IMPACT OF WEATHER ON TRAVEL BEHAVIOR THROUGHOUT THE SEASONS - ANALYSIS OF TWO NATIONAL GERMAN HOUSEHOLD SURVEYS

Pia Tulodetzki
Email: pia.tulodetzki@kit.edu
https://orcid.org/0009-0007-3136-165X

Gabriel Wilkes
Email: gabriel.wilkes@kit.edu
https://orcid.org/0000-0002-1027-2734

Martin Kagerbauer
Email: martin.kagerbauer@kit.edu
https://orcid.org/0000-0003-4252-7874

Peter Vortisch
Email: peter.vortisch@kit.edu
https://orcid.org/0000-0003-1647-2435

Affiliation of all authors
Karlsruhe Institute of Technology (KIT), Institute for Transport Studies
Kaiserstrasse 12, 76131 Karlsruhe, Germany

Word Count: 6728 words + 3 table(s) $\times$ 250 = 7478 words

Submission Date: August, 1 2023

ABSTRACT
We study the impact of weather on travel behavior using two large national household surveys from Germany from 2009 to 2019, and historical weather data from meteorological reanalysis. We specifically focus on home-based trips for work, education and leisure purposes, analyzing mode choice in different weather conditions. We find that all parameters studied—temperature, precipitation and cloud cover—influence mode choice. The impacts differ between different seasons, inside the seasons at comparable conditions, and between different socio-demographic groups. Furthermore, the availability of mobility tools impacts how people react to weather conditions. Bicycle use is affected most by diverse weather conditions, reaching the highest shares in dry and warm conditions. The other modes do not change equally, but show different impacts depending on trip purpose, socio-demographic group and other factors. While we could demonstrate impacts of weather, future research should be undertaken to account for the possible changes in travel behavior in recent years.

Keywords: travel behavior, weather, household survey

INTRODUCTION

Travel demand estimation is a crucial element of transportation planning, as it provides valuable insights for developing efficient transportation systems. The traditional approach to travel demand modeling relies on estimates for an average day of the year. As we know, some factors, such as public holidays and school breaks, change mobility on specific days or periods, leading to variances in travel demand that are difficult to model. Recent advancements in mobility options (e.g., ride-sourcing, bike-sharing, e-scooter sharing, mobility on demand) have resulted in more flexible and dynamic travel behavior. The issue of climate change adds another layer of complexity, as projected increases in temperature and precipitation could impact people's mode choices and behavior. Therefore, it is crucial to consider the diversity in travel behavior concerning flexibility, mobility options, and environmental conditions when making informed planning decisions. In this paper, we want to analyze one environmental condition, which varies significantly throughout the year in some world regions: the weather. Although global warming pertains to overall climate changes that occur over a long period, most regions of the world tend to focus on seasonal changes in weather, such as the typical temperature ranges and precipitation.

In this paper, we present an in-depth analysis of the impact of weather on travel behavior using data from two national household surveys in Germany. We focus on home-based trips, as they provide individuals with their complete choice set, including the ability to adapt to weather conditions, such as changing clothes or modifying travel modes. Our analysis considers trip purposes and sociodemographic factors, such as age and gender, to deepen our understanding of the underlying factors. We analyze how people travel in different weather conditions and seasons, focusing on the changes in transportation modes. To ensure comprehensive coverage of weather data, we use data from a weather model that offers historical weather data from a nationwide grid, providing a detailed and extensive dataset for analysis. This study aims to clarify the effects of diverse weather conditions, such as temperature, precipitation, and sunshine, which exhibit variations across seasons. By shedding light on the relationship between weather and travel behavior in Germany, this study aims to provide transportation planners and policymakers with valuable insights to enhance the accuracy of travel demand models in an era of changing mobility patterns and climate variability.

We will begin by examining the literature on how weather affects travel behavior. Next, we describe the data sources and preparation process, combining two household surveys to create a substantial and diverse database. We then present and analyze our results, focusing on differences between seasons, and conduct a deeper investigation of the fall season. Finally, the discussion section elaborates on the findings and identifies potential avenues for further research.

LITERATURE REVIEW

Extensive research has been conducted regarding the impact of weather on individuals' travel decisions, resulting in a substantial body of scientific knowledge. The primary goal of these studies is to comprehend how different weather conditions impact individuals' mode choices, including walking, cycling, using public transport (PT), or driving a private vehicle. This information is of utmost importance for transportation planning and policymaking, especially concerning global warming. Many different data sources can be used to examine the correlation between weather and mobility. Essential factors to consider in such analysis include the spatial and temporal resolution of the weather data, the specific weather parameters, e.g., temperature and precipitation, and the analyzed period, which primarily depends on the used survey data.

Concerning the survey data, National household surveys offer data on travel behavior over time from a diverse group of people, offering valuable insights into long-term mobility trends and how they are impacted by weather (*1–3*). Other data sources include traffic count data, mainly used for bicycles (*4–6*) or the data from smartcards for PT to investigate passenger numbers throughout different weather conditions (*7*) (Tao 2018), depending on the research focus. Also, the time horizon differs. Some studies focus on particular months or seasons to capture changes in travel behavior, such as Sabir (*3*) and Kashfi et al. (*8*), while other studies involve conducting multiple surveys throughout the year to account for weather changes (as done by Böcker et al. (*9*)). Some studies take a more comprehensive approach and examine travel patterns over a year or longer (as seen in Liu et al. (*10*)). Because work trips generally show a more stable behavior in the choice of means of transport than, for example, leisure trips, these two purposes are explicitly investigated in some studies. Commuting trips, which are necessary for daily life and less flexible, tend to be less affected by weather than leisure trips, which are typically more flexible and discretionary (*11–13*). Some studies focus on home-based trips only to investigate choice behavior when having the full option of modes of transportation. Additionally, trips that do not start at home may be influenced by the mode choice done earlier this day, which might reduce the weather influence seen in the data (*2, 14, 15*).

Spatial resolution and the source of weather data is an essential consideration in weather-mobility studies. Weather data can be obtained from nearby weather stations or measured locally to match individual travel activities (*16–18*). Typically, the data from the closest weather station is matched with the reported trips, resulting in varying accuracy. It still needs to be discussed if analyzing the weather condition during the journey or considering the daily parameters like mean temperature, maximum temperature, and the sum of precipitation deliver the most precise results. Recent studies show significant results for both time levels, potentially preferring daily data to cover up the overall weather conditions and mitigate e.g. the influence of the daily course (*14, 19*).

Temperature and precipitation are the most frequently observed weather parameters, followed by wind and sun duration. Regardless of the chosen data basis, it is uniformly evident that the active modes of transport, especially bicycle use, are most influenced by the weather. Bicycles are mainly used in summer and fall and benefit from relatively high temperatures and dryness - the share decreases significantly when temperatures are low (*20–22*). Weather conditions such as wetness, coldness, and strong winds increase the attractivity of more protected means of transport (*23*). However, these effects are not linear, e.g., the use of bicycles decreases during hot weather, and the use of cars is significantly lower when there is precipitation in the form of snow (*3, 6, 24*).

