Relationships Between Weather and Cycling

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Abstract

As cycling gains more traction and attention as a beneficial mode of urban transportation, different factors have emerged in different regions of the world to influence its adoption and promotion. One of the most wide-spread and colloquial of these factors is that of the weather or climate of the region, and how it may facilitate or, more often, dissuade cycling practices. Although it may appear intuitive that "poor" weather shall negatively impact the amount of cycling that occurs in a region, the reliability of this intuition is challenged by example locations where cycling in "poor" winter conditions is the norm rather than the exception, or where cyclists are relatively indifferent towards rainy weather. As such, the aim of this literature review is to identify the real effects of weather on cycling behaviour in different locations and uncover relationships between secondary covariates and responses to weather. Rainfall, temperature, and wind are identified as the three most important measurable weather parameters that affect cycling behaviour. In most locations, cycling rates drop significantly when it starts to rain, temperature thresholds vary between locations, and the effect of wind is only significant when above 5 Beaufort. Several studies also reveal factors that interact with measurable weather parameters to influence behaviour in significant and seemingly complex ways. These include the trip purpose, traveller sociodemographic, the characteristics of the built environment, and perceptions of normality. The identification of these covariates and a discussion about interrelations amongst them contributes to an explanation of why weather seems to affect cyclists in some places more than in others, while also highlighting directions for future research.

1.Introduction

We were interested in looking at the effects of weather on cycling behaviour. One of the challenges we faced while searching for suitable research papers was the fact that most of the research is from Europe or North America. However, we wanted to look at the effects of weather in different locations, because our assumption was that these effects would be different in different parts of the world, given the differences between climates, cultures, and habits. We managed to find a good and comprehensive literature review article, which led us to a few other good articles from there.

An interesting overall finding from the literature review is that many of the studies cite climate change and its potential effects on our cities as the main reason for carrying out this research and being interested in looking into the effects of weather on cycling behaviour or active mobility in general. It is understood that weather will keep getting more unpredictable in the years and decades ahead, and more extreme weather is likely, while rising temperatures will be evident in many parts of the world. Therefore, many of these researchers are interested in finding how these changes may affect behaviours, as well as what steps we may be able to take to adapt our behaviours to the changing climate.

In this essay, we will first present our findings on the direct effects of weather on cycling behaviour, and then we will discuss some related factors and covariates that seem to be at an interplay with the weather effects. Following this, we provide a synthetical discussion of the research area, identify gaps, and finally reflect on the research process as related to the Integrated Urban Transport course.

2.Direct Weather Effects

The journal articles we reviewed studied a few different weather factors, either on their own or in conjunction. Generally, what we found from the review is that a handful of factors are cited as the most prominent ones in affecting cycling behaviours, namely rainfall or precipitation, temperature, wind, and humidity.

Most of the papers we studied identify rainfall as the single biggest deterrent of cycling. This is the case for most of the locations. Some studies found that there is a large drop in cycling rates with even the smallest hint of rain, after which the decline slows down (Liu et al., 2017, Böcker et al., 2013). Another study concluded that rainfall not only affects cycling rates, but also cycling distances as well (Hong et al., 2020). Böcker et al (2013) mention studies in Canada and the UK that show lower total cycling trips in places with traditionally higher amounts of precipitation than other places. One study mentioned in the literature review article (Böcker et al., 2013) found that light rain mostly has an impact on the clothing worn by cyclists, and only heavier rain impacts cycling rates. We should note here that, even though some studies explicitly identify and mention rainfall as the specific factor, other studies resort to talking about precipitation in more general terms, which may contain different forms of precipitation like rain, snow, etc.

Temperature seems to be the second major factor affecting cycling behaviour. A study conducted in Rotterdam actually found that temperature is more significant than any other factors like rainfall and wind (Helbich et al., 2014). According to Liu et al. (2017), temperature has a strong effect on cycling. Several studies in Europe and Canada showed that cycling rates are positively correlated with temperatures up to 25 degrees Celsius, after which the relationship becomes negative (Liu et al., 2017). This pattern has been observed in many places and from different studies as well. Generally, there seems to be a “bell-curved” relationship of temperature with cycling. The cycling rate generally increases gradually towards a peak before declining relatively sharply thereafter. The peak and slope(s) of that curve seem to be location-specific, meaning that it is different in different parts of the world. For example, a study in Singapore questioned cyclists and identified that temperatures between 29.5C and 31.5C are the most comfortable ones and are in fact seen as “lower temperatures” (Meng et al., 2016) as opposed to some places in Europe or Canada where 25C to 28C were the peak level comfort temperatures identified (Liu et al., 2017; Bean et al., 2021). This is also validated by Böcker et al (2013) who mention several studies that found a positive relationship with temperature up to a certain degree; but especially in hotter climates, temperatures above a certain context-specific threshold had a negative effect on cycling. Another effect of temperature we can spot in different parts of the world is the seasonality. As discovered by a study about bikeshare use in different cities across different climates, the use of bikeshare in temperate climates like that of Paris or Brussels peaked in the summer and dropped in the winter, while in more tropical climates, like that of Brisbane, it remained fairly consistent (Bean et al., 2021).

