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Integrated weather effects on e-cycling in daily commuting: A longitudinal evaluation of weather effects on e-cycling in the Netherlands

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ABSTRACT

While in many regions the conventional bicycle has already been regarded as an environmentally friendly and healthy alternative to the car for daily commuting, societal and policy agendas are also increasingly promoting e-bike adoption. Adding to recent research on e-bike safety, satisfaction with travel and behavioral change, this paper reports on the impact of weather circumstances on the use of the e-bike in daily commuting in an e-cycling incentive program in the province of Noord-Brabant, the Netherlands. The impact of this incentive program was analyzed using a longitudinal design, and it combined travel patterns that were derived from individuals' GPS data over nine months, hourly observed meteorological data, and questionnaires on intended behavior and sociodemographic characteristics. The findings suggest that the presence of snow and ice, total precipitation, and high windspeed negatively affected the choice of commuting to work by e-bike, in this decreasing order of impact. Although the overall impact of air temperature on e-cycling was positive, the likeliness to commute by e-bike decreased at higher air temperatures. E-cycling under specific weather conditions was more likely if participants' intention to e-cycle under such weather conditions was stronger. Our study indicates that the benefits of the e-bike in daily commuting are underestimated in relation to adverse weather conditions. Respondents from households with one car only, therefore, have fewer alternatives in poor weather conditions: for these individuals, only total precipitation and the presence of relatively low air temperature impact e-cycling. In addition, reported gender and high wind speeds might have been expected to influence participation in e-cycling.

1. Introduction

Over the last decades, cycling has become increasingly regarded as an environmentally friendly alternative to car trips for short distances. With increasing concerns about the environmental impact of car traffic, health, and livability, many cities are showing increasing interest in promoting the use of the bicycle as a part of the total urban transportation system (Fishman and Cherry, 2016;

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Handy et al., 2014; Pucher and Buehler, 2012). Regardless of health and environmental benefits related to conventional cycling (c-bikes) for short trips, many travelers choose to use other forms of transportation. Particularly for commuting to work, extensive research has revealed that distance, the built and natural environment, socio-economic factors, psychological factors, and an individual's physical condition may prevent people from commuting using c-bikes (Heinen et al., 2010; Heinen and Handy, 2012; Vandenbulcke et al., 2009; Gatersleben and Appleton, 2007; (MacArthur et al., 2014). Next to these personal and context specific circumstances, bicycle ownership and/or the presence of bike-sharing schemes also influence bicycle use. Although differences in personal factors such as gender and age have not been shown to have a distinctive influence on the likeliness to use shared bicycles, time of day and day of the week, as well as trip purpose have been found to be significantly different across users (Noland et al., 2016; Zhao et al., 2015). With the introduction of the electric peddle supported bicycle (e-bike), new opportunities have occurred where range (distance) and physical effort become less of a barrier compared to the c-bike.

In recent years, the substitution effect of e-bikes has gained increasing attention in research (Fishman and Cherry, 2016). Although several studies provide insights into the adoption of the e-bike and the reduction in trips made by competing modes of transport, information on the specific factors influencing e-cycling is limited. In general, the modal shift to e-cycling is affected by the availability of alternative modes of transport in the specific local context (Kroesen, 2017), the presence of bicycle infrastructure, and the existing cycling levels within a given area (Haustein and Møller, 2016). The shift from c-bikes towards the use of e-bikes has been prominent over the last decade in the Netherlands and Denmark, where cycling has already been common practice for a longer time (Sun et al., 2020; Fishman and Cherry, 2016). In areas with less established cycling cultures, but where public transport is more dominant, notably in many Chinese cities, the recent shift to e-bike usage came at the cost of using public transport, particularly buses (Cherry et al., 2016; Cherry and Cervero, 2007; Kroesen, 2017). In car-dominant areas like many North American and Australian cities where cycling is often still considered to be a fringe activity, e-bikes are substituted more frequently for car travel (Johnson and Rose, 2013; MacArthur et al., 2014; Popovich et al., 2014).

Existing research in the Dutch context on the degree of e-bike substitution and initial mode of transport seems to be inconsistent (Lee et al., 2015; Kroesen, 2017; Plazier et al., 2017; de Kruijf et al., 2018; Sun et al., 2020) because of differences in the availability of, and experience with, alternative modes of transportation, the local context, and the possibility of participating in incentive programs. However, research has shown that the use of e-bikes is influenced by gender, physical condition, car ownership, and household composition, and it has a positive impact on travel satisfaction in daily commuting for short and mid-range distances (de Kruijf et al., 2018). Limitations in range (as a result of the slower speed) and physical effort as a constraint of c-bikes are decreased by the introduction of the e-bikes (de Kruijf et al., 2018; Sun et al., 2020). Many Dutch regions have become aware over the last decade of the technical benefits associated with the e-bike and have accordingly developed cycling policies which emphasize high quality, safe regional cycling routes catering to the mid-range (7.5 – 15 km) cycling trip distances, which is highly relevant for commuting. In addition, they initiate e-cycling incentive programs aimed to engage employers and employees to reduce mental and monetary barriers to e-bike adoption. These policies have contributed to the increasing popularity of the e-bike among all age groups, with 18% of all cycling trips being made by e-bike (KiM, 2018).

