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How does air pollution influence cycling behaviour? Evidence from Beijing

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ABSTRACT

It is widely believed air pollution is an obstacle to cycling as it has negative effects on cyclists' health outcomes and deteriorates their cycling experiences. However, the empirical studies investigating the impact of air pollution on cycling behaviour remains scarce. The aim of this paper is to fill the gap by looking at Beijing as a case study. The authors conducted a survey of 307 cyclists on the days with different levels of air quality in terms of concentration of $PM_{2.5}$ in 2015. The results show that in the polluted weather, those who persist in cycling are more likely to be male, over 30 years old, lower income or those who travel short distances. Specifically, female cyclists have a higher tendency to shift from cycling to public transit than the males and medium and high-income earners are more likely to shift to using a car than low income earners. The residents' subjective perceptions of safety and comfort have major effects on their cycling behaviour. A higher perception of comfort and safety is related to a higher possibility of continuing cycling when air quality became polluted. Cycling for commuting trips is less likely to be replaced by other modes than cycling for non-commuting trips, such as shopping. Results of this study reveal that improving air quality in a metropolitan area such as Beijing has co-benefits of cycling renaissance. The huge investments into cycling infrastructure should be integrated with policies designed to create an attractive environment for cycling.

1. Introduction

It is widely believed that cycling is a sustainable mode of travel. Cycling not only has health benefits as it enhances the level of physical activity, but also contributes to less environmental pollution and greenhouse emissions via reduced levels of car dependence. A cycling-friendly environment is attractive for regular and potential cyclists. The characteristics of a cycling-friendly environment usually include comfortable natural surroundings such as flat topography and warm temperatures along the route, decent built-up areas where cycling routes of choice are embedded, and city and neighbourhood design elements that provide cycling-accessible jobs and service opportunities within smooth and safe corridors (Buehler and Pucher, 2012; Moudon et al., 2005; Pucher and Dijkstra, 2000; Wang et al., 2015). A handful of studies examined the effects of generic weather on cycling in various contexts (Alam, 2015; Helbich et al., 2014; Meng et al., 2016; Motoaki and Daziano, 2015). Uncomfortable weather such as overheating or chilling, as well as excessive precipitation might reduce the attractiveness of cycling. Although abundant research has taken place, four research gaps still need to be filled.

The first gap is that the existing research on the effect of air pollution on cycling has mostly focused on the health risks of cycling when compared with other motorised modes of transport, lacking evidence on how hazardous weather influences cycling behaviour.

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Air pollution may discourage many cyclists from cycling and force them to switch to other travel modes, so understanding the impact of air quality on cycling behaviour may be helpful for environment policies towards more sustainable transportation. The second gap is that there is disproportional evidence on the impacts of some air pollutants like Sulfur Dioxide (SO_2) or Nitric Oxide (NO) on cycling, while the evidence on certain pollutants such as $PM_{2.5}$ on cycling remains rare. $PM_{2.5}$ is important in both environment research and policy, because it has a much more substantial influence on air quality, and it is the main origin of respiratory and chronic diseases (Lelieveld et al., 2015). Additionally, how air quality affects cycling behaviour through psychological perceptions still needs further investigation. Cyclists' psychological perceptions of the environment could also influence their willingness to cycle, whose effect might be substantially distinct from the empirical examined relation based on objective measurements (Baldock et al., 2012; Ma and Dill, 2015). For instance, those who have a stronger tendency to use bicycles may still keep cycling in an environment that is not attractive for common cyclists. Finally, existing literature on the impact of air pollution on cycling behaviour are dominated mainly by information from developed countries, while evidence from developing countries remain rare. The air quality is generally poorer in developing countries compared with the developed ones because of the rapid industrialization and urbanization, while the population density is much higher and active travel is more popular. Thus, investigating the relationship between air quality and cycling behaviour would be urgent for the transportation planning in the developing countries.

The aim of this study is to fill the above gaps by examining the case of Beijing, China. Beijing is the capital city of China. At the end of 2015, the number of permanent residents in Beijing reached 21.7 million, with US$17,064 in GDP per capita. As a country ever dominated by cycling travel just three decades ago, China is now facing a big challenge in the substantial reduction of cycling. For example, cycling decreased from 62.7% in 1986 to 13.9% in 2012, while car use share increased from 5% in 1986 to 32.6% in 2012 in Beijing (Beijing Transportation Research Center, 2005; Zhao, 2011; Zhao et al., 2010,2011). In contrast, the number of private vehicles reached 4.403 million in Beijing in 2015, increasing 0.41 million from 2010 (Beijing Statistical Bureau, 2016). This shift caused a serious problem with traffic congestion, air quality, and health. In 2012, average road speed in rush hour was reduced to 25 km/h and the daily congestion reached four hours (Zhong et al., 2017). Traffic emissions contributed to 22% of the total annual $PM_{2.5}$ in the city (Shi et al., 2017). Polluted days with higher concentrations of $PM_{2.5}$ were linked with respiratory and chronic diseases and also more serious health problems such as cardiometabolic sickness and adverse pregnancy outcomes, based on studies in Beijing (Brook et al., 2017; Song et al., 2017).

With cycling regaining its popularity by promoting physical activity and mitigating the city's traffic congestion and vehicle-related pollution, many cities in China are now providing more policy and infrastructure support for cycling (Beijing Morning Post, 2015). In Beijing, the state and the municipal government has been making efforts to promote cycling. These policies include comprehensive efforts to promote cycling-exclusive infrastructures, priority policies for cyclists, bicycle sharing schemes, and behaviour education. In Beijing, the length of bicycle lanes increased to 700 km in 2016 (Beijing Statistical Bureau, 2016). Apart from privately owned bikes, the amount of public share-bikes increased rapidly. In just two years, 15 bicycle sharing scheme providers added more than 2.35 million dockless share-bikes to Beijing's streets, powered by strong venture capital competition (Beijing Youth Daily, 2017). Promoting cycling has also been addressed in the new Beijing Municipal Master Plan. According to the plan, many policies will be implemented to facilitate cycling in Beijing, for instance, exclusive bicycle lanes, a narrow street cycling priority policy and cycling friendly pilot zones in the coming years (Beijing Traffic Management Bureau, 2010; Central Govenment of China, 2017).

