Science of the Total Environment 889 (2023) 164262

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessing carbon reduction benefits of teleworking: A case study of Beijing

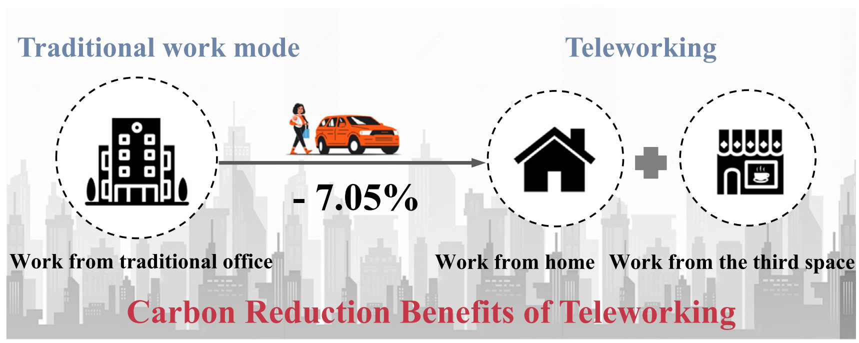
Wenzhu Li [a], Ningrui Liu [a], Ying Long [b,*]

[a] School of Architecture, Tsinghua University, Beijing 100084, China
[b] School of Architecture and Hang Lung Center for Real Estate, Key Laboratory of Ecological Planning & Green Building, Ministry of Education, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- An approach is proposed to assess the carbon reduction benefits of teleworking by industry.
- Carbon emission reductions are computed using large-scale travel survey data.
- Uncertain associated parameters are considered through Monte Carlo simulation.
- 7.05 % of annual carbon emissions by transport in Beijing are declined by teleworking.
- The suggested method can potentially be used in other regions.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Kuishuang Feng

Keywords:
Carbon reduction
Teleworking
Quantitative approach
Commuting distance
Monte Carlo simulation

ABSTRACT

Teleworking can efficiently decrease the energy consumption and carbon emissions related to physical commuting. Previous studies on assessing the carbon reduction benefits of teleworking were customarily performed according to hypotheses or qualitative methods, and disregarded different potentials of different industries for teleworking implementation. In this study, a quantitative approach was proposed to assess the carbon reduction benefits of teleworking in different industries, which was illustrated via the case study of Beijing, China. The teleworking penetrations of different industries were first estimated. Then, the carbon reduction of teleworking was assessed through the decreased commuting distance using the large-scale travel survey data. Finally, the study samples were extended to a citywide scale and the uncertainty of carbon reduction benefits was evaluated with Monte Carlo simulation. The results showed that (1) teleworking can lead to an average of 1.32 (95 % confidence interval (CI): 0.70–2.05) million tons of carbon reduction, accounting for 7.05 % (95 % CI: 3.74 %–10.95 %) of the total carbon emissions by road transport in Beijing; and (2) information and communication, and professional, scientific and technical service industries had higher carbon reduction potential. Additionally, the rebound effect slightly weakened the carbon reduction benefit of teleworking, which was necessary to be considered and mitigated through relevant policies. The proposed method can be also applied to other regions worldwide, helping to exploit future work patterns and realize global carbon neutrality targets.

1. Introduction

During the coronavirus pandemic (COVID-19), tens of millions of people worldwide had to shift to teleworking because of lockdown requirements, as well as self-imposed isolation (Bouziri et al., 2020). In 2020, the proportion of employees in the United Kingdom working from home increased from 5 % to 47 % (Felstead and Reuschke, 2020). Over 37 % of

* Corresponding author at: Tsinghua University, Room 501, Architecture Building, Haidian District, Beijing 100084, China.
E-mail addresses: LiWenzhuArch@163.com (W. Li), liunr18@mails.tsinghua.edu.cn (N. Liu), ylong@tsinghua.edu.cn (Y. Long).

http://dx.doi.org/10.1016/j.scitotenv.2023.164262
Received 28 December 2022; Received in revised form 14 April 2023; Accepted 15 May 2023
Available online 19 May 2023
0048-9697/

European employees worked from home, exceeding 60 % in some European countries, such as Finland (Eurofound, 2020). Meanwhile, almost half of the workforce in the United States worked from home (Brynjolfsson et al., 2020). In 2022, the number of teleworkers reached 461 million in China, accounting for 43.8 % of all Internet users (China Internet Network Information Center, 2022). Under this circumstance, the Chinese government has taken action to enrich teleworking products and services in the "14th Five-Year Plan for Digital Economy Development" (The State Council of the People's Republic of China, 2022). Beijing, as the capital of China, is renowned for its excellent network infrastructure, abundant innovative industries, and millions of workers. Since the outbreak of the pandemic three years ago, Beijing has also been rapidly developing teleworking. For example, the "2022 Beijing Comprehensive Traffic Management Action Plan" encourages teleworking as an approach to regulate transportation demand and promote low-carbon development (Beijing Municipal Commission of Transport, 2022). Currently, teleworking has become a common and widespread way of life worldwide (Bloom et al., 2015).

Teleworking, also called telecommuting, refers to partially or entirely working at home or in an alternative location, such as an adjacent library or a café bar, compared to a centralized workplace in a distant place (Di Marino and Lapintie, 2017). It was initially proposed by Jack Nilles in the 1970s (Nilles, 1975) and could be categorized into two main modes: working from home and working from a third space (e.g., library, café, coworking spaces, etc.). Meanwhile, information and communications technology (ICT) provided significant support for teleworking (Mokhtarian, 1991), such that the ability to work remotely allowed millions of people to maintain their jobs and productivity during periods of harsh lockdowns (Allen et al., 2015). Many activities and tasks can be delivered via remote working, except those requiring interaction with people or using site-dependent equipment (Sostero et al., 2020). According to a recent estimate, 37 % of all employment in the United States may be accomplished permanently at home (Dingel and Neiman, 2020).

Teleworking is widely recognized as a movement that benefits employees and employers. It can increase employees' productivity due to fewer disruptions, flexible longer work hours, more but shorter video conferences, and working at peak hours of productivity as opposed to usual work hours (Atkyns et al., 2002; Grawitch et al., 2010). It has also been advocated to achieve a healthier work-family balance (DuBrin and Barnard, 1993) and reduce exposure to illness or poor weather (Gill, 2006). Consequently, the improvement of employee satisfaction by teleworking due to the advancement of employee morale, a sense of being trusted, and the convenience of a home diet result in less turnover and absenteeism (Allen et al., 2015; Lister and Hamish, 2011). However, it increases the dependence on ICT for work-related communications (Hambly and Lee, 2019) and makes it challenging to manage employees (Pyöriä, 2011). With fewer face-to-face interactions, the employee perception of loneliness and isolation may increase (De Vries et al., 2019), worsening urban sprawl-related social issues (Rhee, 2009). Most problems can be mitigated by enhancing communication technologies and promoting practical leadership skills (Golden et al., 2008). Both working from home and working from a third space in the neighborhood are considered to have the above carbon reduction benefits (Mokhtarian, 1991), while working from the third space also can circumvent the disadvantages of working from home, such as isolation, etc. (Buffer, 2020). Thus, both working from home and a third space in the neighborhood are considered in this study (Fig. 1).

The switch towards teleworking offers a valuable opportunity to reduce road traffic, carbon emissions, energy consumption, and associated environmental impacts (Akbari and Hopkins, 2019; Pratt, 1984). As the transport sector is a significant contributor to urban carbon emissions, reducing commuting travel through teleworking may substantially reduce corresponding carbon emissions (Höjer, 2002; Mokhtarian et al., 1995; O'Leary et al., 2022). Teleworking can provide short-term and long-term impacts for reducing carbon emissions (Dulac, 2013). Short-term impacts are typically the result of daily or weekly decision-making, such as lowering commuting travel or replacing them with a green transportation mode (i.e., walking, cycling, and public transport) (Güereca et al., 2013; Tang et al., 2011). Specifically, teleworking can save commuting time and distance (Nelson et al., 2007), and alleviate traffic congestion, resulting in more efficient travel (Nijland and Dijst, 2015). Meanwhile, if teleworkers only need to make a few roundtrips every week, they may have a better tolerance for public transport, hence lowering the environmental effect of commuting (Tang et al., 2011). The long-term impacts create multiple purchase choices and related social repercussions involving home and vehicle acquisition (Kim et al., 2015). Other studies also illustrate the potential savings on transportation infrastructure, parking expenses, office space, office operation, and associated energy consumption (Fuhr and Pociask, 2011; Nilles, 1990). However, teleworking may require more office space and office amenities at home, such as a dependable broadband network, personal computers, and printers (Yen, 2000) or increase household energy consumption for heating, ventilation, air conditioning, and lighting (Ku et al., 2022). Energy use behaviors may be improved since teleworkers pay for energy consumption at home rather than at work (Andrey et al., 2004).

Therefore, in the context of achieving carbon neutrality, it is vital to precisely evaluate the carbon reduction potential of teleworking. Most previous studies assessed the relationships between teleworking and carbon reduction adopted qualitative methods (Roth et al., 2008), and only a few studies employed quantitative methods, which were generally divided as survey data analysis (Chakrabarti, 2018), scenario modeling (Hofer et al., 2018; Larson and Zhao, 2017), and teleworking pilots' evaluation (Balepur et al., 1998) (Table S1). Survey data analyses utilize publicly accessible datasets on working behavior and travel to assess the effects of teleworking on carbon reduction. Specifically, large-scale national travel surveys and time-series data on work and travel behavior tend to provide stronger evidence (Kim et al., 2015). Nevertheless, the accuracy of survey data analyses is influenced by sample size, which can vary substantially from a few individuals (Andrey et al., 2004) to tens of thousands (Giovanis, 2018). Small sample sizes and unclear survey questions can lead to inaccurate results (Lari, 2012). The scenario modeling method employs simulation models to predict the impacts of teleworking across various levels of teleworking penetration, temporal and spatial scales (Dissanayake and Morikawa, 2008). It offers an opportunity to simulate