Other factors that influence the attractiveness of c-bike commuting are the weather and climatic conditions (Rodríguez and Joo, 2004; Heinen et al., 2010), and several studies have suggested that weather conditions and cycling are strongly and closely linked (Nankervis, 1999; Corcoran et al., 2014). Several studies have demonstrated the effects of daily weather and climatic conditions on a wide range of travel behavior, including transportation mode choice and trip generation (Sabir et al., 2010; Böcker et al., 2013; Creemers et al., 2015; Liu et al., 2015). Especially for active modes such as walking and cycling, inclement weather conditions have a negative impact (more than other modes of travel) because of the exposure to the elements (Nahal and Mitra, 2018). As might be expected, commuters have been shown to be less sensitive to weather changes, compared to non-commuters. For example, poor visibility and heavy rain impact the travel intention, travel time and number of trips for non-commute related travel (Liu et al., 2015). Existing studies of the effects of weather on cycling demonstrate the impact of observed weather conditions, such as wind, total precipitation, and air temperature on cycling. As expected, generally warm and sunny weather positively contributes to walking and cycling, whereas cold, wet, and windy weather conditions show the opposite effect (Nankervis, 1999; Bergström and Magnusson, 2003; Aaheim and Hauge, 2005; Gallop et al., 2011; Sabir et al., 2011; Flynn et al., 2012; Sears et al. 2012; Thomas et al., 2013). The effect of air temperature on cycling has been found to be non-linear in the sense that weather at low air temperatures and also at high air temperatures has a negative impact on cycling (Ahmed et al., 2012; Phung and Rose, 2007; Miranda-Moreno and Nosal, 2011; Lewin, 2011; Böcker et al., 2019). Rain does not only negatively impact cycling at the specific time of cycling, but also significantly affects cycling prior to adverse weather conditions indicating behavioral anticipation (Zhao et al., 2018; Zhao et al., 2019). Recent research on the combined effects of weather conditions on cycling in the Dutch, Danish, and Norwegian context show considerable regional differences with regard to the impact of weather on active travel (Böcker et al., 2019).

To date, research on the relationship between e-cycling and weather conditions is lacking, but it is necessary to gain insight about the commuting patterns by e-bike that are related to adverse weather conditions and to determine the potential of e-cycling as a sustainable mode of transport in transport planning. The effects of weather conditions on e-cycling likely differ from the effects on c-cycling for several reasons (Fishman and Cherry, 2016). First, use of e-bikes, generally results in shorter overall travel times due to the relatively higher speeds of e-bikes; because the duration of exposure to weather decreases, the effect of weather may be different for e-bike commuters. In most weather-cycling related studies, travel time has not been explored sufficiently, although it can be argued that the tolerance to adverse weather conditions is affected by the duration of the exposure (Böcker and Thorsson, 2014). Additionally, it can be questioned whether having access to a car and having a back-up plan to use the car under bad weather conditions will influence e-cycling as it does c-cycling.

In addition, the motor assisted peddle support feature that is associated with e-biking has a mediating effect on thermal (dis) comfort (e.g. Nikolopoulou and Steemers, 2003; Thorsson et al., 2004, 2007; Eliasson et al., 2007) and mechanical (dis)comfort (e.g. Oliveira and Andrade, 2007, see my dissertation for references), which are common effects of using a c-bike in high air temperatures (Heinen and Handy, 2012). Peddle support mediates the effect of weather on *perception of thermal comfort* (i.e. bodily assessment of the thermal conditions as a function of air temperature, solar radiation, relative humidity, wind speed, duration of exposure, clothing, intensity of physical activity, and bodily response in form of sweating), as it interferes with several of these elements. In addition to the possible effect of e-cycling at high air temperatures, less physical effort could negatively affect e-cycling at low air temperatures. The peddle support might further reduce the sensitivity to wind compared to the c-bike and the cycling distance might be expected to be less affected by the impact of total precipitation. Consequently, peddle support likely increases thermal comfort during hot weather (less physical activity intensity, more wind friction), and additionally reduces the discomfort of getting sweaty, reducing sensitivity to heat.

The present study is the first to systematically investigate the impact of weather conditions on expected and actual engagement in e-cycling. This investigation is based on daily commuting data over a period of 9 months, which was combined with meteorological data. The impacts of weather on e-cycling are particularly relevant for commuting because this trip type occurs throughout the year under varying weather conditions. Additionally, as a daily travel type, substituting car travel by e-bike plays an important role in making commuting more sustainable and healthier. Finally, the effects of travel behavior change intentions and car occupation are taken into account. It is likely that participants' expectations and intentions before the program will impact the extent of shifting toward e-bike use, where, according to the Extended Model of Goal-directed Behavior (EMGB) (Perugini and Conner, 2000), the addition of the desire originating from individuals' specific goals influences their behavior. Similarly, car access and having a back-up alternative might influence mode choice.

2. Methods

Although the Netherlands is known for cycling in daily travel, which amounts to a proportion of 28.5%, many people (48.6%) still take the car as driver or passenger to commute to work (KiM, 2018). From a sustainable mobility policy perspective, the introduction of the e-bike opens new opportunities to stimulate behavioral change of employees living a mid-range (5–15 km) distance from work (de Kruijf et al., 2018; Plazier et al., 2017). To incentivize the behavioral change from car-oriented commuting to e-cycling, the regional Noord-Brabant government developed a large-scale e-cycling incentive program (B-Riders) that targeted commuters who lived between 5 and 15 km from their work (Noord-Brabant, 2013). With approximately 1 million people (40% of all inhabitants of the region) living between 5 and 15 km from the major five cities (Eindhoven, Tilburg, 's-Hertogenbosch, Breda, and Helmond), the regional government invited people working in Noord-Brabant to participate in the e-cycling incentive program using regional newspapers and social media.

