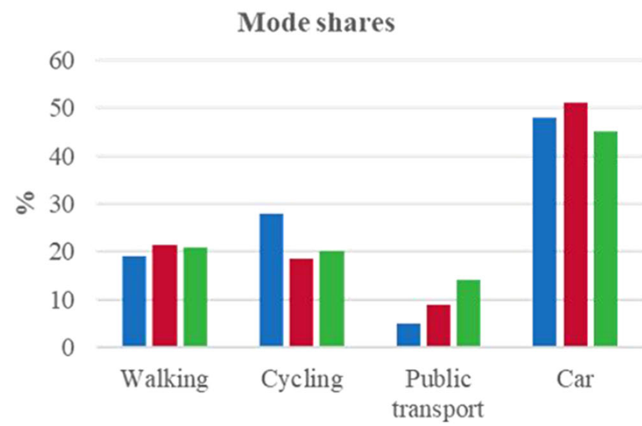

Figure 2. Key features of the study areas. All figures refer to data from 2016 respectively from 2014–2019 (mode share of the Copenhagen Metropolitan Area). Calculated based on data from: Statistics Netherlands (CBS, 2016), Danish National Travel Survey (OECD, 2009), Danish Ministry of social affairs and the interior (Social og indenrigsministeriet, 2016), City of Freiburg (PTV Group, 2017), Statistical state office Baden-Württemberg (Statistisches Landesamt Baden-Württemberg, 2016).

of bicycle accessibility and develop based on these reflections the conceptual model of the analysis.

Accessibility can be defined as 'the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s) at various times of the day' (Geurs & van Wee, 2013, p. 208). Assuming that the temporal dimension of this definition due to congestion is not (yet) a major concern for bicycle traffic, bicycle accessibility essentially depends on the land-use and transport system and the characteristics of the traveler. According to the aforementioned authors, the land-use component primarily describes the spatial distribution of demand (i.e. the places where people live who want to engage in activities) and offer (i.e. destinations which offer the corresponding activity locations). The transport system component captures the resistance that is attributed to overcoming the space between origins and destinations in a given area. When traveling by bicycle, this resistance can for example arise from physical (related to active locomotion) and psychological (due to unsafe feelings) efforts (Annema, 2013).

Travel distance is an often-used operational measure of bicycle accessibility (Vale et al., 2015). According to the definition of accessibility provided above, travel distance compounds the land-use system (determining the distances between origins and destinations) and the transport system (i.e. the cycling network, the cycling facilities and the bicycle itself). This simplification can be problematic in environments, in which only rudimentary cycling infrastructure exists. In such a context, a destination that is further away but connected with a comfortable and safe cycling infrastructure might be more accessible than a closer destination without any cycling facilities (Broach et al., 2012; Prato et al., 2018). By choosing three best-practice regions, however, a good cycling network and adequate bicycle facilities can be expected to be largely in place (see Sec. 3). Consequently, observed cycling distances would mostly depend on the land-use component, the characteristics of the traveler and the type of bicycle.

In this context, bicycle accessibility is ideally assessed based on *acceptable cycling distances* of the potential cycling population. *Acceptable cycling distance* can be introduced as the distance that a person is willing to cycle for a particular activity and destination. By using the *acceptable cycling distances* of the potential cycling population, it is ensured that assessments refer to the highest potential bicycle use. However, data on *acceptable cycling distances* can only be collected in theoretical set-ups. Doubting that (particularly the little experienced) cyclists can realistically estimate their personal bicycle range, we prefer to rely on revealed data in this study.

Based on these reflections, we put forward the conceptual model illustrated in Figure 1. We treat observed cycling distances as the dependent variable, which is explained by the different components of bicycle accessibility and a few control variables. The land-use component refers to the type of activity at the destination that purposed the tour. To avoid any ambiguity, we only look at outbound trips in home-based tours that include a single out-of-home activity. Recent research suggests that this scope covers most activity-traveling by bicycle (Schneider et al., 2020). As argued before, the transport system component has been reduced to the type of bicycle by choosing data from bicycle-friendly areas. Personal characteristics comprise the features of the traveler and his or her social environment and were chosen based on available data (see Sec. 4).

The considered control variables monitor different aspects. Activity duration is a proxy for the importance of an activity (Schneider et al., 2021), expecting that longer durations entail longer distances. Additional daily cycling distances which go beyond the regarded tour (that is the distance to the considered destination and back home) capture the influence of physical constraints. Urban density at the municipal level relates to the land-use system of the respective journey and gives us an idea of the extent to which an expected contrast in terms of spatial availability of destinations affects observed cycling distances. Car availability tests if the presence of a competitor mode affects observed cycling distances. And finally, a variable referring to the included regions tests, if the non-included features of the transport system (characteristics of cycling network and bicycle facilities) are indeed no factor to explain observed cycling distances at the aggregated level of a best-practice region. Furthermore, we check the culture-dependency of the outcomes by interacting all variables with the different regions.

Acknowledging that *observed* cycling distances are likely to be shorter than *acceptable* cycling distances for the same sample, an analysis of cycling distances beyond the mean is crucial. By looking at other parts of the cycling distance distribution (e.g. at the 25 percent longest trips), a notion can be provided of which trip purposes and people can be expected to have higher personal boundaries of acceptable cycling distances.

3. Study areas

This study included data from the Netherlands, the Copenhagen Metropolitan Area (as defined by the Organization for Economic Cooperation and Development (OECD, 2009)) and the Freiburg Region. The geographical outlines, as presented in Figure 2, were chosen with a view to having comparable samples in terms of size and the proportion of observations associated to a highly urbanized or suburban/rural setting.

3.1. Cycling conditions in the three regions

All three European regions are forerunners in bicycle transportation (Buehler & Pucher, 2011; Nielsen et al., 2013; Pucher & Buehler, 2008). In order to understand similarities and differences between the Netherlands (NL), the Copenhagen Metropolitan Area (CPN) and the Freiburg region (FRG), we shortly compare the cycling environments.

3.1.1. Geography and land-use structure

The Netherlands is a mostly flat and highly urbanized country, with large areas being a poly-centric metropolitan area. The characteristic urban landscape in the Netherlands can be linked to a tradition of space-efficient land-use practices, aiming for both compactness and multifunctional land-use (Dieleman & Wegener, 2004). The Copenhagen Metropolitan area comprises mainly the Danish island of Zealand and some smaller neighboring islands in East Denmark and is relatively flat. The city of Copenhagen itself accounts for around 730,000 inhabitants (including Frederiksberg municipality) and is situated in the densely populated *Capital region*. Urbanization in this area has strongly been influenced by the so-called finger plan from 1947, a plan that concentrated the emerging sub-urbanization along five axes (OECD, 2009). The western and southern parts of the Metropolitan area have a mostly rural character with low urban densities and only few urban settlements. The Freiburg Region is an area in south-west Germany which consists of the three districts *City of Freiburg*, *Emmendingen* and *Breisgau-Hochschwarzwald*. It extends from the Rhine river in the west (which also is the border to France) into the *Black Forest* mountain range. The north-south extension is about 50 kilometers. The city of Freiburg, which accounts for around 230,000 inhabitants, is the major city of the region, while the remaining area is mostly rural. Freiburg is often considered to be Germany's leading city in terms of sustainable urban development, including among others sustainable transportation (Buehler & Pucher, 2011; Fitzroy & Smith, 1998) and bicycle-friendly land-use (Broaddus, 2010; Ryan & Throgmorton, 2003).

