

The effects of weather and climate change on cycling in northern Norway

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Weather is identified as one of many factors that influence the demand for cycling. Weather patterns will change due to expected climate change. The aim of this article is to study the extent to which climate change influences the cycling frequency. The analysis in this article is conducted using an econometric model based on data spanning over four years on weather indicators and the cycling frequency in the Norwegian city of Bodø, which is located north of the Arctic Circle. According to the projections for climate change, both temperature and quantity of precipitation are expected to increase in this area during the next century. An important consequence of changes in the climate in the studied region is the reduced duration of what can be characterised as the winter season. However, this consequence is highly uncertain. When using Norway's middle projections for climate change by 2050, the analysis shows a moderate increase in cycling frequency of 6.2%. For the reduced winter period, the cycle rate might be two and three times higher in 2050 compared to the current level. Both estimates assume that every other potential impact on cycling rates remain equal.

Keywords: bicycle use, climate change, precipitation, temperature, weather indicators, wind speed.

1. Introduction

This article investigates the influence of climate change on cycling. Koetse and Rietveld (2009) conclude in their review of empirical findings on the effects of climate change on transportation that 'to date, the consequences of climate change and weather for the transport sector have received relatively little attention'. Moreover, Heinen et al. (2010) remark in their review on bicycle commuting that notably little research has been undertaken into the impact of climate on cycling. In this article, we aim to fill this scientific gap by estimating the future impact of climate change on cycling using an econometric model for an area (northern Norway) where climate change can significantly influence the future variance in day-to-day weather compared with the current variance. According to the Norwegian Public Roads Administration (2009a), the modal share for cycle in this region reaches 4% at maximum during the summer months.

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Weather has been identified as a factor influencing peoples' decision to cycle (e.g., Pucher et al., 1999). In a survey of 1,402 current and potential cyclists in Metro Vancouver, 73 motivators and deterrents for cycling were evaluated (Winters et al. 2011). The findings show that weather was one of the factors that had the most influence on the likelihood of cycling, along with factors such as safety, ease of cycling, route conditions and interactions with motor vehicles. Precipitation (e.g., rain and snow), (strong) wind and temperature (cold or too hot) are often mentioned in empirical studies from all over the world as the weather types that negatively influence bicycle use (e.g. Emmerson et al. 1998; Flynn et al. 2012; Goetzke and Rave 2011; Hunt and Abraham 2007; Richardson 2000; Rietveld and Daniel 2004; Sabir 2011; Winters et al. 2007). Bergström and Magnusson (2003) find a large decrease in the number of bicycle trips and a large increase in car use for commuting purposes during winter in Sweden. Evidence suggests, however, that recreational cycling is more affected by bad weather than utilitarian cycling such as for commuting purposes (Bergström and Magnusson 2003; Brandenburg et al. 2004; Heinen et al. 2010; Richardson 2000; Thomas et al. 2013). Brandenburg et al. (2007) demonstrate the importance of the perception of the weather on the decision to cycle. They find that a relationship exists between weather conditions and cycling for both recreational and commuting purposes. The frequency of use of recreational areas, however, does not depend solely on current meteorological variables such as air temperature and precipitation. They find that the perception of the weather and experiences from the last six days also influence the use of recreational areas. Gebhart and Noland (2014) show that cold temperatures, rain, and high humidity levels reduce both the likelihood of using bikeshare and the duration of trips in Washington DC. An interesting report related to our article is a Norwegian study on the impacts of climate change on travel habits (Aaheim and Hauge 2005). As far as we know, it is the only study that aims to assess the impact of a climate change scenario on travel choices. The authors conclude that for Norway, the scenario leads to an increase in cycling. The total impacts are small, but the authors note that they may be significant in certain places. An important drawback of this study is that the interviews that are the basis for the observations used to estimate the travel choice model are from only 2.5 months.

The aim of this article is to study how the expected changes in climate will influence cycling frequency by altering the weather conditions for riders. The empirical data relate to the city of Bodø located in the northern part of Norway where climate change is expected to be particularly prominent during the next century. In contrast to Aaheim and Hauge (2005), the econometric model used to estimate the climate change impacts on cycling is based on observations over a time period of approximately four years and on reports of actual, rather than intended, travel behaviour. The results presented in this article add to the knowledge base in two ways. First, the article demonstrates how different dimensions of weather influence the demand for bicycle trips. Second, it shows the influence on cycling of expected climatic changes for a region where the climate might change to a relatively great extent. In their climate change assessment report, the Intergovernmental Panel on Climate Change (IPCC 2007) concludes that future warming will be greatest over land and at the highest northern latitudes. Consequently, the results derived in this region cannot uncritically be generalized to other parts of the world.

