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More afraid of the virus than of bad weather? Exploring the link between weather conditions and cycling volume in German cities before and during the COVID-19 pandemic

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A B S T R A C T

Cycling can only unfold its full potential for environmental sustainability, livable cities, and health if people cycle under most seasonal and weather conditions. During the COVID-19 pandemic, many people preferred cycling over public transit, in order to avoid infection. This change may also have affected the weather–cycling association: the pandemic mainly attracted new, fair-weather cyclists; and it may have encouraged cyclists to continue cycling, even under less favorable conditions. In this paper, we explore how the COVID-19 pandemic affected the association between weather and cycling. We analyze data from bicycle counting stations in Germany, combined with city- and hour-specific weather information and a continuous measure of pandemic intensity. The data set contains more than 2.2 million hourly bicycle count observations from 69 counting stations, covering the years 2017–2021. Results from the most transit-oriented cities in the sample, Berlin and Munich suggest that the cycling volume was more dependent on weather conditions at times of high pandemic intensity. This suggests that the pandemic put new people in the saddle, but these additional cyclists were largely fair-weather cyclists who only cycled when the weather was sufficiently nice. For policy, this could set two targets. First, encourage the new pandemic-cyclists to stay on the bike and, second, support them in transitioning into year-round cyclists eventually.

1. Introduction

Individuals and society benefit from cycling. At the societal-level, cycling contributes to environmental sustainability because it neither emits CO_2 nor noise and because it is space-efficient (Brand et al., 2021; Gössling, Schröder, Späth, & Freytag, 2016; Heinen, van Wee, & Maat, 2010). Additionally, it has the potential to make cities more livable and attractive (Gehl, 2013; Larsen, 2017; Sheldrick, Evans, & Schliwa, 2017). For individuals, the bicycle is by far the cheapest means of transport after one's own feet and could enable less affluent members of society to extend their activity space, be independently mobile and participate in social life (Cagney, York Cornwell, Goldman, & Cai, 2020). Furthermore, cycling has been shown to improve physical and mental health, and is promoted by the World Health Organization as a way to achieve daily physical activity (Buehler, Kuhnimhof, Bauman, & Eisenmann, 2019; Götschi, Garrard, & Giles-Corti, 2016; Martin, Goryakin, & Suhrcke, 2014; World Health Organization, 2019). In light of these benefits, policymakers have been enthusiastic about increasing cycling rates during the COVID-19 period (Bryant, 2020; Niedersachsen, 2021; Stuttgarter Zeitung, 2021; Thurau, 2021).

The effectiveness of cycling as a mode of transportation is limited if it is only used during good weather (Hudde, 2023). A cycling pattern that fluctuates by season and weather not only restricts the overall potential of cycling to reduce emissions, promote

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environmental sustainability and improve health, but can also lead to inefficient use of infrastructure and public spaces. The worst-case scenario is that bike lanes are overcrowded when the weather is good, but empty once weather conditions are worse. If bike lanes are left empty for long stretches of time, drivers may protest more fiercely against pro-cycling policies, such as the redistribution of space in favor of cyclists (Wadewitz, 2022). Public support is, however, essential for implementing pro-cycling policies in cities throughout the world (Buehler & Pucher, 2021b; Lanzendorf & Busch-Geertsema, 2014).

During the COVID-19 pandemic, cycling may have become a more attractive means of transport because one of its travel alternatives – public transport – became much less attractive (Buehler & Pucher, 2021a). At least during the pandemic's peaks, usage of public transit was discouraged and many people avoided taking busses, trams, and metros to avoid infection risk (e.g. Beck, Hensher, & Nelson, 2021; Liu, Miller, & Scheff, 2020; Marra, Sun, & Corman, 2022; Parker et al., 2021; Tirachini & Cats, 2020) Indeed, transit rides were substituted with bike rides during the pandemic (Schaefer, Tuitjer, & Levin-Keitel, 2021). If cycling became more attractive, it may have changed the relevance of a factor that generally hinders cycling, namely adverse weather conditions.

The general relationship between weather and cycling has been studied extensively in the literature. Results show that colder temperatures, precipitation, and darkness strongly reduce cycling rates, whereas wind and humidity have a less pronounced negative effect (An, Zahnow, Pojani, & Corcoran, 2019; Spencer, Watts, Vivanco, & Flynn, 2013; Wessel, 2022). Although higher temperatures generally increase cycling, the presence of very high temperatures can reverse this effect (Amiri & Sadeghpour, 2015; An et al., 2019; Flynn, Dana, Sears, & Aultman-Hall, 2012; Gebhart & Noland, 2014; Mathisen, Annema, & Kroesen, 2015; Miranda-Moreno & Nosal, 2011). For a more comprehensive review of weather effects on cycling, however, we refer to Böcker, Dijst, and Prillwitz (2013) and Liu, Susilo, and Karlström (2017).

Importantly for our study, previous work has shown that the weather-cycling link differs between countries and cities (Böcker, Priya Uteng, Liu, & Dijst, 2019; Goldmann & Wessel, 2021; Hudde, 2023). This shows that a strong effect of weather on cycling is not set in stone. Rather, the weather sensitivity of cyclists may depend on cities' and countries' *culture*, broadly understood as "the way that [societies] deal with nature" (Reckwitz, 2021, p. 30). Individual behavior and culture in general can change, and disruptive events and crises can trigger or catalyze such change. In fact, the COVID-19 pandemic could be a "window of opportunity" for potentially long-term change towards sustainable mobility (Büchel, Marra, & Corman, 2022; Schmidt, Sieverding, Wallis, & Matthies, 2021; Sunio & Mateo-Babiano, 2022).