3.1.2. Mode share

The Netherlands is often considered to be the leading bicycle country in the world (Fishman, 2016). The country accounts for the highest nation-wide bicycle mode share with 27 per cent, followed at some distance by Denmark and Germany (Buehler & Pucher, 2012; Harms & Kansen, 2018). All three regions have in common that policies to inverse the decline of bicycle use after the second world war have been implemented from the early 1970s onwards (Buehler & Pucher, 2011; Haustein et al., 2020; Trine & Anne-Katrin, 2012). Some smaller Dutch cities, such as Zwolle or Groningen, now reach mode shares of more than 45% of all inner-urban trips. But also some rather rural areas in the East of the Netherlands exceed the Dutch average, while Rotterdam, the second largest Dutch city, stays with 22 per cent below it (Harms & Kansen, 2018). In the Copenhagen Metropolitan Area, a consistent gradient in bicycle use can be observed between the city of Copenhagen and its periphery. While the city itself accounts for a bicycle mode share of 29 per cent of all trips in 2017, this number is with 21 per cent in 2016 already considerably lower in the Capital region (i.e. city and close periphery) (Capital Region of Denmark, 2016; City of Copenhagen, 2017; Nielsen et al., 2013a). Similarly, the bicycle mode shares of trips within

Table 1. Key features of the employed travel diaries.

Data set name	The Netherlands Netherlands Mobility Panel (MPN)	Copenhagen metropolitan area Danish National Travel Survey (TU)	Freiburg region Travel survey Freiburg Region (ZRF)
Year(s)	2016	2014–2019	2016
Data collection method	Online	Online	Online & telephone
Survey duration	3 days	1 day	1 day
Season of data collection	Autumn	All year	Summer/autumn
Weekday/weekend	Both	Both	Weekday only
Age of participants	>11	>5	>5
Business trips	Yes	Yes	no
Travel distances	Reported	Reported	Calculated using google Distance Matrix API
Further information	Hoogendoorn-Lanser et al., 2015	Christiansen & Skougaard, 2015	–

each of the three districts of the Freiburg region in 2016 were with 34 per cent much higher in the city itself than in the surrounding districts, accounting for 19 and 12 per cent respectively (PTV Group, 2017).

3.1.3. Cycling network

In all three study regions, dense cycling networks exist which are particularly in the highly urbanized zones denser than those of cars (due to the principle of filtered permeability (Melia, 2012)). These networks mainly consist of traffic-calmed streets and bicycle lanes or paths. In this context, some differences can be observed between the regions. Traffic calming in terms of speed reductions seems to be more applied in the Netherlands and in the Freiburg Region than in the Copenhagen Metropolitan Area (see e.g. the speed maps of (CyclOSM, n.d.)). By 2008, 85 percent of the Dutch street network within built-up areas was traffic-calmed (Schepers et al., 2017). Similarly, 90 percent of the citizens lived in traffic-calmed streets in the city of Freiburg (Buehler & Pucher, 2011). Since these streets are restricted to 30 kilometers per hour or lower, speeds between cyclists and cars are similar and, therefore, no separation of both travel modes is usually designed (Schepers et al., 2017). Along streets with higher speed limits, dedicated bicycle facilities are extensively available in all three study areas but with different designs. In both, the Netherlands and Copenhagen physically separated bicycle paths prevail while in Freiburg, on-road bicycle lanes are preferred (Gössling, 2013; Schepers et al., 2017; Stadt Freiburg im Breisgau, 2012). All three regions have introduced a hierarchy to their cycling networks by developing a category of routes (named 'Fietssnelweg' (NL), 'Supercykelstier' (CPN) and 'Rad-Vorrang-Route' (FRG)) which is especially designed for attractive travel times by avoiding or minimizing waiting times at intersections (Capital Region of Denmark, 2016; Govenment of the Netherlands, 2018; Stadt Freiburg im Breisgau, 2012). Another common feature of all three regions is that cycling networks do not end at the municipal borders of Copenhagen, Freiburg and the Dutch cities but also extend to the surroundings (CyclOSM, n.d.). However, while a consistent cycling network exits between cities in the Netherlands and a growing network of *cycle superhighways* connects most municipalities in the *Capital Region of Denmark*, the development of a utilitarian inter-urban network just started in the Freiburg Region (Ministerium für Verkehr und Infrastruktur Baden-Württemberg, 2021).

3.2. Data set preparation

The analysis employed travel diary data from the Netherlands, Denmark and the Freiburg Region. The differences between the diaries are indicated in Table 1. While the Danish National Travel Survey (TU) is an all-year survey, the used travel diary of the Netherlands Mobility Panel (MPN) was collected during several weeks in autumn and the travel survey from the Freiburg Region (ZRF) during 2 months in summer and autumn of 2016. In MPN, respondents were asked to report their trips for three consecutive days, whereas in the TU survey and the ZRF survey, respondents were asked to report their trips for one full day only. Both TU and ZRF include cyclists down to the age of 6, while MPN only includes cyclists above 11 years old. Finally, ZRF does not include business trips.

Considering the scope of the analysis, only outbound trips within simple home-based tours (i.e. tours that include a single out-of-home activity only) by bicycle were selected. Cases with missing information on the variables used in the regression analyses or implausible observations were discarded. Since reported travel distances were not available in the ZRF survey, bicycle travel distances had to be calculated using *Distance Matrix API* from *Google*. In this context, an exploratory analysis of the impact of the different data collection methods was conducted for the MPN, revealing approximately normally distributed deviations, which are not expected to bias our analyses. We removed cycling trip distances larger than 20 kilometers in all data sets based on an outlier analysis of the most affected ZRF data (20 kilometers corresponded to the mean cycling distance plus three times the standard deviation). These outliers initially entailed that trends across the three regions were reversed when comparing mean to median cycling distances. Furthermore, observations that occurred more than once for the same person (e.g. identical 'work' trip observations) were filtered out. Data processing of the TU survey additionally involved the selection of trips that corresponded to geographical boundaries of the Copenhagen Metropolitan area and the calculation of urban densities on a municipality level based on population data from 2016 (Social og indenrigsministeriet, 2016).