Additionally, Böcker et al (2013) cite a study looking at mode choice for going to school in a few different cities which found that the cycling rates triple in the summer over the winter.

Another factor that came up in different studies is wind. As mentioned by Böcker et al (2013), most studies find that there is a negative relationship of wind with cycling. Liu et al. (2017) found that wind speed has a moderate effect on cycling behaviour, and Saneinejad et al. (2012) found that wind affects cyclists in Toronto, even more than pedestrians. As we can see from Böcker et al. (2013) again, the range with which wind is negatively associated with cycling varies from study to study and from place to place, from a weak negative relationship to a strong one. Only a few studies seem to have investigated the wind speed specifically, and they generally find that stronger winds are more strongly associated negatively with cycling than lighter winds. For example, Böcker et al (2013) cite a study that found that only winds of 5 on the scale of Beaufort and up see a decrease in cycling rates. Studies that found weak relationships with wind may be consistent with this finding, as those studies did not observe/record wind speeds above 5bft.

Finally, humidity was mentioned as a factor that may affect cycling use, but this one was not studied by most of the research studies. In fact, only two of the articles we found mention and talk about humidity (Meng et al., 2016; Lee & Pojani, 2019), and they are both from Singapore, which may lead us to believe that humidity might not be a huge factor in a central or northern European context, or a North American one.

3.Covariates Affecting Cycling Responses

The findings presented in the previous section show that the effects of weather on cycling behaviour exhibit some generally consistent and strong relationships in most locations (i.e., a bell-shaped response to a range of temperatures, thresholder responses to wind & rain, etc.). However, observations that the specific parameters and intensities of these relationships change between contexts prompts questions about what covariates and mediating factors may help to explain the different responses to weather in different places. The authors of the two literature reviews to date on the subject (Böcker et al., 2013; Liu et al., 2017) argue that responses to weather cannot be detached from subjective interpretations of weather, which will be related to a variety of factors beyond objective measurements of individual weather parameters (i.e., temperature). Böcker et al. (2013) note that such parameters always co-occur, forming more holistic weather categories that are interpreted differently by individuals of different sociodemographic, inducing reactions to the weather that are embedded within a cultural context. Echoing the importance of cultural-contextual covariates, Hudde (2023) measures the difference between German and Dutch cyclists' responses to weather, showing that the average German cyclist is much more sensitive to weather parameters despite the climates of both countries being quite similar. These findings are demonstrated in Figure 1. Not only do German cyclists stop cycling sooner as temperatures and daylight decrease, but relatively more of them do so. Meanwhile, the 'raininess' of the city seems to affect the German modal split, but not the Dutch modal split. These different responses tacitly reflect those that can be observed between cities in North America, Europe, Australia, and Singapore, but our ability to explain them solely as an effect of differences in objective weather measurements is much more dubious. Hudde speculates that the different responses must be due to cultural differences expressed either directly, through general subjective perceptions about cycling and weather, or indirectly, through the way spaces are planned and what infrastructure/maintenance activities go on. In all, Böcker et al. (2013), Liu et al., (2017), and Hudde (2023) suggest that factors affecting the way a cyclist views the weather as relevant to their life will covary with their observed responses to it. The section hereunder surveys available evidence that relates such factors to cycling-weather responses including trip purpose, demographics & personal factors, built environment characteristics, and the perception of normality.

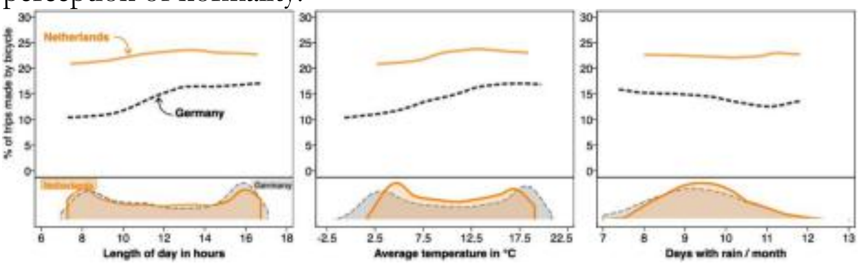


Figure 1: Cycling responses to weather in Germany vs Netherlands, including relative number of observed cities at each weather measurement. Reprinted from Hudde (2023).