In this paper, we explore if the pandemic affected the association between weather and cycling. We analyze hour-specific data from 69 automated bicycle counting stations in 6 German cities and two districts. Data are from the years 2017 to 2021, thus covering both a pre-COVID-19 baseline and almost two years of the pandemic. We combine this bicycle counting data with a city- and hour-specific composite weather index in order to test if the elasticity of weather on cycling differs between varying levels of pandemic intensity. Pandemic intensity is measured by google searches for the term "Corona", thereby reflecting the relevance that Corona played in people's lives. Results show that the cycling volume is more responsive to weather conditions in times of high pandemic intensity. This suggests that the pandemic might have brought new cyclists on the roads who are, however, mainly fair-weather cyclists.

2. How the pandemic might have changed the effect of weather conditions on cycling

The Covid-19 pandemic reduced people's general level of mobility. During extended periods, in Germany and many other countries, public events were canceled, students moved to online teaching, many employees worked from home or had to reduce working hours (Hale et al., 2021). During intense phases of the pandemic, people were suggested to leave the house only for essential trips (Hale et al., 2021). However, the reduction in mobility also had limits. For instance, working from home remained far from universal and no more than a third of employees worked from home (Alipour, Falck, Follmer, Gilberg, & Nolte, 2021). A German case study estimated that, during spring 2020, people cancelled around a third of all trips they would have undertaken in the absence of the pandemic (König & Dreßler, 2021).

This reduction in mobility did not affect all transport models equally. At core, our hypotheses build upon the argument that public transit became a less attractive alternative because of the pandemic (e.g. Beck et al., 2021; Liu et al., 2020; Marra et al., 2022; Parker et al., 2021; Schaefer et al., 2021). In public transport, people are in a closed space with strangers, which may induce fear of infection (e.g. Eisenmann, Nobis, Kolarova, Lenz, & Winkler, 2021; Schaefer et al., 2021). Indeed, people report feeling more uncomfortable on public transit during the pandemic compared to before (Eisenmann et al., 2021). Individual modes of transport, including cycling, did not experience this loss of attractiveness, and some public transport journeys were replaced by cycling during the pandemic (Anke, Francke, Schaefer, & Petzoldt, 2021; König & Dreßler, 2021; Schaefer et al., 2021).

A substitution of transit rides with bike rides can mainly mean two things: people who did not cycle before started cycling or people who sometimes cycled began to cycle more frequently. To illustrate this, we rank people by their cycling propensity and distinguish between people that, pre-COVID, (a) never or rarely cycled, no matter the weather, (b) those that cycled under fair-weather conditions but resorted to the car or public transit for days with bad weather, and (c) those that always cycle, no matter the weather.

First, some people who did not cycle pre-COVID (a) mounted the saddle and started cycling during the pandemic. It seems plausible that these new cyclists are, on average, more susceptible to weather than those with more cycling experience. Previous research showed that inexperienced cyclists are generally more affected by adverse weather and, on the macro level, a more advanced cycling culture is associated with lower effects of seasonal factors and weather on cycling (Goldmann & Wessel, 2021; Hudde, 2023; Motoaki & Daziano, 2015). This means that the new COVID-cyclists may rather become (b) fair-weather cyclists than (c) all-weather cyclists.

Second, in pre-pandemic times, many people cycled under fair-weather conditions but resorted to the car or public transit under bad weather conditions (b). These people may now have an extra incentive to stay on two wheels, even in weather conditions where they would have normally switched to public transit. That is, they move from being (b) fair-weather cyclists towards (c) being all-weather cyclists.

These two processes have different consequences for the observed number of cyclists by weather conditions. First, the new cyclists should increase the cycling volume mainly for periods when the weather is good. By consequence, the elasticity of weather would *increase*. The second mechanism would lead to an increase in the cycling volumes specifically in these times when the weather is bad. By consequence, the elasticity of weather could *decrease*. Thereby, observing if the elasticity increases or decreases can provide clues as to which of the mechanisms is primarily at work. If we observed an increase in the elasticities, this might be attributed to the first mechanism, new cyclists mounting the saddle during the pandemic, whereas the second mechanism was marginally or not at work. If we observed a decrease in the elasticities of weather, this would speak to the second mechanism of people giving greater priority to avoiding public transport than avoiding a bike ride when the weather is bad.

As stated, our key argument is that the bicycle became relatively more attractive because public transit became less attractive. However, the bicycle did not become more attractive relative to individual means of transport, such as walking or driving. Therefore, the changes we discuss should be most evident in those cities where the bicycle mainly competes with public transit, that is, cities with a high pre-COVID modal split share of public transit.

People who want to avoid public transit due to the infection risk and cannot easily switch to walking or driving by car might then choose the bike, but they may also choose to stay at home (Kim, Lee, Ko, Jang, & Yeo, 2021) or delay the trip and wait for better weather. People's ability to delay or skip trips varies from person to person. However, it is often easier to skip or delay a leisure trip than a daily commute. Some employees, especially those working in office jobs, might also have flexible schedules or work-from-home options and therefore delay or avoid trips when the weather is bad (Barbour, Menon, & Mannering, 2021; Liu et al., 2020; Schaefer et al., 2021). However, the majority of employees do not have such options and have to take the trip to work, regardless of weather conditions (Corona Datenplattform, 2021). The share of trips that are commutes versus leisure trips differs by hour of the day. During the morning and later afternoon of weekdays – the so-called rush hours – the share of work trips is higher than during other hours of the day. Therefore, similar as for cities with higher public transit shares, we assume that the changes in cycling should appear more strongly during rush hour than during other times of the day.