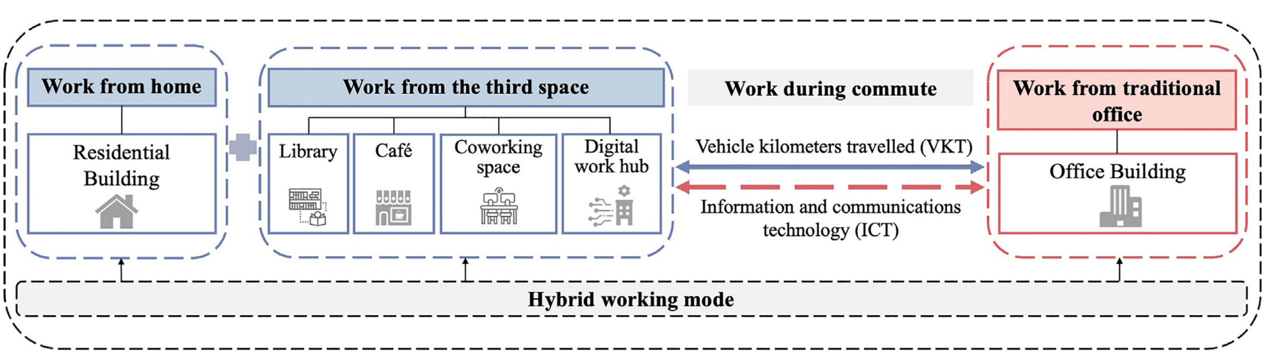


Fig. 1. Relationship between teleworking and traditional office work modes.

multiple scenarios for areas with limited data and provide fast results (Bakaç et al., 2021), however the predictions are difficult to be validated (Hook et al., 2020). The third method, teleworking pilots' evaluation, mainly depends on travel diary data among teleworkers and non-teleworkers, which is costly and labor-intensive for data acquisition and unavailable in most regions. Some studies combine survey data analysis with scenario modeling (Kitou and Horvath, 2008). In each method, specific carbon reduction values are calculated using the Intergovernmental Panel on Climate Change (IPCC) approach. There are two methods of the calculation: multiplying fuel consumption by carbon emission factors and multiplying vehicle kilometers traveled (VKT) by converted carbon emission factors (IPCC, 2006). The latter is considered more accurate and widely used in assessing the carbon reduction potential of teleworking (Koenig et al., 1996; Vu and Vandebona, 2007), when VKT, travel modes, unit fuel consumption, vehicle fuel types, and other requisite data are available (Zhang et al., 2019) (Table S2). Furthermore, uncertainties are involved in the assessment of carbon reduction. Some studies have overlooked the consideration of uncertainties, while others have only provided qualitative descriptions of relevant uncertain parameters (Matthews and Williams, 2005). To quantitatively model uncertainties in carbon reduction, commonly employed methods include Monte Carlo simulation, robust optimization, and modeling to generate alternative scenarios (Yue et al., 2018). Monte Carlo simulation is usually chosen when both the uncertain parameters and their distributions are known, and it has been widely used in uncertainty modeling for carbon reduction through teleworking (Charpentier and Klett, 2000 Kitou and Horvath, 2003). However, there is a lack of systematic quantitative approach in these limited quantitative studies. Previous studies mainly examined the carbon reduction benefits of a certain percentage of telework implementation without considering the varying potentials of implementing teleworking in different industries, which could lead to inaccuracies in the results. Besides, research about the impacts of teleworking on carbon reduction is still lacking in China.

Overall, three challenges of carbon reduction assessment of teleworking are summarized: (1) How can we select the appropriate quantitative approach to assess the carbon reduction of teleworking? (2) How can we consider the effect of different industries on the carbon reduction of teleworking? and (3) How can the carbon reduction of teleworking along with its uncertainty be evaluated? To tackle these challenges, this study aimed to propose a quantitative approach to assess the carbon reduction benefits of teleworking in different industries using large-scale travel survey data, which was applied to Beijing, China. It can provide supportive evidence for the significant potential of teleworking to reduce urban carbon emissions, provide essential references for decision-makers, and contribute to achieving global carbon neutrality targets.

2. Methodology

To quantify the carbon reduction benefits of teleworking accurately and effectively, this study proposed a quantitative approach using large-scale household travel survey data, which considered the varying potential of implementing teleworking in different industries. The approach consists of four steps: (1) estimation of teleworking penetration, (2) estimation of commuting distance, (3) estimation of carbon reduction, and (4) uncertainty analysis (Fig. 2). Firstly, this study explores the practical potential of teleworking among different industries through teleworking penetration and saved commuting VKT using large-scale travel survey data. Then, the carbon reduction from teleworking is calculated and expanded to the citywide scale. Finally, the impact of uncertain associated parameters on the carbon reduction benefits of teleworking is evaluated through Monte Carlo simulation. By integrating large-scale travel survey data analysis, teleworking penetration implementation, carbon reduction calculation based on VKT, and uncertainty analysis, this approach provides a more accurate and reliable quantitative result. The detailed procedures for each step of the approach are presented below.

2.1. Estimation of teleworking penetration

In general, the implementation potential of teleworking varies by industry, which can be assessed using teleworking penetration. Teleworking penetration can be defined as the potential proportion of time spent on teleworking in the total time for working in different industries (Susan Lund et al., 2020). Teleworking penetration depends on the characteristics of activities within each industry, including whether workers need to be physically present to complete tasks, utilize location-specific equipment, or communicate with people (Hatayama et al., 2020). Employers have discovered that it is far more effective to accomplish some work face-to-face than remotely (Susan Lund et al., 2020). Thus, two metrics are devised for teleworking penetration: the maximum penetration, which includes all activities that can be conducted remotely in theory, and the effective penetration, which only consists of those activities that can be performed remotely without sacrificing effectiveness. Due to the differences in industrial divisions between countries, some industries that have been merged or split up need to be carefully distinguished. For example, the wholesale trade and retail trade in Standard Occupational Classification (SOC) codes are two industries, while they are merged into a wholesale and retail trade industry in China.

2.2. Estimation of commuting distance

Teleworking primarily reduces urban carbon emissions by reducing commuting travel. As mentioned in the introduction, the reduced commuting VKT can assess more accurately the subsequent carbon reduction through teleworking (Lachapelle et al., 2018; Zhang et al., 2019). It requires to be estimated through household travel survey data, which are available for many countries or cities, such as the United Kingdom, Canada, Sydney in Australia, and Beijing in China. These data include industry codes, transportation modes, travel purposes, departure time, and arrival time. The commuting VKT in the ith industry with the jth modes of transport, denoted as L_{ij} (m), can be calculated using the average travel speed of different transportation modes and commuting time, as is shown in Eq. (1). Then, the total decreased commuting VKT by teleworking in a day, denoted as $\triangle L$, can be further obtained by the teleworking penetration and commuting VKT, as is shown in Eq. (2).

$$L_{ij} = \sum_{k=1}^{n_k} (T_{ak} - T_{dk}) V_j \tag{1}$$

$$\Delta L = \sum_{i=1}^{n_i} \left(P_i \times \sum_{j=1}^{n_j} L_{ij} \right) \tag{2}$$

where T_a (s) and T_d (s) are, respectively, the arrival time at the office and the departure time from home, V_j (m/s) is the average speed of the jth modes of transport (i.e., car, truck, taxi, motorcycle, etc.), P_i is the teleworking penetration in the ith industry, n_k represents the number of trips in L_{ij}, n_i is the number of industry types, and n_j is the number of transport modes.

2.3. Estimation of carbon reduction

We focused on CO_2 generated from the combustion of vehicle fuels, including light vehicles (i.e., cars, motorcycles, and taxis) and heavy vehicles (i.e., trucks and buses). Green transportation, including walking, bicycling, and e-biking, has zero or negligible carbon emissions (Yang and Ho, 2016). Public transportation, such as subways and buses, has fixed routes and operating times, which implies that the transition of human traveling behavior will not significantly change it. Therefore, the low-carbon travel modes mentioned above were not considered in calculating carbon emissions. It was worth noting that new energy vehicles had been proliferating in China since 2014. The proportion of new energy vehicles would continue to rise with the proposal of carbon neutrality. Therefore, this study also considered the new energy vehicles in computation.

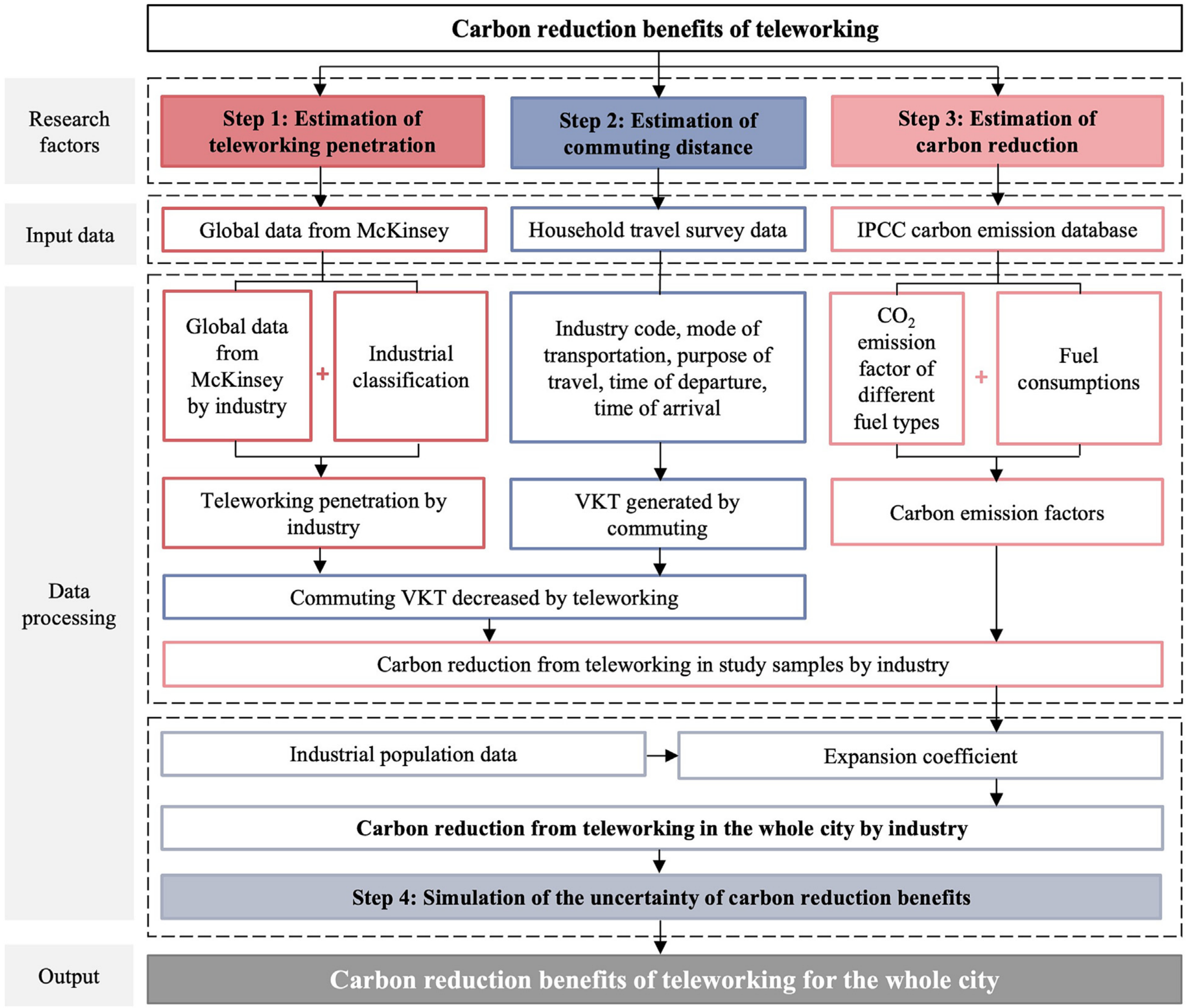


Fig. 2. Four-step approach for assessing the carbon reduction benefits of teleworking.