For this study, the behavior of participants in the e-cycling incentive program was monitored from January 2014 until mid-September 2014. A mixed methods approach was applied to this end using GPS data, which determined whether a commute took place and by what mode. Online surveys were conducted to assess intended e-cycling commuting behavior related to weather conditions.

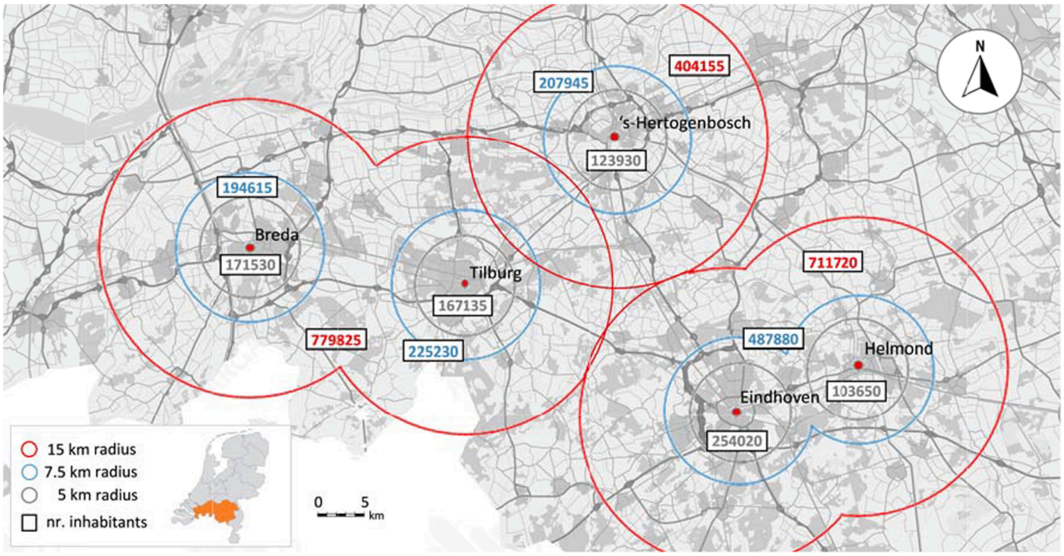

Fig. 1. Overview of the Province of North Brabant, with 5, 7.5 and 15 km radius for main five city centers.

2.1. Study design

The B-Riders incentive program was initiated in 2013, and specifically targeted commuters who travelled to work by car having a minimum of 50% of their working days per week. The participants had to meet three other recruitment conditions, as follows: (i) minimum commute distance of at least 3 km; (ii) 18 to 65 years old; and (iii) working in the province of North-Brabant, the Netherlands (Fig. 1). The region has a population of 2.5 million, with 1.9 million people living within a range of 15 km from the top five city centers.

To stimulate e-bike usage, participants were given financial compensation based on their overall e-bike participation. Because the B-Riders program was developed to reduce regional peak hour car-congestion, a differentiation between peak and off-peak was introduced with €0.15 per kilometer and €0.08 per kilometer, respectively. Participants received a maximum of €1,000 in financial incentives per person over 12 months. To make the program more appealing, participants could earn compensation for e-bike commuting and for e-cycling for other types of trips. The rough pre-study estimation made by the program was an average of 10 km of commute distance, and it would take approximately 1 year to reach the maximum financial compensation. With their explicit approval, the daily activity patterns and travel behavior of all participants were monitored 24/7 with a dedicated smartphone app provided by the program using the smartphones' GPS-sensor. In first 3 three months of the first edition of B-Riders program (which ran from September 2013 until September 2014), the tracking and monitoring technique was optimized. Because of the optimization of the data and the system as a whole, the data of the first three months is not used in this study. From January until September 2014 some participants actually reached the maximum financial incentive by e-cycling to work. The incentive program builds on previous projects in the Netherlands, in which participants received financial compensation upon changing their behavior in a more sustainable mode choice, such as the Spitsmijden (peak avoidance) project (Ben-Elia and Ettema, 2009).

2.2. Questionnaire

In addition to the GPS tracking, a questionnaire was administered via the internet to measure participants' intention to use e-bikes in specific weather conditions and to collect information about the sociodemographic characteristics of the study participants. According to the literature on the adaptation to e-cycling, related variables include personal and household characteristics, work-related circumstances, and spatial characteristics, which were suggested in cycling research (Fishman and Cherry, 2016; Heinen et al., 2010; Plazier et al., 2017; de Kruijf et al., 2018). To take path dependency into account in our analysis, we initially assumed that participants' habitual travel behavior before the incentive program influenced one's behavior in the program. Habit or past behavior have frequently been demonstrated to predict future behavior better than measures of intention and attitude (e.g. Bentler and Speckart, 1979; Verplanken et al., 1997; Verplanken and Aarts, 1999). We expected participants with conventional cycling commute behavior before the program to use the e-bike more frequently regardless of the weather conditions. Therefore, the same control variables are used as in recent studies.