The structure of the article is as follows: Section 2 introduces the model used to explain the relationship between the cycling frequency and weather conditions. Section 3 presents the model's results using empirical data from northern Norway. Section 4 provides a brief review of three expected climate change scenarios for northern Norway. Section 5 relates these climate scenarios with the model's results to assess future cycling demand. Finally, Section 6 provides conclusions and some implications.

2. The model

We aim to identify by econometric analysis how weather, along with other variables, relates to the variation in cycling frequency. Consequently, the dependent variable is the cycle rate calculated as the number of cyclists per 1000 inhabitants per day. In the chosen model, weather is operationalised by the variables temperature (*temp*), precipitation (*rain*) and wind speed (*wind*).⁴ According to Thomas et al. (2013), these variables are among the most important weather parameters to explain fluctuations in cycling demand. Furthermore, it is assumed in the model that the demand for cycling trips is positively related to working days and negatively related to the winter season. Further explanations of the operationalization and transformation of the variables are given later in the section when the model is presented. Finally, earlier studies have noted that many of the same people ride bicycles each day. This means that the number of cyclists at time t depends on the number of cyclists at time $t-1$. Hence, error terms are correlated in time and to correct for such autoregressive serial-correlation, a Prais-Winstone correction is applied. See Wooldridge (2006) for details on correcting for serial correlation by the use of Feasible GLS estimation.

One of the most important aspects of the chosen model specification in equation (1) is that it reflects how cyclists respond to change in weather indicators in practice. Commonly applied models using log-transformations of the explanatory variables cannot be applied due to the nature of the variable rain which frequently has the value 0. Consequently, an exponential specification is applied using logarithmic transformation to estimate the parameters by multivariate OLS-regression. This relatively simple specification follows the principle of parsimony (e.g. Coelli et al. 2005) and has the advantage of handling zero values in the independent variables.

$$cycle_t = e^{\beta_0 + \beta_1 temp_t + \beta_2 wind_t + \beta_3 rain_t + \beta_4 workday_t + \beta_5 season_t + \epsilon_t} \quad (1)$$

For the weather variables *temp*, *wind* and *rain*, it is not reasonable to assume a linear relationship on the cycling rate (e.g. Böcker et al. 2013). This is considered in equation (1) by the exponential specification of the variables. Both wind speed and precipitation are assumed to negatively influence the dependent variable. It is therefore reasonable that $\beta_2, \beta_3 < 0$ which gives negative first-order derivatives ($\partial cycle / \partial wind, \partial cycle / \partial rain < 0$). Since parameters β_2 and β_3 are negative and observed values of wind speed and precipitation are non-negative, the effects of precipitation and wind speed on cycle rate will be represented by a falling curve. All second order derivatives with respect to the weather variables are positive. Consequently, the specification considers that the impact of changes in wind speed and precipitation on cycle rate is highest for low values and as the weather becomes rougher, the negative effect increases less than proportionally. This is reasonable since most people have already chosen other alternatives. If the coefficient is positive, which is the case for *temp*, then both the first and second order derivatives are positive. This is a reasonable relationship considering that temperature in the studied region rarely becomes uncomfortably high (see Table 1).

In (1), the dependent variable, *cycle*, is a relative measure indicating the daily number of cyclists per 1000 inhabitants in the municipality in the specific transport corridor (see section 3 below) at time t . The variable *temp* is measured in degrees Celsius. *Rain* is measured in millimetres of rain

⁴ There could be other weather indicators such as amount of sunshine, cloudiness, snow depth and humidity. The present analysis includes temperature, wind speed and precipitation as relevant weather indicators. This choice is motivated by three reasons. First, some indicators, such as humidity, are rarely presented in weather forecasts and previous studies have argued that humidity is of less relevance to the decision whether to use a bicycle (Sabir 2011). Second, some variables such as amount of sunshine were not available at this measuring point. Finally, some weather variables tend to explain the same type of variation in the cycle rate and a further specification of the model involves higher multicorrelation accompanied by marginal improvements in explanatory power of the model.

(snow in the winter). *Wind* is measured by meters per second.⁵ The dependent variable and independent variables *temp*, *wind*, and *rain* are continuous. The error term ε_t is expected to fulfil the traditional requirements of time series regression analysis.

Further, the variables *workday*, and *season* are dichotomous. The variable *workday* holds the value 1 for Mondays through Fridays with the exception of public holidays. The variable *season* holds the value 1 for observations from October to March when there is a risk of finding snow and ice on the ground in the studied region. Hence, an observation relating to an ordinary workday in the winter season will have the value 1 on both variables.