4.Trip Purpose

Indeed, trip purpose appears to affect the response to weather for cycling trips. Several studies have found that leisure trips are affected by weather much more than work trips. For example, Helbich et al (2014) found that wind and rainfall are not significant factors when it comes to work cycling trips, but they are for leisure cycling trips. They also found that temperature plays a role in both trip types but is more significant for leisure trips. Similar findings are mentioned in Böcker et al (2013), where studies have shown differences between weekdays and weekends, as well as peak hours and off-peak hours denoting a larger effect of precipitation on leisure trips. Liu et al (2017) have concluded that even though rainfall and temperature can account for a large portion of the daily fluctuations in bike usage, there is a clear distinction between weekday flows and weekend flows, which goes to show the difference between leisure trips and utilitarian trips, as they call them. Bean et al (2021) looked at data for bikeshare use from forty different cities in the world and saw that most models place the hour of the day as the most significant factor, for both weekday and weekend trips. For example, they mention that usually weekend cycling trips peak around 2 to 3 in the afternoon in most locations, whereas in a more tropical location the peak was around 5pm. Equivalent results can be inferred for weekdays, with peaks around the morning and afternoon rush hours, or maybe in the middle of the day if the specific location has a cultural tradition like a siesta. We should note here that these weekday effects are only hinted at in this study, and they unfortunately do not provide a specific result on the weekday cycling peaks.

As mentioned above, most studies find that leisure trips are affected more than work trips in most of the locations. The only notable exception we found through our review was in Singapore. Meng et al (2016) found that work trips are more affected by weather than leisure trips. Of course, the weather in Singapore is different than most of the other locations studied in other papers, like in Europe and North America. Singapore has a more tropical climate. But the authors of the study provide a potential explanation for this phenomenon in the work culture of the country. It may be the case that the effect of adverse weather on people's ability to show up to work on time is preventing them from choosing to cycle to work when the weather is not ideal for them. Also, we assume that in Singapore it may be less acceptable to show up at work wet or sweaty, and if the workplace does not have any showers or changing rooms, this makes it almost impossible for people to choose to cycle to work under these conditions (Lee & Pojani, 2019).

5.Demographics & Personal Factors

There is a sub discourse in the literature which explores how the personal characteristics of individual travellers may affect observed sensitivities to changing weather. As Böcker et al. (2013) note, sociodemographic variables are usually included in studies as control variables rather than as mediating variables, but there is still some descriptive evidence on these. Exhibiting one of the most prevalent and consistent relationships among the studied factors is gender. It seems that in most cases where cycling responses to weather are measured, either through trip-making observations or stated-preference surveys, authors find a more sensitive response from female cyclists to 'adverse' weather. Most of the studies measure responses to precipitation, but some also demonstrate relationships with temperature or weather more generally. In Sweden, precipitation was more often cited by females as a barrier for cycling (Böcker et al., 2013; citing Bergström & Magnusson, 2003) - a result replicated in Victoria, Australia, where 47% of female cyclists cited "weather" as a barrier compared to 35% of males (Ahmed et al., 2013). In Australia and Canada, actual reductions in cycling due to precipitation were also observed to be more frequent amongst females (Böcker et al., 2013; citing Keay, 1992 & Chan et al., 2006).

Significant differences in trip-making sensitivity to precipitation were also replicated in Chicago and New York but, notably, only on weekdays in New York and weekends in Chicago (Bean et al., 2021). For temperature, one study observed that, in cold weather in Toronto, female cyclists' tendency to cycle was ~1.5 times more sensitive than males (Saneinejad et al., 2012). Finally, a study in Singapore demonstrates a potential exception to the prevalent relationships found elsewhere. Taking random samples of cyclists on dry and rainy days, authors found a negligible difference in the composition of cyclists - roughly 70% of cyclists were male on each day (Meng et al., 2016). Most authors providing the primary evidence for the above relationships do not attempt to explain them, though other authors have speculated about the potential reasons underlying them. Some have made connections between physical fitness and gender (Motoaki & Daziano, 2015); between gender, differences in the modal split in general, and perceptions of safety and risk (Böcker et al., 2013; Hong et al., 2020; citing Emond et al., 2009); and between gender and "needs" for unique end-of-trip facilities such as change rooms in which to redo makeup or change into skirts for work (Lee & Pojani, 2019).

Another demographic factor that is speculated to be of significance for weather-cycling responses is age. In absence of direct, conclusive evidence, but in acknowledgement that in many locations cycling is generally more prevalent among younger age groups, authors often indicate that age is *likely* to covary alongside weather-cycling sensitivity (Böcker et al., 2013; Liu et al., 2017; Amiri & Sadeghpour, 2015). Liu et al. (ibid) treat advanced ageing as synonymous with disability, indicating a deteriorating ability to "cope" with adverse weather. Moreso related to cycling in general, Liu et al. (2020) note that, for example, elderly people may require more rest after conducting physical activities on a previous day, and that perhaps this need could intersect with weather-related experiences. Amiri & Sadeghpour speculate not in terms of ability, but rather in terms of age "affecting" things like thermal comfort, trip distances, and safety concerns. Meanwhile, Böcker et al. merely regard age as one of many sociodemographic aspects of cultural context that are likely to mediate the experience of weather and cycling. The available evidence that could substantiate these speculations is conflicting and appears inconclusive. The expected relationship was tangentially observed in Stockholm. There, stated weather perceptions amongst adults aged 51-65+ were much more sensitive to changes in actual temperature conditions than those amongst younger people (Liu et al., 2020). In the same study, stronger weather perceptions were shown to correlate well with more/less outdoor leisure-related travel (not cycling, specifically). Conversely, an opposite relationship was indicated by evidence gathered in Toronto, where authors found that younger cyclists' behaviour was more sensitive to colder temperatures than that of older cyclists (Saneinejad et al., 2012).