Table 1
Sample composition of 573 participants.

Variable	Category	Total
Age	25–39 years old	12.22%
	40–49 years old	39.09%
	50–65 years old	48.69%
Gender	Male	46.42%
	Female	53.57%
Education level	Lower education | primary and secondary	12.91%
	Vocational education	34.73%
	Higher education | (applied) scientific	52.36%
Car ownership	1 car	51.51%
	2+ cars	48.49%
Net household income (in € per month)	<3000	44.71%
	3000 to <4000	35.20%
	>4000	20.08%
Household composition	Single	6.56%
	Single parent	3.66%
	Couple without children at home	33.93%
	Couple with children at home	55.85%
Urbanization level at home postal code	Highly urbanized	16.58%
	Moderate urbanized	22.51%
	Less urbanized	30.89%
	Not urbanized	30.02%
Cycle distance	0–5 km	3.66%
	5 < 10 km	20.24%
	10 < 15 km	32.11%
	15 < 20 km	27.40%
	20 + km	16.58%
Flexibility working hours	Yes	57.24%
	No	42.76%

The weather conditions were divided into air temperature (T_a), total precipitation, heavy wind (wind speed 5°Beaufort or higher), and snow/sleet. Participants were asked to report their intention to commute by e-bike to work under specific weather conditions on a seven-point Likert-scale ranging from very unlikely (1 = very unlikely) to very likely (7 = very likely). First, air temperature was divided into the following groups: very cold ($T_a < 0$ °C), cold (0 °C $\leq T_a < 10$ °C), mild (10 °C $\leq T_a < 20$ °C), warm (20 °C $\leq T_a < 30$ °C), and hot ($T_a \geq 30$ °C). Second, the total precipitation was categorized as follows: dry weather, light precipitation (short showers and drizzle), and heavy precipitation. Finally, participants' intention to e-bike in a heavy wind (above 5°Beaufort) and with presence of snow/sleet was documented. In addition, the questionnaire asked participants about their travel behavior during a regular week before starting to commute by e-bike and a set of questions about personal and household characteristics including gender, age, educational level, income, car ownership, household composition, and subjective health status. For each participant, the urbanization level was derived from the postal code of the home location. By adding the postal code of the work location using the GIS (Geographical Information System) fastest path analysis based on the Open Street Map cycling network, commuting e-bike distance was determined.

2.3. Sample demographic information

The study is based on responses from 573 participants. Table 1 specifies the composition of the total sample, including urbanization and the habitual cycling proportion before commuting by e-bike.

Table 1 shows that nearly half of the participants are between 50 and 65 years old and that most have a university or higher vocational degree. This is consistent with the publications that reported that the e-bike is especially popular in older cohorts and among higher educated segments (Fishman and Cherry, 2016; Johnson and Rose, 2013). >50% of the participants belonged to the category "couple with children living at home". Half of the sample (48%) owned at least two cars, and most participants (55%) were in the mid to high income categories (>3,000 euro/month). Additionally, 76% of the participants had a cycle-commute distance of>10 km, suggesting that the e-bike may be an important alternative to car-commuting, which also offers acceptable travel times for longer distances. Finally, 57% of the sample had flexible working hours.

2.4. Daily commute data

Using an integrated data imputation tool, Trace Annotator (Feng and Timmermans, 2014; Feng and Timmermans, 2019), all GPS data were segmented into journeys and stages (segments). The tool imputes, based on location of origin and destination, the specific travel purpose such as work, shopping groceries, social and recreational, for each journey based on location of facilities and information from self-reported data about facility locations. Next, the number of different modes of transport (stages) that were used during one relocation as well as the specific mode of transport per stage were determined. For this research that focused on daily commuting, GPS data was collected from January 2014 until mid-September 2014. A total of 242,179 journeys and 355,996 stages where recorded, and of these 71,772 journeys made by 573 participants from home to work were selected based on the points of origin "home" and destination "work". Trip chains, where participants stay for limited time at a certain location (drinks after work) on their way home are accounted for as separate journey. Table 2 gives an overview of the total of journeys by all modes of transport recorded from January 2014 until mid-September 2014.

2.5. Weather conditions

For this research, hourly meteorological data (air temperature, wind speed, and total precipitation) for the province of North-Brabant were obtained from the Dutch Meteorological Institute (KNMI, 2014) from January 2014 until mid-September 2014, which was related to the available GPS data. The province of North Brabant is situated in the south of the Netherlands, consisting of 4.855 km^2 land surface, is covered by the following three meteorological stations: Gilze-Rijen (51° 34′N, 04° 56′E), Eindhoven (51° 27′N, 05° 23′E), and Volkel (51° 39′N, 05° 42′E). The region can be characterized by a warm to temperate (maritime) climate (Geiger and Pohl, 1954) with mild winters (average minimum air temperature, 7.1 °C), warm summers (average maximum air temperature, 16.3 °C), and relatively stable year-round total precipitation patterns (KNMI, 2014). To link the travel behavior to the meteorological data, participants' home postal codes were assigned to one of the weather stations. To give an indication of weather conditions in the Netherlands, Table 3 describes daily average (Tavg in *C), maximum (Tmax in *C), and minimum (Tmin in *C) air temperature, average (Ws_avg in meters per second) and maximum (Ws_max in meters per second) wind speed, and the average (Pavg in mm per hour) and maximum (Psum in mm) daily total precipitation during months of the study period in Eindhoven.