It becomes apparent how complex the issue is when observing how various groups of people respond to weather conditions. Women tend to be more affected by weather conditions regarding mood and satisfaction than men (*14, 25, 26*). At the same time, young people are more sensitive to lower temperatures and precipitation than older people, particularly for active modes like walking and cycling. In contrast, older people use active modes less under high temperatures Saneinejad et al. (*14*). Additionally, the location of residence can influence the weather's impact on mode choice, with less dense areas being more sensitive to certain weather conditions, especially for cycling (*19, 27*).

In light of numerous studies conducted on weather and its impact on mobility in different regions, it can be observed that the findings tend to be location-specific and cannot be generalized to other areas. The sociodemographics of the respondents, the used weather data, the usual weather in the study area, trip purposes, and routines influence the impact of weather on travel behavior.

Thus, considering the lack of research in Germany and the use of weather stations instead of modern weather models, it is imperative to examine the potential of utilizing high-quality data to isolate the influence of weather on a more comprehensive level. This article aims to contribute to this dialogue by exploring how contemporary weather combined with two national travel surveys from Germany can provide a more accurate understanding of the effects of weather on travel behavior.

DATA AND DATA PREPARATION

Mobility data

We use the data from travel diaries from two distinct national household surveys conducted in Germany. The first dataset is the cross-sectional survey "Mobility in Germany" (MiD) conducted in 2017 (*28*), comprising 960,619 trips. In MiD, individuals reported their trips on a single designated day throughout the year, allowing for the generation of mobility data covering all seasons and months. The second dataset stems from the longitudinal survey "German Mobility Panel" (MOP) conducted between 1994 and 2022 (*29*), filtered for this study to the lapse between 2009 and 2019, encompassing 628,371 trips. MOP is a panel survey where individuals record their one-week trips for three consecutive years. This survey is only conducted during fall (mainly September to October).

The household data went through several filtering criteria to accurately depict the weather's influence on mobility decisions. The analysis only involves trips where the main mode of transport is by foot, bicycle, using a car as a driver or passenger, or using public transport (PT). All trips on days reported by respondents as atypical (such as vacation days, and days out of their usual surroundings). As the next filtering step, we selected trips highly likely to have originated from home. For both datasets, only trips where the preceding trip was stated as "towards home" or the trip was their first trip of the day and the respondents stated to start from home are included. These filtered datasets ensure that the analysis captures the weather's impact on mobility decisions made from home and allows for more precise observations and conclusions regarding weather influences on transportation choices.

For all analyses presented in the results, the values are weighted at the person level considering sociodemographic characteristics of the entire German population.

Overall, through this data merging and harmonization, we compiled year-round mobility data based on MiD, and a particularly large dataset specifically for the fall season by combining MOP and MiD, which enable the analysis of seasonal disparities, as well as specific patterns during one season.

Weather data

This study uses historical weather data from the ECMWF-ERA5 dataset (*30*). This is based on so-called reanalysis, which uses weather models fed with observational data from weather stations, satellite data, and other environmental information, providing various weather parameters.

Our approach differs from most travel studies, which combine reported trips with weather station data. There are several differences: Instead of limited, singular points of observation, there is a continuous grid of data points. Therefore, they are less sensitive to place-specific phenomena, such as a local downpour. Additionally, they contain meteorological parameters not available from weather stations, such as cloud cover.

The ERA5 dataset has a spatial resolution of 0.25 degrees in both latitude and longitude, giving roughly a 31km grid, and is available royalty-free. Three weather parameters—temperature 2m above ground[1], total precipitation, and cloud cover—were queried from the dataset for our analysis. We processed the data using the Python libraries xarray (*31*) and cfgrib (*32*). In ERA5, the parameters are available at an hourly resolution. We aggregated and converted them as follows:

- Temperature: Maximum temperature during the day, converted from Kelvin to degree Celsius (°C).[2]
- Precipitation: Sum of the precipitation among all hours of the day, converted from m to mm.[3]
- Cloud cover: Number of hours per day where cloud cover is lower than 20%.

Combining weather and travel data

The trip data needs to be matched with the weather data, considering location and time. In MiD, the geometrical center of the individuals' residential postal codes was chosen for the spatial matching. In MOP, truncated postal codes and district codes are given, which are intersected and the centroids of these units were used. For these locations, the corresponding grid cell from the weather data is retrieved. We transformed the trip timestamps from the survey data to Coordinated Universal Time (UTC) to match the trip timestamps with the meteorological data.

We follow the meteorological classification of seasons, assigning each season to three months. For instance, fall is defined as September, October, and November. The analysis is undertaken for the trip purposes going to work, going to the place of education and leisure. Therefore, we include both the very routinized and more flexible trips.

RESULTS RELATED TO SEASONS

Travel behavior by seasons

First, we examine the variations in mode shares across different seasons, see Table 1. Consistent with existing literature, work trips exhibit the highest stability in overall mode shares with small differences between the seasons. We assume that this is because these trips are characterized by strong routines. However, bicycle usage for commuting trips is subject to notable seasonal variations, with the share highest in summer at 14.4% and dropping to 10.0% in winter. Interestingly, trips made by foot show a distinct pattern, with the highest share occurring during winter at 8.8%, suggesting that colder temperatures influence individuals to opt for walking. In contrast, the use of car as driver and passenger remains stable throughout the seasons, showing that individuals who choose the car for commuting trips maintain their mode choice regardless of the time of year. Notably, PT usage shows a slight increase during winter, having a share of 16.5%, compared to summer, with a share of 15.2%. It is plausible that individuals who derive pleasure from cycling during the warmer seasons partly select walking or using PT as means of transportation during the colder months. For education trips the bicycle mode share declines from 23.4% in summer to 13.4% in winter. Conversely, PT experiences an increase from 24.5% in summer to 32.1% in winter. The use of modes hardly changes. The observed fluctuations in bicycle and PT mode shares emphasize that people who make educational trips switch between bicycle and PT throughout the seasons, preferring protected vehicles during spring and winter and bicycles in summer and fall.

[1] This is the standard air temperature.