Other studies that attempted to find such evidence failed to demonstrate a significant relationship between age and weather-cycling sensitivity. Amiri & Sadeghpour (2015), while demonstrating that older age is indeed related to a reduced inclination towards multimodal cycling trips, and an increased likelihood to use cycling for commuting over other purposes, found that cold weather in Calgary did not seem to impede cyclists in the 44+ age group more than those in younger groups. Meng et al. (2016) likewise found no significant difference in cyclists' age composition on wet days vs dry days in Singapore.

Experience level with cycling, as a personal factor mediating responses to weather, has more consistent evidence supporting it than age. This evidence is, however, often less direct than the evidence associated with gender. The most direct and clear evidence comes from New York state, where Motoaki & Daziano (2015) utilized a hybrid-choice latent-class model to demonstrate that less-skilled (and less-experienced) cyclists consider rain to be 2.5 times more bothersome than more-skilled cyclists, and snow to be 4 times more bothersome. They also showed that colder temperatures were significant for negatively impacting attitudes of more skilled cyclists, while warmer temperatures were more significant for positively impacting attitudes of less-skilled cyclists. Similarly, Ahmed et al. (2013) found that "casual" cyclists (cycling < 3 days per week) were twice as likely to mention weather as an influence on their decision to cycle compared to "committed" cyclists in Victoria, Australia. This more direct evidence is also supported by findings that are somewhat more tangential, but perhaps still quite indicative. Hong et al. (2020) found that, shortly following the construction of Glasgow's first modern cycling infrastructure projects, which generated a substantial number of new cyclists, rainy weather reduced cycling on the new cycling paths more so than on any other type of road/path. They speculate that this is likely due to the new paths attracting a relatively high volume of newer/casual cyclists, who are perhaps more sensitive to the rain. On the other hand, Amiri & Sadeghpour (2015) found that frequent, more-experienced cyclists in Calgary did not mind cycling in temperatures as low as -20C. Lee & Pojani (2019) provide potential reasons behind observed relationships between experience level and weather-cycling sensitivity. They report anecdotes from planners in Singapore, stating that experienced cyclists "employ various mechanisms to cope with the less desirable aspects of the local climate. For example, when there is rain, they may delay their departure time or use protective clothing" (Lee & Pojani, 2019).

Other sociodemographic factors are also likely important. For example, one study from Canada relates higher bodyweights of cyclists to higher sensitivity to snow and lesser sensitivity to wind (Böcker et al., 2013; citing Chan et al., 2006). Another study from the USA relates "ethnic diversity" and inner-city areas to a lesser likelihood to perceive weather as a barrier compared to people in rural areas, who are less "ethnically diverse" (ibid; citing Wilcox et al., 2000). As indicated by the latter findings, it may be difficult to disentangle certain sociodemographic groups from specific locations, and therefore also from what modal habits they may already be inclined to build. Location may extend to the formation of certain health factors and experience levels. Indeed, it seems important to examine the mediating effects of the built environment upon cyclists' sensitivity to weather, while keeping in mind also its potential entanglement with sociodemographic.

6.Built Environment Characteristics

Urban form and location have some direct evidence highlighting its substantial effects. Helbich et al. (2014) provide a clear demonstration through their observations of travel behaviour in the Greater Rotterdam area. They show that the effects of temperature, wind, and precipitation on cycling in less-dense peripheral areas are much more significant than in denser urban areas - with the exception of wind in the densest high-rise areas of downtown Rotterdam (Figures 2 & 3). The authors speculate that the microclimate created by denser urban forms functions to alleviate the negative effects of colder temperatures by providing heat, of hotter temperatures by providing shade, and of wind by providing shelter. To explain the mediating effect on precipitation, as well as on all other weather parameters, they propose that the denser urban form also enables shorter trip distances and, therefore, lesser time exposed to the elements. The larger negative effect of wind in high-rise areas is explained by the wind-turbulence effect associated with skyscraper buildings. The results from Rotterdam are consistent with earlier findings from Australia, which indicated that cycling volumes were much more sensitive to wind and rain in suburban, "exposed" areas compared to inner-city, "sheltered" areas (Böcker et al., 2013; citing Phung & Rose, 2008). Alongside these findings it should be noted that modal choice more generally can be very insensitive to the weather in suburban areas if those areas are car-dependent, as was demonstrated in Bergen, Norway (ibid, citing Aaheim & Hauge, 2005).