Finally, further processing was conducted to make all three data sets comparable and to merge them into a single data file. In this context, weekend data and business trips (i.e. trips during working hours) were removed. In addition, variables were renamed and recoded into comparable categories across data sets.

Table 2. Sample composition with descriptive statistics.

	Total		NL		CPN		FRG	
	N (%)	Mean	N (%)	Mean	N (%)	Mean	N (%)	Mean
Activity type [km]								
Work	1557 (26)	4.68	492 (23)	4.46	628 (30)	4.90	437 (25)	4.63
Escort	298 (5)	1.48	119 (5)	1.61	79 (4)	1.38	100 (6)	1.40
Education	1121 (19)	3.17	286 (13)	4.75	466 (22)	2.48	369 (22)	2.83
Shop	972 (16)	1.73	453 (21)	1.88	273 (13)	1.87	246 (14)	1.31
Service	224 (4)	2.25	100 (5)	2.20	29 (2)	2.36	95 (5)	2.27
Leisure	560 (9)	2.69	190 (9)	2.50	171 (8)	3.02	199 (12)	2.60
Visit	358 (6)	2.88	130 (6)	2.92	147 (7)	2.92	81 (5)	2.75
Sport	697 (12)	2.30	315 (14)	2.33	225 (11)	2.34	157 (9)	2.20
Other	178 (3)	2.18	88 (4)	2.38	62 (3)	2.03	28 (2)	1.90
Gender [km]								
Female	3266 (55)	2.68	1271 (59)	2.69	1088 (52)	2.90	907 (53)	2.41
Male	2699 (45)	3.43	902 (41)	3.54	992 (48)	3.38	805 (47)	3.35
Age classes [km]								
Under 20	1439 (24)	2.67	355 (16)	3.97	574 (28)	1.97	510 (30)	2.55
20–39	1590 (27)	3.36	603 (28)	2.98	651 (31)	3.70	336 (20)	3.40
40–64	2137 (36)	3.25	800 (37)	3.03	632 (30)	3.84	705 (41)	2.96
65+	799 (13)	2.36	415 (19)	2.37	223 (11)	2.48	161 (9)	2.18
Education [km]								
Nonacademic	3806 (64)	2.83	1497 (69)	2.99	1211 (58)	2.71	1098 (64)	2.75
Academic	2159 (36)	3.35	676 (31)	3.16	869 (42)	3.72	614 (36)	3.03
Household members [km]								
1	844 (14)	2.96	397 (18)	2.65	339 (16)	3.40	108 (6)	2.76
2	1665 (28)	3.08	606 (28)	2.72	639 (31)	3.52	410 (24)	2.93
3	1014 (17)	3.01	306 (14)	3.06	359 (17)	3.18	349 (21)	2.79
4 or more	2452 (41)	3.00	864 (40)	3.44	743 (36)	2.66	845 (49)	2.85
Car availability [km]								
No car availability	2567 (43)	2.91	642 (30)	3.42	1235 (59)	2.83	376 (40)	2.56
Requires planning*	1658 (28)	3.39	587 (27)	3.09	621 (30)	3.71	683 (26)	3.17
High car availability	1740 (29)	2.82	944 (43)	2.76	224 (11)	3.22	653 (34)	2.69
Land-use context [km]								
Suburban/rural	2491 (42)	2.87	984 (45)	3.02	843 (41)	2.51	664 (39)	3.11
Highly urbanized**	3474 (58)	3.12	1189 (55)	3.06	1237 (59)	3.56	1048 (61)	2.69
Type of bike [km]								
Normal bicycle	5493 (92)	2.94	1786 (82)	2.86	2037 (98)	3.12	1670 (97)	2.81
E-bike	472 (8)	3.91	387 (18)	3.87	43 (2)	3.77	42 (3)	4.41
Activity duration [h]	5965	3.74	2173	3.06	2080	4.56	1712	3.60
Additional cycling distance [km]	5965	3.23	2173	3.21	2080	2.48	1712	4.17

*Refers to car sharing within household (number of people with driving license > number of cars in the household), among friends or commercial car sharing.
**Refers to urban densities larger than 1500 inhabitants/km^2 on a municipality level for the Netherlands and Copenhagen Metropolitan area, includes only the core-city of Freiburg (excluding villages that administratively belong to the municipality) for the Freiburg Region.

3.3. *Sample* description

The final data set contains 5,965 bicycle trips stemming from 4,674 different travelers. The composition of the sample with regard to the variables employed in the regression analyses (see Sec. 4) is shown in Table 2. In the following, we discuss some remarkable features of the sample that should be considered when analyzing the model results.

Since TU travel surveys are collected throughout the whole year, the data from the Copenhagen Metropolitan area account for somewhat higher shares of mandatory activities ('work' and 'education'), whose frequency drops less during winter (Nielsen et al., 2016). Remarkable are also the shares of 'education' and 'shop' trips in the Dutch subset. The lower share of 'education' trips in the Netherlands (and likewise, trips of the youngest age class 'Under 20′) seems to be related to the fact that the MPN only includes children from 12 years onwards while this boundary is lower in the TU and ZRF data (6 years). A follow-up analysis, however, revealed that the lack of younger children does not seem to be accountable for the outstandingly long 'education' trips in the Netherlands compared to the other two regions. The high share of 'shop' observations in the Netherlands could be, again, related to the age composition in this subset since shopping is expected to be more an adult task in the household. Another interesting feature is the consistent preponderance of female travelers across all regions. This characteristic is in line with former evidence, noting that women cycle more often than men (Haustein et al., 2020). A striking outcome are the differences regarding *car availability*. While we can only speculate about the limited car availability of the Danish subsample, boundary conditions such as outstandingly high car registration taxes (Haustein et al., 2020) (which might primarily discourage people from buying a car for who the bicycle is a viable alternative) certainly play a role. A last note on the sample composition concerns the few e-bike observations, which are mostly related to the Dutch subsample. While there are indications from e-bike sales that the Netherlands is the leading country in terms of relative e-bike possession, comparable data on e-bike mode shares across countries are still missing.

4. Quantile and ordinary least square regression models

The conceptual model, in which a continuous outcome (observed cycling distances) is explained by a set of explanatory variables, is a typical use case of multivariate regression

Table 3. Principle of estimating all effects of weighted effect-coded main and interaction terms by using 4 complementary models.

	Model 1		Model 2		Model 3		Model 4	
Variables	Main effect	Interaction effect	Main effect	Interaction effect	Main effect	Interaction effect	Main effect	Interaction effect
Variable A (categories: Cat1, Cat2)	Cat1	Cat1* Level1 Cat1* Level2	Cat1	Cat1* Level2 Cat1* Level3	Cat2	Cat2* Level1 Cat2* Level2	Cat2	Cat2* Level2 Cat2* Level3

analysis (Wakefield, 2013). The postulated research goals from Sec. 2 require using more than one regression technique. First, we are interested in exploring the effects of explanatory variables on other parts than only the mean of the cycling distance distribution (e.g. on the 25 percent longest trips). And second, we want to investigate a rich set of independent variables and related interaction terms, resulting in a large number of (mostly categorical) explanatory variables.