[2] For our readers that are more familiar with values in Fahrenheit (F): 5 °C = 41F, 10°C = 50F, 15°C = 59F, 20°C = 68F, 25°C = 77F

[3] In imperial units: 0.1mm is around 0.004in, 1mm is around 0.04in, 5mm is around 0.2in

TABLE 1 Modal split of trips in different seasons by purpose

	Spring	Summer	Fall	Winter
Work				
sample size	*20,064*	*18,375*	*49,257*	*12,586*
by foot	6.4%	6.3%	7.4%	8.8%
bicycle	13.6%	14.4%	15.6%	10.0%
car as driver	61.7%	61.1%	59.0%	61.1%
car as passenger	3.3%	3.0%	3.9%	3.7%
public transport	15.0%	15.2%	14.2%	16.5%
Education				
sample size	*7,651*	*5,747*	*13,902*	*5,609*
by foot	23.4%	23.7%	23.8%	22.4%
bicycle	16.5%	23.4%	18.7%	15.2%
car as driver	6.7%	6.6%	6.1%	7.0%
car as passenger	23.7%	22.9%	23.9%	22.8%
public transport	29.8%	23.4%	27.5%	32.5%
Leisure				
sample size	*31,998*	*31,132*	*71,611*	*17,234*
by foot	33.3%	29.9%	(25.7)%	39.6%
bicycle	14.9%	19.0%	(14.2)%	7.7%
car as driver	26.3%	26.0%	(33.9)%	26.0%
car as passenger	19.1%	18.6%	(18.1)%	19.6%
public transport	6.4%	6.5%	(8.1)%	7.3%

Leisure trips show the highest volatility among all trip types, especially for active transport modes. Bicycle usage has the highest share during summer, accounting for 19.0% of all trips, but drops to 7.7% in winter. Conversely, walking shows the highest mode share during winter at 39.5%, while it decreases to 25.7% in fall. These changes indicate that people switch between walking and cycling on leisure trips throughout the seasons. In contrast, all other means of transportation show stable mode shares for leisure trips, suggesting that these modes are less sensitive to seasonal changes. PT slightly increases in winter, maybe due to individuals opting for a protected means of transportation in colder weather conditions.[4]

Our analysis reveals evident seasonal changes in mode shares, with work and educational trips displaying less sensitivity to these variations than leisure trips. The use of car as driver is found to be the least influenced by seasons, suggesting that individuals who choose to drive have a more routinized behavior, irrespective of the time of year, while active modes of transportation vary over the seasons.

Differentiating the Impact of Seasons and Weather Conditions

After looking at seasonal variations, we aim to explore how people respond to similar weather conditions in different seasons. Understanding these dynamics allows a deeper comprehension of how weather influences travel behavior and whether they happen on a long-term, seasonal, or

[4]Roundtrips are partially included in leisure in the MID dataset, and are excluded from MOP data. This explains larger differences between fall and the other seasons concerning average modal split, as roundtrips are often undertaken walking, but are excluded to a major proportion in fall due to including the MOP dataset.

short-term choice based on the weather of that day. We use categories according to daily maximum temperatures, with five-degree Celsius steps ranging from 5 to over 20 °C, and analyze the three most relevant seasons for each temperature interval. Due to relatively small samples, we do not analyze education trips.

Figure 1 presents the modal shares for work trips. For temperatures between 5 and 10°C, between spring and winter there is a one percentage point difference in modal shares of bicycles (winter: 10.1%, spring: 11.1%). In contrast, during fall, bicycle share is 4 percentage points higher than in winter (14.4%). In the 10 to 15°C range, which is a high temperature for winter in Germany, the bicycle mode share is 7.7% during winter and between 13.8 and 15.4% for spring and fall. Correspondingly, the share of car and PT are especially high during winter. This shows that the influence of seasons is larger than temperature. For days in the 15 to 20°C range, active modes have the lowest shares in summer, while the car has the highest share in summer. This is presumably because these temperatures are considered cold in summer. Conversely, bicycle usage is highest during fall, and the shares for spring and summer are nearly identical. For days with a maximum temperature exceeding 20°C, the bicycle mode share is 2.3 percentage points higher in spring than in summer and 3.5 percentage points higher in fall. This indicates that warm days in spring and fall have a higher bicycle mode share than in summer, when warm temperatures are more common. Furthermore, PT and car usage as driver show a decrease in fall, indicating that in typically colder seasons, people tend to use active transportation more when it is warm outside.

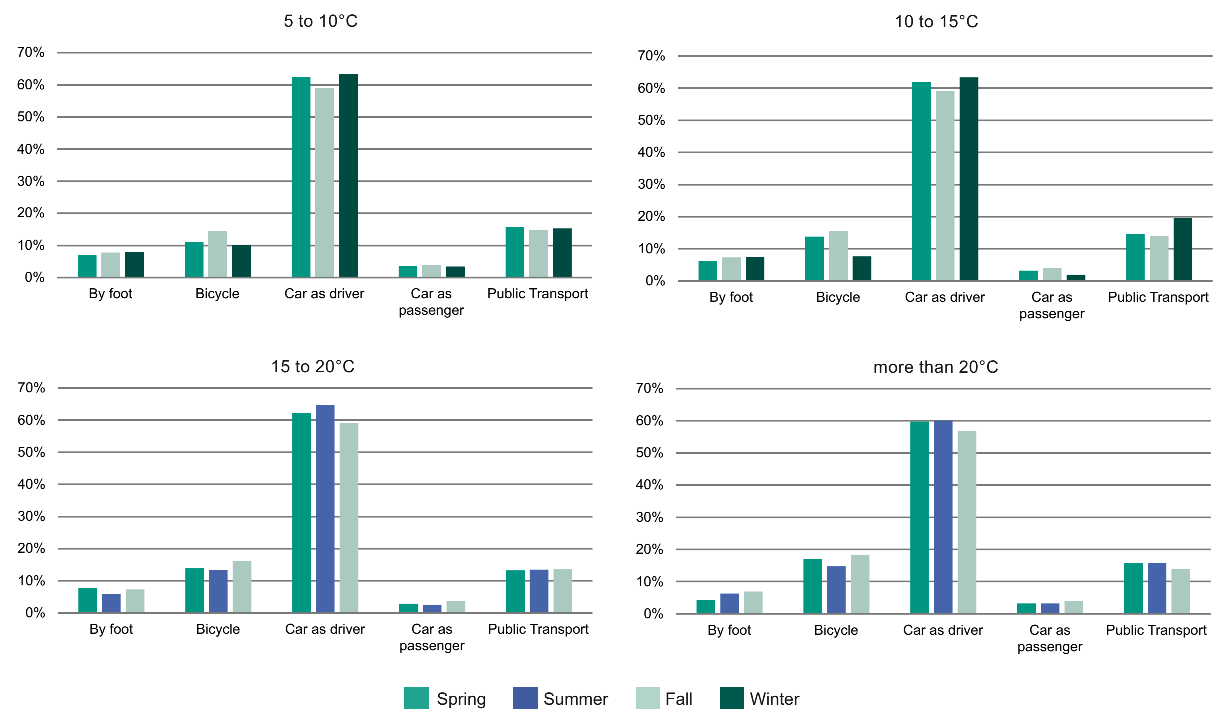

FIGURE 1 Modal split for work trips in different seasons by temperature level

For leisure trips, we observe even stronger changes, see Figure 2. For temperatures between 5 and 10°C, the share of leisure trips made by foot is 5.5 percentage points higher in winter (37.7%)