However, air pollution could be a barrier to the potential renaissance of cycling in Beijing. In 2015, Beijing had 303 days with $PM_{2.5}$ concentration higher than the daily limit of 25 μg/m^3, which is seen as a minimum health level by the World Health Organization (WHO, 2006). Even when considering the mildest WHO Interim Target 1 of 75 μg/m^3 adopted by the Chinese government, Beijing still had 142 days with $PM_{2.5}$ exceeding this criteria (Fontes et al., 2017; U.S. Department of State, 2016). Such bad air pollution created an unattractive environment for cycling and affected cycling trips in Beijing. However, the impact of $PM_{2.5}$ on cycling behaviour in a developing metropolis like Beijing remains scarce.

This paper provides evidence that air pollution influences cycling behaviour. It aims to investigate whether air pollution may contribute to bicycle behaviour changes, and how does this happen where perception and socio-economic variables are mediators. The authors did a survey that collected questionnaires from 307 cyclists on the days with different levels of hazardous air quality. The remaining part of the paper is organized as follows. Section 2 reviews the relationship between air pollution and cycling behaviour. Section 3 introduces the data context and the survey content. Sections 4–6 present results and discussion of the modelling findings and policy implications. Section 7 provides a summary and policy implications based on the research findings.

2. Literature review

2.1. Air pollution, cycling and health

This section reviews the existing literature investigating the impact of air pollution on cycling and the related health outcomes and potential determinants of cycling behaviour. There have been multiple studies examining the health impact of cycling in polluted air. It is generally believed that residents inhale more hazardous pollutants during transportation (for example, black carbon; (Dons et al., 2012)). There are two contradicting arguments regarding the health performance of cycling in polluted days, with one suggesting that the active travel benefits of cycling outweigh the health risks of air pollution (summarised by Cepeda et al. (2017)) and the other stating that the risks of ambient pollutants for cyclists cannot be negated (Briggs et al., 2008). These arguments come from studies either comparing health benefits and risks of cycling or horizontally comparing exposure in different modes of transport. We review the recent literature and summarise three reasons that potentially lead to the different conclusions in the above two issues.

Table 1
Studies on mode-specific $PM_{2.5}$ exposure (μg/m^3).

Study	Context	Cycling	Walking	Bus	Metro	Car
Kaur et al. (2005)	London, UK	33.5	27.5	34.5		38
McNabola et al. (2008)	Dublin, Ireland	80.5	64.8	115.8		85.5
Boogaard et al. (2009)	Netherlands	44.5				49.4
Panis et al. (2010)	Belgium	27.2				23.2
De Nazelle et al. (2012)	Barcelona, Spain	35	21.6	25.9		35.5
Huang et al. (2012)	Beijing, China	49.1		42.4		
Wu et al. (2013)	Foshan, China	76.8	74.1	75.9	27.9	56.8
Yan et al. (2015)	Beijing, China		49.9[a]	38.9[a]	61.8[a]	
Goel et al. (2015)	Delhi, India	207[b]	234	277/140[c]		180/56[d]
Rivas et al. (2017)	London, UK			14	35	7
Okokon et al. (2017)	Helsinki, Finland	27		29		33/14[e]
	Rotterdam, Netherlands	32		21		31/24[e]
	Thessaloniki, Greece	41		85		56/24[e]

[a] PM concentration.
[b] Motorised, two wheel.
[c] Open window/air-conditioned bus.
[d] Open window/air-conditioned car.
[e] Open/closed window car.

First, the pollutants used to measure the health outcome influence the results. The use of air pollution indicators such as particulate matter (by mass or volume), black carbon, CO, or ultrafine particles might yield different results across different modes of transport. For example, Yan et al. (2015) found in Beijing that compared with using bus or subway, pedestrians receive less exposure when measuring $PM_{2.5}$ mass concentration and particle number concentration indicators but more exposure when using benzo(a) pyrene toxic equivalents. de Nazelle et al. (2016) summarized ten European cases in which pedestrians faced exposure to higher levels of black carbon, but less $PM_{2.5}$, CO, or ultrafine particles than bus passengers on average. Fontes et al. (2017) identified changes in long-term annual, seasonal, and daily $PM_{2.5}$ concentration in China's five megacities.

Secondly the results are also sensitive to the geographical context. For example, results from the international contexts indicated that mode-specific pollutant exposure varied significantly across developed and developing countries, as shown in Table 1. Increasing evidence from developing industrial economies such as India and China show higher $PM_{2.5}$ exposure in cars (especially air-conditioned vehicles) in urban areas, compared with Western cities such as Copenhagen, New York and Tokyo, where the average density of $PM_{2.5}$ is 10–20 μg/m^3. These lower readings are around 1/7th of the concentration in Delhi (150 μg/m^3; Goel et al. (2015)) and a quarter of that from Beijing (83 μg/m^3 in 2015; U.S. Department of State, 2016). In addition, air circulation in vehicle micro-environments has an impact on the results. For example, in Helsinki, Okokon et al. (2017) found that cyclists were exposed to higher $PM_{2.5}$ levels than open-window car riders, but lower levels than closed-window ones. In Delhi, active travellers are also exposed to higher levels of $PM_{2.5}$ than passengers in air-conditioned buses but lower than passengers in open-window buses.

Thirdly, the health indicators that often varied between different studies could also lead to debatable results. Some authors used exposure indicators, and others used inhalation indicators. Some studies suggested that though car users are exposed to more air pollution, cyclists inhale pollutants that are more hazardous, and they suffer from worse health impairment when taking higher breath rates and the longer travel duration of active travel into account (Briggs et al., 2008; Cepeda et al., 2017; Goel et al., 2015). Other researchers found that even taking higher breathing rates into account, cyclists had less exposure than car users in a city with a very low $PM_{2.5}$ concentration, for instance, in Copenhagen (Rank et al. (2001).

Although several previous studies linked the relationship between air quality, cycling behaviour and health outcomes, some research gaps remain. First, the existing literature mainly focused on the impact of air quality on health outcomes of cyclists, while studies that explored the impact of air quality on cycling behaviour remain rare. It is likely that hazardous air pollutants prevent cyclists from cycling and compel them to transfer to other travel modes; however, the existing literature could not detect these travel mode switches. Second, the evidence from the developing economies context is relatively rare and recent, considering the research and policy significance of this issue. The extent of air pollution and the share rate of cycling are both higher in high-density cities in the developing countries. Finally, compared with other pollutants, the empirical studies on the impact of $PM_{2.5}$ on cycling are relatively scarce. Since $PM_{2.5}$ has a much more substantial influence on air quality than other major pollutants such as SO_2 and NO, it reflects visually on the perception of air quality level by general travellers. It is also a main cause of respiratory and chronic diseases in extremely hazardous weather. We therefore focus on its measurement across different modes of transport.