Weather effects on mobility were analyzed using meteorological variables from hourly meteorological data. The reason for hourly

Table 2
Trips by all modes based on the purpose of 573 participants January to September 2014.

	Work	Groceries (daily)	Groceries (non-daily)	Services	Social	Recreational	Leisure	Home	Rest	Total
Total of journeys	71,772	29,184	12,872	1,230	26,623	13,290	6,081	80,310	817	242,179
Percentage purpose	30%	12%	5%	1%	11%	5%	3%	33%	0%	100%
Average journeys per person.	125	51	22	2	46	23	11	140	1	423

Table 3
Average daily air temperature, wind speed and total precipitation on a monthly basis from January to September 2014 (KNMI, 2014).

	T avg (°C)	T min (°C)	T max (°C)	Ws_avg (m/s)	Ws_max (m/s)	P avg (mm)	P max (mm)
January	5.8	−2.7	14.1	4.4	12.0	1.4	7.3
February	6.5	−0.6	14.0	5.3	13.0	1.5	8.1
March	8.7	−2.5	22.3	3.3	10.0	0.6	7.0
April	12.3	−1.5	23.9	3.0	10.0	0.7	6.3
May	13.6	−0.6	28.2	3.5	11.0	3.4	30.8
June	16.6	6.3	29.3	2.8	8.0	0.7	7.2
July	19.9	5.2	33.4	3.1	8.0	4.3	23.5
August	19.9	5.2	33.4	3.1	8.0	4.3	23.5
September	15.9	5.2	25.0	2.3	7.0	1.4	30.0

variables is three-fold. First, the GPS data (time of departure and arrival, mode choice, distances) are collected on a continuous basis, which enables a data merge on an hourly basis. Total precipitation (P_h) is defined by the categories dry ($P_h = 0$ mm/hour), light total precipitation ($0 < P_h \leq 2$ mm), and heavy total precipitation ($P_h > 2$ mm/hour). Second, commuter e-cycling is likely to be more affected by the total precipitation at the time of travel than the total precipitation on a daily level. However, it is likely that expected total precipitation in the afternoon might have an impact on the choice to go by e-bike to work in the morning. For example, when deciding to take the e-bike to work, people are likely also to consider the predicted weather for their return trip home later that day. Next to the hourly total precipitation, the afternoon total precipitation (as predicted weather) is aggregated from the hourly total precipitation from 15:00 until 19:00. Third, according to Böcker (Böcker et al., 2015), mode choice related to air temperature on the hourly level revealed roughly the same picture and performance as the average daily air temperature. Next to the hourly air temperature (Ta_h), for each weather station, the data are translated into the same classes as the questionnaire, enabling a comparison between the stated intention and the actual weather circumstances. Participants had to report on their intention to use an e-bike to commute to work with heavy wind (indicated by wind speed 5 Beaufort or more), which can be compared with measurements of 8 m per second by weather stations.

2.6. *Statistical modelling techniques*

To explore the impact of weather circumstances on e-cycling for all participants during their daily commute, a series of four incremental multilevel binary logistic regression analyses were performed. First, a base model explored the relationship between e-cycling and the personal and household characteristics together with urbanization level, cycling distance, and the share of past conventional cycling to work. Therefore, the proportion of regular cycling before entering the program is considered. Second, to address the impact of weather conditions, a second model added the following weather-related variables: observed air temperature when departing for work, wind speed, total precipitation when departing for time as well as the total precipitation in the afternoon period (as proxy variable for the expected total precipitation), and presence of snow/ice. In a third model, the effect of the combination between the air temperature, total precipitation, and wind speed at the departure time to work and the stated e-cycling behavior on actual e-cycling were explored. Therefore, the participants' stated intention of using an e-bike under the actually observed weather conditions was added as an explanatory variable. Finally, to test the impact of the availability of a second car in the household on the sensitivity to weather conditions, we added interaction terms between availability of a second car and gender, air temperature, windspeed, and total precipitation on e-cycling. The hypothesis was that having access to a car as a back-up plan for bad weather conditions will influence the probability of e-cycling on days with bad weather.

3. Results

3.1. *Descriptive statistics*

To gain insight into the relationship between the use of an e-bike or the car to commute to work based on the weather conditions, all home to work trips with their specific date and time were merged with the observed weather condition data. Table 4 shows the data for

Table 4
Total number of trips per mode of 573 participants based on air temperature, total precipitation, and wind speed between January 2014 and mid-September 2014.

	Air temperature (°C)			Total precipitation (mm)			Wind speed (m/s)	
	(very) cold	Mild	Warm/hot	Dry	Light precipitation	Heavy precipitation	Not strong	Strong
	$T < 10$	$10 \leq T < 20$	$T \geq 20$	0 mm	0–2 mm	>2 mm.	(0–8 m/s)	(8 + m/s)
CAR (n, %)	6,829	14,036	3,906	10,604	10,104	4,063	24,416	355
	31%	35%	34%	31%	34%	40%	33%	42%
EBIKE (n, %)	15,353	26,235	7,592	23,992	19,203	5,985	48,684	496
	69%	65%	66%	69%	66%	60%	67%	58%
Total	22,182	40,271	11,498	34,596	29,307	10,048	73,100	851

all commuting trips between January 2014 and mid-September 2014, and the relationship between the mode of transport and the momentary air temperature, total precipitation, and wind speed at the time of use. Because of the low number of observations of air temperatures below 0 °C and above 30 °C, these values are integrated into the adjacent category.