than in spring (33.3%). In contrast, bicycle usage shows the opposite trend (12.0% in spring, 8.5% in winter). At 10 to 15°C, we observe an increase of almost ten percentage points in leisure trips made by foot during winter compared to spring and fall. Here, bicycle usage is highest in spring, with 17.1%. It remains on a higher level in winter than in fall, emphasizing that warm weather, relative to the typical weather of the season, has a more decisive influence on bicycle usage than only the temperature itself. PT usage is highest in winter, nearly doubling the share observed in spring. This suggests that people opt for PT during colder months to avoid exposure to cold weather conditions. At 15 to 20°C, leisure trips on foot are similar in summer and spring, but there is an increase of about five percentage points in fall. Bicycle usage, however, is lowest in summer, with 14.6%, despite being the highest in the overall share. While 15 to 20°C maximum is not a high temperature for summer, compared to spring, people react with higher bike shares in spring than in summer. Interestingly, car usage as a driver is highest in summer, potentially caused by the above-mentioned effect. For maximum temperatures exceeding 20°C, bicycle usage remains almost the same for all three seasons, suggesting that warm days, irrespective of the season, result in a consistent bicycle mode share of around 20%. In conclusion, high temperatures result in the lowest overall changes in mode shares between the seasons but create the highest shares of active mobility. The same temperatures are perceived differently depending on the season, leading to variations in mode choices under similar conditions.

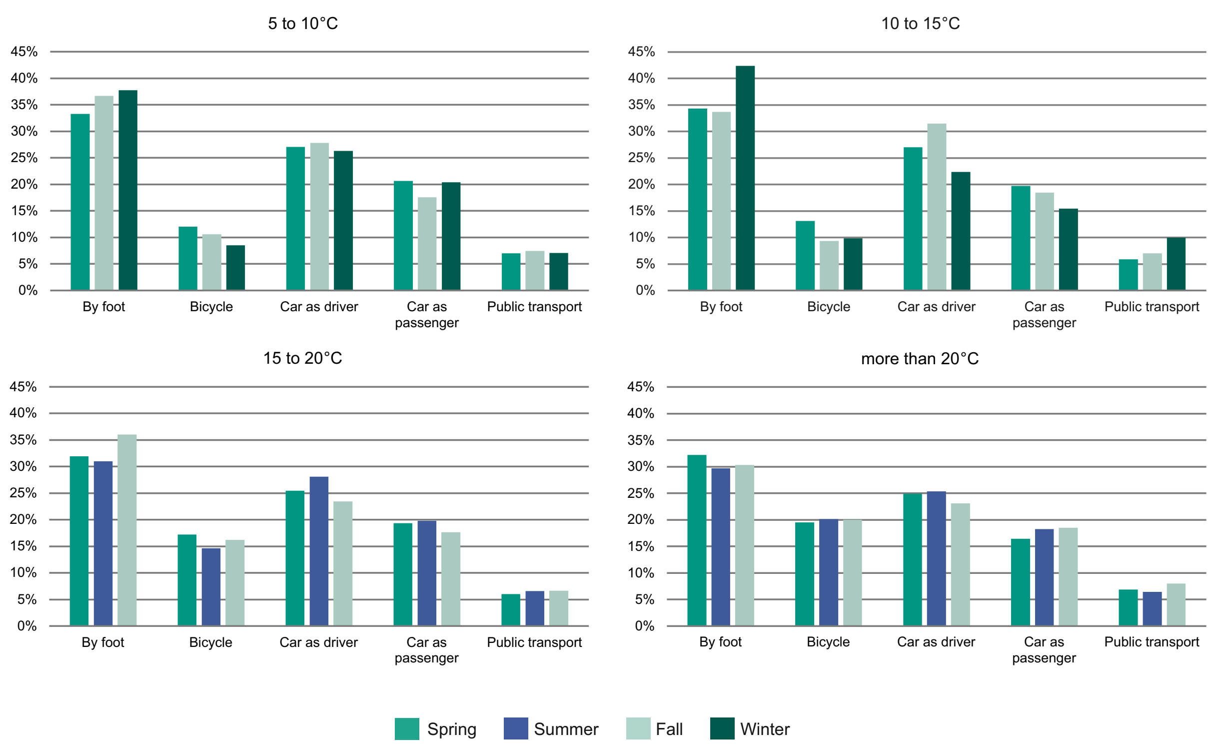

FIGURE 2 Modal split for leisure trips in different seasons by temperature level

In the following we compare work and leisure trips on days without or with very few precipitation (less than 1mm of precipitation throughout the day) to days with more than 5mm of precipitation in the different seasons.

Figure 3 shows the results for work trips. In winter, trips made by foot have the highest share under dry conditions (9.3%), dropping to 6.6% on wet days. Summer and fall show an increase in work trips made by foot with precipitation occurring, potentially due to the higher temperatures during these seasons. Regarding bicycle usage, the share is almost the same on dry days in spring and summer. However, in spring, the share drops by about 2.3 percentage points from dry to wet days, while it increases in summer. Surprisingly, the variation in bicycle shares between dry and wet days in winter is very small (9.9% and 9.1%), indicating that some people use the bike on their work trips regardless of the weather. Car usage as a driver remains roughly stable, with a significant influence of precipitation observed only in winter: In winter, the share of car trips increases by about seven percentage points on wet days, indicating a strong sensitivity to precipitation in the coldest season. Regarding PT, when precipitation occurs, the share drops by about 3.4 percentage points in winter and slightly by about 1.4 percentage points in fall and summer.