2.2. Conceptualize the relationship between air pollution and cycling behaviour via perceptions

This section conceptualizes the impact of air pollution on cycling behaviour on the basis of the theory of planned behaviour proposed by Ajzen (1991). According to this theory, distinct attitudes, subjective norms from society and perceived behavioural control may contribute to behaviour variations. Air quality, as an important element of physical environment, could also influence cycling behaviour of people through psychological and perceptive processes. Fig. 1 conceptualizes how air quality converts to

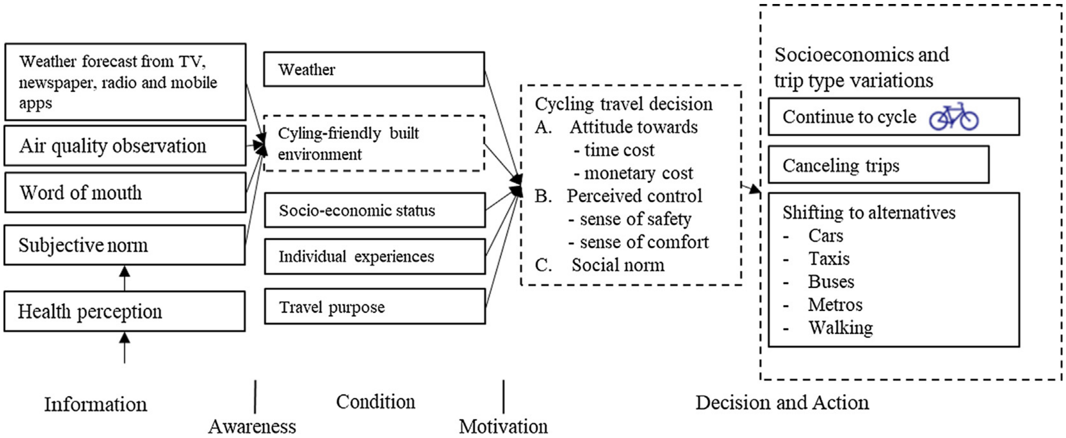

Fig. 1. Cycling decision process in polluted air.

individual cycling behaviour. Based on the literature on travel behaviour research, air quality could transform into different cycling behaviour responses in three consecutive steps:

(1) **Information**: People form preliminary perceptions of air pollution based on information from various media sources, their observation, others' testimonies, and their physical responses, motivate their different awareness of air pollution.
(2) **Condition:** According to the socio-ecological model, people's cycling behaviour is also shaped by various human-environment factors, including the physical environment, built environment, and individual physical condition and travel experiences. These factors could all meditate the motivation of cycling of people. There is abundant empirical literature reviewing the "condition" factors influencing cycling and these factors can be summarized as:
   (a) ***Weather:*** In general, comfortable temperatures serve as supportive factors towards cycling (Heinen et al., 2010; Helbich et al., 2014; Nosal and Miranda-Moreno, 2014; Wadud, 2014). High temperatures during summer or in tropical areas, such as Singapore (Meng et al., 2016) or cold temps during winter or in cold and even frigid areas such as Norway (Alam, 2015) and Vermont United States (Spencer et al., 2013) all discourage cycling. Excess precipitation, such as rain and snow also discourage cycling, even in high-intensity cycling cultures (Dolati, 2014; Helbich et al., 2014). A combination of dry, calm, sunny and warm weather promotes cycling over other modes of transport (Böcker et al., 2016).
   (b) ***Cycling-friendly built environment:*** Cycling-friendly built environments are also important to encourage cycling. Many empirical studies found that built environment characterized by high urban density and mixed-used development (Pucher and Buehler, 2006), safe and comfortable cycle routes (Majumdar and Mitra, 2015; Spencer et al., 2013), and high connectivity of streets associated with more utilitarian cycling trips (Moudon et al., 2005). In contrast, disordered urban sprawl discouraged cycling (Campbell et al., 2016; Pucher and Buehler, 2006; Vandenbulcke et al., 2011). Additionally, provision of cycling-friendly facilities such as convenient access to public bicycles or green space (Cole-Hunter et al., 2015), abundant lighting (Spencer et al., 2013), and various supporting facilities such as storage and showers at destinations (Heinen et al., 2010) provided incentives to increase cycling intensity.
   (c) ***Socio-economic status:*** Different socioeconomic groups have divergent cycling behaviours due to different perceptions of time, safety, and household responsibility. For example, males tend to take more (Godefroy and Morency (2012); Pucher et al., 2011) and longer (Dolati, 2014) cycling trips. The effect of income is less consistent, which might be due to the confounding influence of car ownership and health concerns (Heinen et al., 2010). "Role models" of cycling from family, friends, neighbours and other inhabitants of the city and community activities encouraging cycling also play important roles in encouraging cycling (Sherwin et al., 2014; Wang et al., 2015).
   (d) ***Individual experiences:*** People's experiences affect their behaviour (Sönmez and Graefe, 1998). Experienced cyclists are more likely to hold positive attitudes (Fernández-Heredia et al., 2014; Meng et al., 2016). Controlling for other variables, less experienced cyclists are 2.5 and 4 times more affected than more skilled cyclists in rain and snow respectively (Motoaki and Daziano, 2015). Moreover, more experienced cyclists are also less reliant on cycling-supportive facilities or infrastructure (Larsen and El-Geneidy, 2011).
   (e) ***Travel purpose:*** Compared with non-work trips, commuting trips are less flexible in time, frequency, and route choice, and have less elasticity in response to weather or environmental change. Thus, recreational cycling is more sensitive to weather relative to commuting (Brandenburg et al., 2004; Helbich et al., 2014). An important reason is that recreational cycling is less utilized and much more flexible than commuting (Ahmed et al., 2013). Similar variations also exist between weekdays and weekends (Nosal and Miranda-Moreno, 2014). Moreover, recreational cyclist also put bicycle facility provision at a more important role in their cycling experience, than commuters (Larsen and El-Geneidy, 2011; Sherwin et al., 2014).
(3) **Decision and action:** The next step after information and condition is decision and action. In this step, attitudes and perceptions towards the surrounding environment considering individual capabilities and limits could convert to people's perceptive control