In equation (1), it is assumed that parameters β_0, β_1 and β_4 are positive and β_2, β_3 and β_5 are negative. These a-priori assumptions on the coefficients imply a positive (negative) effect of *temp* (*wind* and *rain*) on cycling rate. Moreover, the variables interact with each other and the impact of one variable depends on the value of the other variables. The cross derivative with respect to *temp* and *wind* is negative, $\frac{\partial^2 cycle_t}{\partial temp_t \partial wind_t} < 0$, which implies that higher wind speed would reduce the positive impact of temperature on cycling rate. The reasoning is similar for the relationship between *temp* and *rain*. Furthermore, the cross derivative with respect to *wind* and *rain* is positive, $\frac{\partial^2 cycle_t}{\partial wind_t \partial rain_t} > 0$, meaning that more precipitation reduces the negative impact imposed by wind speed on cycle rate. Also, the expected negative coefficient for *season* makes it possible for *workday* to impose less influence on the cycle rate in the winter season. The elasticity, $EL_{cycle_t temp_t} = \beta_1 temp_t$, increases with the value of $temp_t$. The interpretation is opposite for the elasticity with respect to wind speed and precipitation.

3. Empirical data and results

3.1 The data set

The empirical data on weather indicators and the number of cyclists relates to the city of Bodø, which is located in the northern part of Norway. Due to its location at the tip of a peninsula facing the Atlantic Ocean north of 67 degrees latitude, the climate is relatively harsh. The settlement is primarily located on the southern side of the peninsula and is oriented on an east-west axis. The main transport corridor, including bicycle lanes, follows the settlement along the east-west axis. The road and cycle infrastructure has been unchanged in the studied time period. Figure 1 show the main road, Rv80, and the location of the electronic bicycle counter.

For illustrative purposes, the distribution of cyclists throughout a random week in the spring of 2011 (9-15th May) is presented in Figure 2. According to the variation in cycle frequency throughout the day it is reasonable to expect that commuters dominate on this cycle route in the morning and afternoon. The counter is located east of the city centre and the number of business trips is low. Alternative routes with lower standard are located north of the main road and pass through residential areas and recreation areas. These routes facilitate lower average speed and are used for shorter leisure trips.

⁵ The weather variables indicate the weather on the same day the trip is made. According to the psychological effects identified by Brandenburg et al. (2007), it could be relevant to introduce lagged weather variables but this is not done for two reasons. First, the wide availability of weather forecasts with relatively high predictability for the next day makes it possible for cyclists to adapt to the weather. Second, the lagged variables do not explain additional variation when running the model.



Figure 1. Location of the electronic bicycle counter.

The empirical data relies on three sources that were made available in relation to a project assessing the welfare effects of constructing a protective shelter for cyclists along parts of the main transport corridor⁶. First, weather observations are obtained from the weather station at Bodø airport operated by The Norwegian Meteorological Institute (2014).⁷ Observations of temperature, wind speed and precipitation are obtained on a daily basis. The Norwegian Meteorological Institute has different approaches for measuring each of the weather variables. Temperature is averaged from measures in the beginning of each hour between 18:00 the previous day and 18:00 the day of report (UTC time). Wind speed is averaged from 10 minutes middle values measured at 00, 06, 12 and 18 hours. Precipitation is reported as the total amount of precipitation between 07:00 the previous day and 07:00 the day of report. Hence, in the subsequent analysis the value of precipitation at day t applies the observation reported for day $t-1$. Second, the population for the municipality of Bodø is reported by Statistics Norway (2014) as of 1 January each year. The population is used to calculate the cycling rate per 1000 inhabitants. Finally, the number of bicycles is registered by an electronic counter managed by the Norwegian Public Roads Administration (NPRA). Counts are made by an inductive loop placed in the asphalt of the cycle path and can be regarded as objective and reliable information. According to the directions of NPRA this method has weaknesses in case of very low speed (e.g. heavy queuing) or if loops are located too deep, in both cases the reported counts can be too low (Norwegian Public Roads administration, 2009b). However, these problems have not occurred at the counter which has been used to generate the data for the present analysis. Trips are counted continuously and reported hourly for trips heading both to and from the city centre. Figures are aggregated to a daily basis to match the characteristics of the meteorological data.

⁶ The protective shelter (cycle tube) is accounted for by Jensen and Risan (2007). The expected costs exceed the estimated benefits, and the project is unlikely to be realised.

⁷ This refers to station no. 82290 located at Lat. 67.2672, Lon. 14.3588. The extracted weather variables for the time period in question are coded by the Norwegian Meteorological Institute as FFM (*wind*), RR (*rain*) and TAM (*temp*). The publicly available database is operated by the Norwegian Meteorological Institute (2014).