3. Data and methods

3.1. Data sources

Our data cover the period from January 1, 2017, to December 31, 2021. This period allows us to study the effect of weather on cycling volumes before and during the COVID-19 pandemic. We collect data on cycling volumes, weather conditions, and the course of the pandemic.

In order to measure cycling volumes, we use hourly count data from 69 automated counting stations in 6 German cities (Berlin, Bremen, Heidelberg, Kiel, Munich, Münster) and 2 districts (Rhein-Kreis Neuss and Rhein-Sieg-Kreis, which include suburban, small-town, and rural areas in the surrounding of the cities Düsseldorf and Bonn). Fig. 1 maps these locations. The counting stations are installed by EcoCounter and measure passing cyclists with the help of below-surface induction loops. They have a self-reported accuracy of around 95 % and are commonly used in related cycling studies (Kraus & Koch, 2021; Miranda-Moreno & Nosal, 2011; Nosal & Miranda-Moreno, 2014). We only consider bicycle counts that were conducted during the day (5:00 to 22:59), so that we analyse 2,091,116 hourly bicycle count observations.

Weather conditions for each city and district are taken from the nearest weather stations of the Deutscher Wetterdienst (DWD). Here, we collect hourly data on precipitation (mm), air temperature (°C), wind speed (m/s), and cloudiness (in eighths of the sky that are covered by clouds). In addition, we use the R-Package "suncalc" (Thieurmel, Elmarhraoui, & Thieurmel, 2019) to create a variable that reflects the share of minutes within an hour that has natural daylight, i.e. that lie between sunrise and sunset.

Additional dummy variables account for school holidays and public holidays.

As a proxy for people's perceived pandemic threat and changes therein, we collect data on how often people in Germany searched for the term "Corona" in Google (Google Trends, 2022).[2] Internet searches have been found to be a valid indicator of public attentiveness to selected issues (Ripberger, 2011). Compared to objective measures of pandemic threat or intensity (such as case numbers or hospitalizations), Google searches better capture the degree of relevance that Corona played in people's lives. It is a proxy for the degree to which the topic of COVID-19/Corona occupied people's minds and thereby close to the degree to which people felt threatened by infection (Jimenez, Estevez-Reboredo, Santed, & Ramos, 2020). Our approach is thus comparable to Liu et al. (2020), who also use Google searches as a proxy for people's awareness of Covid-19 and find that a higher awareness is associated with lower public transit demand. An additional benefit of Google search trends is that they are not distorted by changes in measurement, e.g. testing intensity.

For our robustness analyses, we replace Google-search data with two alternative indicators of pandemic intensity: (1) the COVID-19 Government Response Tracker, specifically their "Stringency Index", which captures governments' "containment and closure policies, sometimes referred to as lockdown policies" (Hale et al., 2021). (2) Change in time spent in transit stations, as a measure of (Covid-induced) transit-avoidance, published in the "Google Covid-19 Community Mobility Reports" (Google LLC, 2020). More information on these alternative measures, as well as a table with summary statistics and a correlation plot for the weather variables can be found in

[2] Among the German public, the term "Corona" is much more prevalent than other terms, e.g., "COVID-19".

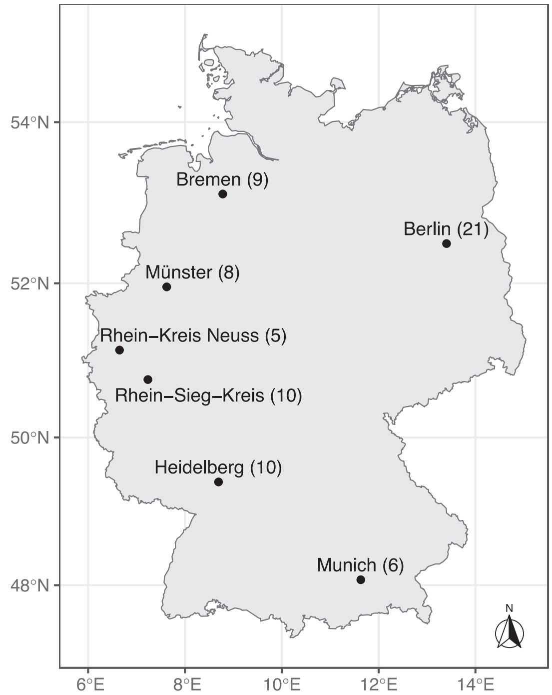

Fig. 1. Map of the sample cities and districts (number of counting stations in brackets).

the Online Supplementary Material.

3.2. Creation of an index for cycling-friendly weather and daylight conditions

We aim to condense the information from the five weather and daylight indicators into one composite indicator. This indicator should reflect the overall weather and daylight conditions for cycling, with better weather conditions leading to more cycling. In the subsequent analysis, we will then evaluate whether the impact of this composite indicator on cycling levels remains constant during different states of the pandemic.