The IPCC approach based on commuting VKT is adopted to estimate CO_2 emissions (Mi et al., 2017). Let EF_j (kg CO_2/km) denote the CO_2 emission factors of the jth modes of transport, which can be calculated by:

$$EF_j = Y_j \times N_j \times H_j \times O_j \quad (3)$$

where Y_j (L/km) is the fossil fuel consumption of the jth modes of transport; N_j (Kcal/L) is the net calorific value, which represents the amount of heat emitted by the combustion of a unit of fossil fuel; H_j (kgCO_2/Kcal) is the carbon content that reflects the CO_2 emitted per unit of heat released; and O_j is the oxygenation rate of the combustion of fossil fuels. After distinguishing the fuel types of different travel modes, we brought in the data of calorific value, carbon content, and fossil fuel consumption per 100 km, as the oxygenation rate was equal to unity. Additionally, the EF_j (kg CO_2/km) for the new energy vehicles was obtained by multiplying the electricity carbon emission factor (kg CO_2/(kW·h)) by the electricity consumption per kilometer ((kW·h)/km) and was then divided by the grid transmission efficiency.

Let C_{ij} (kgCO_2) denote the carbon emission in the ith industry with the jth modes of transport, and $\triangle C$ (kgCO_2) represents the total annual carbon reduction by teleworking, which is calculated as follows:

$$C_{ij} = EF_j \times L_{ij} \quad (4)$$

$$\Delta C = D \times \sum_{i=1}^{n_i} \left[EC_i \times \left(P_i \times \sum_{j=1}^{n_j} C_{ij} \right) \right] \quad (5)$$

where D is the number of workdays per year, and EC_i is the expansion coefficient of the ith industry, which is calculated by the ratio of the total industrial population in the city to the industrial population in the survey data. Then, the citywide quantitative assessments can be obtained, solving the problem that household travel survey data include only a portion of the municipal population. When calculating the EC_i using the population data in different industries, some employees cannot be divided into a specific industry, including individual business households, rural contracting households, and individual partnerships. They can be considered as the total industrial population data according to the proportion of employees by industry.

2.4. Uncertainty analysis

The uncertainties of assessing carbon reduction from teleworking are caused by the uncertainties involved in the estimation of teleworking penetration in various industries, speeds of transport modes, and fuel consumption. This study modeled the inherent uncertainties of carbon reduction benefits using Monte Carlo simulation as influencing parameters and their distributions were known in this study. The Crystal Ball software implemented in Microsoft Excel 2021 was used to perform the simulation (Gonzalez et al., 2005). It was assumed that the travel speeds and carbon emission factors both followed normal distributions, with a coefficient of variation of 0.3 (Kitou and Horvath, 2008). Since teleworking penetration without losing work effectiveness was considered the most likely value, we assumed that teleworking penetration followed a triangular distribution with the minimum and maximum values derived from effective penetrations and maximum penetrations, respectively. These uncertain parameters were considered statistically independent. 100,000 simulations were performed to obtain a stable result.

3. Case study

Beijing is located in northern China, which is also the capital of China, as shown in Fig. 3. As an international metropolis, Beijing's urbanization has advanced steadily during the last three decades. The residential population was 21.89 million in 2021, including 11.58 million employees. The tertiary industry increased yearly, accounting for 81.0 % of whole industries (Beijing Statistical Yearbook Committee, 2022). Among them, commuting trips accounted for 51.2 % with a total of 35.30 million weekday trips (Beijing Transport Institute, 2022), where cars were the most commuting travel mode. Under the influence of the pandemic in recent years, traffic congestion improved compared to previous years. However, traffic congestion still existed in the central urban area during peak hours. Meanwhile, Beijing, as a pioneer city in the “Low-carbon City” plan, has introduced related policies to encourage teleworking as a means of regulating transportation demand. Therefore, the transitions in the lifestyle of people and the impact of teleworking on commuting in Beijing are of research significance and representativeness for low-carbon urban development.

3.1. Data sources

3.1.1. Data of teleworking penetration

Since teleworking penetrations in different industries of Beijing are difficult to acquire, we first used existing global data from McKinsey Global Institute (MGI). Such data analyzed 2000 activities and 800 occupations in nine countries and established a workforce model based on data from the Occupational Information Network (O*NET), which also included information from China (Susan Lund et al., 2020). They estimated the time spent on each activity by industries and evaluated the theoretical feasibility of conducting each work activity remotely. For example, estimating project costs or drawings can be accomplished remotely in the construction industry, while operating heavy-duty equipment cannot. The proportion of time that was spent remotely for each activity was calculated to establish the theoretical feasibility of teleworking penetration in each industry (Table S3). As the teleworking penetration is mainly estimated on the basis of industry characteristics, it usually does not significantly vary with time and space. Thus, it is reasonable to use global data to assess the teleworking penetration of industries in Beijing. It should be noted that the proposed method in this study is generic and the specific data in a region, if available in future works, can be used in a same manner.

3.1.2. Data of travel

The travel data was derived from the Fifth Beijing Official Household Travel Survey (BOHTS) conducted by the Beijing Municipal Commission of Transport (2015). Since 1986, five rounds of cross-sectional BOHTS (i.e., 1986, 2000, 2005, 2010, and 2015) have been carried out to support the enhancement of transportation strategies in Beijing. The BOHTS was conducted based on Traffic Analysis Zones (TAZ) as the spatial unit. It was based on a 24-h travel diary that included 227,435 trips from 101,815 participants in 40,003 households, representing 0.9 % of the total population in Beijing. Each trip record had various trip attributes, including industry type (e.g., Mining, Manufacturing, Construction, etc.), travel mode (e.g., car, bus, motorcycle, walking, etc.), departure time, arrival time, and travel purpose (e.g., working, schooling, social visit, personal affairs, etc.). In this study, we selected trips generated for working purposes with carbon-emitting travel modes. First, 48,405 participants traveling for working purposes were selected. Then, 13,267 participants traveling with carbon-emitting travel modes were further selected, including car, combination bus, truck, motorcycle, taxi, shuttle bus, and school bus. After removing outlier records, our final research sample included 13,191 employees who provided 27,224 trips. Fig. 4 shows the sample selection and Fig. S1 provides additional data details.

Several other multisource data used in this study were shown in detail in Table 1. It was worth noting that the number of new energy vehicles accounted for 0.5 % of the total number of motor vehicles in Beijing in 2015 (27,875 out of 5,619,000). Therefore, 0.5 % of the commuting distances generated by motor vehicles need to be multiplied by the carbon emission factors of new energy vehicles instead of gasoline or diesel vehicles' carbon emission factors. Combining the above multisource data, we could compute the carbon reduction benefits of teleworking in Beijing.

3.2. Results

3.2.1. Teleworking penetrations in different industries

Due to differences between the industrial classification of China and SOC codes, the data of 16 industries could be directly matched from the

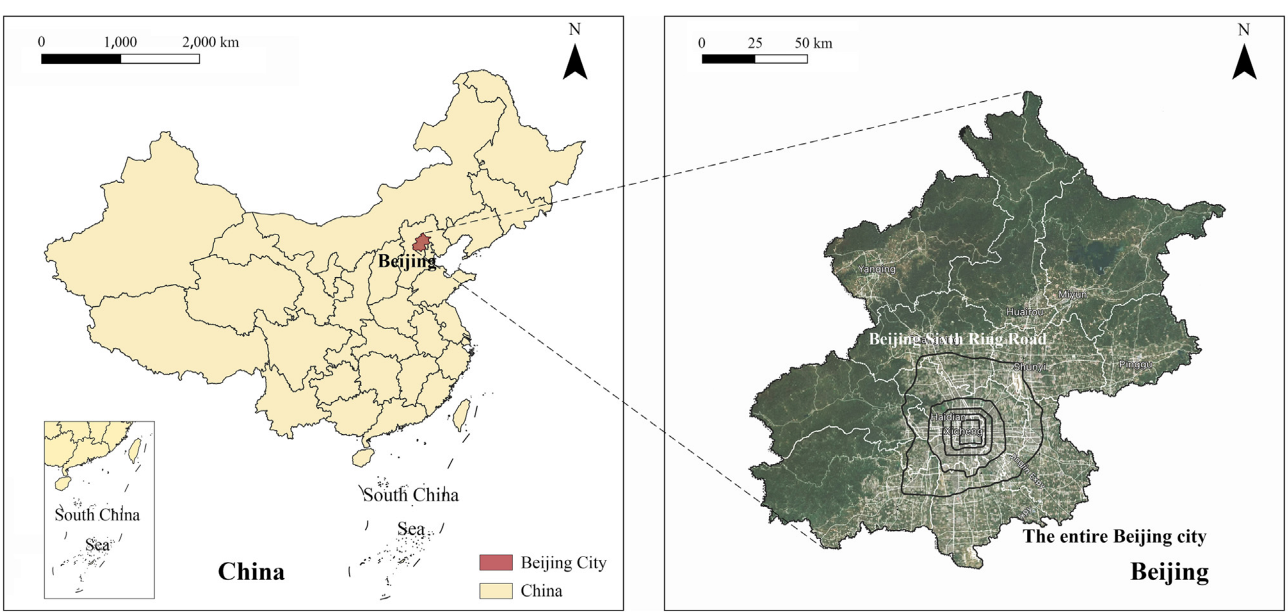


Fig. 3. Study area of Beijing, China.