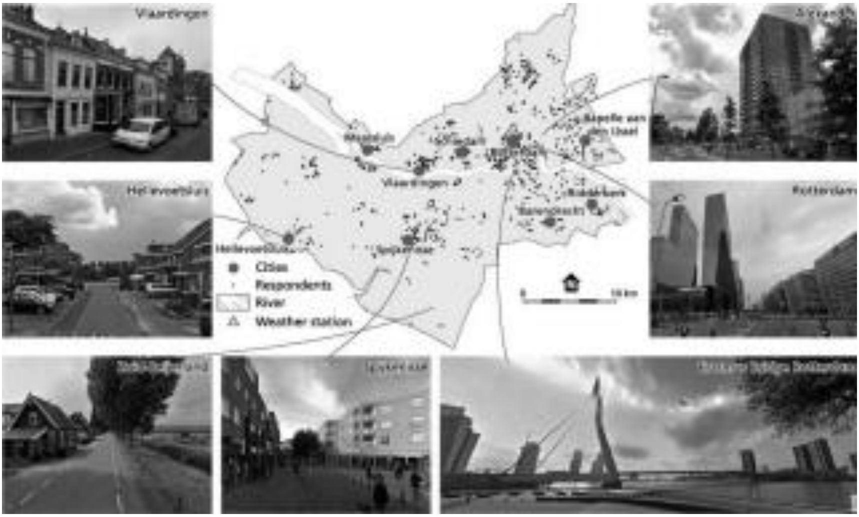
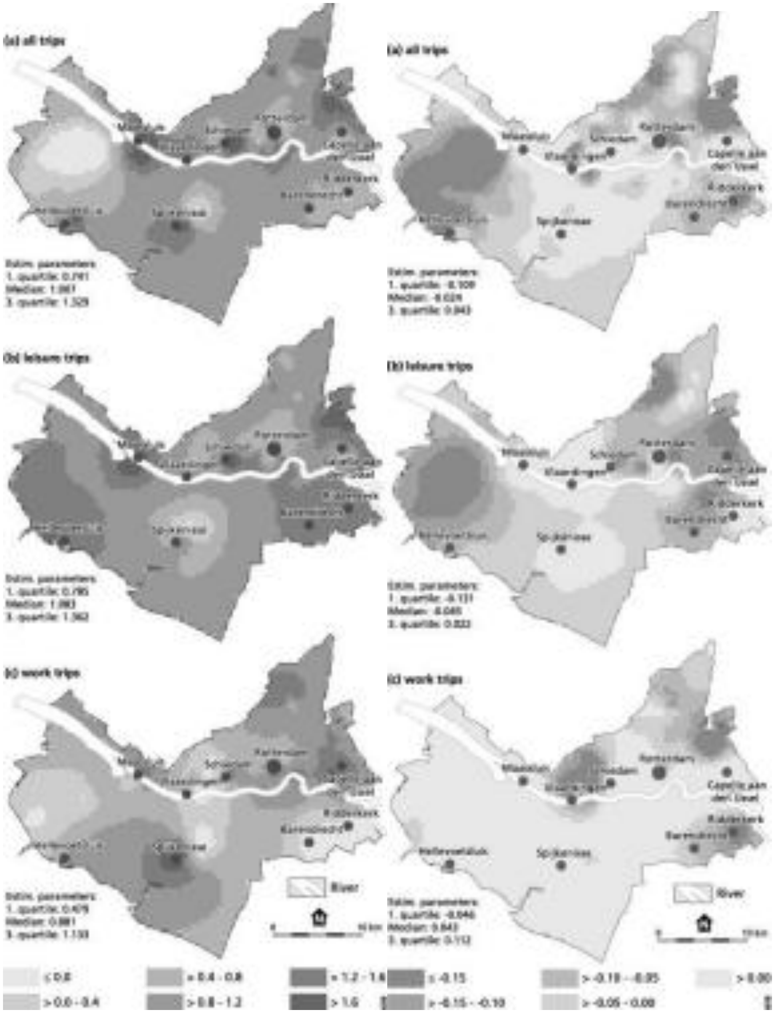


Figure 2: Legend of Greater Rotterdam locations. Reprinted from Helbich et al. (2014).


(a) all trips
(a) all trips
(b) leisure trips
(b) leisure trips
(c) work trips
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Estim. parameters
River
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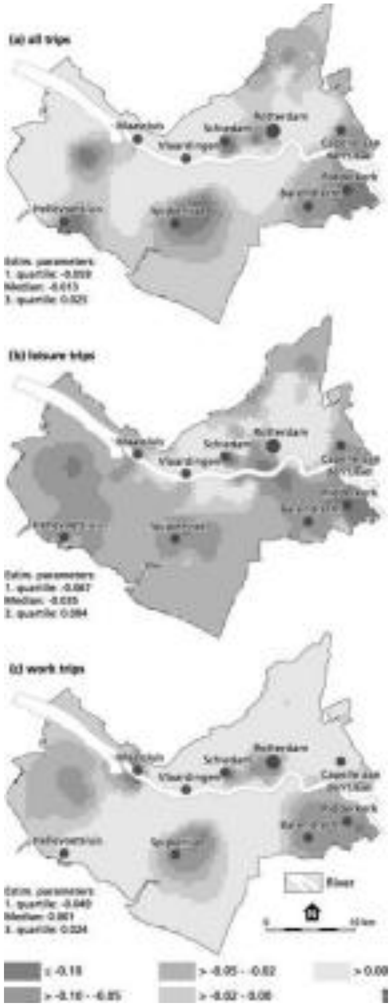

Figure 3: Significance of weather effects on cycling for air temperature (left), wind (middle), and precipitation (right). Reprinted from Helbich et al. (2014).