To create our composite weather indicator, we set up a poisson regression model (for similar approaches, see e.g., Hong, McArthur, & Livingston, 2020; Kraus & Koch, 2021; Niemeier, 1996). We use hourly cyclist counts as our dependent variable and the five hour-specific indicators for weather and daylight as independent variables. To capture potentially non-linear effects of weather conditions on cycling, some data transformations are necessary.[3] For precipitation, we create a dummy variable that indicates if it has rained more than 0.25 mm in an hour or not (Angel, Sando, Chimba, & Kwigizile, 2014). For temperatures, we account for the nonlinear relationship with cycling by including a linear, a quadratic, and a cubic term in our regression model. Wind speed, cloudiness, and daylight enter the regression model as linear variables. Also, we standardize these five independent variables over the entire dataset in order to ensure that they have the same scale and can easily be combined into one composite indicator later on.

Additionally, we include dummy variables for public holidays and school holidays as control variables, as well as station (μ_i), month (η_m), and weekday*hour (θ_{wh}) fixed effects to control for location characteristics, seasonal trends over the course of a year (e.g. seasonal work), and mobility patterns over the course of the week (e.g. rush hours, weekends). The resulting fixed effects poisson regression model can be written as

$$\begin{aligned} \ln count_{it} = {} & \beta_1 * precipitation_{it} + \beta_{2.1} * temperature_{it} + \beta_{2.2} * temperature_{it}^2 + \beta_{2.3} * \\ & temperature_{it}^3 + \beta_3 * windspeed_{it} + \beta_4 * cloudiness_{it} + \beta_5 * daylight_{it} + \beta_6 * \\ & public\_holiday_{it} + \beta_7 * school\_holiday_{it} + \mu_i + \eta_m + \theta_{wh} + \epsilon_{it}. \end{aligned}$$

We then use this regression model to calculate the composite weather indicator in two steps. First, we run the above regression model with all data from the years 2017 to 2019 to estimate the impact of each variable on cycling levels under pre-pandemic conditions. Second, we use the hereby estimated regression coefficients of the five weather and daylight variables ($\widehat{\beta}_1$ to $\widehat{\beta}_5$) and, for each

[3] The rationale behind these data transformations is to improve the fit of the final composite weather indicator with the number of cyclists. Using only linear terms would lead to significant differences between the composite weather indicator and the number of cyclists under the more extreme weather conditions.

observation in our dataset, multiply them with the corresponding values of the standardized independent variables according to

$$weather\_index_{it} = \widehat{\beta}_1{*}precipitation_{it} + \widehat{\beta}_{2.1}{*}temperature_{it} + \widehat{\beta}_{2.2}{*}temperature^2_{it} + \widehat{\beta}_{2.3}{*}temperature^3_{it} + \widehat{\beta}_3{*}windspeed_{it} + \widehat{\beta}_4{*}cloudiness_{it} + \widehat{\beta}_5{*}daylight_{it}.$$

This gives us a composite weather indicator that captures how better weather and daylight conditions lead to more cyclists. Indeed, we confirm that the number of cyclists between 2017 and 2019 increases rather linearly with higher values of this composite indicator, thereby underlining its appropriateness for the following analysis.

4. Results

4.1. Context: Pre-pandemic mobility behavior in the locations studied

Before going into cycling patterns in relation to pandemic intensity, we provide background on general mobility patterns in the locations studied. Fig. 2 plots the pre-pandemic modal split in the cities. Data are from the large-scale survey study Mobility in Germany (Nobis & Kuhnimhof, 2018). The sample is restricted to relatively short-distance trips of up to 10 km, because these could realistically be cycled by people with regular levels of fitness.

The theoretical section argued that people might become more weather-resilient cyclists because they try to avoid public transit. Therefore, Fig. 2 orders the locations according to their share of trips that are made by public transit.

The large cities, Munich and Berlin, have high public transit shares and moderate cycling shares. The mid-sized university towns, Heidelberg and Münster, have moderately low transit shares and high cycling shares. Bremen is in between the transit-focused large cities and the cycling-focused university cities, somewhat closer to the university cities. Interestingly, the cumulative share of transit and cycling trips is about equal, at around 40 %, in these five cities. The two districts, Rhein-Sieg-Kreis and Rhein-Kreis Neuss, have low shares of both cycling and transit. In these districts, the majority of short-distance trips are made by car.

Based on our theoretical reasoning, we expect to see the greatest changes in the elasticity of weather on cycling in the transit-oriented cities of Munich and Berlin, and the least changes in the car-oriented districts of Rhein-Sieg Kreis and Rhein-Kreis Neuss. The three other cities, Bremen, Heidelberg, and Münster should lie in between.

4.2. Context: Time trend of cyclists, weather index, and Google search trends

Fig. 3 plots the three central variables, the number of cyclists, the abovementioned weather index, and the smoothed frequency of Google searches for the term "Corona" from 2019 to 2021. Both bicycle ridership and weather conditions follow a clear seasonal pattern, with better weather conditions and more cyclists in summer months. The two curves run very similarly, thereby underlining the good fit of our estimated weather index as a proxy for weather-related cycling conditions. Google searches for the term "Corona" were basically non-existent until late 2019, but began to increase dramatically in early 2020 and peaked in March 2020 when the WHO declared the spread of the virus to be a pandemic. In the summer of 2020, the pandemic situation became somewhat more relaxed and there were fewer Google searches for "Corona". In early autumn 2020, when infection case numbers increased again, Google searches for "Corona" began to rise as well again and remained fairly high until spring 2021. Google searches were again lower in summer 2021, followed by a subsequent increase at the end of the year. Overall, this pattern seems to capture the dynamics of COVID-19 and people's fear thereof well.