The first goal can be achieved using quantile regression (Koenker & Bassett, 1978). This regression technique allows for estimating the parameters of the explanatory variables for any quantile of interest. Another advantage of quantile regression is that there are no underlying parametric assumptions regarding the residuals (homoscedasticity and normally distributed residuals). Yet, quantile regression results are difficult to interpret when confronted to a large number of categorical variables (as we intend to do here). In such a case, all reference categories of dummy-coded categorical variables are confounded in the intercept, representing a meaningless benchmark group for the estimates of dummy-coded categories.

For this reason, the second goal can be better attained using ordinary least square regression (OLS) in combination with weighted effect coding. In weighted effect coding, estimated effects do not refer to an omitted category but to the sample mean (te Grotenhuis et al., 2017b). This coding technique entails that estimated regression coefficients remain stable regardless of the omitted category. By estimating models with complementary omitted categories, all effects can be estimated and merged into a single results table. The principle is illustrated in Table 3 (see also (Schneider et al., 2021) for a more detailed explanation). While weighted effect coding can be applied in combination with any generalized linear model (te Grotenhuis et al., 2017b), its design around the sample mean makes it incompatible with quantile regression.

4.1. Quantile regression

Considering the elaborated difficulties of interpreting quantile regression models with many categorical variables, we opted for a parsimonious model. Obviously, such a model has to include the *type of activity* since this is the primary research interest. In addition, we added *gender* and *age* as typical control variables. Furthermore, we also included the *type of bicycle* since e-bike distances are expected to be considerably longer (Kroesen, 2017). We estimated the effects of these variables on three different quantiles, namely the 50th (median), 75th and 90th quantiles. The reasoning for investigating more the effects on the right-tail of the cycling distribution is that we expect more insightful differences between the included explanatory variables when distances are getting longer. For parameter estimation, we used the R package *quantreg* (Koenker, 2018). To link quantiles straightforward to cycling distances, we provide an empirical cumulative density distribution (CDF) of the cycling distances in the sample.

4.2. OLS regression

The purpose of the OLS regression models is to exploit the full potential of the data set with regard to relationships between explanatory variables and observed cycling distances. We selected the specified explanatory variables from the conceptual model (Figure 1) and interacted them with the three regions. More specifically, we included the categorical variables *activity type*, *gender*, *age classes*, *education*, *number of household members*, *car availability*, *land-use context* and *type of bicycle* (see Table 2). Furthermore, the continuous variables *activity duration* and *additional cycling distance* were considered. All categorical variables were weighted effect coded using the R package *wec* (Nieuwenhuis et al., 2017). Continuous variables were mean-centred. The same R package was employed to code the interaction terms between all explanatory variables and the three regions (te Grotenhuis et al., 2017a). The OLS regression models were estimated using the R package *stats* (R Core Team, 2013).

In OLS regression, a prerequisite for reliable estimates is that the residuals are normally distributed and homoscedastic (Field, 2009). In our data, these assumptions were violated, leading to biased standard errors and, as a consequence, to potentially wrong significance values for the regression coefficients. A generalization of the results beyond the sample is therefore problematic and the results from the OLS regression will only be used to highlight further factors that are potentially important to assess bicycle accessibility. In contrast, the estimates of the quantile regression should refer to the underlying population.

5. Results and discussion

In this section, we describe the outcomes of the analysis. We show and discuss the cumulative distance distribution of cycling trips and the results of the quantile regression analysis in Secs. 5.1 and 5.2 respectively. The results of the OLS regression analysis are presented in Sec. 5.3. A critical discussion follows in Sec. 5.4.

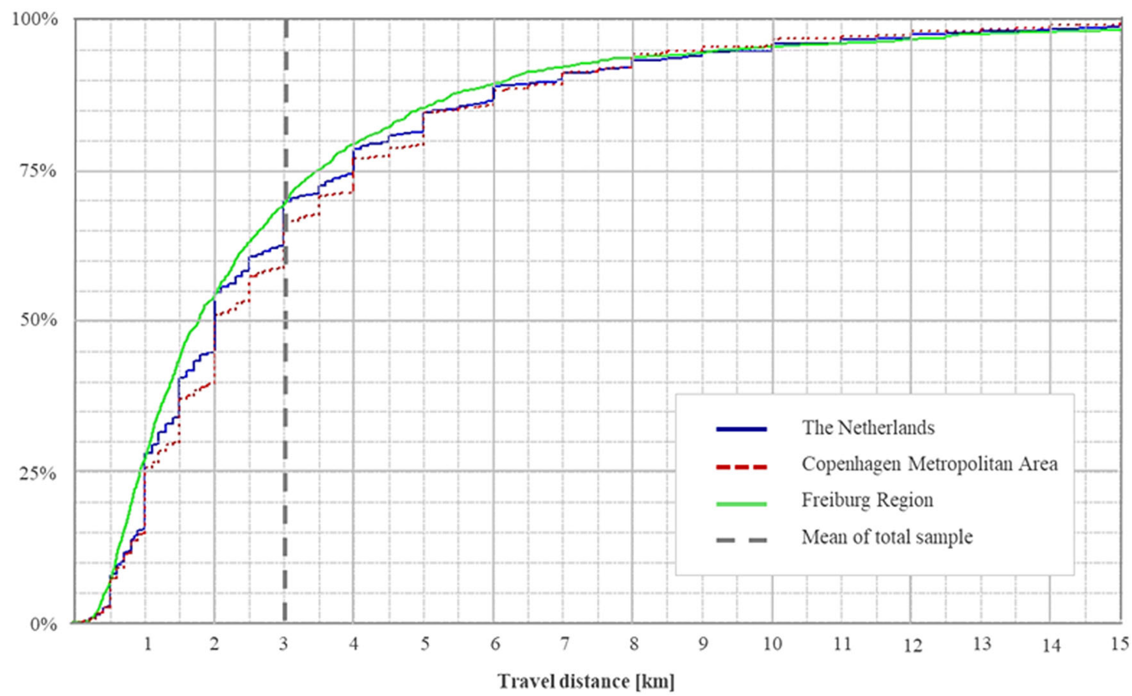

Figure 3. Empirical cumulative distribution of cycling trip distances toward a destination.

Table 4. Parameter estimates of the quantile regression models for the 50th, 75th and 90th quantiles of distances traveled by bicycle.