Where urban form and location may be considered one side of the built-environment coin, cycling infrastructure can be considered the other. Indeed, one of the limitations of the available evidence on urban form is that it cannot be disentangled from the potential effect of the cycling infrastructure in the denser study areas simply being better. This was not controlled for in the referenced studies. Only some limited, tangential evidence regarding the effect of improved cycling infrastructure on weather sensitivity, per se, is available. There is consistent evidence that improved cycling infrastructure, including separated bike paths or lanes, more generally increases the rate of cycling (Böcker et al., 2013; Amiri & Sadeghpour, 2015; citing several authors), and that some absolute increase in cycling persists even in adverse weather (Amiri & Sadeghpour, 2015). Maintenance seems an important component of infrastructure; cyclists in cold climates, when asked about barriers to cycling, often cite snow removal as the most important aspect of winter maintenance (ibid). Evidence from elsewhere suggests that end-of trip facilities are another important component; cyclists in Australia state that facilities such as secure parking, showers, changing rooms, and lockers encourage them to cycle more in adverse weather conditions (Ahmed et al., 2013). This is echoed by the speculations of planners in Singapore when they were asked how to improve cycling in adverse weather conditions (Lee & Pojani, 2019). These planners mentioned other infrastructural components as equally important, including shaded cycling paths, traffic calming at intersections, path connectivity at residential neighbourhoods, and softer policies such as cycling education. For them, improving weather sensitivity directly was not as important as improving infrastructure and safety more generally. Finally, the findings of Hong et al. (2020) in Glasgow indicate that improved infrastructure initially attracts newer and more casual cyclists who are more sensitive to the rain. This makes the entire composition of cyclists relatively more sensitive to certain aspects of the weather - perhaps only temporarily. Thus, while it may seem like a truism that improved infrastructure will, over time, improve cycling both within and regardless of adverse weather, it is obvious that the effects of infrastructure will be mediated by those of experience, trip purpose, and habit.

7.Perception of Normality

Perhaps intersecting with built environment conditions and aspects of sociodemographic identity are culturally embedded perceptions of what cycling behaviour is "normal". Limited evidence seems to suggest that "normal" weather corresponds to travel behaviours that individuals are already habituated to performing. Perceptions that weather is normal, or close to the historical mean for a given time (month) and geographic location, were shown to correspond to feelings of indifference in individuals in Stockholm (Liu et al., 2020). Such feelings were also shown to not significantly affect outdoor leisure travel behaviour; that is, people continued doing what they normally did - regardless of what it was - when they felt that the weather was normal for the time/place. This included winter conditions that may be considered harsh when compared to, for example, summer. Only relatively extreme feelings about the weather, which corresponded to relatively extreme deviations from the historically average weather for the time/place, were shown to affect travel behaviour (ibid). Meanwhile, conceptions about what weather conditions are normal for outdoor travel have also been shown to vary between cultural contexts. For a set of similar objective weather measurements, surveys inquiring "how do you experience the current weather today… good or bad for outdoor activity?" yielded clear cultural differences in weather perception between Japanese and Swedish populations (Liu et al., 2017; citing Thorsson et al., 2007). Hudde (2023) likewise points out that Dutch people do not seem to conceive of or talk about cycling as a seasonal activity as pervasively as German people do, and that this may contribute to the differences observed in Figure 1. This author also speculates that the way society and individuals conceive of themselves in terms of their sociodemographic identities (age, gender, class, etc.), and how they perceive these characteristics as related to cycling, may also affect their propensity to cycle in different weather conditions. The above findings and conjecture, together, may be taken to indicate that the normality of cycling in certain weather or seasons may also be a cause of cycling in that weather or season, rather than merely an effect of it, and that this normality is somehow flexible between contexts.

8.Discussion & Conclusion

8.1 Synthesis

This survey of the available literature on the relationships between cycling and weather has provided answers to several questions, but it has also prompted new ones. New questions, to be addressed by further research, can be identified through both synthetical discussion of available evidence as well as methodological discussion of existing studies. We will start with the former.

Available evidence makes a few things relatively clear. It is evident, for example, that precipitation categorically induces a decreased rate of cycling on a given day and, in each place, doing so at the first hint of it and having a lessened effect for further precipitation thereafter. It is also apparent that winds may only become significantly negative for the general cyclist when they are aptly strong (above 5bft). There is further evidence to support yet another intuitive relationship - that a comfortable range of temperatures exist above or below which some segment of the population begins to prefer other modes, perhaps believing it too hot or cold to cycle. The basic nature of these relationships between measurable weather parameters and cycling behaviour is clear and relatively consistent. Complicating the matter, it is also clear that the intensity and detail of them crucially vary between study locations, and that this is at least partly because they are mediated by the numerous covariates identified in this essay. Some covariates are more easily grasped than others; that a denser, sheltered urban form and smaller trip length will reduce the perceived severity of weather for a cyclist is, perhaps, obvious. What is not so obvious is precisely how or why a given sociodemographic segment reacts and behaves differently with respect to weather and cycling, or why the magnitude and direction of the relationships can vary between locations. Nor is it obvious how these segments, their built environment, their existing work/leisure habits, and their broader cultural context interact to sustain a general sense of normality or abnormality towards certain weather/cycling practices. The entanglement of these covariates will be explored to identify gaps in the existing literature and outline the trajectory of this research area.