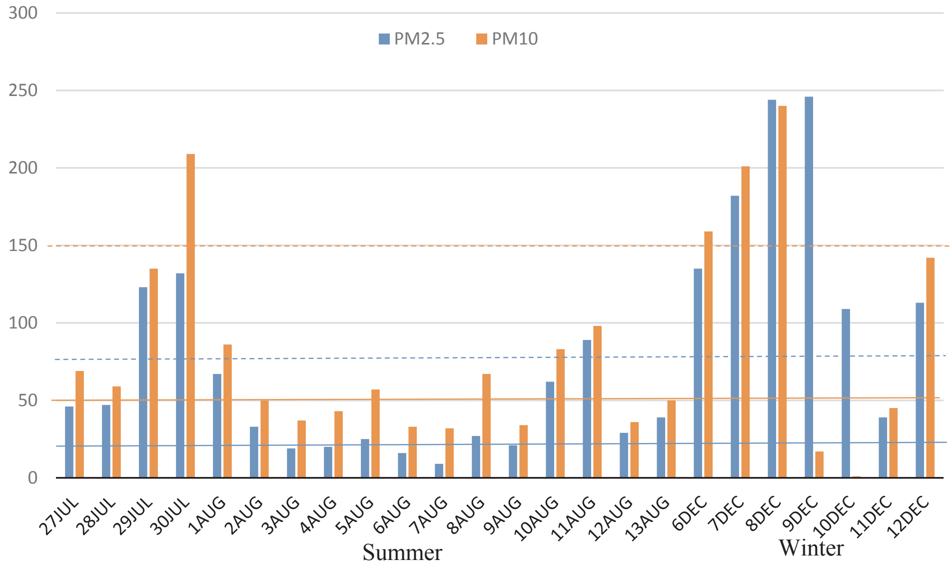

Fig. 2. Daily average of $PM_{2.5}$ concentration in Beijing (Unit: μg/m^3/day). Data source: Beijing Municipal Environmental Protection Bureau. Note: The solid reference lines in blue and orange are health standard reference lines set by WHO for $PM_{2.5}$ (25 μg/m^3/day) and PM_{10} (50 μg/m^3/day), respectively. The dash reference lines in blue and orange are health standard reference lines set by Chinese government for $PM_{2.5}$ (75 μg/m^3/day) and PM_{10} (150 μg/m^3/day), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

over air pollution. Moreover, they also weigh the relative time and monetary cost savings of cycling relative to the other modes and social norms over other factors. These perceptive considerations combine to determine whether people take the bicycle or alternative modes for a trip (Verma et al., 2016). For example, subjective perceptions of cycling safety and comfort could also be meditated by socio-economic factors (Heinen et al., 2010; Spencer et al., 2013). Low-income cyclists are less likely to switch to other travel modes on polluted days (Rind et al., 2015). This means that low-income people may be more tolerant to air pollution, and thus they may still ride bicycles in heavy pollution. In comparison, elderly people or physically vulnerable individuals may be more sensitive to polluted weather due to health constraints (Von Lindern et al., 2016).

In view of the scarce evidence on the impact of air quality on cycling behaviour through people's perceptions, this paper explored how air pollution influenced people's cycling behaviour changes, specifically concerning the mediating role of perceptions.

3. Methodology

3.1. Survey and data

Data used in this study came from a data set collected in various locations during different periods. The data was collected in summer (July 27th to August 13th, 2015) and winter (December 6th to December 12th, 2015) in 2015. In these two periods, there were obvious variations in air quality that could represent the yearlong air quality differences in Beijing. Fig. 2 shows the daily average $PM_{2.5}$ and PM_{10} concentrations during these two survey periods. In the figure, the World Health Organization (WHO) 25 μg/m^3 daily limit and its Interim Target 1 of 75 μg/m^3 daily adopted by the Chinese government are presented as references for comparison. The comparison shows that the pollution level of $PM_{2.5}$ of most days exceed the standard proposed by WHO. Although the air quality in the summer was generally better than the winter, variations still existed among these survey days. $PM_{2.5}$ level in many surveyed days exceeded the WHO level, and even the limit set by the Chinese government. Thus, the air quality in these surveyed days enables us to compare the impact of different air quality on cycling behaviour. This survey employed a three-stage sampling technique. At the first stage, nine areas in Beijing in the downtown and near suburb (2nd ring road, Sanlihe, Nanluoguxiang, Shichahai, the Olympic Centre, West Zhongguancun, Qingta, Fangzhuang; shown in Fig. 3) were chosen in terms of the location relative to the city center, variations in cycling support facilities (The Beijing News, 2015), the built environment, and the proportion of total residents. At the second stage, the residents at the cycling parking areas, near metro stations or the road crossings, were chosen randomly. They were asked "Have you often cycled in Beijing this year?" If the answer was "Yes", the survey went to the third stage, and these who cycled in 2015 were invited to fill out a questionnaire. The residents who answered that they did not cycle usually were not asked to fill out a questionnaire. A sample of 307 out of 431 filled questionnaires were analysed in the study. The others were dropped from this study because of missing data.

All the information used in this study came from the survey. The survey included the following information for every respondent: (1) cycling experiences and daily cycling trip information; (2) perceptions about the air pollution and cycling environment; (3)