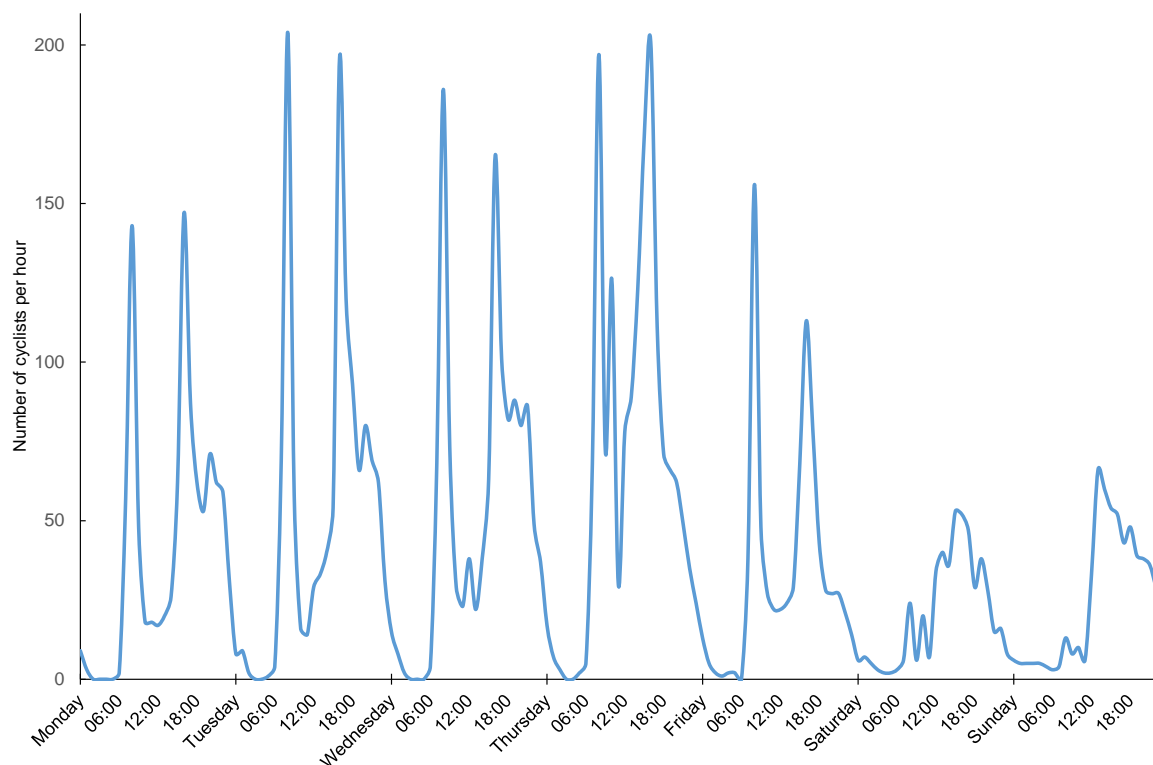


Figure 2. Variation in cycle intensity in a typical week in the spring of 2011 (9-15th May).

The period of registration lasted approximately 4 years from 18 October 2007 to 25 October 2011, producing 1,469 observations. The variables *cycle*, *temp*, *wind* and *rain* had a number of missing values producing a total of 103 incomplete observations. There was no apparent pattern for the missing observations, and they are therefore not subject to any remedies in the analysis. In total, the daily registrations gave 1,366 complete observations to be analysed. Table 1 presents descriptive statistics for the untransformed variables in the data set.

Table 1. Descriptive statistics (1,366 observations)

Variable	Mean	Std. dev.	Min.	Max.	Median
Cycle rate (trips/1000 inh.)	7.1	6.1	0.04	33.4	5.3
<i>temp</i> (°C)	5.4	6.3	-14	22.3	5.4
<i>wind</i> (m/s)	6.5	2.9	1.3	17.4	6.1
<i>rain</i> (mm)	2.9	5.3	0	48.5	0.5
<i>workday</i> (1 = yes)	0.67	0.47	0	1	1
<i>season</i> (1 = winter)	0.50	0.50	0	1	0

The dependent variable is a relative measure of the number of cyclists relative to the total population. Population has a slightly increasing trend which is expected to give an increasing absolute value of the number of cyclists. However, how cycle rate is influenced by population growth is uncertain. The independent variables *temp*, *wind* and *rain* vary throughout the year in naturally reoccurring patterns.

3.2 Model results

The results using the data presented in Section 3.1 for the specification in (1) are presented in Table 2.⁸ The model produce an R^2 of 0.68 and the F-test indicates good model fit. All variables are significant at the 1% level and have signs in accordance with the a-priori assumptions. An average Variation Inflation Factor (VIF) of 1.6 indicates that multi-correlation is acceptable. The residuals have expected values close to 0 but deviates from normality by high kurtosis. A further study of the residuals indicates that the model predicts more correctly the cycle rates in the summer compared to the winter season when cycle intensity is low. The large sample size ensures that the results are consistent according to the central limit theorem. Due to the presence of serial correlation indicated by the data examination in Section 3.1, the model is estimated using the Prais-Winsten correction, which produces a Durbin Watson statistic of 2.08 and a rho-value of 0.65. This indicates that problems with auto-correlation have effectively been resolved.