Which covariates seem related to each other? To start, it is difficult to separate trip purposes from frequency/regularity of cycling, and therefore also from personal experience with cycling. Evidence shows that in nearly all study locations commutes were much less sensitive to the weather than other trip types. Presumably, this is because such trips are on a strict schedule and are likely not optional - if there is no alternative mode immediately available, I must cycle to work regardless of the weather. However, it is also true that if a person is on such a regular cycling schedule, they are bound to gain more experience than a person who only cycles for leisure (sometimes) on weekends. As such, the evidence regarding higher experience seems to be in some part interchangeable with the evidence regarding commutes; commuters may be less sensitive because they are more experienced, or those with more experience are less sensitive because they are often commuters. It is plausible that both are true to some extent. It is also plausible that the infamously difficult-to-observe phenomenon called "habit" is partly responsible. If an experienced commuter-cyclist happens to own a public-transport ticket - can access an alternative - that they may choose to cycle in the rain anyway is perhaps not entirely explained by a conventional understanding of "experience". A more precise characterization of the mechanism by which "experience" affects travel behaviour may be warranted. Referring to the previous example, perhaps the cyclist decides to continue cycling in the rain rather than switch modes because they are *comfortable* cycling. This comfort is likely related to knowing how to cycle in the rain effectively, but also with the idea that it is *uncomfortable* to break a habit they are used to practicing. Thus, investigation into relationships between trip purpose, experience, habit, and the contextual factors that shape them may prove productive.

Next, gender, age, and social identity can be related to cultural perceptions of normality. We have gathered evidence in this essay which suggests that cyclists' reactions to the weather can and do vary along sociodemographic lines. For example, female cyclists are often quicker to change their cycling behaviour with the weather and older cyclists are *sometimes* more sensitive than younger ones. Although it may be tempting to look at this evidence and attempt to explain it in terms of biological necessity, this should not be done without first reflecting on how society can affect the way a specific group of people regards themselves, others, and the built environment, or how their feelings may translate into complex behaviours. For example, authors have attempted to explain gender-related evidence enumerated in this essay in terms of women's' and men's relative physical fitness and risk/safety perceptions (Motoaki & Daziano, 2015; Hong et al., 2020; citing Emond et al., 2009). These explanations are plausible, and there is ample evidence to suggest they should be taken seriously. However, the notion that observed differences in physical fitness or risk perception are simply caused by a difference of physiology is highly suspicious; it is not because of mere biology that women exercise less than men, or that women have more reasons to feel unsafe cycling down the street to the store. These things are contributed to in part by the organization and perception of identities within society. This is at least more flexible than genetic endowment. By the same token, not even mentioning the conflicting evidence surrounding it, the mechanism by which age affects cycling behaviour and weather sensitivity should not be accepted as a self-evident matter of physical necessity. While it may be true that age increases the risk of developing physical disabilities, age *itself* need not be regarded as one. What a person thinks when they regard themselves as "old", and how they think "oldness" relates to transportation, are neither biologically caused nor random. As Hudde (2023) suggests, cycling in the

Netherlands is not apparently spoken or thought of as associated with a particular age group or gender, and it is perhaps for this reason that relatively more women and elderly people cycle there. This could also partially explain Dutch cyclists' distinctly low sensitivities to adverse weather - in the Netherlands, cycling is less conditional in general. All of this is to argue that the *meaning* of "woman" and "old" are contingent upon social systems in addition to physical ones, that these meanings may be flexible, and that they may affect cycling and weather sensitivity observations.

Finally, we can speculate about the relationship between infrastructure, the built environment, and normality. Infrastructure, as a specific and often identifiable component of the built environment, may palpably communicate to the population that cycling is a "normal" mode of transportation. This is perhaps related to and offset by the normality of car-transport communicated by nearby car infrastructure; even if cycling infrastructure is strong, I am unlikely to view it as a normal thing to use on rainy days if I am constantly comparing it to 3 lanes of car traffic nearby. So, while evidence shows that infrastructure can serve to increase cycling rates, its configuration may also serve to change perceptions about the role of cycling as a mode of transportation, solidify its status, and change the way cycling is practiced in different weather conditions.

In all, as speculated by Böcker et al. (2013) and Hudde (2023), culturally contingent perceptions surrounding weather, seasonality, cycling, and travelling may contribute to how cyclists tend to respond to weather. The way in which the built environment, sociodemographic identities, and trip purposes intersect to manifest behaviour and normality can be speculated upon as above, but it is not well accounted for by current evidence.