	Effects on quantiles		
	Q50 *Estimate (p-value)*	Q75 *Estimate (p-value)*	Q90 *Estimate (p-value)*
(Intercept)	**3.71** ($p < .001$)	**6.25** ($p < .001$)	**9.90** ($p < .001$)
Work is reference			
Escort	**−2.57** ($p < .001$)	**−4.34** ($p < .001$)	**−6.25** ($p < .001$)
Education	**−1.01** ($p < .001$)	**−1.44** ($p < .001$)	**−1.90** ($p < .001$)
Shop	**−2.35** ($p < .001$)	**−3.84** ($p < .001$)	**−5.80** ($p < .001$)
Service	−2.02 ($p < .001$)	**−3.14** ($p < .001$)	**−5.00** ($p < .001$)
Leisure	**−1.61** ($p < .001$)	**−2.44** ($p < .001$)	**−3.90** ($p < .001$)
Visit	−1.61 ($p < .001$)	**−2.26** ($p < .001$)	**−3.40** ($p < .001$)
Sport	**−1.71** ($p < .001$)	**−2.84** ($p < .001$)	**−4.80** ($p < .001$)
Other	**−2.18** ($p < .001$)	**−3.34** ($p < .001$)	**−4.70** ($p < .001$)
Male is reference			
Female	**−0.36** ($p < .001$)	**−0.60** ($p < .001$)	**−1.20** ($p < .001$)
Age 40–64 is reference			
Age < 20	**−0.35** ($p < .001$)	**−0.80** ($p < .001$)	**−0.90** ($p < .001$)
Age 20–39	**0.26** ($p < .001$)	0.20 ($p = .068$)	0.10 ($p = .546$)
Age 65+	−0.07 ($p = .155$)	−0.23 ($p = .127$)	0.00 ($p = 1.000$)
Normal bicycle is reference			
E-Bike	**0.84** ($p < .001$)	**1.43** ($p < .001$)	**2.50** ($p < .001$)

5.1. Cumulative distance distribution

Figure 3 shows the empirical cumulative cycling distance distributions (CDF) of the sample of all three considered regions. Since the MPN and TU data sets included reported travel distances, which are often rounded (Witlox, 2007), visible steps occur every 0.5 kilometers. In contrast, the calculated travel distances in the ZRF data set have a smoother curvature. Nonetheless, all three curves are quite similar, emphasizing the notion that (at least) in bicycle-friendly environments cycling distances follow a characteristic distance distribution. The CDF indicates that bicycle-friendly land-use schemes are in place in all three regions, since 50 per cent of the trips are shorter or equal to only two kilometers. Interestingly, the graphs also show that there seems to be a lower threshold distance for cycling as few observations are recorded for distances shorter than 500 meters. In this distance range, many people might rather walk than cycle.

5.2. Quantile regression model

Table 4 shows the estimated parameters of the three quantile regression models. It can be seen that most estimates are highly significant. The interpretation of these *p*-values is that we can be relatively confident that the same effects also hold in the population underlying our sample. The estimates of the different variables relate to the reference group expressed by the intercept. The three intercepts show the estimated cycling distances for the 50th, 75th, and 90th quantiles of male commuters aged 40-64 who use a conventional bicycle. Compared to this reference group, most estimates gradually decrease when moving from the Q50 to the Q90 model. As a consequence, it can be concluded that the reference group is a major driver of longer cycling trips.

The results suggest that trip purpose has a much stronger effect on observed cycling distances than all included control variables, regardless of the considered quantile. In particular, ‘escort’, ‘shop’ and ‘service’ trips seem to be much shorter than the work trips of the reference group. As a consequence, the related destinations (daycare, elementary school, grocery shops, medical centers, etc.) should be placed close to (or within) residential zones. On the contrary, ‘education’ was the trip purpose that deviated least from cycling distances to ‘work’. This means that also for education, people often travel longer distances. While there is an increasing gap between female and male cyclists when distances are getting longer, a similar effect was not found for age. Only the youngest age class was accounting for an increasingly negative effect compared to the reference group across the

Table 5. Parameter estimates of the OLS regression models.

	Main effect	Interaction effects		
		NL	CPN	FRG
	Estimate (p-value)	*Estimate (p-value)*	*Estimate (p-value)*	*Estimate (p-value)*
Intercept (=sample mean distance)	**3.02** ($p<.001$)	–	–	–
NL	**0.11** ($p=.026$)	–	–	–
FRG	−0.06 ($p=.282$)	–	–	–
CPN	−0.06 ($p=.276$)	–	–	–
Work	**0.60** ($p<.001$)	**−0.59** ($p<.001$)	**0.42** ($p<.001$)	0.06 ($p=.697$)
Escort	**−0.91** ($p<.001$)	0.37 ($p=.069$)	**−0.69** ($p=.016$)	0.10 ($p=.679$)
Education	0.17 ($p=.086$)	**0.70** ($p<.001$)	−0.02 ($p=.543$)	**−0.45** ($p=.001$)
Shop	**−0.58** ($p<.001$)	**0.26** ($p=.014$)	**−0.39** ($p=.0211$)	−0.04 ($p=.800$)
Service	−0.09 ($p=.637$)	−0.08 ($p=.710$)	−0.60 ($p=.200$)	0.26 ($p=.219$)
Leisure	0.00 ($p=.970$)	**−0.39** ($p=.012$)	0.09 ($p=.616$)	**0.30** ($p=.049$)
Visit	0.04 ($p=.779$)	0.01 ($p=.968$)	−0.15 ($p=.378$)	0.25 ($p=.326$)
Sport	**−0.29** ($p=.005$)	−0.04 ($p=.716$)	−0.09 ($p=.575$)	0.20 ($p=.288$)
Other	**−0.43** ($p=.036$)	0.22 ($p=.279$)	−0.41 ($p=.143$)	0.21 ($p=.650$)
Activity duration [h]	**0.24** ($p<.001$)	**0.09** ($p<.001$)	**−0.13** ($p<.001$)	**0.06** ($p=.041$)
No e-bike	**−0.12** ($p<.001$)	−0.02 ($p=.143$)	**0.02** ($p=.011$)	0.24 ($p=.549$)
E-bike	**1.44** ($p<.001$)	0.08 ($p=.143$)	**−0.99** ($p=.011$)	−0.01 ($p=.549$)
Female	**−0.22** ($p<.001$)	−0.03 ($p=.479$)	0.04 ($p=.426$)	0.00 ($p=.936$)
Male	**0.28** ($p<.001$)	−0.04 ($p=.479$)	−0.04 ($p=.426$)	0.00 ($p=.936$)
Age < 20	**−0.46** ($p<.001$)	**0.52** ($p=.006$)	**−0.55** ($p<.001$)	0.26 ($p=.074$)
Age 20–39	**0.22** ($p<.001$)	**−0.18** ($p=.026$)	0.10 ($p=.206$)	0.14 ($p=.251$)
Age 40–64	**0.14** ($p=.020$)	−0.01 ($p=.833$)	**0.32** ($p<.001$)	**−0.27** ($p=.002$)
Age 65+	0.01 ($p=.956$)	−0.15 ($p=.170$)	0.22 ($p=.207$)	0.04 ($p=.840$)
Nonacademic	**−0.09** ($p=.005$)	−0.07 ($p=.058$)	0.03 ($p=.468$)	0.06 ($p=.224$)
Academic	**0.15** ($p=.005$)	0.15 ($p=.058$)	−0.04 ($p=.525$)	−0.11 ($p=.224$)
1 pers. Household	−0.08 ($p=.403$)	−0.04 ($p=.706$)	0.03 ($p=.802$)	0.05 ($p=.852$)
2 pers. Household	−0.06 ($p=.378$)	−0.09 ($p=.268$)	0.04 ($p=.657$)	0.08 ($p=.462$)
3 pers. Household	−0.07 ($p=.385$)	−0.10 ($p=.402$)	0.06 ($p=.539$)	0.02 ($p=.838$)
4 or more pers. household	0.10 ($p=.063$)	0.12 ($p=.083$)	−0.08 ($p=.344$)	−0.06 ($p=.382$)
No car availability	−0.04 ($p=.496$)	0.16 ($p=.093$)	−0.04 ($p=.419$)	−0.09 ($p=.358$)
Requires planning	0.11 ($p=.073$)	−0.15 ($p=.064$)	0.06 ($p=.475$)	0.12 ($p=.270$)
High car availability	−0.05 ($p=.439$)	0.01 ($p=.788$)	0.06 ($p=.871$)	0.01 ($p=.876$)
Highly urbanized	−0.01 ($p=.682$)	0.01 ($p=.840$)	**0.15** ($p<.001$)	**−0.18** ($p<.001$)
Suburban or rural	0.02 ($p=.682$)	−0.01 ($p=.840$)	**−0.22** ($p<.001$)	**0.29** ($p<.001$)
Additional bike distance [km]	**0.01** ($p=.022$)	−0.02 ($p=.055$)	0.00 ($p=.687$)	**0.01** ($p=.031$)