Table 2. Estimation results using the Prais-Winsten correction for serial correlation

Variable	Coefficient	Std.err.	t-value
Constant	1.3908	0.0643	21.6
<i>temp</i>	0.0534	0.0044	12.0
<i>wind</i>	-0.0539	0.0046	-11.6
<i>rain</i>	-0.0145	0.0020	-7.5
<i>workday</i>	0.9519	0.0227	41.8
<i>season</i>	-0.9794	0.0682	-14.4

The direct effect of an increase in *temp* (*wind* and *rain*) is a greater (reduced) cycling rate. In line with the a-priori assumptions of the coefficients presented in Section 2, the direct effects of both *wind* and *rain* are negative.

The demand elasticity with respect to the weather indicators (see footnote 3) can be calculated using the average values in Table 1 and the estimated coefficients in Table 2. The elasticity of cycle rate with respect to temperature, wind speed and precipitation are 0.29, -0.35 and -0.04 , respectively. Hence, for marginal changes from average values wind speed has greatest impact on cycling rate followed by temperature, while rain has the lowest impact. It must be emphasised that these elasticity values relate to deviations from the mean value. Hence, they represent the response to changes in weather indicators when the temperature is a few degrees above the freezing point and some amount of wind and precipitation are present.

Table 3. Cycle rate sensitivity for deviations from average values in weather indicators.

Variable	Low (-1 standard deviation)		High (+1 standard deviation)	
	Cycle rate	Deviation	Cycle rate	Deviation
<i>temp</i>	3.00	-1.20	5.88	1.68
<i>wind</i>	4.91	0.71	3.59	-0.61
<i>rain</i>	4.38	0.18	3.89	-0.31

Using the year-round mean values presented in Table 1 for all variables in combination with estimated coefficients in Table 2, the predicted cyclist rate is 4.2 trips per 1000 inhabitants. The

⁸ A logarithmic transformation was applied to make the OLS regression. Hence, the coefficients were obtained by the function $\ln[cycle_t] = \beta_0 + \beta_1 temp_t + \beta_2 wind_t + \beta_3 rain_t + \beta_4 workday_t + \beta_5 season_t$.

sensitivity of cycle rate for ± 1 standard deviation in the three weather indicators is illustrated in Table 3 when holding all other variables at the average values. It can be concluded that a reduction (increase) in temperature by 1 standard deviation reduces (increases) the cycle rate by 1.20 (1.68). The effect is smallest for changes in rain where the low case represents zero precipitation. Consequently, the sensitivity analysis presented in Table 3 supports the ranking of elasticity values.

The control variables *workday* and *season* have signs in accordance with the a-priori assumptions ($\beta_4 > 0, \beta_5 < 0$). Hence, the positive effect of workdays is reduced in the winter season compared to the summer season. These control variables are generally highly significant, and the magnitude is considerable. Compared to the average value of 4.2 the cycle rate increases by 37% at workdays and by 63% in the summer. The impacts of these variables are further elaborated on in Table 4.

4. Data on weather impacts due to climate change

To assess the impact of climate change on cycling in Bodø using the econometric model presented in Section 2, we require weather projections for the region. We have chosen the year 2050 as the future year to illustrate possible changes in cycling rates.

For potential future weather changes, we use an official report by the Norwegian government on climate change and the policies required to manage its challenges (NOU 10 2010). This report includes projections for weather indicators such as temperature, precipitation and wind speed for each decade until 2100, using the period from 1961-1990 as a reference. The projections are related to a background report initiated by the government (Hanssen-Bauer et al. 2009).⁹ Despite a high degree of uncertainty, the estimates are the best documented climate projections available for Norway and have been used for example in studies for the development of the summer tourist season in northern Norway (Førland et al. 2013). For the relevant region of Norway, the expected changes in temperature and rain by 2050 for the low, middle and high scenarios are presented in Table 4. Our data set ranges from 2008 to 2011 and is thereby assumed to represent the decade including 2010.