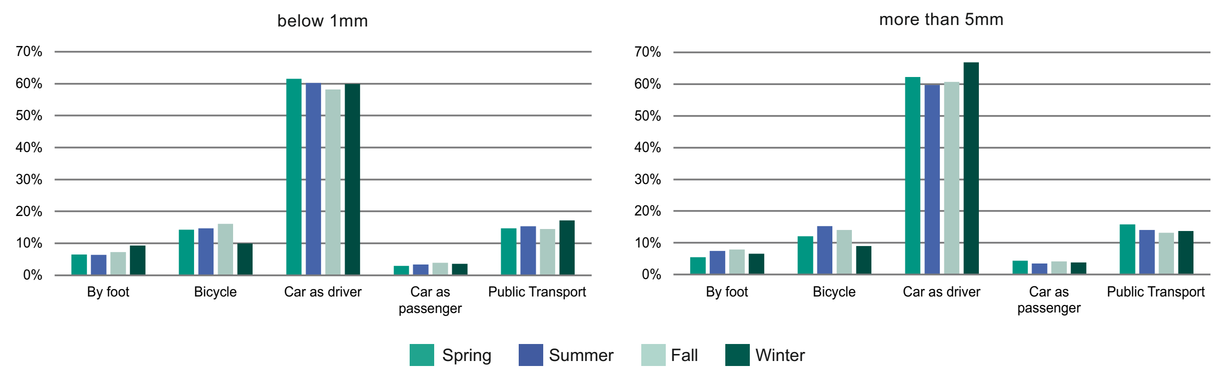

FIGURE 3 Modal split for work trips in different seasons by precipitation

Concerning leisure trips (see Figure 4), when it is dry, the share of trips made by foot is lowest in spring, with a share of 31.1%, while being at 41.1% in winter. While the share of walking in summer and winter is hardly negatively affected by precipitation, during spring, the modal share of walking increases by 3.3 percentage points and in fall, it decreases by 2.1 percentage points. Bicycle usage is consistently lower in wet conditions by about 5 percentage points in spring and fall, while in summer it is even 7 percentage points lower. In winter, the bicycle share is hardly affected, suggesting that individuals who use the bike in winter are less precipitation-sensitive, just as observed for work trips. Car usage as a driver rises significantly on wet days in fall (from 25.8% to 33.2%) and in summer (from 23.0% to 27.1%).

Overall, the results highlight the varying responses to precipitation and demonstrate the impact of weather conditions on mode choices for work and leisure trips. The effect of precipitation varies throughout the year, mainly for the active transport modes. A particular share of people seems to change their behavior due to the weather. At the same time, there remains a group of less weather-sensitive people, who, e.g., ride their bicycle in winter, and people who do not change their behavior in general, e.g., always driving a car.

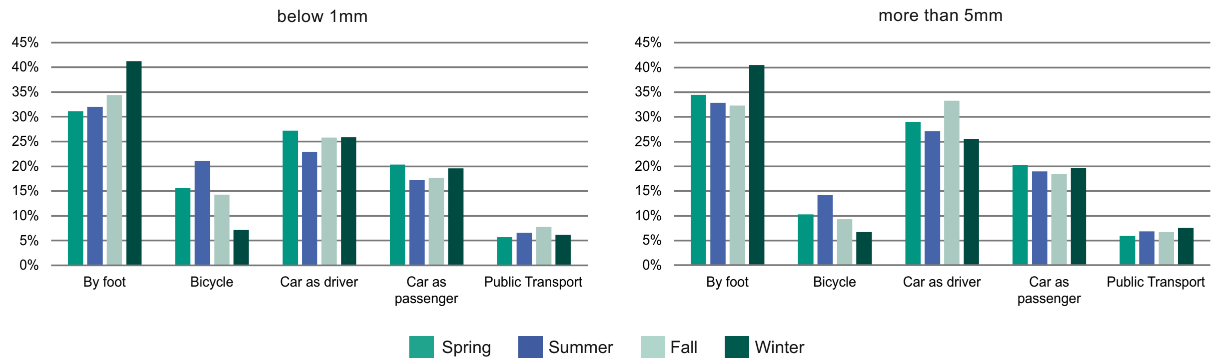

FIGURE 4 Modal split for leisure trips in different seasons by precipitation

RESULTS FOR FALL

In the following, we analyze further aspects of weather and travel behavior during fall, combining also sociodemographic characteristics. The temperature range is always given between 5 and 25°C as this is the relevant range for this season in Germany. An introductory remark: as will be seen in the tables given, the results are less stable than those for the different seasons - in several result rows there are outliers. Therefore, we focus on those results that show a clear pattern or trend.

Temperature, precipitation and cloud cover

At first, we analyze the impact of temperature and precipitation on travel behavior differentiated by the three different trip purposes (see Table 2). It can be observed that concerning temperature, the modal split of work trips changes most related to the bicycle. With rising temperature, the bicycle is used more as a mode of travel (14.4 to 18.1%). Simultaneously, PT and car as driver reduce their shares slightly (from 14.8 to 12.8% and from 59.0 to 57.4%, respectively). Concerning precipitation, the opposite can be observed: with more precipitation the bicycle share decreases (from 16.1 to 14.1%) while the share of car as driver increases (57.9 to 60.7%). PT is affected slightly negatively when high levels of precipitation occur (decrease from 14.5 to 13.2%).

Trips with education purpose are affected slightly differently. Bicycle share increases with rising temperature from 17.7% in the temperature range 5 to 10°C to 27.3% in the temperature range 15 to 20°C. However, car as passenger is affected most negatively, decreasing from 17.6 to 12.9%. Effects of precipitation are similar: increased shares of car as driver and car as passenger, however, the bicycle share is affected only at more substantial precipitation levels.

Regarding leisure trips, the changes are most dominant with respect to the bicycle: With rising temperature, the share of bicycle trips increases from 11.5 to 18.0%. In contrast, car as driver and car as passenger decrease slightly. Walking has its highest share at 5 to 10°C range with 28.4%, while at higher temperature levels the share is between 24.1 and 25.2%. Concerning precipitation, bicycle use decreases by 2.6 percentage points, which is far less than the differences that occur by changing temperature. Other modes such as car as driver, car as passenger and walking increase slightly.

TABLE 2 Modal split of trips during fall by purposes and weather parameters

	Temperature				Precipitation				Low cloud cover		
	5 to 10°C	**10 to 15°C**	**15 to 20°C**	**20 to 25°C**	**<0.1mm**	**0.1 to 1mm**	**1 to 5mm**	**>5mm**	**<8 h**	**8 to 16 h**	**>16 h**
Work											
sample size	*8,306*	*15,860*	*14,211*	*4,784*	*17,619*	*12,529*	*11,887*	*6,818*	*41,035*	*4,883*	*2,935*
by foot	7.8%	7.4%	7.3%	7.6%	7.6%	6.8%	7.4%	7.9%	7.4%	7.7%	6.9%
bicycle	14.4%	15.5%	16.1%	18.1%	16.1%	16.2%	15.3%	14.1%	15.4%	16.6%	17.4%
car as driver	59.0%	59.2%	59.2%	57.4%	57.9%	58.6%	59.8%	60.7%	59.3%	56.5%	58.1%
car as passenger	3.9%	4.0%	3.8%	4.1%	4.0%	4.0%	3.5%	4.1%	3.8%	4.8%	4.2%
public transport	14.8%	13.9%	13.6%	12.8%	14.5%	14.4%	14.0%	13.2%	14.2%	14.4%	13.5%
Education											
sample size	*2,493*	*4,494*	*3,731*	*1,364*	*5,010*	*3,507*	*3,374*	*1,907*	*11,698*	*1,330*	*770*
by foot	16.4%	16.3%	13.5%	16.4%	16.7%	14.3%	16.6%	15.1%	15.9%	13.9%	18.5%
bicycle	17.7%	23.8%	27.3%	21.6%	22.4%	24.1%	22.8%	19.8%	22.8%	23.6%	17.3%
car as driver	11.4%	11.7%	10.1%	10.2%	10.3%	10.0%	11.8%	13.0%	11.2%	9.7%	8.9%
car as passenger	17.6%	14.3%	11.1%	12.9%	13.7%	14.6%	13.6%	15.6%	14.1%	13.1%	17.2%
public transport	36.8%	33.9%	38.0%	38.9%	37.0%	37.0%	35.1%	36.5%	36.0%	39.6%	38.0%
Leisure											
sample size	*11,304*	*23,597*	*21,128*	*8,372*	*28,871*	*17,471*	*15,922*	*8,791*	*57,531*	*7,916*	*5,608*
by foot	28.4%	25.2%	24.1%	24.3%	25.6%	25.1%	26.0%	26.1%	25.9%	25.6%	23.4%
bicycle	11.5%	13.1%	15.9%	18.0%	15.2%	14.3%	13.5%	12.6%	13.9%	15.3%	17.0%
car as driver	33.8%	35.3%	34.6%	32.1%	33.6%	33.4%	34.2%	35.8%	34.2%	32.9%	32.9%
car as passenger	18.2%	18.6%	17.7%	17.1%	17.5%	18.9%	18.1%	18.3%	18.0%	17.6%	19.6%
public transport	8.1%	7.8%	7.7%	8.4%	8.0%	8.3%	8.1%	7.2%	8.0%	8.6%	7.0%