three quantiles. An explanation for the surprisingly insignificant estimates of the oldest age class could be that older people are more likely to own and use an e-bike (Kroesen, 2017), a factor which might offset to some extent lower physical capabilities. More importantly, however, seems to be the scarcity of data associated with this age class in the tails of the distribution. The positive and increasing estimates of the *e-bike* across the considered quantiles show that electrification has the potential to extend the bicycle range considerably.

5.3. Linear regression model

Table 5 presents the main and interaction effects of the OLS models described in Sec. 4. Due to weighted effect-coded categorical variables and the mean-centred continuous variables, all four estimated models could be merged into a single results table. The adjusted R squared of all models was 0.22. This is an acceptable value for an exploratory analysis, considering that the data stems from three different data sets. In the following, we highlight and discuss relevant main and interaction effects with regard to bicycle accessibility.

5.3.1. Main effects

The intercept represents the mean distance of the total sample (around three kilometers) to which all main effects refer. As a consequence, it is straightforward to interpret the effects of all variables. For instance, the model suggests that Dutch people cycled on average $3.02+0.11=3.13$ kilometers. In comparison, people from the Copenhagen Metropolitan Region and the Freiburg region cycled with $3.02–0.06=2.96$ kilometers slightly shorter. This outcome is in line with the similar CDFs presented in Figure 3, suggesting that overall cycling behavior is quite similar in all three *regions*.

Concerning the *type of activity*, 'work' trips were related to the longest estimated mean distances with 3.62 kilometers. In contrast, 'escort' and 'shop' trips accounted for the shortest mean distances among all considered activity types with estimated 2.11 and 2.44 kilometers respectively. All other activity types deviated by not more than estimated 0.29 kilometers from the sample mean. The estimated mean distances of the different activity types have to be interpreted together with the estimate of *activity duration*. The model results suggest that per hour of activity duration an extra 0.24 kilometers must be added. As a consequence, the gap in cycling distances between typically short activities, for instance 'escort', and longer activities, such as 'work' or 'education', increases. Overall, the results suggest that people cycle longer for mandatory activities of long durations.

Regarding the *type of bicycle*, the results are not surprising. With an estimated mean distance of 4.46 kilometers, the use of the e-bike has by far the largest effect of all included variables. This outcome is in line with former evidence (Banerjee et al., 2022)

In terms of personal characteristics, male cyclists were estimated to cycle 0.50 kilometers longer than female cyclists. This *gender* difference is supported by former research (Heinen & Van Wee, 2010). Furthermore, cyclists with an *academic* background cycle estimated 0.24 kilometers longer than cyclists with a nonacademic education. This outcome might be linked to different lifestyles and the respective role of the bicycle in these lifestyles (the bicycle as being a part of a healthy lifestyle versus being simply a mobility tool). Another explanation could be that job opportunities for highly specialized persons are often further away from home. The results further suggest that there are systematic differences between *age classes*. Similar to the outcomes of the quantile regression, the largest deviations were found between people younger than 20 and people between 20 and 39 years with estimated mean cycling distances of 2.56 and 3.24 kilometers, respectively. Regarding *household size*, only negligible differences were found between people living in differently composed households.

Finally, the included control variables revealed several interesting insights. *Car availability, urban density* (at the municipality level) and *additional cycling distances* (in addition to the cycling distance to the destination and back home) were not related to any considerable effect. Differently than expected people without car availability were not related to longer estimated mean distances. An explanation of this finding could be residential self-selection (van Wee & Cao, 2020). With regard to urban density, the outcome suggests that the higher density of opportunities (which is usually associated with more urbanized areas) rather affects the cycling mode share than the observed cycling distances. Concerning additional cycling distances, the results indicate that physical constraints were not a major factor for explaining the cycling distances in our sample. However, since many people only make two trips per day (Schneider et al., 2020) (entailing that no additional cycling distance has been covered), it has to be questioned how conclusive this result is.

In summary, these results further refined the analysis of the quantile regression by including more variables and fully disentangling their effects. With regard to bicycle accessibility, the results suggest that there might be a different bicycle range depending on the type of activity performed at the destination and its duration. Furthermore, the reach can be considerably extended by the e-bike. In addition, cycling distances are subject to the personal characteristics of the cyclist, most notable its gender and age.