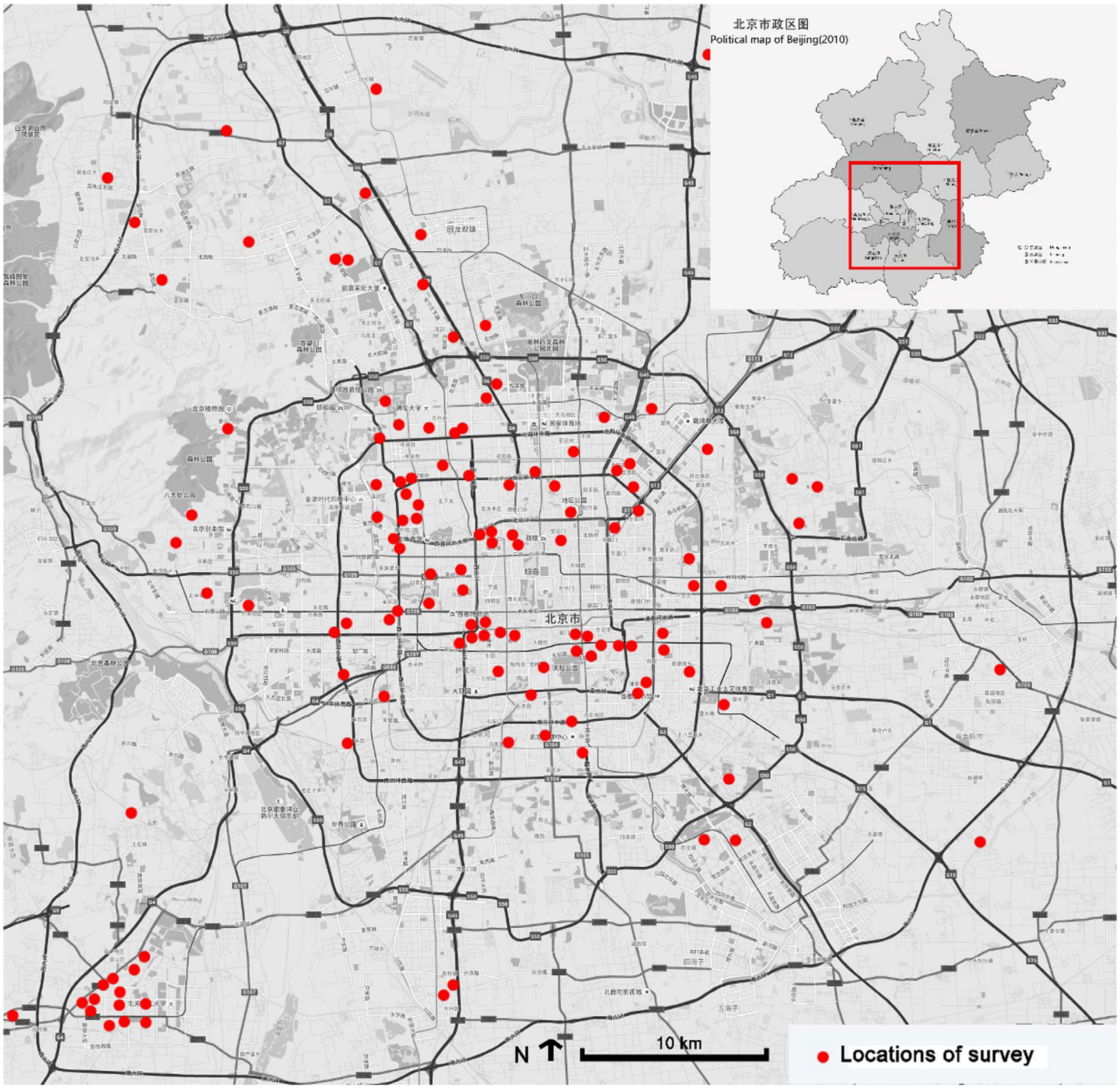

Fig. 3. Survey locations in Beijing.

Table 2
The socio-demographic information of the respondents.

Individual-level variable	Sample	
	n	%
Gender		
Male	152	49.51%
Female	155	50.49%
Age		
30 and under	200	65.15%
Over 30 years old	107	34.85%
Education		
High school and below	166	54.08%
College and above	141	45.92%
Personal monthly income (CNY)		
< 3000	101	32.90%
3000–8000	178	57.98%
> 8000	28	9.12%

potential mobility changes facing air pollution; and (4) individual and family socio-economic attributes. Table 2 shows the socio-demographic information of the respondents in the survey. The survey shows that the respondents were disproportionally young in terms of age and were from the low-income population. It was obviously identified that age was right skewed and income was left skewed. The finding regarding age was consistent with previous studies (Dill and Voros, 2007), while the finding regarding income inferred that low-income people, who had fewer travel choices in daily travel, could depend on cycling more. Lacking feasible choices for motorized travel modes, cycling could be a desirable way in substitution for walking.

Cycling travel data in the survey included the individual travel characteristics for six purposes of cycling (work/school, picking up children, shopping, recreation, exercise and other), for instance, weekly cycling frequency, average duration, and origin-destination information for every trip. The respondents were asked to rank their main non-work destinations in terms of travel frequency, and only the primary visited destinations for every travel purpose were picked as the main destinations. Cycling distance was calculated in ArcGIS 10.0 with the reported origins and destinations. Multiple questions on perceptions of air quality, cycling environment, and potential changes in cycling behaviour on polluted days were the main parts of the survey. These questions mainly compromised of the following parts: (1) **Perceptions towards air quality.** A multiple-choice question of the cognitions of air pollution in terms of various sources, including forecasts from TV or mobile apps, personal physical condition (coughing, expiratory dyspnoea, etc.), air visibility and others. (2) **Perceptions towards cycling environment.** Respondents were asked to select one choice among five-point scales (strongly dissatisfied, dissatisfied, neutral, satisfied, strongly satisfied) concerning five dimensions of cycling travel (time cost, road safety, comfort, transport convenience, and monetary cost). In order to explore the impact of air pollution, the respondents were asked to give answers to each question in two different scenarios (in polluted days and unpolluted days). (3) **Potential cycling behaviour changes in polluted days.** The respondents were asked whether they would continue cycling when facing different scenarios of haziness (light, medium, and heavy in terms of the intensity), and if so, they were asked further whether they would continue cycling for different travel purposes (e.g., work, recreation, grocery shopping, etc.); if not, they were asked to provide the main reasons for giving up cycling. Cycling distance and duration in these three scenarios were collected if applicable and compared with the data during polluted days. A separate question was also designed to ask respondents what mode of travel they would shift to (walking, bus, metro, car, taxi or other) when faced with hazy weather, and they were also asked to further report the level of change in each mode using five-point scales (strongly reduce, reduce, unchanged, increase, strongly increase).

The variables and according measurements are shown below in Table 3.

Table 3
Independent variables included in the models.

Category	Variable	Explanation and measurement
Socio-demographics	Gender	Binary variable (1 = female, 0 = male)
	Age	Binary variable (1 = over 30 years old, 0 = 30 or under)
	Monthly income	Categorical variable (Unit: CNY, meaured by montly individual income, =1 if monthly individual income < 3000, =2 if monthly individual income is from 3000 to 8000, =3 if monthly individual income > 8000
	Education	Binary variable (1 = college or above, 0 = below college education)
Housing location	Residential location	Binary variable (1 = living within 15 km buffer from the city centre of Beijing [Tiananmen Square], 0 = others)
Built environment	Exclusive bicycle lane	Binary variable (1 = perceived bicycle route on the way is mainly exclusive cycling right of way, 0 = perceived very few or no exclusive cycling rights of way)
	Vehicle disturbance	Binary variable (1 = perceived not disturbed by vehicle flows along the route, 0 = others)
Cycling behaviour	Average cycling trip distance	Binary variable (1 = > 3 km average cycling trip distance, 0 = 3 km or under) or Continuous variable (average cycling distance per trip in regular weather, in km)
	Trip duration by cycling: Commute	Average cycling trip duration for commute trips in normal weather (minutes)
	Trip duration by cycling: Shopping	Average cycling trip duration for shopping trips in normal weather (minutes)
	Trip duration by cycling: Recreation	Average cycling trip duration for recreational trips in normal weather (minutes)
Subjective well-being	Health condition	Binary variable (1 = in fair or poor health condition, 0 = in good health)
Perception of air pollution	Perception of safety	Perceptual levels of safety in cycling, for days with heavy or mild hazardous air quality respectively (−2 = very dissatisfied, −1 = dissatisfied, 0 = neutral, 1 = satisfied, 2 = very satisfied)
	Perception of comfort	Perceptual levels of comfort in cycling, for days with heavy or mild hazardous air quality respectively (−2 = very dissatisfied, −1 = dissatisfied, 0 = neutral, 1 = satisfied, 2 = very satisfied)
	Perception of economy	Perceptual levels of affordability of cycling, for days with heavy or mild hazardous air quality respectively (−2 = very dissatisfied, −1 = dissatisfied, 0 = neutral, 1 = satisfied, 2 = very satisfied)

Table 4
Characteristics of hazardous pollution and cycling intensity.