As an indicator if the weather is (subjectively) pleasant, we use the parameter cloud cover. It can be seen that there is a remarkable influence: Comparing days with high and low cloud cover, the bicycle share increases from 15.4 to 17.4% for work trips and from 13.9 to 17.0% for leisure trips. For all trip purposes, the share of car as driver decreases when low cloud cover prevails.

In summary, bicycle use is most affected, for all trip purposes. The highest shares can be observed at low precipitation and high temperatures. However, the modes that lose shares are distinct between the different trip purposes. For work trips, it is car as driver and PT, for education trips it is car as passenger, and for leisure trips it is walking and car as driver and passenger. Cloud cover alone also has a visible influence.

Influence of mobility tools available

We analyzed our dataset regarding correlations between the weather's influence on modal split at work trips, grouped by the availability of car availability, transit pass ownership and bicycle ownership (mobility tools). The full results are depicted in Table 3 .

Persons that always have a car available increase their share of bicycle from 8.2% to 11.8% at higher temperatures. However, this happens only when temperatures reach at least 20°C. At the same time, usage of car as driver decreases from around 77 to 74.1%, also walking decreases from 6.0% to 4.9%. In comparison, people that do "sometimes" have a car available show a change in bicycle use from 28.4 to 35.8%, and show a strong increase already at 15°C. Furthermore, they seem to change their mode from PT to bicycle. People that do not have a car available hardly change their travel mode depending on the temperature.

Analyzing the influence of bicycle ownership it can be observed that only those having a bicycle change their travel behavior: With rising temperature, the bicycle share increases from 17.4 to 21.6%. This is at the expense of car as a driver and PT. People without a bicycle do hardly change their travel behavior, especially not in a consistent manner.

When differentiating people by PT pass ownership, it is remarkable that people having a transit pass decrease their PT usage by nearly 7 percentage points (from 69.1 to 62.2%) between low and high temperature levels. Simultaneously, the usage of bicycle increases from 8.4 to 13.5%. People without a transit pass have a smaller variation of travel behavior: while the bicycle share increases with higher temperatures, the differences are smaller (from 16.3 to 19.3%).

We also analyzed people that state to be members of car-sharing companies (not depicted in the table). They present an especially large variance in travel behavior depending on temperature: Bicycle share increases by 23 percentage points, PT decreases by 16 percentage points. However, as the samples are relatively small (between 97 and 294 trips), these results should only be seen as indicative.

Influence of sociodemographic characteristics on weather sensitivity

At last, we analyze people's reactions to weather by age and gender (also depicted in Table 3). Concerning gender, we differentiate between male and female, as only these categories are available in our data. For simplicity, we differentiate between the age groups "between 18 and 49 years" and "50 years and older".

Remarkably, male persons of 50 years and older do not show any clear changes in travel behavior with changing temperatures. They seem to make nearly the same decisions independent of temperature - at least in the temperature levels and the season we are analyzing.

Younger men change their behavior over the whole range of temperatures, a pattern of

TABLE 3 Modal split of trips to work depending on mobility tools and age and gender

	5 to 10°C	10 to 15°C	15 to 20°C	20 to 25°C	5 to 10°C	10 to 15°C	15 to 20°C	20 to 25°C
by mobility tools								
car								
	always available				**sometimes or never available**			
sample size	*6,042*	*11,691*	*10,584*	*3,475*	*1626*	*3157*	*2905*	*951*
by foot	6.4%	5.1%	5.4%	4.9%	11.3%	12.9%	11.6%	13.5%
bicycle	8.2%	9.4%	9.5%	11.8%	30.8%	30.3%	34.0%	34.8%
car as driver	76.7%	77.1%	77.2%	74.1%	15.9%	17.2%	15.7%	17.4%
car as passenger	3.0%	2.9%	2.4%	3.2%	5.6%	5.6%	6.6%	6.1%
public transport	5.7%	5.5%	5.5%	6.0%	36.5%	34.0%	32.1%	28.3%
bicycle								
	bicycle available				**no bicycle available**			
sample size	*6,732*	*12,755*	*11,510*	*3,959*	*1,474*	*2,970*	*2,650*	*770*
by foot	7.6%	6.9%	7.1%	7.5%	9.3%	9.5%	8.3%	8.2%
bicycle	17.4%	18.7%	19.8%	21.6%	1.5%	1.6%	1.4%	1.0%
car as driver	57.7%	57.5%	57.0%	55.9%	64.1%	66.6%	67.8%	64.7%
car as passenger	3.8%	3.7%	3.4%	3.9%	3.9%	5.2%	5.1%	4.9%
public transport	13.5%	13.2%	12.6%	11.1%	21.2%	17.1%	17.5%	21.3%
transit pass								
	owns transitpass				**without transitpass**			
sample size	*1,183*	*2,433*	*2,255*	*731*	*4,517*	*8,179*	*6,549*	*2,389*
by foot	4.5%	6.9%	7.0%	6.2%	8.5%	8.0%	7.9%	8.3%
bicycle	8.4%	10.7%	10.3%	13.5%	16.3%	17.1%	17.9%	19.3%
car as driver	13.1%	14.6%	13.4%	13.6%	67.7%	68.4%	68.9%	65.5%
car as passenger	4.9%	3.2%	4.8%	4.5%	3.4%	4.1%	3.6%	4.2%
public transport	69.1%	64.7%	64.5%	62.2%	4.1%	2.3%	1.7%	2.6%
by age and gender								
	between 18 and 49 years				**50 years and older**			
female								
sample size	*2,106*	*4,031*	*3,511*	*1,312*	*1,978*	*3,702*	*3,475*	*1,051*
by foot	9.2%	7.1%	8.8%	8.6%	10.3%	8.5%	8.1%	7.6%
bicycle	13.9%	16.1%	13.7%	17.6%	12.3%	13.4%	13.9%	18.8%
car as driver	59.4%	57.5%	61.1%	56.5%	55.4%	59.6%	56.6%	54.3%
car as passenger	4.9%	4.4%	3.6%	3.8%	5.5%	4.6%	4.3%	4.7%
public transport	12.5%	14.9%	12.9%	13.4%	16.5%	13.9%	17.1%	14.6%
male								
sample size	*2,308*	*4,286*	*3,708*	*1,331*	*1,868*	*3,746*	*3,438*	*1,067*
by foot	6.3%	6.4%	5.5%	6.3%	6.1%	8.3%	6.6%	7.4%
bicycle	15.2%	16.7%	19.4%	19.8%	14.6%	14.0%	15.3%	14.8%
car as driver	59.2%	59.0%	58.7%	57.9%	63.9%	64.1%	61.5%	62.0%
car as passenger	2.5%	3.3%	3.2%	4.0%	2.8%	3.3%	4.1%	4.0%
public transport	16.8%	14.6%	13.1%	12.0%	12.5%	10.2%	12.6%	11.8%