Table 4. Expected change in year average values for weather indicators in the Bodø region by 2050 compared to 2010

Variable	Low	Middle	High
<i>temp</i>	0.8°C	1.2°C	1.7°C
<i>rain</i>	1.6%	6.8%	15.6%

In Norway, it will be warmer in all parts of the country for all four seasons in 2050. In the middle scenario, the expected change in temperature for the region where Bodø is located is 0.31°C each decade. According to the middle scenario, this amounts to an increase by 2050 of approximately 1.9°C and 1.2°C relative to 1990 and 2010, respectively. There will be an increased number of days with large amounts of precipitation and higher than average precipitation in all regions of Norway in all seasons. For the middle scenario, the expected changes in precipitation for the region where Bodø is located are approximately +1.7% each decade. This represents an increase of 10.4% and 6.8% by 2050 relative to 1990 and 2010, respectively.

⁹ The team that produced the report included researchers from The Norwegian Meteorological Institute, the Norwegian Water Resources and Energy Directorate, The Bjerknæs Centre for Climate Research, The Nansen Environmental and Remote Sensing Center and the Institute of Marine Research.

The climate models show little or no evidence of changes in average wind speed in Norway toward 2100. However, there are indications that high wind speeds will occur more frequently because of a possible shift northwards of storm lanes and polar low pressure areas. Nevertheless, we assume no changes in the average wind speeds in the Bodø region by 2050 compared with the current situation. Changes in the probability for icing cannot be derived from the current models. However, the snow season will be shorter in the whole country toward the end of the century. The change will be most prominent at low altitudes, where the middle scenario suggests that the snow season could be reduced by 2-3 months. Hence, regions that currently have snow for 2-3 months can be expected to have no snow at the end of the century (NOU 10 2010). Bodø is located in the lower regions, and for illustrative purposes, we assume in the following analysis that the snow season will be reduced by 2 months by 2050. Also, it is expected in the climate models that situations characterised as extreme weather will occur more frequently.

5. Climatic change and cycle rate

In this section, we present the predicted changes in the cycle rate for 2050 in two parts. The aim of this section is to relate the climatic changes described in section 4 to the impact of weather indicators on cycle rate derived in section 3. The first part gives estimates when we do not account for changes in the duration of the seasons and extreme weather changes, while in the second and third part we do account for these possible changes. We carry out this two-part presentation because the change in season durations and the extreme weather are highly uncertain. In our view, by presenting our estimates in two parts, we communicate this high level of uncertainty more clearly. Note that the climate change projections do not view changes in the season durations as highly uncertain; the projections emphasise uncertainty about the length of these changes.

5.1 Part 1 - Not accounting for changes in season duration

Using the year-round mean values presented in Table 1 for all variables, the predicted cyclist rate is 4.2 trips per 1000 inhabitants. The predicted cycle rate for different scenarios is given in Table 5 and separated according to the type of day and the season. The projected cycle frequency by 2050 ranges from 4.4 to 4.6, depending on the climate scenario, and is derived by the use of input variables from Table 4. Hence, in the middle scenario, the effect of changes in the weather variables accounts for a 6.2% increase in the annual average daily cycle rate.

Table 5. Daily cycle rate predicted by the model

Type of day	Season	Current	2050 climate projection		
			Low	Middle	High
Work	Summer	9.4	9.8	10.0	10.2
Work	Winter	3.5	3.7	3.7	3.8
Non-work	Summer	3.6	3.8	3.8	3.9
Non-work	Winter	1.4	1.4	1.4	1.5
Cycle rate using annual average values		4.2	4.4	4.5	4.6

A considerable portion of the projected increase in cycling toward 2050 is due to expected population growth (Statistics Norway 2014).¹⁰ If the cycle rate is converted to the number of

¹⁰ Statistics Norway (2014) projects population only until 2040 on the municipality level. The projection takes into account growth for the whole country, aging and immigration. According to the middle growth scenario

cyclists, this “volume factor” alone increases the daily number of cyclists through this transport corridor by approximately 70. The extra increase in daily cyclists that can be related to changes in climate is 9, 13 and 18 for the low, middle and high climate scenarios, respectively.

5.2 Part 2 - Changes in season duration

What is considered an extreme event is relative and strongly depends on context (Stephenson 2008). The concept of “extremeness” has several dimensions like, for example, the rate of occurrence, magnitude/intensity, and temporal duration and timing. An important consequence of changes in the climate is the reduced duration of what can be characterised as the winter season in the studied region. The recently published climate strategy plan from the municipality of Bodø, expects the growth season (defined by days with higher than 5 degrees Celsius) to increase with 30 to 40 days by the year 2050 (Municipality of Bodø, 2014). Naturally, there will be an even greater increase in the number of days with less than 5 degrees but still not freezing. As mentioned previously, these are highly uncertain projections, but we can use our model to look at the possible consequences. Currently, snow and ice can be expected on the ground over a 6-month period starting in mid-October and lasting until April.¹¹ The climate projections suggest roughly that the winter season will be reduced to approximately 4 months. Our model results indicate that by 2050 the cycle rate will increase for these two months from 3.7 to 10.0 for workdays and from 1.4 to 3.8 for holidays, respectively.