Commuter cycling variable	Mean	Minimum	Maximum	IQR
Total trips by cycling per week	5.34	0	60	4
Distance per trip (km)	5.5623	0	47.1	4.7
Duration per trip (minutes)	23.63	0	140	20
Travel distance per week (km)				
In light haze ($35.5 \le PM_{2.5} \le 55.4$)	78.79	0	200	50
In moderate haze ($55.5 \le PM_{2.5} \le 150.4$)	57.69	0	300	50
In heavy haze ($PM_{2.5} \ge 150.5$)77	38.04	0	450	50
Travel times per week (minutes)				
In light haze ($35.5 \le PM_{2.5} \le 55.4$)	73.49	0	200	50
In moderate haze ($55.5 \le PM_{2.5} \le 150.4$)	55.31	0	300	60
In heavy haze ($PM_{2.5} \ge 150.5$)	38.34	0	400	50

Note: IQR refers to the interquartile range, which reflects the amount of data in the middle; The minimum 0 means the respondents had no cycling travel during the period.

4. Descriptive results

Table 4 shows preliminary descriptive statistics of individual cycling distance and duration in different levels of exposure to air pollution. In general, travel distance and travel time both decreased with elevated levels of pollution. In other words, many people chose to reduce cycling in face of air pollution. Tainio et al. (2016) concluded from various global cases that even in areas with $PM_{2.5}$ concentrations of higher than 100 μg/m^3, harm only exceeded benefits after 1.5 h of cycling per day, when compared with an indoor environment. It seems that in Beijing ($PM_{2.5}$ of 83 μg/m^3 on average), the health impairment of cycling due to air pollution did not outweigh its physical benefits when using this criterion, even though people felt discouraged and experienced some level of frustration. Some respondents with these types of emotions also expressed in words on the questionnaire:

"*I have to wear a mask again. it's uncomfortable.*"
"*I feel exhausted again even though the air pollution lasted only a few days.*"
"*I feel guilty having my daughter inhale pollutants again, since cycling is the most convenient way to pick her up from school.*"

Fig. 4 shows the travel mode shift when weather changed from high quality to polluted weather. Hazy weather could substantially reduce cycling and even active travel, with 68% of respondents reducing cycling and 64% reducing walking outdoors. In the meantime, cyclists would be very likely to switch to motorized travel modes, because 49% of the respondents reported an increase in

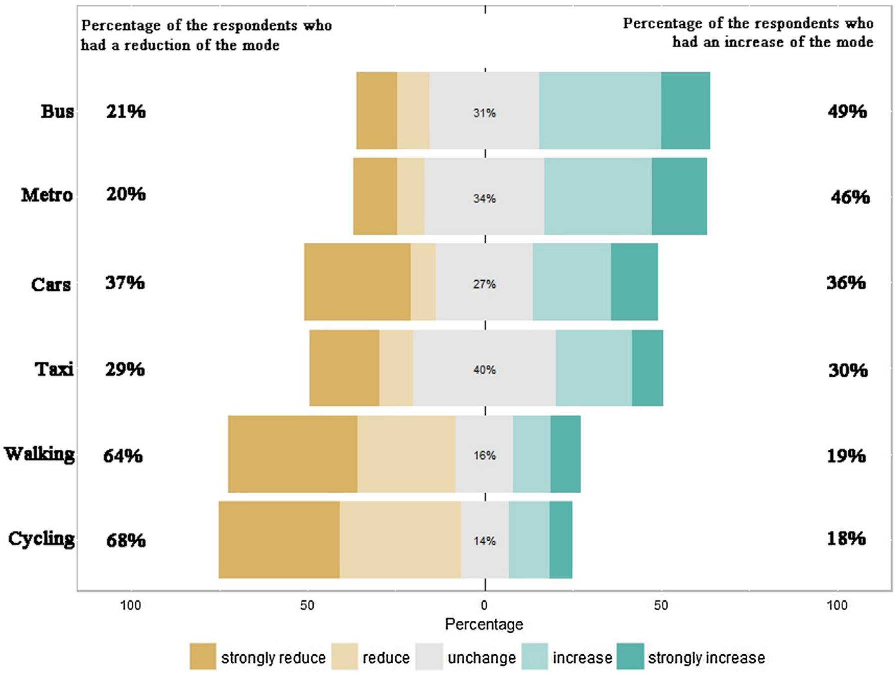

Fig. 4. Travel mode shifts when weather changed from high-quality to polluted.

Table 5
Result of the binary logit regression on cycling in the hazy weather.

Variable	Coef.	Std. Err.	$P > z$	[95% Conf.	Interval]
Socio-demographics					
Age: over 30 years old	0.6657	0.285	0.02	0.107	1.2243
Female	−0.9941	0.2884	0.001	−1.5592	−0.4289
Low income	0.5799	0.2972	0.051	−0.0025	1.1623
Housing location					
Living in the city centre	−0.9583	0.2927	0.001	−1.532	−0.3846
Exposure intensity in cycling					
Average cycling distance	−0.6886	0.2836	0.015	−1.2445	−0.1328
Subjective attitude and well-being					
Perceived level of safety in cycling	1.799	0.7226	0.013	0.3828	3.2151
Perceived level of comfort in cycling	1.23	0.5859	0.036	0.0817	2.3783
Perceived health condition	−0.3739	0.2806	0.183	−0.9238	0.1759
Constant	−2.1868	0.659	0.001	−3.4783	−0.8952
Log likelihood = −160.68175		Number of observations		=	307
		Pseudo R^2		=	0.1609

bus use, and 46% of the respondents had an increase in metro trips. Interestingly, the percentage of the respondents who reported they had a reduction in car use (37%) was higher than the percentage of the respondents who reported an increase in car use (36%). This was mainly because the municipal government applied a car use control policy in the heavy polluted weather. According to the policy, cars with plate numbers ending with either odd or even numbers were not allowed on roads at certain times. Therefore, the percentage of the respondents who used cars was less than those who took the metro or the bus. The details of socioeconomic variations in the change of travel mode will be explored in the next section.