8.2 Gaps in the methodology

Beyond the gaps generated by the discussion above, we noticed a methodological pattern in many of these articles and in how they conducted their research. This pattern creates gaps of its own. Many of the articles used objective measurements, like the observed exact temperature at a specific location or the exact amount of precipitation at a given time, to try and explain some subjective human behaviours, even if these behaviours were observable in a way. This has led us to think about the methodology of using objective indicators to explain subjective behaviours. As we know, humans don't always behave in an expected or rational way, so we believe that studying the effects of weather from a subjective perspective might be an important opportunity to uncover effects that were not clear before. One such example could be the effect of forecasts on people's behaviour. We know that many times what is forecasted is not really what ends up happening. So, by taking the observable measurements to explain people's behaviour, might be misguided if the people had different information before starting their trips or before making their decisions as to which modes they will use.

Another related issue is the study of individual weather parameters. Many of the studies we reviewed were focused on the effect of single parameters on their own. While this might be important to understand the effects of each individual factor, we saw that there is a gap in studying many of these factors together. None of these phenomena occur on their own or in isolation. They always co-occur with other factors, and they all together make up the weather experienced by people. Even though there was mention of this in some of the studies we reviewed, we found that it hasn't been researched in detail. For example Böcker et al (2013) mention the researched effects of wind, and how one study showed that wind combined with specific temperatures can be perceived either as good or as bad, depending on the temperature. We would like to see further research on similar topics on the effects of weather factors combined.

We were also interested in finding how media representations affect attitudes towards cycling in different weather conditions and in turn behaviours. This is another gap we identified, even though it's slightly different than the direct or indirect effects of weather on cycling. But we do believe that the media and other cultural institutions have the power to influence perceptions.

For example Hudde (2023) mentions that in Germany there is a term, "Fahrradsaison", which means "cycling season" and it is portrayed in different media, government communications, and so on. But the existence of a cycling season, subconsciously denotes the existence of a season that is not for cycling. Another example is looking up cycling images on Google. Depending on the country you're in, you may get very different results. In the Netherlands you may get more images with average people cycling in the city, whereas in the UK you may get more images with professional or competitive cyclists. All these nuances have a subconscious effect on the development of a cycling culture and the attitudes and perceptions surrounding it.

A gap we identified that is related to how data is grouped and categorized, is regarding the grouping of different forms of precipitation. We noticed that many times this is researched under the general term of "precipitation", which usually includes rain and snow, when these types are very different from each other, and when not all snow is the same. The findings of Motoaki & Daziano (2015) highlight why this is important: "less-skilled cyclists consider rain to be 2.5 times more bothersome than more-skilled cyclists, and snow to be 4 times more bothersome". Perhaps it would be useful to start separating the forms of precipitation, and even the types of snow as well. This would provide researchers a much clearer picture as to how each of these types of precipitation impacts human behaviour.

Finally, an obvious gap we have identified and already mentioned before, is the location of the studies done so far. Most research studies are overwhelmingly based in North-Western Europe, North America, and Australia. These places cover but a small sample of the different climates and weather conditions on this planet. So we hope that in the future we can get a richer diversity of locations when studying the effects of weather on cycling or transportation in general.

8.3 The way forward & policy recommendations

Based on our findings and the gaps we identified, we believe that there is room to grow and develop the field of weather research on cycling and transportation behaviours. Having studied some of the effects of weather on cycling and how it influences behaviours and habits, we have come to understand and recognize some solutions to certain weather-related problems associated with cycling. Some policy recommendations we have identified and would like to see implemented include:

- *Trees for hotter climates*

  Planting trees and creating tree canopies above cycling paths is a great way to provide natural shading and cover for cyclists, especially in hotter climates where hot temperatures and scorching sunlight can discourage people from cycling. Obviously this does not only help to improve cycling rates, but it has an overall positive effect in the environment of the city and the aesthetics as well.
- *Safe cycling infrastructure*

  As we've seen from Hudde (2023), safe cycling infrastructure is the main way we can encourage more cycling and help everyone regardless of skills or background to get on a bike and travel around. This does not only include separate cycle paths, but it requires a holistic approach in terms of land use and transportation policy, where walking and cycling are placed as top priorities. Hong et al (2020) also provide recommendations in the direction of facilities at work like bike parking and showers. Or increasing the safety with regulations, speed limits and so on, can have a great impact on groups who are more affected by the perceived safety like women. In their words: "Interestingly, we can see that safe cycle paths are more sensitive to the seasonality effects. This implies that less-skilled people or casual cyclists use these paths more when weather is better."

- *Urban density*
  We have also recognized density as an important factor that may contribute to more cycling rates, as distances become shorter and therefore people need to be exposed to the elements for a shorter amount of time when cycling. This goes back to the 15- minute-city concept as well.
- *Employer support*
  Employers can utilize schemes or other incentives to encourage their employees to cycle to work. They can achieve this by providing bike parking and other facilities on site, and utilizing discount schemes for bikeshare systems or for purchasing bikes.

9. References

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