decreasing PT and car use can be seen (from 16.8 to 12.0%, and from 59.2 to 57.9%, respectively). There is an increase from 15.2% to 19.4% in bicycle share from the temperature interval 5 to 10°C to the interval 15 to 20%. In contrast, among women, a remarkable change of mode choice starts to set in only at the temperature level of 20 to 25°C with increased bicycle share. Among older women, this substitutes walking, among younger women no clear substitute is identifiable.

At very low temperatures (not depicted in the table), among the older age group, male people tend to use car more often, while female persons tend to use it less: Between the temperature levels 0 to 5°C and 10 to 15°C there is an increase in the share of car in modal split of 10 percentage points among women and a decrease of 3 percentage points among men.

DISCUSSION

In our study, we combined two national household surveys to obtain a large dataset which allows to analyze the impact of weather on travel behavior. We focused on home-based trips where the degrees of freedom in mode choice are largest.

We found that the same temperature and precipitation generate different modal shares in the different seasons. Therefore, apparently, similar weather conditions are perceived differently between seasons. We explain this behavior with the fact that when temperature is relatively high compared to other days in the same seasons, this might be due to sunshine. Related to this, we also see a positive impact of having low cloud cover on travel behavior in fall. Thus, having pleasant days with sunshine may lead to higher use of active modes. However, this possible relationship needs further research for clarification.

We can see that sociodemographic characteristics and the availability or ownership of mobility tools has an impact on the influence weather has on travel behavior. People not always having a car available, owning a bicycle or owning a transit pass show the largest changes in travel behavior depending on the weather conditions - shifting from PT to bicycle at higher temperatures. People not having a bicycle, and also people "never" having a car available hardly change their travel behavior with changing temperatures. This is probably due to limited alternatives. We assume that nowadays (the data is from 2009 to 2019), this may be different due to an increase in sharing services.

Also, the sociodemographic differences in weather's influence on travel behavior are interesting. Older men react the littlest on changing conditions, thus, when policy wants to change their behavior, it could make sense to point their attention towards the changing weather conditions and to re-think their travel behavior. However, further analysis should be undertaken to strengthen this observation, mainly with more data, as well as with more weather conditions.

Precipitation decreases bicycle modal share in all seasons and for all trip purposes. There are differences in magnitude, having largest impacts for leisure trips. However, as precipitation is sometimes a relatively local phenomenon, we would like to repeat our analysis with grid zones of larger resolution, i.e., to have grid zones smaller than 31 km edge length.

In recent years there were major changes in mobility: New sharing modes such as bike sharing and e-scooter sharing have arisen or were scaled up, and due to home-office and video conferences people can execute their activities more flexibly than before the Covid pandemic. These changes are not represented in the data we analyzed, as the data is from the years 2009 to 2019. Therefore, it would be useful to repeat the analysis with newer data. Furthermore, in future research, the possible changes in activities, trip rates and trip lengths should be analyzed.

Although we had a large dataset, when analyzing specific weather situations for specific sociodemographic groups the sample quickly gets small. Therefore, there might be a bias if certain weather situations only occur jointly with other special conditions. It would be promising to use an even larger dataset. Also further statistical methods such as regression and statistical tests should be applied to this data.

Besides seasons, we used daily maximum temperature, the sum of daily precipitation and the number of hours with low cloud cover in our study as weather parameters, since in preliminary tests these have shown to be most determining. However, other parameters, such as daily average temperature or temperature and precipitation at the hour of travel could be meaningful as well. Testing which parameter or which combination of parameters has most influence should be analyzed in the future. Also, it may be sound to consider the daytime brightness in combination with weather. Furthermore, future research should attempt to determine which spatial resolution of weather and mobility data is required for significant results.

Generally, the analysis was undertaken from a European perspective, where the four seasons prevail. Depending on the climate of a place of study, other differentiation criteria would make sense (e.g., travel behavior in rain seasons vs. dry seasons).

CONCLUSIONS

In our study we analyzed the impact of weather on home-based trips made on ’regular’ days, combining two large household surveys with weather data from a reanalysis model. We could clearly show that travel behavior is weather-dependent. The influence differs between different sociodemographic groups and between people with and without certain mobility tools. All three weather parameters analyzed - maximum daily temperature, sum of daily precipitation and number of hours of low cloud cover - show variations in travel behavior.

In our work, thanks to analyzing these datasets, we could show some new aspects. However, isolating the exact effects of different parameters is difficult. Therefore, more research needs to be done to accurately gather them. Furthermore, even larger datasets should be used to analyze the influences in different circumstances and to have enough data to analyze different sociodemographic groups.

Overall, we do see large variations depending on the weather conditions. As this is relevant for transport planning, we suggest considering it more in travel behavior studies. With large weather datasets available and the computational ability to handle large datasets, we now have the possibility to do so. Furthermore, these findings help to develop strategies that consider travel behavior in new weather conditions, that will occur due to climate change.