5.3.2. Interaction effects

The interaction effects relate to the respective main effect and indicate differences between the three considered regions. For instance, 'work' trips in CPN were estimated to $3.02 + 0.60 + 0.42 = 4.04$ kilometers. Interestingly, this value is considerably further than in FRG and in NL with estimated 3.68 and 3.03 kilometers respectively. The particularly long estimated commute distances for the Danish context might be linked to a focus of local cycling policies on commuters, for whom the network is optimized (Capital Region of Denmark, 2016; Gössling, 2013). Regarding other activity types, both 'escort' and 'shop' trips were particularly short in CPN with estimated 1.42 and 2.05 kilometers. In comparison to NL, this signifies a difference of 1.06 and 0.65 kilometers, suggesting that related destinations are more densely distributed. An outstanding difference between regions was revealed for education trips, where the Dutch estimate is 0.68 kilometers meters longer than in FRG and even 1.15 than in CPN. This result is in line with former evidence, showing that trips to more distant secondary schools (further away than three kilometers) are largely traveled by bicycle in the Netherlands (Van Goeverden & De Boer, 2013). A last remarkable deviation was found for 'leisure' trips between FRG and NL, suggesting that people from the German subset cycled estimated 0.69 kilometers further than from the Dutch subset. A possible explanation for this finding could be that FRG is a touristic region in which an extensive leisure cycling culture (mountain biking race biking, bicycle touring) exists. As a consequence, the delimitation between traveling and activity participation might partly blur, entailing that the bike ride to the leisure activity location becomes part of the leisure experience.

With regard to activity duration, an interesting outcome is the deviation of the Danish estimate in comparison to the two other regions. While the cycled distance grows by 0.33 kilometers per hour of activity duration in NL, it only increases by 0.11 in CPN. This difference seems to be partly caused by different mean activity durations (see Table 2). A follow-up analysis revealed that in particular average 'work' and 'education' durations were longer in CPN.

The effect of the e-bike is considerably different between the three regions. It is much larger in both the Netherlands and the Freiburg Region than in the Copenhagen Metropolitan Area. This finding might in parts be explained by the relatively little data available for CPN and FRG. Yet, the magnitude of the differences of around one kilometer raises the question, if there are different e-bike user groups (e.g. commuters compared to pensioners) and if the cycling infrastructure accommodates the needs of e-bike users differently.

Concerning personal characteristics, larger differences were only revealed with regard to the effects of age. Most outstanding is the deviation in the youngest age class between NL and CPN. This observation might be linked to typical infrastructure features, which result in different levels of exposure to motorized traffic. While Copenhagen guidelines promote separation at sections by (only) a kerbstone and mixed zones at intersections (City of Copenhagen, 2014), the Dutch counterparts advocate more physical separation along main roads and complete segregation at (busy) intersections (CROW, 2017). Both features of Dutch infrastructure design are particularly in favor of more vulnerable (including young) cyclists.

While *urban density* was not related to any noteworthy effect at the level of the whole sample, a difference of up to 0.51 kilometers was found between CPN and FRG. For the former, estimated distances were longer in municipalities with high urban densities and shorter in suburban or rural environments. In contrast, the inversed relationship was found for the Freiburg region. A follow-up analysis revealed that due to the smaller city size, particularly 'work' and 'education' trips toward Freiburg were longer than those within it. Conversely, the city of Copenhagen is considerably larger and many surrounding municipalities still account for high urban densities according to the definition employed in this research (i.e. more than 1,500 inhabitants per square kilometer).

To sum up, the interaction terms revealed region-specific peculiarities. At the level of the land-use system, the observed differences point to slightly different spatial availabilities of activity locations. At the level of the transport system, indications were found that the respective cycling network and infrastructure design affects the observed cycling behavior. And last but not least, the cycling cultures seem to differ regarding some aspects, such as the way how the e-bike is used and the question how free children move in traffic by bicycle.

5.4. Limitations

While our approach to look at observed cycling distances in best-practice environments within an accessibility framework provided valuable insights, it comes with four limitations. First of all, we do not have data of cases, in which destinations were not accessible by bicycle due to distance or inappropriate infrastructure. As a consequence, there is a risk of overestimating critical distance values of bicycle accessibility. However, we argue, that by choosing regions with high mode shares of the bicycle, we ensure that observed cycling distances are not restricted to few types of cyclists only (Dill & McNeil, 2013), but represent the whole potential cycling population. Consequently, the risk of overestimating accessible distances due to the profile of the sample is reduced.

Second, we do not have information on acceptable cycling distances. While every revealed bicycle trip can be interpreted as a data point of existing (subjective) bicycle accessibility (otherwise the trip would not have taken place by bicycle), we do not know how much further a person would have cycled if necessary. By implication, the values of this analysis are conservative estimates of distance ranges within which destinations should be placed. Yet, while too long distances are an exclusion criterion for bicycle use, an underestimation is less problematic in practice.

Third, we only looked at cycling trips departing from home, a study frame that is largely characterized by private bicycle use. While this scope relates to the most frequent use case of bicycle transportation, other scenarios are of raising interest. Considering the recent developments of multimodal mobility services, future research could shed light on the reach of users of bicycle sharing systems. Such knowledge could, for example, be useful to assess the effects of on-demand bicycle fleets on the accessibility toward destinations around public transport hubs. And finally, all results from the analysis relate to the cycling networks and bicycle facilities available in the three regions. Since these are of higher standards than what can be found in many other places (see Sec. 3), one has to be cautious when transferring the results to other contexts.

6. Implications for urban planning and policy making

In this section, we first discuss the larger lessons learnt from this study from a practitioner's perspective before shortly comparing our results to current practice by the example of "The 15 minute city."

6.1. Principal lessons learnt

Based on the conducted analysis, three lessons can be learnt. The first lesson refers to the question how to define bicycle accessibility in practical terms. In theory, a destination is accessible for a person as long as it lies within the range of what he or she is willing and capable to cycle given the features of the transport system. From an efficiency point of view (i.e. not imposing more than the necessary requirements on land-use planning), one might therefore be tempted to approximate boundary values and set these values as thresholds of bicycle accessibility. The results from the three regions, however, suggest orientating bicycle-friendly planning at lower values. For all three regions, the CDF of cycling distances showed that a high concentration of observed trips had only very short distances. Considering that high mode shares can only be reached if a large part of the potential cycling population (i.e. all people for whom cycling is in principle an option) has access to their daily-life destinations by bicycle, accessibility should be ensured for the less performing cyclists, regardless of what the majority of the cycling population would have been willing to cycle. As a positive side-effect, accessibility for pedestrians at the land-use level might be achieved at the same time.

Second, the outcomes of the conducted analyses suggest adjusting critical cycling distances to the type of activity performed at the destination and the profile of a destination's target group rather than using a universal value. All models highlighted the importance of the type of activity at the destination. In addition, if younger people are a target group, distances should be adapted in accordance with the estimates of this age class. In this context, we recommend using the estimates from the median quantile regression model as a benchmark for catchment areas of a destination. This model displays effects on average behavior instead of on mean distances (which are naturally more affected by more performant cyclists and outlier observations).