4.3. Overall changes in the weather elasticity

We start our empirical analysis by estimating the following fixed effects poisson regression model for bicycle count data from 2019 to 2021 for all cities of our sample[4]:

$$\ln count_{it} = \beta_1{*}weather\_index_{it} + \beta_2{*}covid_{it} + \beta_3{*}weather\_index_{it}{*}covid_{it} + \beta_4{*}public\_holiday_{it} + \beta_5{*}school\_holiday_{it} + \mu_i + \eta_m + \theta_{wh} + \epsilon_{it}$$

Fig. 4 then plots the predicted number of cyclists per counting station, depending on the favourability of the weather conditions, and by level of pandemic intensity. The two curves reflect days with no pandemic intensity (solid line, with orange-coloured / lighter 95 % Cis) and days with higher pandemic intensity (dotted line, with blue-coloured / darker 95 % Cis), respectively.[5] The results show that the impact of weather conditions on cycling levels indeed depends on the pandemic intensity. This is also confirmed by our

[4] In order to avoid confounding of Covid-effects with long-term changes in cycling behavior and to reduce overlap with the period for which the weather index was calibrated, we focus only on the years from 2019 to 2021 in this part of the regression analysis.

[5] The google-search variable is scaled to a range from 0 to 100. The curve labelled "high pandemic intensity" is estimated for the value 40 on this scale. As a reference, over the period of the first major lockdown, March–May 2020, the average value is 43. For the second main COVID-19 wave, December 2020 to February 2021, the average is 35. Hence, "high pandemic intensity" refers to a situation that is less severe than spring 2020 more severe than winter 2020/21. "No pandemic" refers to a search value of 0.

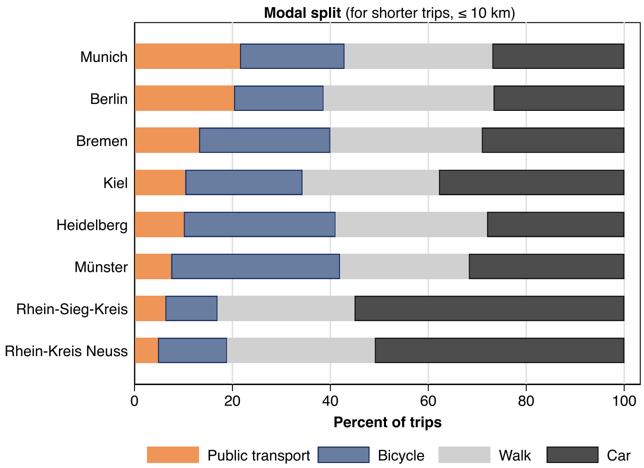

Fig. 2. Pre-pandemic modal splits in the analyzed cities and districts.

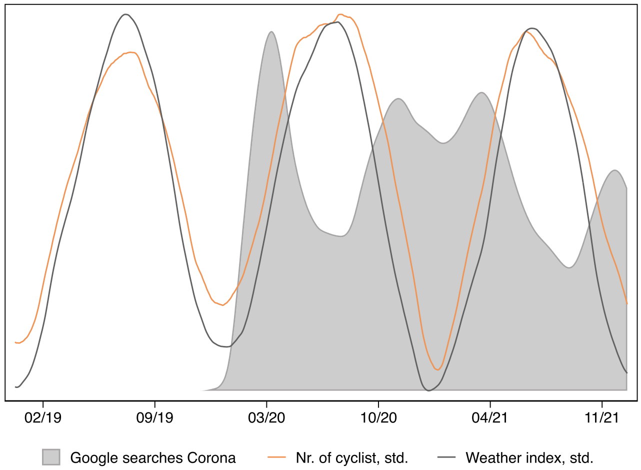

Fig. 3. Pandemic intensity (measured by Google Search Trends), bicycle ridership and weather conditions over time. Results for all cities and districts combined.

robustness analyses, which are presented in the Online Supplementary Material.

Generally, both marginal effect curves increase with better weather conditions, which reflects the positive impact of good weather and the negative impact of bad weather on cycling levels that we have established in Section 3.2. The blue curve increases steeper than the orange one, which implies that people react stronger to weather under higher pandemic intensity than under lower pandemic intensity. However, this combined curve hides substantial variation between the location-groups.

4.4. City-specific changes in the weather elasticity

Next, we turn to Fig. 5, which shows results separately for the seven locations studied. Based on the city-specific modal shares and the depicted marginal effects, we again divide the cities into three groups.

The first group consists of Berlin and Munich. For these two cities with a relatively high modal share of public transit, we find that both curves are at quite similar levels when the weather is bad. That is, at times of bad weather, there were similarly many cyclists on the road, irrespective of the pandemic intensity. When weather conditions improve, however, the curve for days with higher pandemic intensity becomes steeper than the one for days with lower pandemic intensity. Hence, good weather conditions lead to stronger increases in cycling when the pandemic intensity is high, compared to when it is low. The pandemic intensity consequently increased cyclists' sensitivity to weather conditions in these two cities.