5. Regression analysis

In this section, two separate models explore the impact of hazy weather on cycling behaviour. The first model, a binary logistic model, was conducted to explore whether people chose to continue cycling or not in the hazy weather. The second model further employed a multinomial logistic model to investigate the mode choice changes in the hazy weather, with a comparison between those who continue cycling or give up cycling in the hazy weather. It should be noted that though the data structure has the characteristics of nested data, with samples from the same locations that share the same built environment characteristics, all the variables used in the survey were the individual perceptions. Thus, multilevel model techniques were not adopted in the paper.

Table 5 shows the regression results of cycling decisions in hazy weather. The dependent variable “1” refers to “continued cycling in the hazy weather” while “0” refers to “no cycling in the hazy weather” in the binary logit regression. Respondents’ attitudes toward cycling played an important mediating role among all the variables. Having a higher sense of safety and comfort in cycling was significantly associated with deciding to cycle in hazy weather. In other words, a positive image on cycling in terms of cycling experiences relative to other travel modes was very essential towards cycling even in polluted weather. It implied that encouraging people to nudge preferences for cycling was very important to nurture their cycling habits.

Additionally, socio-economic status also significantly influenced people’s cycling decisions in hazy weather. Residents with lower incomes, those over 30 years old and male respondents were more likely to continue cycling in hazy weather. One of the major reasons for this is that cycling is cheaper than other travel modes. In addition, passengers can travel door to door by cycling, which saves transfer and waiting time for a short-distance trip. Table 5 shows that the respondents who lived in the city centre were more likely to give up cycling in the hazy weather than other people. One of reasons for this may be that pollution was worse in the city centre in the hazy weather in Beijing (Fontes et al., 2018). Table 5 also shows that the people who had longer cycling distances were more likely to give up cycling in hazy weather.

The second logistic model further explores the mode choice changes from good-quality weather to hazy weather. Table 6 presents the results. The results show that perceptions towards cycling play an important role in potential cycling behaviour changes facing hazy weather. A higher perceived health condition could significantly lead to a lower possibility of cycling and a higher possibility of driving in hazy weather. This result may be explained by the fact that healthier people are more considerate about their potential illness, and are more likely to give up cycling, which exposes them to potential sources of air pollution. Increases in perceived safety in cycling associated with a lower probability of substituting cycling with public transit in hazy weather. A higher safety perception means higher individual confidence in arriving at the destination by cycling without physical harm. Moreover, perceived comfort with cycling could also reduce the possibility of driving even in hazy weather. Perceived comfort refers to cycling experiences of being active on a bicycle other than being inactive in a vehicle. It also includes the infrastructure planning towards a bicycle-friendly environment, such as facilities that support cycling, exclusive bicycle lanes, and calm zones. These supporting facilities and areas could significantly improve the cycling experiences of the cyclists in hazy weather, with a higher possibility of being involved in transport injuries. Such bicycle-friendly design will not only protect cyclists from faster motorised traffic, but also cross-protect slower pedestrians (Kerr et al., 2016). This result implies that a balance needs to be made between city-level pollution mitigation

Table 6
Multinomial logistic regression for mode shifting from high-quality weather to polluted weather.

Reference group (stick to cycling)	Vehicle	Transit	Walk
Socio-economics			
Female	0.5913(0.088)	0.7662(0.013)	−0.192(0.786)
Age: over 30 years old	−0.588(0.097)	−0.634(0.042)	−0.027(0.97)
personal monthly income: RMB			
3000–8000	0.9384(0.015)	0.6351(0.049)	−0.918(0.211)
> 8000	1.390(0.029)	0.4289(0.478)	−0.440(0.729)
education(college and above)	−0.078(0.817)	0.1935(0.515)	2.314(0.008)
Housing location			
Outside the city centre	0.2842(0.412)	0.4556(0.134)	−.111(0.868)
Exposure intensity in cycling			
Average cycling trip distance	0.7621(0.044)	1.159(0)	0.7155(0.334)
Commute trip duration by cycling	−0.020(0.06)	−0.015(0.092)	−0.018(0.482)
Shopping trip duration by cycling	0.0138(0.127)	0.0087(0.288)	0.0283(0.087)
Recreational trip duration by cycling	−0.000(0.997)	0.0009(0.837)	−0.034(0.077)
Subjective wellbeing			
Perceived health condition	0.8300(0.023)	−0.033(0.911)	−0.719(0.298)
Perceived level of safety in cycling	−0.166(0.842)	−1.34(0.068)	−1.50(0.327)
Perceived level of comfort in cycling	−1.42(0.042)	−0.898(0.155)	−1.64(0.233)
Constant	−0.687(0.429)	0.7277(0.315)	−0.128(0.932)
Log likelihood = −326.35			
Number of obs	307	Prob > chi2	0
LR chi2(95)	82.38	Pseudo R2	0.1121

Note: The values in bracket is p-values.

priorities and investment into sustainable transportation. This can be evidenced by a lack of willingness to shift to transit in hazy weather when perceptions of safety and comfort level are high. However, three perception variables have no significant differences between cycling and walking. A possible reason is that these perceptions could be very similar to walking compared with cycling in hazy weather.

Socio-economic factors were also found to have a significant impact on behaviour change in the face of hazy weather. Females were more likely to switch to vehicle and public transit in the face of hazy weather. One possible reason is that males cycle more persistently in comparison with women because of their ongoing commitment towards physical activity and better physical strength. In contrast, women are more sensitive to air pollution and related illnesses. Income is also a determinant of travel mode change in the hazy weather. Compared with the low-income population, the middle-income population is more likely to take the car or transit, and the high-income population is more likely to switch to cars in the hazy weather. The comparison between different income groups found that whether or not to switch to motorised travel modes in hazy weather depended heavily on financial constraints. Higher-income earners were more likely to choose motorized modes for comfort, health, and swiftness. It is very likely that the low-income population is not willing to give up cycling through means of self-selection because they lack other means of transport or financial resources.

Higher levels of cycling, measured by average cycling trip distance and duration also influence the cycling behaviour changes in hazy weather. With long average cycling distances to destinations, respondents have a higher probability of choosing buses, metro, and cars for general travel. These shifts, however, vary between different travel purposes. Commuting trip duration is positively associated with possibility of continuing cycling. One possible reason is that these commuting cyclists may be more familiar with the cycling routes and are not familiar with driving and transit routes that may also risk delaying them in hazy weather. This result adds to the existing literature by providing the evidence that commuting cycling travel is not only less susceptible to generic weather changes such as precipitation, temperature or wind, but also to hazardous air pollution such as hazy weather.