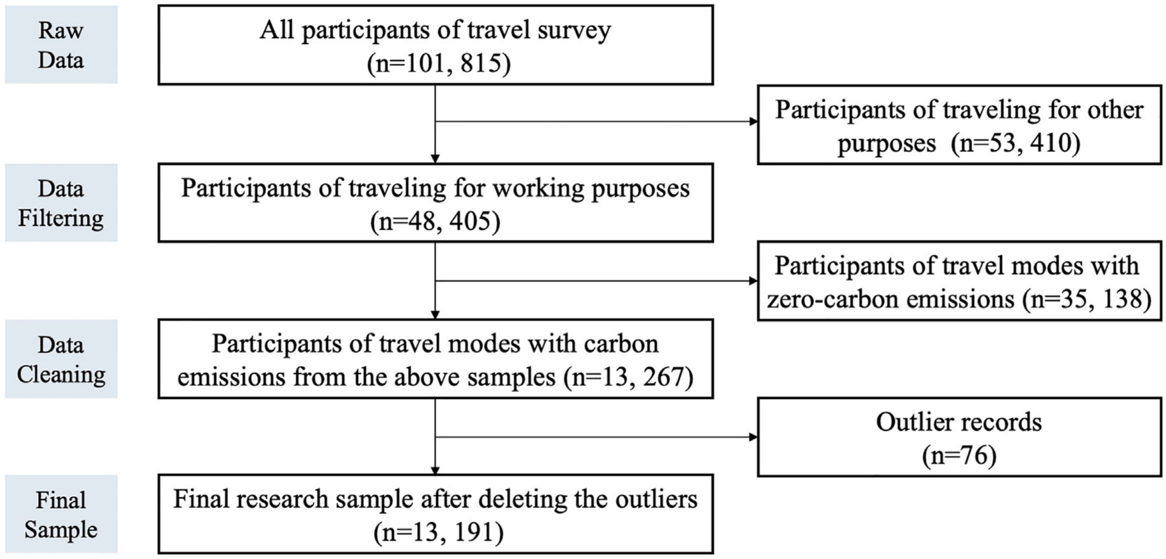


Fig. 4. Procedure of sample selection.

global data of MGI, while 4 industries (i.e., electricity, heating, gas, and water supply; wholesale and retail trade; rental business; international organization) needed to be further explored. The wholesale trade and retail trade were merged into a wholesale and retail trade industry in China. Therefore, we averaged these two industries' upper and lower values to obtain the new teleworking penetration. The rental business was included in real estate. The electricity, heating, gas, and water supply industry belonged to utilities. The international organization had similar characteristics to government administrative support. Therefore, they took the same value as these industries. Combining the global data of 16 industries and revised data of 4 industries, the teleworking penetration values of 20 industries were obtained.

As shown in Fig. 5, several industries have more significant potential for teleworking, including financial and insurance, information and communication, public facilities management, and professional, scientific and technical service. Among them, the finance and insurance industry has the greatest teleworking penetration, reaching 76 % and 86 %. In contrast, manual or physical activities, along with those requiring fixed equipment, such as accommodation and food services, agriculture, forestry, and fishing, have the lowest potential for teleworking. Education has the most significant flexibility of working remotely due to the largest upper and lower spreads, which are 33 % and 69 %. While teaching can move to remote work via online video, both parents and teachers think teaching face-to-face is much more effective. Teleworking penetrations in other industries range from 15 % to 45 %, suggesting that teleworking one or two days per week is more applicable in most industries.

3.2.2. Vehicle kilometers traveled (VKT) of commuting

Using Eq. (1), the commuting times and distances were estimated via the processed large-scale travel survey data. Fig. 6 (a) shows the composition of travel modes. It reveals that commuting carbon emissions are mainly generated from private cars, compared to motorcycles, taxis, school buses, etc. Fig. 6 (b) gives the number of employees in different industries, which indicates that most commuters are engaged in tertiary industries, such as transportation and storage, information and communication. Thus, there is a high potential for teleworking implementation in these industries. Fig. 6 (c) shows that the most common commuting time for a single trip is between 0.40 h and 0.60 h, with a median of 0.67 h, while 0.50 h is the most frequent choice. As shown in Fig. 6 (d), a large proportion of the calculated daily commuting distances, including multiple trips within 24 h, are between 9.00 km and 17.00 km, with a median of 19.87 km (Table S4 and S5). The total commuting distance in the study samples was calculated as approximately 314,527 km per day. According to Eq. (2), the estimated reductions in the commuting distance were about 103,043 and 132,996 km per day when teleworking penetrations were taken as the effective and maximum values, respectively. The commuting VKT of the

Table 1
Description of other data used in this study.

Data	Description	Data source
Chinese industrial classification data	20 categories in Industrial Classification for National Economic Activities.	National Bureau of Statistics, 2016. (http://www.stats.gov.cn/xxgk/tjbz/gjtjbz/201710/t20171017_1758922.html)
Travel speeds data	Average speeds during morning and evening peak in Beijing. Normal speeds of various transportation modes.	Beijing Transport Institute, 2016. (https://www.bjtrc.org.cn/List/index/cid/7.html) Handbook on Statistics on Road Traffic (Yang et al., 2002).
Carbon content data	H_j (kgCO_2/Kcal) indices	2006 IPCC Emission Factor Database (https://www.ipcc-nggip.iges.or.jp/public/2006gl/)
Fossil fuel consumption data	Y_j (L/km) indices	Ministry of Industry and Information Technology of the People's Republic of China, 2022, (https://yhgscx.miit.gov.cn/fuel-consumption-web/mainPage) and several studies (Huo et al., 2012; Huo et al., 2011; Zhang et al., 2014)
Calorific value data	N_j (Kcal/L) indices	Bureau of Energy of the Ministry of Economic Affairs, 2016. (http://www.stats.gov.cn/tjsj/tjcbw/201706/t20170621_1505833.html.)
CO_2 emission factors of new energy vehicles data	EF_j (kg CO_2/km) of new energy vehicles	Several studies (Sun et al., 2020; Tang et al., 2022)
Population data	Number of Population in different industries of Beijing in 2015	Beijing Statistical Yearbook Committee., 2016. (http://nj.tjj.beijing.gov.cn/nj/main/2016-tjnj/zk/indexch.htm)

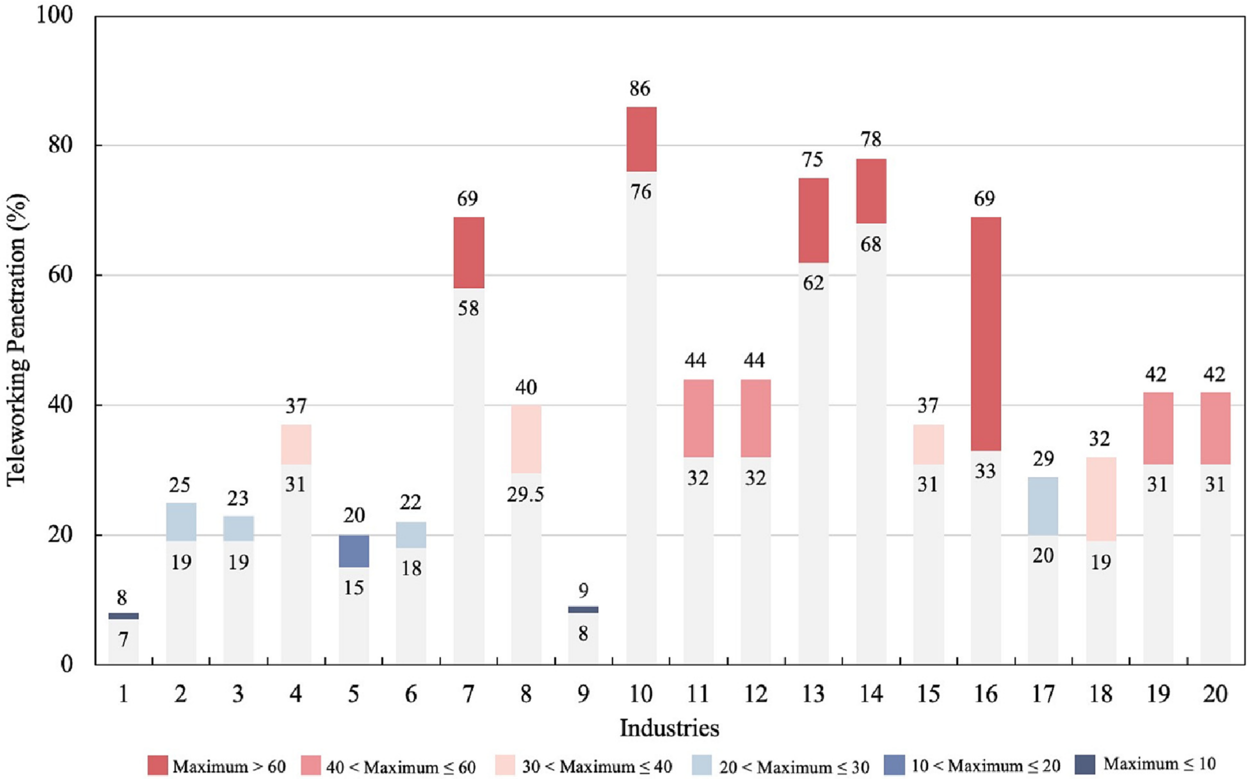


Fig. 5. Maximum and effective penetrations of teleworking by industry.
Note: 1. Agriculture, Forestry, and Fishing; 2. Mining; 3. Manufacturing; 4*. Electricity, Heating, Gas, and Water Supply; 5. Construction; 6. Transportation and Storage; 7. Information and Communication; 8*. Wholesale and Retail Trade; 9. Accommodation and Food Services; 10. Financial and Insurance; 11. Real Estate; 12*. Rental Business; 13. Professional, Scientific and Technical Service; 14. Water Conservancy, Environment, and Public Facilities Management; 15. Residential Assistance, Maintenance, and Other Service; 16. Education; 17. Health Care and Social Assistance; 18. Arts, Entertainment and Recreation; 19. Government Administrative Support; 20*. International Organization.
Nos. 4, 8, 12, and 20 were revised, while the others were acquired by McKinsey Global Institute analysis. The upper and lower values were maximum penetrations and effective penetrations, respectively.

sample can be reduced by 32.76 % to 42.28 % by teleworking, which shows the potential of teleworking to alleviate traffic congestion and reduce commuting.

3.2.3. Carbon reduction benefits of teleworking

The values of EF_j were estimated using Eq. (3) and presented in Table S6. The daily carbon emissions from commuting VKT in the sample were computed as 101.48 tons. The emissions were 101.32 tons when considering the use of new energy vehicles. Due to the decrease in commuting distance, the application of teleworking by industries reduced 33.30 and 43.34 tons of CO_2 per day, when took the effective and maximum penetrations, respectively. Although the use of new energy vehicles had a minimal impact on this outcome, they accounted for more than 5 % of all motor vehicles in recent years with rapid development, which would lead to a significant reduction in future transportation carbon emissions.