The second group consists of three cities with a relatively high modal share of cycling: Heidelberg, Münster, and Bremen. In Münster and Heidelberg, bicycle ridership is significantly lower when the pandemic intensity is high, which is reflected by the generally lower curve. Both cities are student-dominated, and universities' closure and move to remote learning likely contributed to a generally lower level of mobility and decrease in cycling. Presumably, there were simply fewer people in town at times of high

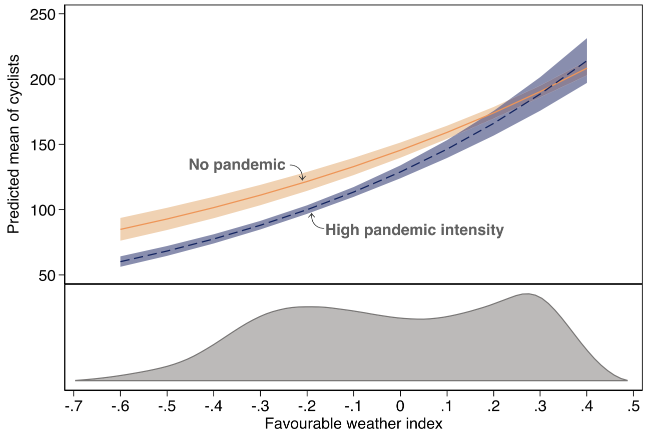

Fig. 4. Model-predicted cycling levels, by weather conditions and pandemic intensity. Estimated for all cities combined.

pandemic intensity. In Bremen, on the other hand, overall bicycle ridership appears to be barely affected by pandemic intensity. The main similarity of these three cities, however, is that the slopes of the two respective marginal effect curves are quite similar, indicating that the impact of weather on cycling is relatively similar between days with lower and higher pandemic intensity. This reflects that improvements in weather conditions lead to similar increases in bicycle ridership, irrespective of the pandemic intensity. Consequently, a higher pandemic intensity did not lead to cyclists becoming more or less sensitive to weather conditions in these three cities.

The third group consists of the districts Rhein-Kreis Neuss and Rhein-Sieg-Kreis. Here, the modal shares of cycling and public transport are lower, and individual mobility is more car-oriented. Similar to the first group, the respective marginal effect curves are again steeper for days with higher pandemic intensity, with the difference between the curves being more pronounced in Rhein-Sieg-Kreis compared to Rhein-Kreis-Neuss. This indicates that – similar to the first group – good weather conditions increase bicycle ridership even more when pandemic intensity is high.

4.5. By hours of the day

In Fig. 6, we differentiate between the typical commuting hours, on weekdays from 6:00 to 8:59 and from 16:00 to 18:59 on the one hand, and the other hours of the day or weekends on the other hand. Based on the idea rush-hour trips are more often work trips that cannot be avoided or delayed, we expected changes in cycling should appear more strongly during rush hour than during other times of the day. However, for both periods, the curves for days with higher pandemic intensity are steeper than for days with lower pandemic intensity. This suggests that the impact of pandemic intensity on cyclists' weather elasticities is rather similar for typical commuting hours and other hours of the day.

5. Discussion

This study investigated whether the effect of favorable weather conditions on cycling behavior in Germany changed in response to the COVID-19 pandemic. We combined hourly cycling count information with hourly weather data and a continuous measure for people's perceived pandemic threat. Our sample included more than 2.2 million hourly bicycle count observations from 69 counting stations, covering the years 2017–2021.

We argued that people tried to avoid public transit during the pandemic out of fear of infection. To avoid transit, people preferred individual means of transport, such as cycling. This increase in relative attractiveness may manifest in two ways. First, it could be that some people who rarely or never cycled in the pre-pandemic period now started cycling. These newcomers are more likely to be fair-weather cyclists who resort to other means of transport when the conditions are less comfortable (Motoaki & Daziano, 2015). Second, some people who were previously fair-weather cyclists might now also use the bicycle under more challenging weather conditions to avoid public transit. Overall, we expected that the degree of change depends on the transit-orientation of a city: the higher the public transit share in a city, the more transit trips could be replaced by the bicycle.

Results from the two transit-oriented metropoles of Munich and Berlin point to the first explanation. The more intense the pandemic, the more the volume of cycling was dependent on the weather. This suggests that the pandemic did put new people in the saddle, but these additional cyclists were largely fair-weather cyclists who only cycled when the weather was sufficiently nice.

In the less transit-oriented student cities, Münster and Heidelberg, the weather-dependence of cycling did not change during the pandemic. It is noteworthy, though, that even before the pandemic, cyclists in these cities were generally much more weather-resilient than their counterparts in Berlin or Munich. The most salient finding from these cities is the overall lower number of cyclists. A likely explanation for this is that there were simply fewer people in these cities during the pandemic. Almost all university education moved online and many students left the university towns or never moved there in the first place. Further, these cities have a high share of knowledge workers, who were much likely than others to switch to working-from-home, which reduced their overall mobility (Minkus,