6. Conclusions and implications

Our main conclusion is that expected changes in the climate will have some impact on the cycling frequency in the city of Bodø by altering the weather conditions for riders. The climate effects are most likely too low to have any short-term effects on the behaviour of cyclists. However, our study indicates that by 2050 climate change might cause an increase in the use of bicycles. Using the middle scenario for climate changes, weather indicators such as temperature, wind speed and precipitation account for a total increase in cycling frequency of about 6.2% by 2050 assuming that all other things (e.g., policies, peoples tastes, prices for other transport modes) remain equal. The influence is higher for workdays compared with non-workdays. The change in the cycle rate due to climate change is considerably higher if it is assumed that, as suggested by the climate change predictions, the winter season in 2050 will be two months shorter compared to current winters. For example, if these months could be regarded as non-winter, then the predicted cycling rate could be more than doubled in this period, again assuming *ceteris paribus*. Climate change projections for northern Norway suggest that winter’s duration will change, but the impact is highly uncertain.

Our study shows that by using empirical data from northern Norway ranging over four years, it can be estimated that the elasticity of demand for cycling trips with respect to average values for temperature, wind speed and precipitation are 0.29, -0.35 and -0.04, respectively. Climate change is expected to increase temperatures and the amount of precipitation, and the effects will be most prominent in the winter. The effects of increasing precipitation and temperature will partly counteract each other with respect to the demand for cycling trips. A weakness in the model is that very low cycle rates are not predicted properly. Hence, an extension of the current

provided the population will be 62071 in 2040. Continuing the trend for the period from 2035 to 2040 produces a population forecast of about 65300 in 2050.

¹¹ This assumption is supported by the fact that car drivers in northern Norway are allowed to use winter tires with spikes from 15 October to 1 May (The Norwegian Ministry of Transport and Communication 1990). An indication that the duration of winter is changing is the proposed change in the law to reduce the period when spiked tires are allowed.

analysis would be to adjust the estimates according to the error terms to improve the estimates with respect to seasonal effects.

In our view, the policy implications of this study are modest. Policy makers in the northern parts of Europe could take into account the effects of climate change on their future demand prognoses for cycling projects. Such demand prognoses are relevant, for example, when assessing the effectiveness and efficiency of cycling policies.¹² Still, the climate effects on cycling are not very large and will take place to some extent only in the long run. It is likely that the climate change effects on cycling volumes are even smaller for other regions of Europe where average temperatures are higher and cycling can take place year round, implying that in these other regions no cycling policy actions seem required based on our results. However, to generalise the results and to be more certain about the policy implications, it would be better to expand the analysis as performed in this study to other areas where climate change holds other characteristics. The prediction on future weather is uncertain, particularly for extreme weather. A more detailed analysis of the impact of different climate scenarios on cycling can be based on simulations of weather patterns. There could of course be other related climatic consequences that extend beyond changes in temperature, precipitation and wind speed that could influence cycling policy (e.g. rising sea level). However, such consequences are outside the scope of this article.

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References

- Aaheim, H.A. and Hauge, K.E. (2005). *Impacts of climate change on travel habits*. CICERO, Oslo, Norway.
- Bergström, A. and Magnusson, R. (2003). Potential of transferring car trips to bicycle during winter. *Transportation Research Part A*, 37(8), 649-666.
- Bodø municipality (2014). 'Forslag til kommunedelplan klima og energi. Bodø kommune 2014-2024', September 2014. In Norwegian.
- Brandenburg, C., Matzarakis, A. and Arnberger, A. (2004). The effects of weather on frequencies of use by commuting and recreation bicyclists. In Matzarakis A., de Freitas C.R. and Scott D. (eds) *Advances in Tourism Climatology*, Freiburg.
- Brandenburg, C., Matzarakis, A. and Arnberger, A. (2007). Weather and cycling - A first approach to the effects of weather conditions on cycling. *Meteorological Applications*, 14(1), 61-67.
- Böcker, L., Dijst, M, and Prillwitz, J. (2013). Impact of Everyday Weather on Individual Daily Travel Behaviours in Perspective: A Literature Review. *Transport Reviews*, 33(1), 71-91.
- Coelli, T., Prasada Rao, D.S., O'Donnell, C.J. and Battese, G.E. (2005). *An introduction to efficiency and productivity analysis*. (2nd ed.), Springer, NY.
- Emmerson, P., Ryley, T.J. and Davies, D.G. (1998). The impact of weather on cycle flows. *Traffic Engineering & Control*, 39(4), 238-243.
- Flynn, B.S., Dana, G.S., Sears, J. and Aultman-Hall, L. (2012). Weather factor impacts on commuting to work by bicycle. *Preventive Medicine*, 54(2), 122-124.