Using Eq. (4) and Eq. (5), as there were 250 working days throughout 2015, the potential impact of teleworking resulted in a reduction of 1.15 and 1.49 million tons of CO_2 per year in Beijing when teleworking penetration took the maximum and lower values (Table S7). According to the energy consumption data of transportation in the National Bureau of Statistics, total carbon emissions generated by transport in Beijing were calculated as 18.73 million tons in 2015 (Sun et al., 2020). Although the carbon reduction benefit from teleworking was a small fraction of millions of tons of carbon reduction targets, it could result in a 6.14 % and 7.96 % reduction of the whole carbon emissions by road transport in Beijing.

The carbon reductions from teleworking by industry in Beijing are shown in Fig. 7. Two industries had a higher potential to achieve carbon reduction through teleworking implementation, which were information and communication, and professional, scientific and technical service. Among them, the latter contributed the most. The primary and secondary industries (agriculture, forestry, and fishing; mining; electricity, heating, gas, and water supply, etc.), as well as international organization, accommodation and food services, residential assistance, maintenance, and other services, had limited potential for carbon reduction through teleworking.

3.2.4. Uncertainty of carbon reduction benefits of teleworking

The uncertainties of teleworking penetrations, travel speeds, and carbon emission factors on carbon reduction benefits were evaluated using Monte Carlo simulation. The results showed that the carbon reduction reached an average of 1.32 (95 % CI: 0.70–2.05) million tons of CO_2 in 2015, accounting for 7.05 % (95 % CI: 3.74 %–10.95 %) of the overall carbon emissions by road transport in Beijing (Fig. 8). As the above calculation mainly focused on the differences in teleworking penetration, this Monte Carlo simulation could effectively help recognize the influence of uncertainties in all parameters on the potential carbon reduction.

4. Discussion

4.1. Academic contributions

This study proposed a quantitative approach using actual large-scale travel survey data to estimate carbon reduction from commuting trips, which could bridge the gap between the carbon reduction benefits of teleworking and its implementation potential with industry characteristics.

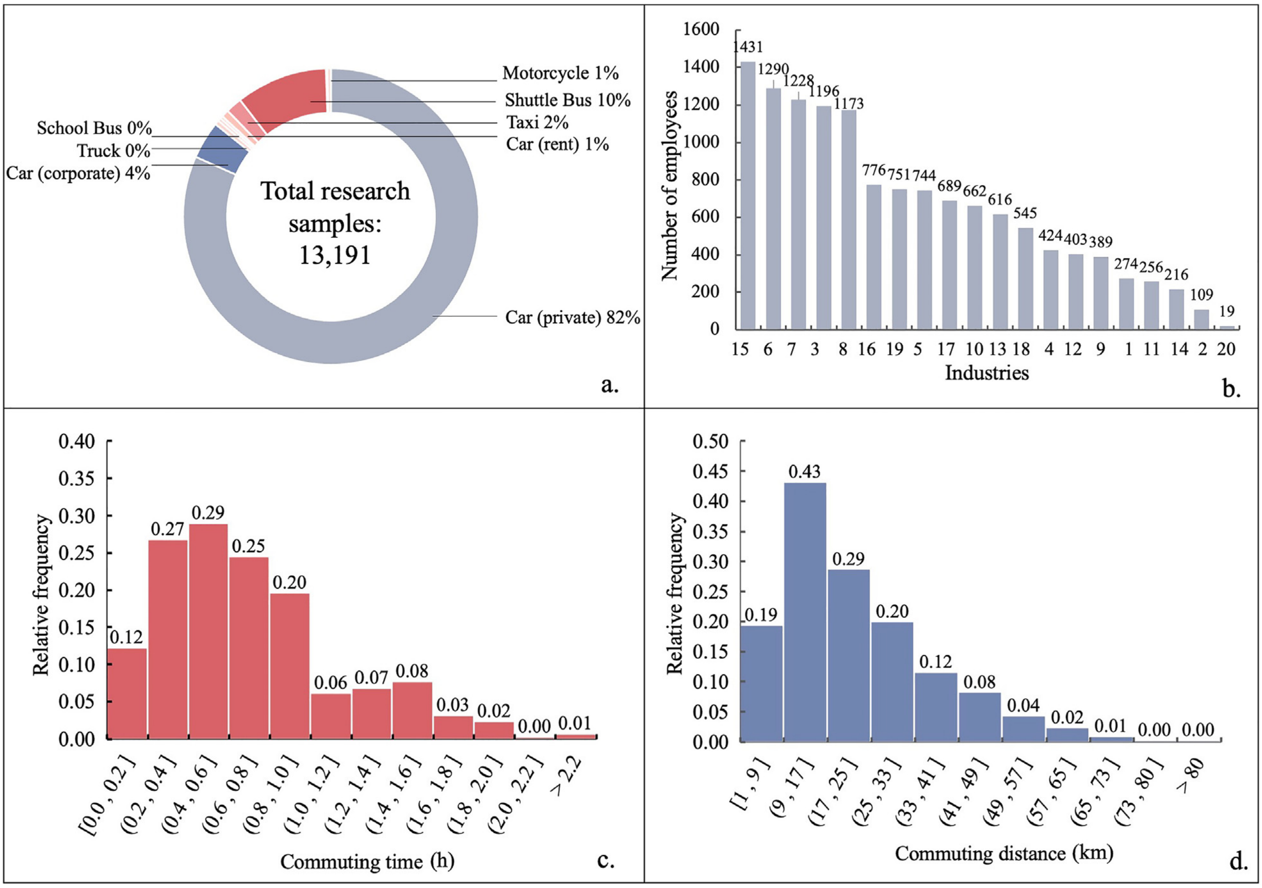


Fig. 6. Statistical results of the research samples.

(*a*) Composition of transportation modes. (*b*) Number of employees in industries. (*c*) Relative frequency of commuting time per trip. (*d*) Relative frequency of commuting distance per day.

Note: 1. Agriculture, Forestry, and Fishing; 2. Mining; 3. Manufacturing; 4*. Electricity, Heating, Gas, and Water Supply; 5. Construction; 6. Transportation and Storage; 7. Information and Communication; 8*. Wholesale and Retail Trade; 9. Accommodation and Food Services; 10. Financial and Insurance; 11. Real Estate; 12*. Rental Business; 13. Professional, Scientific and Technical Service; 14. Water Conservancy, Environment, and Public Facilities Management; 15. Residential Assistance, Maintenance, and Other Service; 16. Education; 17. Health Care and Social Assistance; 18. Arts, Entertainment and Recreation; 19. Government Administrative Support; 20*. International Organization.

Compared with previous related studies, this study increased the accuracy of estimation from the following two perspectives. First, this study considered different levels of teleworking penetration in different industries, while previous studies adopted an average or a certain percentage (i.e., 20 %, 40 %, 60 %, etc.) teleworking penetration coefficient for the estimation (Bussière and Lewis, 2002; Giovanis, 2018). Second, this study used large-scale travel survey data to evaluate the commuting trips, considering the actual travel mode, travel distance, and traffic situation in Beijing, which was more practical than scenario modeling (Jaff and Hamsa, 2018; Tenailleau et al., 2021). The case study in Beijing demonstrated the feasibility of this approach and showed that 7.05 % (95 % CI: 3.74 %–10.95 %) of total carbon emissions generated by transport could be reduced by teleworking in Beijing in a year.

4.2. Explanation about the estimated carbon reduction in different industries in Beijing

The estimated carbon reduction potential through teleworking in this study, which is 7.05 % of transportation carbon emissions and 0.85 % of total carbon emissions in Beijing, is close to the results in previous related studies. Balepur et al. (1998) have shown that carbon reductions in VKT of teleworking can reach up to 20 %. Other studies also indicate that teleworking may reduce carbon emissions by 0.14 % to 80 %, primarily by reducing commuting trips (Larson and Zhao, 2017), with the higher estimate assuming a five-day teleworking routine for the whole population (Kitou and Horvath, 2003). The above results can support the feasibility and accuracy of the approach in this study to some extent.

When exploring the potential of teleworking in reducing carbon emissions by industry, higher teleworking penetration and original carbon emissions without teleworking result in greater carbon reduction potential. The original carbon emission generation is influenced by the number of employees and commuting distance. Information and communication industry, and professional, scientific and technical service industry have higher teleworking penetration and a larger workforce, leading to significantly higher carbon reduction potential. The manufacturing industry has lower teleworking penetration, but due to its large carbon emission and workforce, it still has moderate carbon reduction potential. Although the financial and insurance industry has the highest teleworking penetration, its original low carbon emissions lead to a moderate carbon reduction potential among industries. Some primary and secondary industries, as well as accommodation and food services, residential assistance, maintenance, and other services, have limited carbon reduction potential through teleworking, which may be caused by the higher proportion of required physical activities or lower workforce size. Furthermore, previous research indicated that teleworking penetration was highest in professional, managerial, executive, and associated occupations with highly educated workers (Helminen and Ristimäki, 2007), as expertise in digital technologies and equipment was essential for working remotely (Barrero et al., 2021; Hostettler Macias et al., 2022).