As shown in previous research (de Kruijf et al., 2018), the proportion of participants in the incentive program who e-cycled to work was relatively high with an average of 67%. From all three air temperature categories, the highest proportion of commuting by e-bike (69%) occurred at air temperatures below 10 °C. With an increase in the air temperature, the proportion of e-cycling in the daily commute compared to using a car slightly decreased. With total precipitation, a stronger effect was noticeable, where the use of the e-bike decreased from 69% in dry weather to 60% in heavy rain. Although there were few trips under conditions with hard winds, the proportion of e-bike use compared to the car were the lowest (58%). Combinations of these individual weather conditions influenced the choice to commute by e-bike.

Table 5

Binary regression analysis of weather conditions on e-cycling in daily commuting.

		MODEL 1		MODEL 2		MODEL 3		MODEL 4	
Variable	Category	B	Sig.	B	Sig.	B	Sig.	B	Sig.
Intercept		−0.1668	0.444	−0.0958	0.658	−1.7154	**0.000**	−1.6524	**0.000**
Age	25–39 years	−0.3917	**0.020**	−0.4020	**0.016**	−0.4311	**0.009**	−0.4308	**0.009**
	40–49 years	−0.0937	0.451	−0.0990	0.421	−0.1054	0.388	−0.1048	0.391
	50–64 years	–	–	–	–	–	–	–	–
Gender	Male	−0.1795	0.089	−0.1960	0.061	−0.1930	0.063	−0.2445	0.095
	Female	–	–	–	–	–	–	–	–
Physical condition	Bad	−0.1601	0.351	−0.1699	0.318	−0.1084	0.520	−0.1115	0.509
	Neutral	0.1100	0.451	0.1018	0.481	0.1314	0.359	0.1286	0.370
	Good	0.0863	0.491	0.0967	0.435	0.1231	0.316	0.1236	0.314
	Excellent	–	–	–	–	–	–	–	–
Car ownership	1 car	−0.0644	0.549	−0.0547	0.607	−0.0730	0.489	−0.1345	0.372
	2 + cars	–	–	–	–	–	–	–	–
Household income (in € per month)	< 3,000	0.3000	**0.019**	0.2891	**0.022**	0.2818	**0.024**	0.2844	**0.023**
	3,000–< 4,000	0.2401	0.065	0.2258	0.079	0.2280	0.074	0.2290	0.073
	> 4,000	–	–	–	–	–	–	–	–
Household composition	Single	−0.1339	0.593	−0.1135	0.647	−0.1096	0.656	−0.0954	0.700
	Single parent	−0.1033	0.723	−0.0787	0.785	−0.0532	0.853	−0.0406	0.888
	Couple without children	0.1949	0.440	0.1802	0.471	0.1866	0.451	0.1730	0.487
	Couple with children	–	–	–	–	–	–	–	–
Residence urbanization	Highly Urbanized	−0.2609	0.094	−0.2618	0.090	−0.2501	0.102	−0.2494	0.103
	moderate urban.	−0.1681	0.245	−0.1713	0.232	−0.1725	0.224	−0.1721	0.226
	Less urbanized	−0.0506	0.699	−0.0513	0.692	−0.0464	0.717	−0.0500	0.697
	Not urbanized	–	–	–	–	–	–	–	–
Cycle Distance (per commute trip)	0–5 km	0.4792	0.107	0.5374	0.068	0.5299	0.070	0.5328	0.068
	5–<10 km	0.7117	**0.000**	0.7547	**0.000**	0.7414	**0.000**	0.7408	**0.000**
	10–<15 km	0.6641	**0.000**	0.6963	**0.000**	0.6625	**0.000**	0.6610	**0.000**
	15–<20 km	0.4795	**0.003**	0.5090	**0.001**	0.4961	**0.001**	0.4951	**0.002**
	20 + km	–	–	–	–	–	–	–	–
Cycling Share	c-cycling share	0.3901	**0.019**	0.3882	**0.018**	0.3205	**0.049**	0.3248	**0.046**
Air temperature at cycling start (in °C)	T < 7.5	–	–	0.6507	**0.000**	0.7179	**0.000**	0.7611	**0.000**
	7.5 ≤ T < 12.2			0.4511	**0.000**	0.4950	**0.000**	0.5035	**0.000**
	12.2 ≤ T < 16.0			0.2339	**0.000**	0.2590	**0.000**	0.2698	**0.000**
	16.0 ≤ T < 19.1			0.2131	**0.000**	0.2269	**0.000**	0.2521	**0.000**
Wind speed at cycling start		–	–	−0.1009	**0.000**	−0.0978	**0.000**	−0.1023	**0.000**
Total precipitation (mm) in cycling hour		–	–	−0.2508	**0.000**	−0.1352	**0.000**	−0.2379	**0.000**
Total precipitation (mm) afternoon		–	–	−0.0147	**0.002**	−0.0108	**0.022**	−0.0107	**0.024**
Ice		–	–	−0.4854	**0.000**	−0.4921	**0.000**	−0.5017	**0.000**
Air temperature × intended behavior		–	–	–	–	0.0807	**0.000**	0.0820	**0.000**
Total precipitation (hour) × intended behavior		–	–	–	–	0.1616	**0.000**	0.1551	**0.000**
Wind speed & intended behavior		–	–	–	–	−0.0021	0.802	−0.0022	0.796
Car possession × gender		–	–	–	–	–	–	0.1001	0.618
Car possession × air temperature (in °C)	T < 7.5	–	–	–	–	–	–	−0.0172	**0.047**
	7.5 ≤ T < 12.2							−0.0016	0.746
	12.2 ≤ T < 16.0							−0.0013	0.712
	16.0 °C ≤ T < 19.1							−0.0027	0.329
Car possession × wind speed		–	–	–	–	–	–	0.0091	0.318
Car possession × total precipitation		–	–	–	–	–	–	0.1513	**0.000**
Random effect covariance		1.290	0.000	1.342	0.000	1.313	0.000	1.288	0.000