¹² An example relevant to this case is the construction of a protective "cycle tube" mentioned in section 3.1 with the purpose of reducing weather problems for cyclists (see Jensen and Risan 2007). The results of our model can be useful when predicting increased cycle use due to improved weather conditions.

Førland, E.J., Steen Jacobsen, J.K., Denstadli, J.M., Lohmann, M., Hanssen-Bauer, I., Hygen, H.O. and Tømmervik, H. (2013). Cool weather tourism under global warming: Comparing Arctic summer tourists' weather preferences with regional climate statistics and projections. *Tourism Management*. 36, 567-579.

Gebhart, K., and Noland, R.B. (2014). The impact of weather conditions on bikeshare trips in Washington, DC. *Transportation*, 41(6), 1205-1225.

Goetzke, F. and Rave, T. (2011). Bicycle use in Germany: Explaining differences between municipalities with social network effects. *Urban Studies*, 48(2), 427-437.

Hanssen-Bauer, I., Drange, H., Førland, E. J., Roald, L. A., Børsheim, K. Y., Hisdal, H., Lawrence, D., Nesje, A., Sandven, S., Sorteberg, A., Sundby, S., Vasskog, K. and Ådlandsvik, B. (2009). *Klima i Norge 2100. Bakgrunnsmateriale til NOU Klimatilpassing*. September 2009, Norsk klimasenter, Oslo. (In Norwegian).

Heinen, E., van Wee, B. and Maat, K. (2010). Commuting by bicycle: An overview of the literature. *Transport Reviews*, 30(1), 59-96.

Hensher, DA, Brewer, A (2001). *Transport: an economics and management perspective*. Oxford University Press, Oxford.

Hunt, J.D. and Abraham, J.E. (2007). Influences on bicycle use', *Transportation*. 34(4), 453-470.

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team]*. Pachauri, R.K. and Reisinger, A. (eds.). IPCC, Geneva.

Jensen, G. and Risan, T.C. (2007). Planning for "Bicycle tube". *Nordic Road and Transport Research*, 2, 23.

Koetse, M.J. and Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D*, 14(3), 205-221.

NOU 10 (2010). *Tilpassing til eit klima i endring. Samfunnet si sårbarheit og behov for tilpassing til konsekvensar av klimaendringane*. Servicesenteret for departemental Informasjonsforvaltning, Oslo (In Norwegian).

Pucher, J., Komanoff, C., Schimek, P. (1999). Bicycling renaissance in North America? Recent trends and alternative policies to promote bicycling. *Transportation Research Part A*, 33(7/8), 625-654.

Richardson, A.J. (2000). *Seasonal and Weather Impacts on Urban Cycling Trips*. The Urban Transport Institute, Victoria, Australia.

Rietveld, P. and Daniel, V. (2004). Determinants of bicycle use: Do municipal policies matter? *Transportation Research Part A*, 38(7), 531-550.

Sabir, M. (2011). *Weather and travel behaviour*. Research Series, Vrije Universiteit, Amsterdam.

Statistics Norway (2014). *Population*. http://www.ssb.no/english/subjects/02/befolkning_en/.

Stephenson, D.B. (2008). *Definition, diagnosis, and origin of extreme weather and climate events* (Vol. 348). Cambridge University Press, New York.

The Norwegian Meteorological Institute (2014). *eKlima*. Free access to weather- and climate data from Norwegian Meteorological Institute from historical data to real time observations. <http://eklima.met.no>.

The Norwegian Ministry of Transport and Communication (1990). FOR 1990-01-25 nr 92: Forskrift om bruk av kjoereto, §1-4, part 2 (In Norwegian).

The Norwegian Public Roads Administration (2009a). *Handlingsplan for gjennomgående sykkelvegnett i Bodø*. Report May 2009 (In Norwegian).

The Norwegian Public Roads Administration (2009b). *Veileder i trafikkdata*. Technology department (In Norwegian).

Thomas, T., Jaarsma, R. and Tutert, B. (2013). Exploring temporal fluctuations of daily cycling demand on Dutch cycle paths: The influence of weather on cycling. *Transportation*, 40(1), 1-22.

Winters, M., Davidson, G., Kao, D. and Teschke, K. (2011). Motivators and deterrents of bicycling: Comparing influences on decisions to ride. *Transportation*, 38(1), 153-168.

Winters, M., Friesen, M.C., Koehoorn, M. and Teschke, K. (2007). Utilitarian Bicycling. A Multilevel Analysis of Climate and Personal Influences. *American Journal of Preventive Medicine*, 32(1), 52-58.

Wooldridge, J.M. (2006). *Introductory econometrics: a modern approach*. (3rd ed.). Thomson South-Western, Mason, OH.