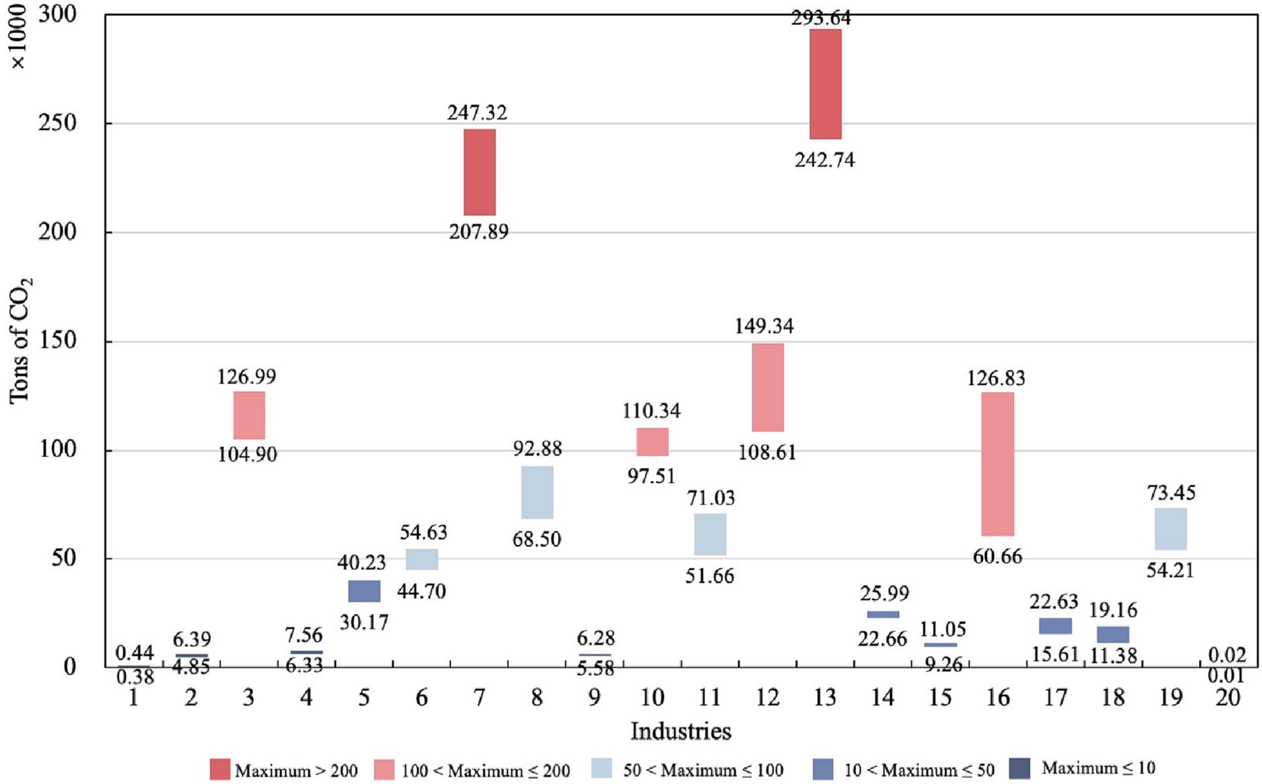


Fig. 7. Carbon reduction through teleworking by industries of Beijing in 2015, when effective and maximum penetrations are taken respectively.
Note: 1. Agriculture, Forestry, and Fishing; 2. Mining; 3. Manufacturing; 4*. Electricity, Heating, Gas, and Water Supply; 5. Construction; 6. Transportation and Storage; 7. Information and Communication; 8*. Wholesale and Retail Trade; 9. Accommodation and Food Services; 10. Financial and Insurance; 11. Real Estate; 12*. Rental Business; 13. Professional, Scientific and Technical Service; 14. Water Conservancy, Environment, and Public Facilities Management; 15. Residential Assistance, Maintenance, and Other Service; 16. Education; 17. Health Care and Social Assistance; 18. Arts, Entertainment and Recreation; 19. Government Administrative Support; 20*. International Organization.

4.3. Rebound effects of teleworking implementation on carbon reduction

Although various researchers hold that teleworking has a significant carbon reduction potential, some studies show a lower reduction in carbon emission when taking rebound effects into account (O'Brien and Aliabadi, 2020). The rebound effect refers to the possible additional increase in carbon emission through several pathways due to teleworking, except for the carbon reduction from commuting trips or office energy use. There are

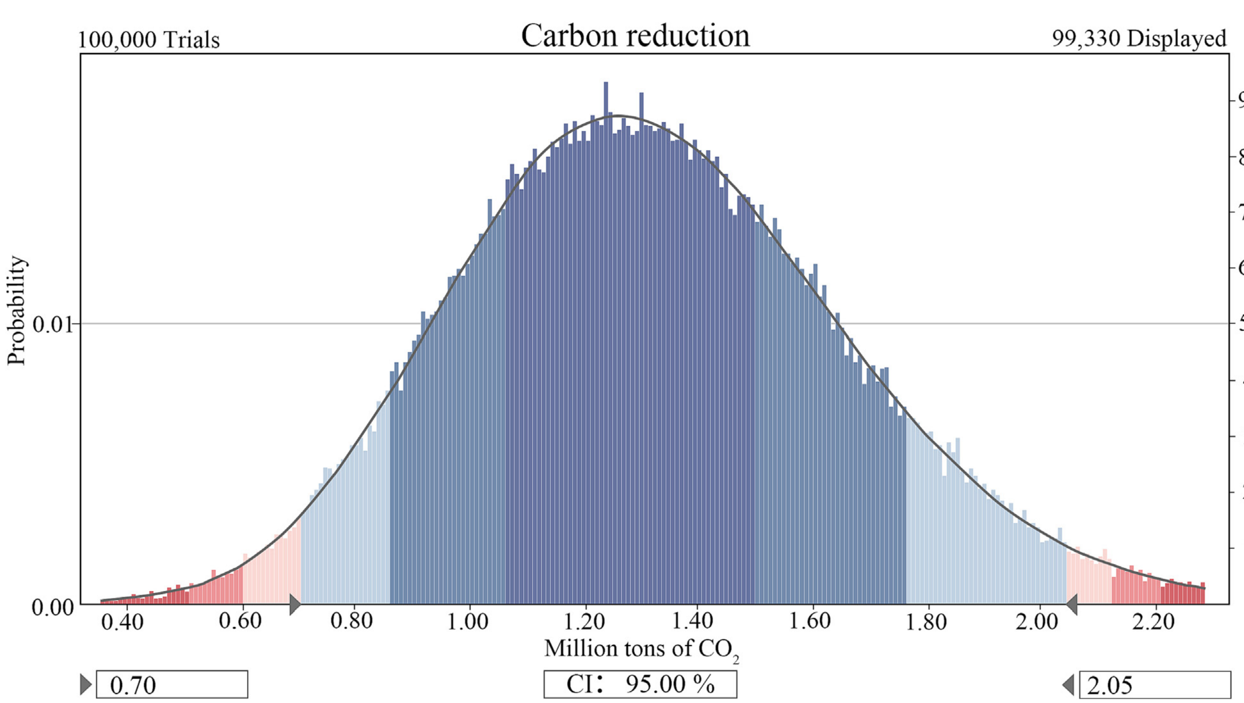


Fig. 8. Distribution of carbon reduction and its corresponding 95 % confidence interval in Beijing.

two main pathways for rebound effect (Table S8). First, teleworkers can move to the suburbs due to teleworking, while non-teleworkers can have more opportunities to live closer to their workplaces. As teleworkers save the time spent on commuting, they may produce more personal trips for leisure activities (Cerqueira et al., 2020; Shabanpour et al., 2018). Second, although teleworking can reduce office space and energy use (Williams, 2003), home-based teleworking also increases household energy consumption from ICT equipment, lighting, and air conditioning.

Nevertheless, multiple studies demonstrated that teleworking could still achieve energy conservation and carbon reduction despite the rebound effect. We conducted a literature review from the Web of Science database (Table S9) in order to investigate the impact of rebound effects on the carbon reduction benefits of teleworking. When only commuting trip is considered, nearly all studies indicate that teleworking has carbon reduction benefits through reducing commuting distance. Total commuting travel can be reduced by 1 % to 28 % (Mitomo and Jitsuzumi, 1999; Martens and Korver, 2000). When rebound effects from non-work trips are taken into account, most studies still suggest a reduction of total commuting travel by 0.69 % to 67 % (Shabanpour et al., 2018; Henderson and Mokhtarian, 1996). However, a small proportion of studies suggest that it may actually increase travel distance, with a range of 0.40 % to 15.70 % (E Silva and Melo, 2018; Zhu, 2012). When considering the combined effects of transportation, office and household energy use, almost all studies suggest a net carbon reduction, with a range of 0.16 % to 80 % (assuming teleworking for 5 days a week) (Matthews and Williams, 2005; Kitou and Horvath, 2003).

Due to significant differences in regions, methods, and scenarios among different studies, we adjusted the studies considering combined rebound effects to the scenario with universal 20 % teleworking penetration for the equivalent comparison. The adjusted results showed a net carbon reduction of 0.14 % to 2.5 % was adopted (Larson and Zhao, 2017; Kitou and Horvath, 2003), with 0.16 % to 0.23 % net annual carbon reduction in the whole lifecycle perspective (including commuting travel, non-work travel, home energy use, and office energy use) (Roth et al., 2008). In this study, the carbon reduction accounted for 0.85 % of the total carbon emissions of Beijing in 2015. When transformed to the scenario with a teleworking penetration of 20 %, the carbon reduction accounted for 0.42 %. The results without considering the rebound effects in this study are slightly higher than those in the literature. In consequence, teleworking does offer significant potential for reducing car emissions, but it may be slightly weakened when all rebound effects are taken into account (O'Brien and Aliabadi, 2020). Guerin (2021) also confirms that the rebound effect is almost negligible in a comparative lifecycle assessment, which does not outweigh the environmental benefits of teleworking.

4.4. Policy implications and future trends

Our calculated results are based on the situation in Beijing before the outbreak of the pandemic and consider the teleworking penetration based on industry characteristics. With the outbreak of the COVID-19 pandemic in 2020, the widespread implementation of mandatory work-from-home policies led to a sharp decrease in road traffic in Beijing (Beijing Transport Institute, 2022). In the post-COVID-19 scenario, some companies are transitioning from mandatory work-from-home to flexible work arrangements (Šmite et al., 2023). The hybrid working mode of combining teleworking and offline work may be universal and adopted by more companies during this period (Brynjolfsson et al., 2020). For example, Microsoft permitted employees to work from home for no more than 50 % of their work hours, and Facebook planned to make 50 % of employees telework within the next five to ten years (Farooq and Sultana, 2021). In 2021, Alibaba, the largest e-commerce company in China, announced that it would adopt a more flexible work schedule and permit employees to work outside of the office one day per week (Coote et al., 2021).

In addition, with the development of advanced technologies, the increase in employees engaged in high-tech industries, and the development of new travel modes will be more beneficial to implementing teleworking. Emerging technologies, such as artificial intelligence, the Internet of Things, extended reality, robotics and automation, will further promote the transformation of teleworking at different levels (Turan, 2021). Meanwhile, the emergence of innovation clusters and coworking spaces provides new possibilities for developing hybrid working modes and urban workspaces (Yu et al., 2019). Autonomous vehicles (AVs), shared vehicles, and ride-sharing services can provide new travel modes and possibilities for low-carbon transportation (Soukhov and Mohamed, 2022). Accordingly, teleworking will generate more carbon reduction benefits in the future.