A third observation from the analysis is that even in cycling-friendly areas, some features of the transport system can make a substantial difference in terms of accessibility. Not surprisingly, the e-bike has the potential to extend the reach of the bicycle considerably. This is particularly true for user groups that are more subject to physical constraints such as pensioners or cargo bike users. In addition,

Table 6. Reference points of bicycle accessibility derived from "The 15-minute city" and the Q 50 model of the quantile regression.

"The 15-minute city"	Calculated mean distance [km]
Scenario: Average cycling speed = 12 km/h	3.00
Scenario: Average cycling speed = 15 km/h	3.75
Scenario: Average cycling speed = 18 km/h	4.50
Q50 model of the quantile regression (see Table 4)	**Estimated median distance [km]**
Scenario: Male, escort, aged 40–64, ordinary bicycle	1.14
Scenario: Female, aged 20–39, service, ordinary bicycle	1.59
Scenario: Female, commuter, aged 40–64, ordinary bicycle	3.35
Scenario: Male commuter, aged 20–39, e-bike	4.81

differences between the three regions indicate that some features of the bicycle infrastructure can also affect bicycle accessibility. Based on the performed analyses, it seemed that the prevailing infrastructure in the Copenhagen Metropolitan Area facilitates high travel speeds by bicycle, resulting in a larger reach for commuters. At the same time, this research also provided some signals that this achievement might be at the expense of more vulnerable or less performing cyclists such as children. From a societal perspective, however, a focus on the latter group could be more beneficial on the long run, considering the effects on *travel socialization* (Baslingtion, 2008) and health (Fox, 2004). A way to deal with contradicting requirements toward bicycle facilities could be to develop hierarchic cycling networks (similar to road networks) which consist of different categories, each of them accommodating the needs of a particular user group or activity type.

6.2. Implications for practice by the example of "The 15-minute city"

In recent years, a much-noticed concept dealing with bicycle accessibility is "The 15-minute city." It is based on the principal idea that all daily-life destinations should be accessible within 15 minutes by foot or by bicycle from home (Moreno et al., 2021). By using travel time as an indicator of accessibility, the approach takes into account people's varying physical capabilities. However, since a travel time of 15 minutes can translate to different distance ranges depending on a set of contextual factors (e.g. fitness of the cyclist, cycling network design, number of intersections …), the concept remains a theoretical construct for urban planners. Nonetheless, cities like Paris have adopted the concept as a guiding principle for future urban developments.

To determine the accessible area by bicycle, we exemplarily used average cycling speeds of 12, 15 and 18 kilometers per hour (see Table 6). As a result, the model of "The 15 minute city" suggests that all basic amenities should be found within 3.00, 3.75 or 4.50 kilometers. For the sake of comparison, Table 6 additionally presents several distance estimates from the median regression model, relating to different scenarios with regard to activity type, personal characteristics and the type of bicycle.

Compared to these benchmark values, "The 15 minute city" seems to provide a reasonable framework of bicycle accessibility for commuting. However, other types of destinations appear to be overestimated. For instance, the results from this study suggest that childcare facilities or healthcare centers should be found within one to two kilometers from home. In terms of travel time, this would mean a "5 or 10 minute city." This example shows that the results of our study can improve current models of bicycle accessibility by providing differentiated benchmark values that can be tailored to a scenario of interest.

7. Conclusions and future research

In this paper, we have empirically studied cycling distances in three outstanding cycling areas, namely the Netherlands, the Copenhagen Metropolitan Area and the Freiburg Region. Using the scope of outbound trips in home-based tours that involved a single destination only, we related a rich set of factors referring to land-use system, transport system, the features of the traveler and some further control variables to observed cycling distances.

The results showed that cycling distances were similarly distributed in all three regions with a high concentration of short trips around one kilometer and increasingly less observations once distances were getting longer. The total sample accounted for a median of two kilometers and a mean of around three kilometers. The quantile regression revealed that male commuters aged 40 to 64 cycling to 'work' and e-bike users cycled longer distances, while 'escort' and 'shop' trips, being a female cyclist and having an age younger than 20 were particularly short. In addition, the OLS models indicated the positive relationship between activity duration and observed cycling distances and revealed a few remarkable differences between the three regions, most outstandingly the effects of the youngest age group and the e-bike.

The contribution of this paper is to provide differentiated knowledge on how far people cycle in bicycle-friendly environments. The many observed short distances suggest that best-practice bicycle planning entails to provide destinations at distances that are probably much shorter than what most people would have accepted to cycle. In this way, a diversity of different types of cyclists can reach their daily-life destinations by bicycle. The high concentration of short trips despite performant cycling facilities also allows to conclude that bicycle-friendly land-use planning should be prioritized to bicycle-friendly transport system planning. The importance of proximity is highlighted by the noteworthy absence of an urban density effect, too. While lower urban density levels in the countryside (with a corresponding lower density of activity locations) was not linked to longer cycling distances, the bicycle usage rather declined. Nonetheless, the results from this study suppose that even in best-practice environments, the features of cycling network and facilities can increase bicycle accessibility for dedicated user groups.

The conducted comparison of our results with the "The 15 minute city" shows a limitation of this theoretical concept of bicycle accessibility. Recognizing the elegant simplicity of the "The 15 minute city" idea (which surely contributes to its political resonance), it lacks the necessary contextual differentiation to be applied in practice. The outcomes of our empirical study can help to refine such theoretical models. By providing tangible reference points for different situations, they can help urban planners to assess bicycle accessibility in an existing urban structure or for a planned urban development.

Based on the findings of this study, some recommendations can be derived regarding how to develop highly bicycle-accessible urban environments. First, bicycle use has to be facilitated in the neighborhood. Various daily-life destinations such as supermarkets, daycare facilities or primary schools should be placed within this perimeter. Such a small-scale land-use structure could be accompanied by extensive traffic calming measures, accommodating the needs of various different cyclist types. Second, high urban densities and mixed-use zoning should be favored at the level of the whole (poly-centric) metropolitan area, increasing the probability to find other frequent destinations such as work or higher education within bicycle reach. Since the planner has less influence on these origin-destination relations, a safe and comfortable cycling network along all important transport corridors should be built to increase bicycle accessibility via the transport system. Thirdly, the promotion of e-bikes seems to be a further tool to improve bicycle accessibility, in particular for longer distances.

Several directions for further research arise from this study. First, the different effects of the e-bike on observed cycling distances in the Netherlands and the Copenhagen Metropolitan Area raise the question under which circumstances the e-bike becomes an effective tool to increase bicycle accessibility. Next, better data availabilities regarding bicycle network and facility characteristics could allow to further disentangle the effects of land-use and transport system on observed cycling distances. And last, a study design that identifies boundary values of *acceptable cycling distances* might be of great help to assess the potential of cycling in environments of lower urban density.

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