3.2. Regression models

Four incremental multilevel binary logistic regression analyses were performed on factors influencing the choice of commuting by e-bike or a competitive mode of transport, where each model builds upon the previous model to understand the impact of additional variables (Table 5). Overall, the four models indicate that the actual choice of commuting to work by e-bike is not systematically related to most personal and household characteristics of participants in the incentive program such as age, gender, income, or household income and composition. Only the youngest group of participants (aged 25 to 39 years old) had a significantly lower probability of e-cycling compared to the age group 50 to 64-year-olds, whereas a low household income (<3,000 euro a month) of participants (compared to high incomes) had a significantly higher probability of e-cycling as a result of the incentive program. Additionally, cycling distances above 5 km and using a c-bike to commute to work before participating in the program positively affected e-cycling.

The base model was extended with weather conditions as explanatory variables (model 2). Because of the uneven distribution of trips over the air temperature classes, air temperature is represented as quintiles (boundaries 7.5 °C, 12.2 °C, 16.0 °C, 19.1 °C). For the impact of weather conditions, the results showed that wind speed, total precipitation, and the presence of snow/ice negatively influenced te probability of e-cycling. Although it was of less impact than the total precipitation at the time of cycling, total precipitation in the afternoon (as proxy for predicted weather) had a significant impact on the choice of taking the e-bike to work. This suggests that commuters take into account expected weather conditions during the commute back home when deciding about their travel mode. An increase in air temperature also had a negative effect on e-cycling, where it might have been expected that under warmer weather circumstances, e-cycling would be more pleasant. Extending the model with the intention to cycle under specific conditions (model 3) revealed that, as expected, the stated intention of e-cycling under the observed weather conditions had a positive effect on e-cycling probability for air temperature and total precipitation, but not for wind speed.

Finally, we extended model 3 with interaction to account for moderation effects of weather conditions by car access (model 4). This model indicates that participants from multiple person households with only one car had fewer alternatives under poor weather conditions and they were more likely to e-cycle. For specific weather conditions, we found that both the combinations between car possession and heavy wind as well as car possession and air temperature had no significant impact on e-cycling, except at relatively low air temperatures (below 7.5 °C). However, participants with two or more cars in their household were less likely to e-cycle. Although gender was shown to be an influential factor for conventional cycling in previous studies, there was no significant relationship between gender and car possession compared to e-cycling.

4. Discussion

This paper reported on the impact of objective weather conditions on e-cycling within an e-cycling incentive program in the province of Noord-Brabant, the Netherlands. In the program, participating car-commuters were incentivized to use of e-bikes in daily commuting, earning monetary incentives for each kilometer that they e-cycled. With a longitudinal design based on GPS-data and objective meteorological data, this study observed the impact of weather conditions on e-cycling. The main objective was to gain insight into e-cycling behavior under adverse weather conditions, where the use of the e-bike would mitigate range restrictions and physical effort, which are main barriers in conventional bicycle use for daily commuting (Heinen et al., 2010; Heinen and Handy, 2012). This is because of the electric peddle support of the e-bike.

Our study showed that e-cycling was affected by weather conditions, especially air temperature, total precipitation, wind speed, and the presence of snow/ice. Although snow and ice were not common weather occurrences during the study period, the presence of snow and ice on the cycle path had the highest impact on the choice not to commute to work by e-bike. Second, where a positive effect might have been expected on the relationship between e-cycling and air temperature, actual e-cycling behavior showed the opposite effect. This remain remarkable, as outcomes of previous studies showed that high air temperature has a negative impact on cycling only for heat with air temperatures above 25°Celcius (Ahmed et al., 2012; Phung and Rose, 2007; Miranda-Moreno and Nosal, 2011; Lewin, 2011; Böcker et al., 2019), where it should be noted that in our study, high air temperatures were less frequent compared with other studies, with a maximum air temperature of 33.4 °C. Third, both heavy winds and total precipitation negatively influenced e-cycling, where total precipitation had the higher impact than heavy winds. The lower impact of heavy wind on e-cycling may be because the electric peddle support partly mitigates the (negative) physical effort of the conventional bicycle (Heinen et al., 2010). In practice, combined effects of weather conditions occurred and influenced e-cycling.