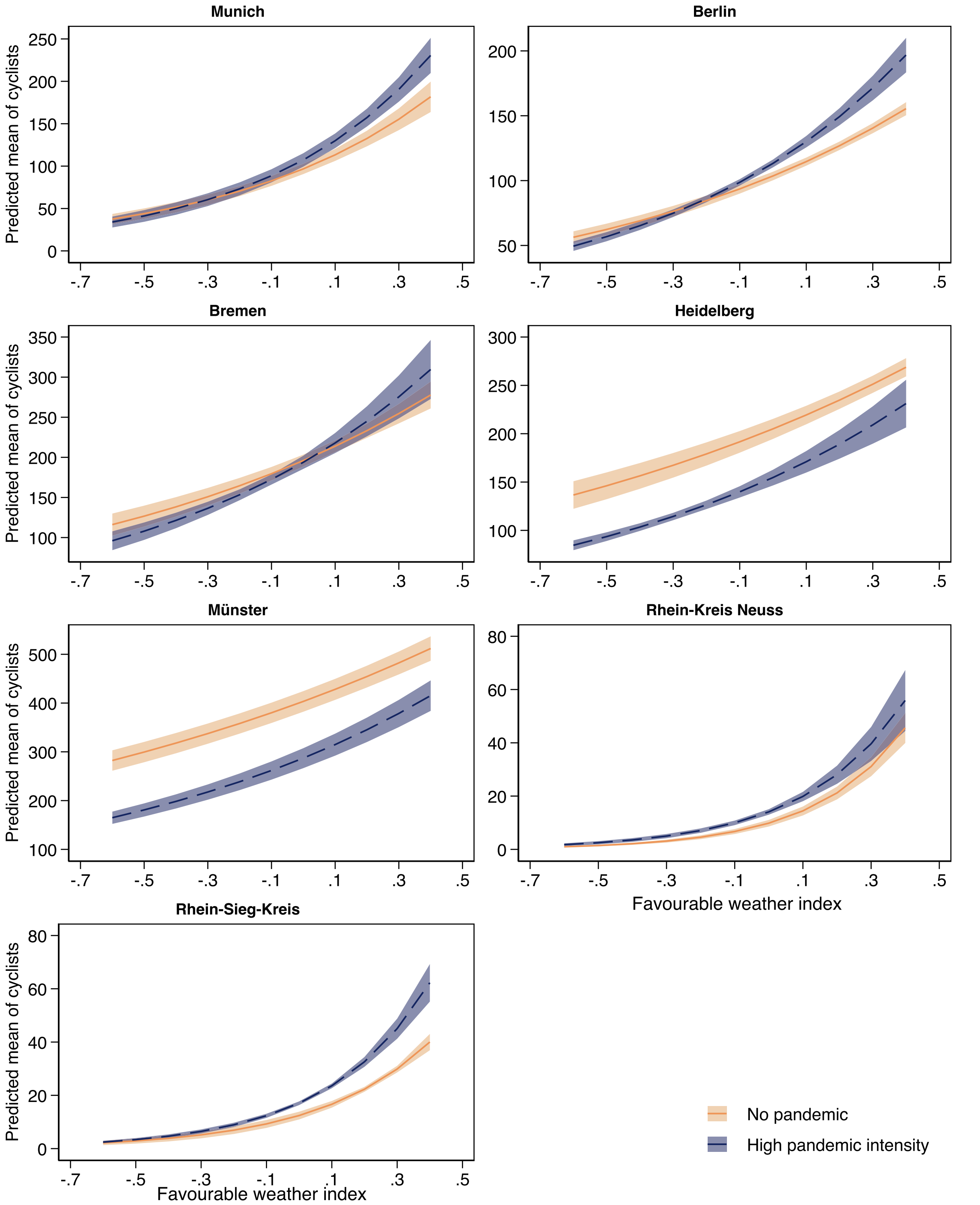

Fig. 5. Model-predicted cycling levels, by weather conditions and pandemic intensity. Estimated separately for all cities and districts.

Groepler, & Drobnič, 2022; Schröder et al., 2020).

In the two car-centered and more rural districts, Rhein-Sieg Kreis and Rhein-Kreis Neuss, cycling was generally very dependent on weather. This dependence on weather increased even more during the pandemic, which counters our theoretical reasoning. We expected little change in these districts because here, the bicycle mainly competes with the car, and car trips became no less attractive

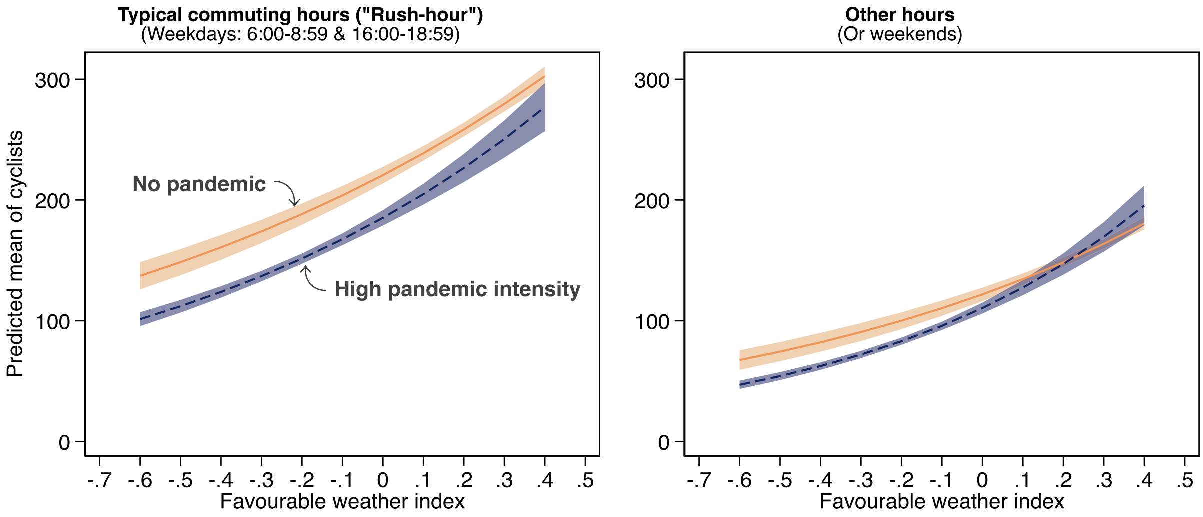

Fig. 6. Model-predicted cycling levels, by weather conditions and pandemic intensity. Estimated separately, by time of day.

during the pandemic. A potential post-hoc explanation is that the cycling travel observed here is largely leisure travel, for example, people taking a recreational cycling tour. With the pandemic, many leisure facilities, such as cafés, swimming pools, or amusement parks were closed, leaving cycling as one of the few remaining leisure options. Of course, whether people go cycling for fun is highly dependent on the weather.