During this period, policy interventions and management measures are needed to support the hybrid working modes of specific industries and expand the environmental benefits of teleworking. The rebound effects can be mitigated through appropriate policy formulation to maximize the carbon reduction benefits of teleworking as well (Guerin, 2021). First, from the view of industry management, it is necessary to encourage industries with high carbon reduction potential (i.e., information and communication, and professional, scientific and technical service) or teleworking penetration (i.e., financial and insurance) to implement hybrid working modes. After implementing teleworking, effective utilization of space and downsizing of office size can be considered, including the use of rotating office desks. Distributed work hubs can also be advocated. Second, from the view of employees, those with longer commuting distances should be encouraged to telework if possible. These employees can be also encouraged to set up energy-efficient household offices, including energy-efficient lighting, air conditioning systems, and household appliances. Meanwhile, employee training and appropriate certifications will be needed, along with relevant courses to emphasize and guarantee the feasibility of teleworking. Third, from the view of transportation management, teleworking can also be incorporated into transportation demand management and low-carbon transportation policy systems. Companies, governments, and urban planners still need to assess their long-term teleworking deployment strategies.

4.5. Limitations and future research

This study still has some limitations, which are worth further research in the future. First, the rebound effects need to be further considered to identify the extent that it weakens carbon reduction from a lifecycle perspective. Second, this study uses the global data of teleworking penetration from McKinsey Global Institute instead of local data in Beijing. Future studies can perform the estimation with local teleworking penetration if relevant data are available. Third, future studies can focus on the impacts of teleworking on the spatial distribution of urban workspaces and residential spaces. Fourth, it is worthwhile for future research to investigate the associations between carbon reduction potential and other socioeconomic variables, such as educational background, population density, and income level.

5. Conclusions

This study proposed a quantitative approach for assessing the carbon reduction from teleworking in different industries, applied the approach in a case study of Beijing, China, and obtained accurate carbon reduction results of teleworking. The systematic quantitative approach integrated the practical potential of teleworking among different industries using teleworking penetration and commuting trips using large-scale travel survey data. Thus, a more accurate result was obtained about carbon reduction in the mobility field compared with other quantitative studies. Then, all uncertain influencing parameters were evaluated using Monte Carlo simulation, and the rebound effects were discussed. The results of the case study in Beijing showed that (1) the average carbon reduction by teleworking was 1.32 (95 % CI: 0.70–2.05) million tons, accounting for 7.05 % (95 % CI: 3.74 %–10.95 %) of the total carbon emissions by road transport in Beijing; and (2) information and communication, and professional, scientific and technical service industries had high carbon reduction potential. Additionally, the rebound effect may slightly weaken the carbon reduction benefit of teleworking, which is necessary to be considered and mitigated through relevant policies. This study can offer a good reference for adopting a hybrid working mode combining teleworking and offline work in specific industries in China, which can also be applied to other regions. Overall, teleworking may potentially serve as a long-term solution from the perspective of urban planning to reduce carbon emissions.

CRediT authorship contribution statement

Wenzhu Li: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Visualization, Validation, Writing – original draft. **Ningrui Liu:** Methodology, Software, Investigation, Validation, Writing – review & editing. **Ying Long:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National "Ten Thousand Talents Program" [Grant No. 20211700110]. The authors also thank Mr. Yu Hu, Dr. Tangqi Tu, and Mr. Meng Lu for providing feedback on the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164262.

References

Akbari, M., Hopkins, J.L., 2019. An investigation into anywhere working as a system for accelerating the transition of Ho Chi Minh city into a more livable city. J. Clean. Prod. 209, 665–679.

Allen, T.D., Golden, T.D., Shockley, K.M., 2015. How effective is telecommuting? Assessing the status of our scientific findings. Psychol. Sci. Public Interest 16 (2), 40–68.

Andrey, J.C., Burns, K.R., Doherty, S.T., 2004. Toward sustainable transportation: exploring transportation decision making in teleworking households in a mid-sized Canadian city. Canadian J. Urban Res. 257–277.

Atkyns, R., Blazek, M., Roitz, J., 2002. Measurement of environmental impacts of telework adoption amidst change in complex organizations: AT&T survey methodology and results. Resour. Conserv. Recycl. 36 (3), 267–285.

Bakaç, C., Zyberaj, J., Barela, J.C., 2021. Predicting Telecommuting Preferences and Job Outcomes amid COVID-19 Pandemic: A Latent Profile Analysis.

Balepur, P.N., Varma, K.V., Mokhtarian, P.L., 1998. Transportation impacts of center-based telecommuting: interim findings from the Neighborhood Telecenters Project. Transportation 25 (3), 287–306.

Barrero, J.M., Bloom, N., Davis, S.J., 2021. Why Working from Home Will Stick. National Bureau of Economic Research.

Beijing Municipal Commission of Transport, 2015. http://jtw.beijing.gov.cn/ (accessed October 02, 2021).

Beijing Municipal Commission of Transport, 2022. http://www.beijing.gov.cn/zhengce/zcjd/202206/t20220617_2743491.html [accessed April 08, 2023].

Beijing Statistical Yearbook Committee, 2016. http://nj.tjj.beijing.gov.cn/nj/main/2016-tjnj/zk/indexch.htm [accessed November 22, 2021].

Beijing Statistical Yearbook Committee, 2022. https://nj.tjj.beijing.gov.cn/nj/main/2022-tjnj/zk/indexch.htm [accessed April 02, 2023].

Beijing Transport Institute, 2016. https://www.bjtrc.org.cn/List/index/cid/7.html [accessed November 02, 2021].

Beijing Transport Institute, 2022. https://www.bjtrc.org.cn/List/index/cid/7.html. (Accessed 2 April 2023).

Bloom, N., Liang, J., Roberts, J., Ying, Z.J., 2015. Does working from home work? Evidence from a Chinese experiment. Q. J. Econ. 130 (1), 165–218.

Bouziri, H., Smith, D.R., Descatha, A., Dab, W., Jean, K., 2020. Working from home in the time of covid-19: how to best preserve occupational health? Occup. Environ. Med. 77 (7), 509–510.

Brynjolfsson, E., Horton, J.J., Ozimek, A., Rock, D., Sharma, G., TuYe, H.-Y., 2020. COVID-19 and Remote Work: An Early Look at US Data. National Bureau of Economic Research.

Buffer, 2020. The 2020 State of Remote Work. Available from: https://lp.buffer.com/state-of-remote-work-2020.

Bureau of Energy of the Ministry of Economic Affairs, 2016. . (accessed November 22, 2021) http://www.stats.gov.cn/tjsj/tjcbw/201706/t20170621_1505833.html.

Bussière, Y., Lewis, P., 2002. Impact of telework and flexitime on reducing future urban travel demand: the case of Montreal and Québec (Canada), 1996-2016. WIT Transactions on The Built Environment. 60.

Cerqueira, E.D.V., Motte-Baumvol, B., Chevallier, L.B., Bonin, O., 2020. Does working from home reduce CO_2 emissions? An analysis of travel patterns as dictated by workplaces. Transp. Res. Part D: Transp. Environ. 83, 102338.

Chakrabarti, S., 2018. Does telecommuting promote sustainable travel and physical activity? J. Transp. Health 9, 19–33.

Charpentier, R.R., Klett, T.R., 2000. Monte Carlo simulation method. US Geological Survey World Energy Assessment Team, ed., US Geological Survey World Petroleum Assessment.

China Internet Network Information Center, 2022. The 50th statistical report on China's internet development. http://www.cnnic.net.cn/n4/2022/0914/c88-10226.html.

Coote, A., Harper, A., Stirling, A., 2021. The Case for a Four-day Week. Polity Press Cambridge, UK.

De Vries, H., Tummers, L., Bekkers, V., 2019. The benefits of teleworking in the public sector: reality or rhetoric? Rev. Public Pers. Adm. 39 (4), 570–593.

Di Marino, M., Lapintie, K., 2017. Emerging workplaces in post-functionalist cities. J. Urban Technol. 24 (3), 5–25.

Dingel, J.I., Neiman, B., 2020. How many jobs can be done at home? J. Public Econ. 189, 104235.

Dissanayake, D., Morikawa, T., 2008. Impact assessment of satellite centre-based telecommuting on travel and air quality in developing countries by exploring the link between travel behaviour and urban form. Transp. Res. A Policy Pract. 42 (6), 883–894.

DuBrin, A.J., Barnard, J.C., 1993. What telecommuters like and dislike about their jobs. Business Forum. California State University, Los Angeles, School of Business and Economics, p. 13.

Dulac, J., 2013. Global Land Transport Infrastructure Requirements. vol. 20. International Energy Agency, Paris, p. 2014.

E Silva, J.d.A., Melo, P.C., 2018. Does home-based telework reduce household total travel? A path analysis using single and two worker British households. J. Transp. Geogr. 73, 148–162.

Eurofound, 2020. Living, Working and COVID-19. COVID-19 Series. Publications Office of the European Union, Luxembourg.

Farooq, R., Sultana, A., 2021. The potential impact of the COVID-19 pandemic on work from home and employee productivity. Meas. Bus. Excell. 26 (3), 308–325.

Felstead, A., Reuschke, D., 2020. Homeworking in the UK: Before and during the 2020 Lockdown.

Fuhr, J.P., Pociask, S., 2011. Broadband and telecommuting: helping the US environment and the economy. Low Carbon Econ. 2 (01), 41.

Gill, T., 2006. Countering the economic effects of bird flu through teleworking. J. Bus. Contin. Emerg. Plan. 1 (1), 27–36.

Giovanis, E., 2018. The relationship between teleworking, traffic and air pollution. Atmos. Pollut. Res. 9 (1), 1–14.

Golden, T.D., Veiga, J.F., Dino, R.N., 2008. The impact of professional isolation on teleworker job performance and turnover intentions: does time spent teleworking, interacting face-to-face, or having access to communication-enhancing technology matter? J. Appl. Psychol. 93 (6), 1412.

Gonzalez, A.G., Herrador, M., Asuero, A.G., 2005. Uncertainty evaluation from Monte-Carlo simulations by using Crystal-Ball software. Accred. Qual. Assur. 10 (4), 149–154.

Grawitch, M.J., Barber, L.K., Justice, L., 2010. Rethinking the work–life interface: It's not about balance, it's about resource allocation. Appl. Psychol. Health Well-Being 2 (2), 127–159.

Güereca, L.P., Torres, N., Noyola, A., 2013. Carbon footprint as a basis for a cleaner research institute in Mexico. J. Clean. Prod. 47, 396–403.

Guerin, T.F., 2021. Policies to minimise environmental and rebound effects from telework: a study for Australia. Environ. Innov. Societal Trans. 39, 18–33.

Hambly, H., Lee, J.D., 2019. The rural telecommuter surplus in Southwestern Ontario, Canada. Telecommun. Policy 43 (3), 278–286.