When it comes to non-work trips, respondents often take walking as a substation of cycling. Specifically, with longer cycling trip durations to regular shopping destinations, people often prefer walking to shop. Respondents may change their shopping destinations on hazy days and shop at close locations. This phenomenon could be explained by spatial diversification theory (Hanson, 1980), claiming that shopping destinations of consumers are not fixed. Even within the same niche, such as supermarkets, customers might seek to change destination on special occasions (such as discount promotions, or difficulty in travelling to customary destinations by cycling in hazy weather in this case). For recreation destinations (such as public parks and city squares), where options for travel are generally fewer, walking becomes less attractive than using a bicycle to access a destination on hazy days. One possible reason is that cycling may not only serve as a travel means to these destinations, but also an important part of the journey that gives the respondents pleasure and special experiences other modes cannot provide.

6. Discussions and policy implications

This study aims to investigate how hazy weather could change cyclists' cycling behaviours and shape their travel mode choices.

This study contributes to the existing literature by providing evidence regarding the impact of $PM_{2.5}$ on cycling behaviour from the perspective of perceptions borrowing the theory of planned behaviour. It also enriches the present studies by adding evidence from a fast-growing metropolis in the developing context. In the following section, several theoretical and policy implications are discussed.

Firstly, the study found that hazy weather could significantly reduce cycling and encourage people to switch to other travel modes, especially motorized travel modes. This finding provides evidence that environmental protection is an important prerequisite for sustainable transportation. Clean air could increase the visibility on the way and remove people's fear of health problems on polluted days. Thus, good air quality is essential for people to cycle safely and in good health conditions. The most important implication for this study is that the government must invest more to make the sky bluer, which may potentially encourage more people to cycle.

This study also shows that people who changed their travel modes from cycling to motorised modes had a higher tendency to travel by bus or metro than by car. It seems that policies designed to limit car use in hazy weather can reduce the pollution caused by cars. However, it should be recognised that the growing car-sharing business, which provides people an alternative way of continuing to use cars in hazy weather, could counteract the positive effects of the municipal car use limiting policies.

Additionally, the study also found that the transport disadvantaged, who are deprived of transport and financial resources, such as the low-income population, people who are over 30 years old, females, and people who live in the suburban areas are more inclined to continue cycling in the hazy weather, while better educated and higher-income cyclists are more sensitive to the worsening of air quality than other people. These individuals are more likely to reduce cycling when they experience hazy weather. This might be because of their higher awareness of the health risks and the necessary precautions in hazardous weather. These transport disadvantaged are also victims in the environmental justice discourse. In hazy weather, they have fewer choices and so have less of a chance of switching to motorized travel modes. This situation means that they have to be exposed to the air pollution in the hazy weather, and inhale more environmental pollutants produced by more vehicles due to the hazy weather. What is worse, these disadvantaged social groups are also more susceptible to health problems. In most cases, these transport disadvantaged choose to cycle not due to their preferences for cycling, but as a forced decision due to their financial constraints. City administrations should provide both interim policies and long-term planning to reduce social costs and exclusion to the largest extent possible before the environment fully recovers. The governments should invest more towards these people to encourage them to take public transit and other healthier modes on hazy weather days. Meanwhile, the governments should also subsidize more towards these groups of people for perioral health checks to prevent chronic illnesses.

Moreover, perceptions about cycling are found to have an extra effect on cycling in air pollution, controlling for other variables. Perceptions of comfort and safety towards cycling relative to other travel modes significantly contributes to the higher possibility of continuing cycling in air pollution, which is consistent with many existing studies on clean air (Motoaki and Daziano, 2015). This study adds to the existing literature by providing the encouraging role of positive images of cycling in air pollution. That is to say, positive perceptions of safety and comfort towards cycling may reduce perceptive risks of cycling in the polluted air. In this sense, behaviour education towards positive images of cycling is also important. Policies should nudge cycling habits in the following ways: first, cycling management is very important towards a cycling renaissance. Perceived traffic disturbance and exclusive bicycle lanes are two important elements affecting perceptive bicycle safety. The local governments should provide a more connected exclusive bicycle lane system joining communities and main destinations. Moreover, it is important to give road rights back to the cyclists. Local laws and regulations should be launched to manage the situations such as occupying spaces of cyclists by casual parking and exceeding speed limitations on the roads. Additionally, providing other bicycle-friendly supporting facilities, such as bicycle racks, improved lighting systems, and improved green space can all contribute to the cycling-friendly environment. The "soft strategies," such as cycling promotion movements and the "green" travel behaviour campaign, which are run by the municipal government and local communities, are beneficial, in that they can nurture a good atmosphere for using bicycles. Nevertheless, it should be noted that cycling in hazy weather still has health risks for the cyclists, though a positive image of cycling contributes to more use of bicycles in air pollution. Thus, these strategies should be integrated with environmental protection initiatives to promote sustainable and healthy travel.

7. Conclusions

Cycling has become a well-recognised global travel mode for promoting environmental protection, energy savings, and physical benefits. However, implications drawn from cleaner air quality contexts might underestimate the health risk of cycling in highly polluted urban contexts, where levels of $PM_{2.5}$ are much higher than the criteria set by the WHO. This study contributes to the existing body of knowledge by extending weather's effect on cycling into a highly polluted context, taking Beijing as a case study. The results show that air with higher concentration of $PM_{2.5}$ contributes to a lower possibility of continuing cycling, with socio-economic variations. People with higher probabilities of persisting in cycling in polluted air are more likely to be male, over 30 years, lower income, or those who live in outside the city centre. Perceptions could play an important role in mediating cycling behaviour in the polluted days. More positive perception regarding comfort and safety of cycling could contribute to a higher possibility of continuing cycling on the polluted days. When it comes to the potential behaviour change in hazy weather, public transit and private vehicle are the most popular substitutes among regular cyclists in Beijing, but higher-income cyclists more often switch to private vehicles rather than public transit. However, people of lower socio-economic status may be more likely to continue cycling in hazy weather.

For future research, a longitudinal study might be able to examine the causal effects of perceived pollution and cycling behaviour change. A larger sample size or the assistance of advanced data collection techniques such as big data may be helpful to gain a deeper understanding and more nuanced results. Moreover, a more detailed and structured survey design could help to better understand the cognitive and psychological process of how perceptions towards the surrounding environment transform cycling behaviour and respective changes.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.trd.2018.07.015.

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