Our analyses have limitations. Cycling count data have unique advantages – they are accurately measured, large-scale, and available as a continuous time-series, spanning pre-pandemic and pandemic periods with a high degree of temporal differentiation – but they also have disadvantages compared to individual-level data. Most centrally, count data do not allow to trace changes in behavior at the individual level and they do not offer insights into people's intentions, preferences, or fears. Therefore, we could not test our hypothesized mechanisms directly. Rather, we developed predictions about the aggregate-level patterns we would observe, if the hypothesized micro-level processes were at work. Then, we contrasted the empirically observed associations between cycling counts, weather, and pandemic intensity with our predictions. Our empirical approach based on count data thus allows us to capture patterns and trends at a population level, which enhances the generalizability of our findings. On the other hand, this approach requires more caution when drawing conclusions about the underlying behavioral processes. For such inferences, large-scale individual-level panel data would be necessary.

With individual-level panel data, we could more directly test who those people are that changed their cycling behavior in response to the pandemic. In particular, we could test how and why they changed it. This could uncover potential differences between social groups, e.g., by age-group, family situation, or level of education.[6] Our analyses suggest that, in Berlin or Munich, previous non-cyclists turned into fair-weather cyclists. With individual-level panel data, we could test this hypothesis more directly. However, such data is not available. Existing travel panel studies, such as the German Mobility Panel have comparatively small samples and surveys are only conducted in a few weeks in early autumn, which did not include the peaks of pandemic threat (Ecke, Chlond, Magdolen, Hilgert, & Vortisch, 2020). Large-scale, multi-topic studies such as the German Socio-Economic Panel do not include sufficient information on mobility behavior. To provide scientific evidence on people's mobility behavior and to advise policymakers during the transition to sustainable mobility, researchers need access to large-scale panel data with mobility information and interviews distributed throughout the year.

These limitations set the foundation for future research. For one, it would be desirable to find out whether the COVID-induced fair-weather cyclists will become more resilient over time, maybe turning into year-round cyclists even when the threat of the pandemic is eliminated. Whereas the data to study this might be hard to come by, it would make it possible to study the general process behind it. Is a two-stage process a common phenomenon, where new cyclists start out as fair-weather cyclists and then become more resilient over time? Is fair-weather cycling a stepping stone to becoming a year-round cyclist? Do such processes differ between social groups?

Our analyses suggest that, in metropoles like Berlin and Munich, the pandemic brought out new cyclists, who were more often fair-weather cyclists. This is a success for these cities, because any increase in cycling is good news for environmental sustainability and people's health. A first policy-target could thereby be to keep these new cyclists in the saddle, also when the pandemic threat has

[6] During periods of the pandemic, students (from elementary school to university) moved completely to learning-from-home, whereas the majority of employees continued to work on-site, even at the peaks of the pandemic (Alipour et al., 2021). Further, people with higher education much more often had working-from-home options (Minkus, Groepler, & Drobnič, 2022; Schröder et al., 2020) whereas those with lower education were more affected by reduced working hours or job loss (Schröder et al., 2020). In sum, research suggests moderately larger reductions in overall mobility in more privileged neighbourhoods and for people with higher levels of education as well as members of larger families (Trasberg & Cheshire, 2023; Molloy et al., 2021).

vanished. However, cycling can only unfold its full potential if people keep cycling throughout the seasons and in most weather conditions. Comparative evidence among German and Dutch cities shows that there is vast potential for more year-round cycling in places like Berlin and Munich (Goldmann & Wessel, 2021; Hudde, 2023). This brings up a next potential policy target: supporting these new fair-weathered cyclists in transitioning into year-round cyclists eventually.

To increase the resiliency to bad weather, various policy measures could be undertaken. For instance, safe cycling infrastructure can help to improve cyclists' resilience to bad weather (Hong, Philip McArthur, & Stewart, 2020). In line with this, cycling in more densely built areas is more weather-resilient than in less densely built areas (Helbich, Böcker, & Dijst, 2014). Moreover, selected policy instruments such as longer green-light phases during rain might help to reduce the exposure to rain and thus to increase resilience to bad weather. As the weather resilience appears to be generally higher in places with many cyclists and a strong cycling culture, any policy measures aimed at fostering the cycling culture and establishing year-round cycling as a societal *normality* could help fair-weathered cyclists in the transition towards resilient, everyday cyclists (Goldmann & Wessel, 2021; Hudde, 2023). In general, however, the literature on the effects of specific policy measures specifically aimed at increasing the weather resilience of cyclists is rather scarce, and thus provides an interesting avenue for future research.

CRediT authorship contribution statement

Ansgar Hudde: Conceptualization, Methodology, Data curation, Formal analysis, Visualization. **Jan Wessel:** Conceptualization, Methodology, Data curation, Formal analysis, Visualization.

Declaration of Competing Interest

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

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2023.11.016.

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