Although recent studies report about the adaptation of the e-bike mostly for the older age groups, male gender, and a higher educational level (Fishman and Cherry, 2016; Kroesen, 2017), in this study, only the youngest age group (below 40 years old) e-cycled significantly less compared to the oldest group of working people. This indicates that e-cycling has become more common in recent years in the middle-aged commuter group, which might be related to the life phase where households with young children for example need more trip chains in daily activity patterns. To date, many studies have focused on either behavioral intention or on a behavioral change (Gärling and Fujii, 2009). Our study shows that participants who stated before the study that they had a high intention of using the e-bike under adverse weather conditions showed significant positive actual behavior during the program for air temperature and total precipitation, as might have been expected.

However, there is no direct and significant relationship between a heavy wind in combination with the intended and the actual e-cycling behavior. It can be argued that the peddle support only partly mitigates the extra physical effort that is required because of strong winds than expected by participants before the program, causing differences between the intended and actual behavior under strong winds.

These weather circumstances could, therefore, be less of an impact on e-cycling in daily commuting than on conventional cycling, strengthening the reasoning from a policy perspective to invest in e-cycling as environmentally friendly alternative to car commuting. As not all population segments are equally interested in arguments of environmentally friendly behavior change, a more specific target group approach is therefor recommended.

Finally, this paper established to what extent availability of a car as an alternative to the e-bike in combination with gender and specific weather conditions affects e-cycling. Although previous research has shown differences in the e-cycling behavior between men and women (de Kruijf et al., 2018), the combination of gender and car availability did not affect e-cycling significantly in this particular study. The total precipitation in combination with car possession, however, was shown to have a significant impact on e-cycling. Participants with only one available car in the household tended to e-cycle more under rainy circumstances than those with an available car as an alternative. Additionally, air temperature in combination with car possession by the household slightly affected e-cycling. Although the e-bike mitigates the effects of effort compared to the conventional bicycle and increases commuting via cycling for mid-range distances (de Kruijf et al., 2018), adverse weather conditions somewhat limit the choice to leave the car permanently. However, from a policy perspective, the study shows that both men and women more often choose to commute to work by e-bike than by car, indicating that the e-bike can be regarded as a structural commuting mode of transport for short and mid-range distances despite light adverse weather conditions. This could be because of a conscious choice related to the higher purchase value of the e-bike compared to the conventional bicycle. Where the effects seem positive, the extent of these effects can be argued in relation to the e-cycling incentive program conditions. The results of the present study can be helpful for further strengthening Dutch cycling policies which target commuter cyclists. For example, commuters being less sensitive to changes in weather conditions in combination with the development of high quality and safe regional cycling routes decreases existing mental, natural and physical barriers (Heinen et al., 2010) and increases the bicycle use in daily commuting. Given the rapidly increasing sales rate (38%) of e-bikes between May 2019 and 2020 (BOVAG, 2020), and the government and employer led incentive programs, e-bikes could function under many weather circumstances as a sound alternative for car-commuting. Although it is likely that not all commuters will fully switch to using e-bikes in all weather conditions, a vast amount of car-commuting trips can be substituted with effective cycling policy measures (de Kruijf et al., 2018).

Overall, the results indicate that e-bikes have a clear potential to substitute car use in commute trips. A reduction in car use of more than 60% is very significant and raises the question whether the car is still needed as a back-up in case of e.g., adverse weather conditions, or whether this could be fulfilled by public transport or forms of shared mobility. Answering this question is speculative and requires insight into the reasons of using the car. If this reason is adverse weather, (almost) door-to-door services such as car sharing may be more attractive than public transport, which still requires access and egress travel often by walking or cycling. The variation in car share across weather conditions suggests, however, that weather is not the main reason for car use. Another possible reason for car use may be the opportunity to have more complex trip patterns, have serve passenger trips etc. Such needs or not likely met by public transport, but more likely by shared mobility options, suggesting some potential for these services to replace private car trips. Further research will be needed to explore this.

This study had some limitations. First, the research was based on a large-scale e-cycling incentive program, where car-commuters were incentivized to switch to e-cycling on a voluntarily basis. It remains unclear if commuters would show comparable behavior without participating in an incentive program because their personal and household characteristics as well as the social context may vary, and their motivation to take up e-cycle may also vary. It, therefore, remains uncertain to what extent participants' behavior deviates from average where participants in the program are more likely to commute via e-cycling. Second, it remains uncertain to what extent the weather conditions affected e-cycling for other travel purposes and in other spatial contexts. Because of the regional nature of the incentive program, similar effects are not expected in other contexts (e.g., in different geographical contexts or without providing incentives). For the relationship between active travel and weather circumstances in different countries, these variations are already confirmed (Böcker et al., 2019). Third, it is uncertain if similar behavior is shown by the participants over a longer period compared to the current study. Behavioral changes brought about by incentive programs (Ettema et al., 2010) will not necessarily be sustained when the incentive ends.

CRediT authorship contribution statement

Joost de Kruijf: Conceptualization, Formal analysis, Methodology, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Peter van de Waerden:** Writing - original draft, Writing - review & editing. **Tao Feng:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Lars Böcker:** Conceptualization, Writing - review & editing. **Dea van Lierop:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Dick Ettema:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Martin Dijst:** Writing - review & editing.

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