ACKNOWLEDGEMENTS

The research was undertaken as part of the project DAKIMO - Data and AI as Enablers for Sustainable Intermodal Mobility. This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the “Innovations for Tomorrow’s Production, Services, and Work” Program and implemented by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the content of this publication.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Pia Tulodetzki (PT), Gabriel Wilkes (GW), Martin Kagerbauer (MK), Peter Vortisch (PV); data collection: GW, PT; analysis and interpretation of results: PT, GW, MK; draft manuscript preparation: PT, GW, MK, PV. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Böcker, L., T. Priya Uteng, C. Liu, and M. Dijst, Weather and daily mobility in international perspective: A cross-comparison of Dutch, Norwegian and Swedish city regions. *Transportation Research Part D: Transport and Environment*, Vol. 77, 2019, pp. 491–505.
2. Ton, D., D. C. Duives, O. Cats, S. Hoogendoorn-Lanser, and S. P. Hoogendoorn, Cycling or walking? Determinants of mode choice in the Netherlands. *Transportation Research Part A: Policy and Practice*, Vol. 123, 2019, pp. 7–23.
3. Sabir, M., *Weather and travel behaviour*. Ph.D. thesis, Vrije Universiteit Amsterdam, 2011.
4. Miranda-Moreno, L. F. and T. Nosal, Weather or Not to Cycle. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2247, No. 1, 2011, pp. 42–52.
5. Goldmann, K. and J. Wessel, Some people feel the rain, others just get wet: An analysis of regional differences in the effects of weather on cycling. *Research in Transportation Business & Management*, Vol. 40, 2021, p. 100541.
6. Ahmed, F., G. Rose, and C. Jacob, Impact of weather on commuter cyclist behaviour and implications for climate change adaptation. *33rd Australasian Transport Research Forum*, 2010.
7. Singhal, A., C. Kamga, and A. Yazici, Impact of weather on urban transit ridership. *Transportation Research Part A: Policy and Practice*, Vol. 69, 2014, pp. 379–391.
8. Kashfi, S. A., J. M. Bunker, and T. Yigitcanlar, Understanding the effects of complex seasonality on suburban daily transit ridership. *Journal of Transport Geography*, Vol. 46, 2015, pp. 67–80.
9. Böcker, L., M. Dijst, and J. Faber, Weather, transport mode choices and emotional travel experiences. *Transportation Research Part A: Policy and Practice*, Vol. 94, 2016, pp. 360–373.
10. Liu, C., Y. O. Susilo, and A. Karlström, Examining the impact of weather variability on non-commuters' daily activity–travel patterns in different regions of Sweden. *Journal of Transport Geography*, Vol. 39, 2014, pp. 36–48.
11. Heinen, E., K. Maat, and B. van Wee, Day-to-Day Choice to Commute or Not by Bicycle. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2230, No. 1, 2011, pp. 9–18.
12. Sabir, M., J. Van Ommern, M. J. Koetse, and P. Rietveld, Impacts of weather conditions on destination choice of leisure trips. *50th Congress of the European Regional Science Association*, 2010.
13. Liu, C., Y. O. Susilo, and A. Karlström, Investigating the impacts of weather variability on individual's daily activity–travel patterns: A comparison between commuters and non-commuters in Sweden. *Transportation Research Part A: Policy and Practice*, Vol. 82, 2015, pp. 47–64.
14. Saneinejad, S., M. J. Roorda, and C. Kennedy, Modelling the impact of weather conditions on active transportation travel behaviour. *Transportation Research Part D: Transport and Environment*, Vol. 17, No. 2, 2012, pp. 129–137.
15. Liu, C., Y. O. Susilo, and A. Karlström, Measuring the impacts of weather variability on home-based trip chaining behaviour: a focus on spatial heterogeneity. *Transportation*, Vol. 43, No. 5, 2016, pp. 843–867.

16. Lin, T.-P., Thermal perception, adaptation and attendance in a public square in hot and humid regions. *Building and Environment*, Vol. 44, No. 10, 2009, pp. 2017–2026.
17. de Montigny, L., R. Ling, and J. Zacharias, The Effects of Weather on Walking Rates in Nine Cities. *Environment and Behavior*, Vol. 44, No. 6, 2012, pp. 821–840.
18. Liu, C., Y. O. Susilo, and A. Karlström, Weather variability and travel behaviour – what we know and what we do not know. *Transport Reviews*, Vol. 37, No. 6, 2017, pp. 715–741.
19. Helbich, M., L. Böcker, and M. Dijst, Geographic heterogeneity in cycling under various weather conditions: evidence from Greater Rotterdam. *Journal of Transport Geography*, Vol. 38, 2014, pp. 38–47.
20. Böcker, L., M. Dijst, and J. Prillwitz, Impact of Everyday Weather on Individual Daily Travel Behaviours in Perspective: A Literature Review. *Transport Reviews*, Vol. 33, No. 1, 2013, pp. 71–91.
21. Thomas, T., R. Jaarsma, and B. Tutert, Exploring temporal fluctuations of daily cycling demand on Dutch cycle paths: the influence of weather on cycling. *Transportation*, Vol. 40, No. 1, 2013, pp. 1–22.
22. Brandenburg, C., A. Matzarakis, and A. Arnberger, Weather and cycling—a first approach to the effects of weather conditions on cycling. *Meteorological Applications*, Vol. 14, No. 1, 2007, pp. 61–67.
23. Aaheim, H. and K. Hauge, *Impacts of Climate Changes on Travel Habits: A National Assessment Based on Individual Choices*. CICERO - Center for International Climate and Environmental Research, Norway, 2005.
24. Cools, M., E. Moons, and G. Wets, Assessing the Impact of Weather on Traffic Intensity. *Weather, Climate, and Society*, Vol. 2, No. 1, 2010, pp. 60–68.
25. Connolly, M., Some Like It Mild and Not Too Wet: The Influence of Weather on Subjective Well-Being. *Journal of Happiness Studies*, Vol. 14, No. 2, 2013, pp. 457–473.
26. Bergström, A. and R. Magnusson, Potential of transferring car trips to bicycle during winter. *Transportation Research Part A: Policy and Practice*, Vol. 37, No. 8, 2003, pp. 649–666.
27. Phung, J. and G. Rose, Temporal variations in usage of Melbourne's bike paths. *30th Australasian Transport Research Forum*, 2008.
28. Nobis, C. and T. Kuhnimhof, *Mobilität in Deutschland 2017 - Mobility in Germany 2017*. BMVI, infas, DLR, IVT, infas 360., Bonn, Berlin, 2018.
29. Vallée, J., L. Ecke, B. Chlond, and P. Vortisch, *Deutsches Mobilitätspanel (MOP) – Bericht 2021/2022. German Mobility Panel - Report 2021/2022*. Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), 2022.
30. Hersbach, H., B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, and J.-N. Thépaut, *ERA5 hourly data on single levels from 1959 to present*, 2018.
31. Hoyer, S. and J. Hamman, xarray: N-D labeled arrays and datasets in Python. *Journal of Open Research Software*, Vol. 5, No. 1, 2017.
32. Russel, I. and B. Raoult, *cfgrib: A Python interface to map GRIB files to the NetCDF Common Data Model following the CF Convention using ecCodes*, 2023.