Hatayama, M., Viollaz, M., Winkler, H., 2020. Jobs' Amenability to Working from Home: Evidence From Skills Surveys for 53 Countries. World Bank Policy Research Working Paper (9241).

Helminen, V., Ristimäki, M., 2007. Relationships between commuting distance, frequency and telework in Finland. J. Transp. Geogr. 15 (5), 331–342.

Henderson, D.K., Mokhtarian, P.L., 1996. Impacts of center-based telecommuting on travel and emissions: analysis of the Puget Sound Demonstration Project. Transp. Res. Part D: Transp. Environ. 1 (1), 29–45.

Hofer, C., Jäger, G., Füllsack, M., 2018. Large scale simulation of CO_2 emissions caused by urban car traffic: an agent-based network approach. J. Clean. Prod. 183, 1–10.

Höjer, M., 2002. A hundred nodes in the Stockholm region: a simple calculation of the effects on commuting. Environ. Plan. B Plan. Des. 29 (2), 197–217.

Hook, A., Sovacool, B.K., Sorrell, S., 2020. A systematic review of the energy and climate impacts of teleworking. Environ. Res. Lett. 15 (9), 093003.

Hostettler Macias, L., Ravalet, E., Rérat, P., 2022. Potential rebound effects of teleworking on residential and daily mobility. Geogr. Compass 16 (9), e12657.

Huo, H., Yao, Z., He, K., Yu, X., 2011. Fuel consumption rates of passenger cars in China: labels versus real-world. Energy Policy 39 (11), 7130–7135.

Huo, H., Wang, M., Zhang, X., He, K., Gong, H., Jiang, K., Jin, Y., Shi, Y., Yu, X., 2012. Projection of energy use and greenhouse gas emissions by motor vehicles in China: policy options and impacts. Energy Policy 43, 37–48.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/ [accessed November 02, 2021].
Jaff, M.M., Hamsa, A.A.K., 2018. Estimating commute-travel implications of telecommuting by female employees in Kuala Lumpur, Malaysia. J. Traffic Transp. Eng. 5 (2), 148–155.
Kim, S.-N., Choo, S., Mokhtarian, P.L., 2015. Home-based telecommuting and intra-household interactions in work and non-work travel: a seemingly unrelated censored regression approach. Transp. Res. A Policy Pract. 80, 197–214.
Kitou, E., Horvath, A., 2003. Energy-related Emissions From Telework. ACS Publications.
Kitou, E., Horvath, A., 2008. External air pollution costs of telework. Int. J. Life Cycle Assess. 13 (2), 155–165.
Koenig, B.E., Henderson, D.K., Mokhtarian, P.L., 1996. The travel and emissions impacts of telecommuting for the State of California Telecommuting Pilot Project. Transp. Res. C Emerg. Technol. 4 (1), 13–32.
Ku, A.L., Qiu, Y., Lou, J., Nock, D., Xing, B., 2022. Changes in hourly electricity consumption under COVID mandates: a glance to future hourly residential power consumption pattern with remote work in Arizona. Appl. Energy 310, 118539.
Lachapelle, U., Tanguay, G.A., Neumark-Gaudet, L., 2018. Telecommuting and sustainable travel: reduction of overall travel time, increases in non-motorised travel and congestion relief? Urban Stud. 55 (10), 2226–2244.
Lari, A., 2012. Telework/workforce flexibility to reduce congestion and environmental degradation? Procedia Soc. Behav. Sci. 48, 712–721.
Larson, W., Zhao, W., 2017. Telework: urban form, energy consumption, and greenhouse gas implications. Econ. Inq. 55 (2), 714–735.
Lister, K., Hamish, T., 2011. WORKshift Canada: The Bottom Line on Telework. Telework Research Network.
Martens, M., Korver, W., 2000. Forecasting and assessing the mobility effects of teleservices: scenario approach. Transp. Res. Rec. 1706 (1), 118–125.
Matthews, H.S., Williams, E., 2005. Telework adoption and energy use in building and transport sectors in the United States and Japan. J. Infrastruct. Syst. 11 (1), 21–30.
Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y.-M., Liu, Z., Hubacek, K., 2017. Chinese CO_2 emission flows have reversed since the global financial crisis. Nat. Commun. 8 (1), 1–10.
Ministry of Industry and Information Technology of the People's Republic of China, 2022. . (accessed April 24, 2022) https://yhgscx.miit.gov.cn/fuel-consumption-web/mainPage.
Mitomo, H., Jitsuzumi, T., 1999. Impact of telecommuting on mass transit congestion: the Tokyo case. Telecommun. Policy 23 (10 − 11), 741–751.
Mokhtarian, P., 1991. Defining Telecommuting. Institute of Transportation Studies, UC Davis, Institute of Transportation Studies, Working Paper Series 1305.
Mokhtarian, P.L., Handy, S.L., Salomon, I., 1995. Methodological issues in the estimation of the travel, energy, and air quality impacts of telecommuting. Transp. Res. A Policy Pract. 29 (4), 283–302.
National Bureau of Statistics, 2016. . (accessed November 02, 2021) http://www.stats.gov.cn/xxgk/tjbz/gjtjbz/201710/t20171017_1758922.html.
Nelson, P., Safirova, E., Walls, M., 2007. Telecommuting and environmental policy: lessons from the ecommute program. Transp. Res. Part D: Transp. Environ. 12 (3), 195–207.
Nijland, L., Dijst, M., 2015. Commuting-related fringe benefits in the Netherlands: interrelationships and company, employee and location characteristics. Transp. Res. A Policy Pract. 77, 358–371.
Nilles, J., 1975. Telecommunications and organizational decentralization. IEEE Trans. Commun. 23 (10), 1142–1147.
Nilles, J., 1990. The State of California Telecommuting Pilot Project Final Report. JALA associates, inc, Los Angeles.
O'Brien, W., Aliabadi, F.Y., 2020. Does telecommuting save energy? A critical review of quantitative studies and their research methods. Energy Build. 225, 110298.
O'Leary, H., Parr, S., El-Sayed, M.M., 2022. The breathing human infrastructure: integrating air quality, traffic, and social media indicators. Sci. Total Environ. 827, 154209.
Pratt, J.H., 1984. Home teleworking: a study of its pioneers. Technol. Forecast. Soc. Chang. 25 (1), 1–14.
Pyöriä, P., 2011. Managing telework: risks, fears and rules. Manag. Res. 34 (4), 386–399.
Rhee, H.-J., 2009. Telecommuting and urban sprawl. Transp. Res. Part D: Transp. Environ. 14 (7), 453–460.
Roth, K.W., Rhodes, T., Ponoum, R., 2008. The energy and greenhouse gas emission impacts of telecommuting in the US. 2008 IEEE International Symposium on Electronics and the Environment. IEEE, pp. 1–6.
Shabanpour, R., Golshani, N., Tayarani, M., Auld, J., Mohammadian, A.K., 2018. Analysis of telecommuting behavior and impacts on travel demand and the environment. Transp. Res. Part D: Transp. Environ. 62, 563–576.
Šmite, D., Moe, N.B., Klotins, E., Gonzalez-Huerta, J., 2023. From forced working-from-home to voluntary working-from-anywhere: two revolutions in telework. J. Syst. Softw. 195, 111509.
Sostero, M., Milasi, S., Hurley, J., Fernandez-Macías, E., Bisello, M., 2020. Teleworkability and the COVID-19 Crisis: A New Digital Divide? JRC Working Papers Series on Labour, Education and Technology.
Soukhov, A., Mohamed, M., 2022. Occupancy and GHG emissions: thresholds for disruptive transportation modes and emerging technologies. Transp. Res. D Transp. Environ. 102.
Sun, Y., Zhang, Y., Liu, X., 2020. Driving factors of urban transportation CO_2 emission in Beijing: an analysis based on the urban development perspective. Urban Environ. Stud. 1, 81–95.
Susan Lund, A.M., Manyika, James, Smit, Sven, 2020. What's Next for Remote Work: An Analysis of 2,000 Tasks, 800 Jobs, and Nine Countries. McKinsey Global Institute.
Tang, W., Mokhtarian, P.L., Handy, S.L., 2011. The impact of the residential built environment on work at home adoption and frequency: an example from Northern California. J. Transp. Land Use 4 (3), 3–22.
Tang, Y., Mao, B., Zhou, Q., Gao, Q., 2022. Impact Analysis on Carbon Emission Factor in Operations of Electric Vehicle. Transport Energy Conservation & Environmental Protection (018-003).
Tenailleau, Q.M., Tannier, C., Vuidel, G., Tissandier, P., Bernard, N., 2021. Assessing the impact of telework enhancing policies for reducing car emissions: exploring calculation methods for data-missing urban areas–example of a medium-sized European city (Besançon, France). Urban Clim. 38, 100876.
The State Council of the People's Republic of China, 2022. http://www.gov.cn/zhengce/zhengceku/2022-01/12/content_5667817.htm [accessed April 02, 2023].
Turan, S.G., 2021. The Relationship Between Technoference, Work-family Interface, and Telework in the Age of 4IR, Future of Work, Work-family Satisfaction, and Employee Well-Being in the Fourth Industrial Revolution. IGI Global, pp. 279–296.
Vu, S., Vandebona, U., 2007. Telecommuting and its impacts on vehicle-km travelled. International Congress on Modelling and Simulation. University of Canterbury, Christchurch, New Zealand, Citeseer.
Williams, E.D., 2003. Assessing the potential of telecommuting as an energy savings technology in Japan. IEEE International Symposium on Electronics and the Environment, 2003. IEEE, pp. 147–152.
Yang, C.W., Ho, Y.L., 2016. Assessing carbon reduction effects toward the mode shift of green transportation system. J. Adv. Transp. 50 (5), 669–682.
Yang, S., Kunyao, Z., Liu, Y., 2002. Handbook on Statistics on Road Traffic. China Architecture & Building Press, China.
Yen, J.-R., 2000. Interpreting employee telecommuting adoption: an economics perspective. Transportation 27 (1), 149–164.
Yu, R., Burke, M., Raad, N., 2019. Exploring impact of future flexible working model evolution on urban environment, economy and planning. J. Urban Manag. 8 (3), 447–457.
Yue, X., Pye, S., DeCarolis, J., Li, F.G., Rogan, F., Gallachóir, B.Ó., 2018. A review of approaches to uncertainty assessment in energy system optimization models. Energy Strat. Rev. 21, 204–217.
Zhang, S., Wu, Y., Liu, H., Huang, R., Yang, L., Li, Z., Fu, L., Hao, J., 2014. Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing. Appl. Energy 113, 1645–1655.
Zhang, L., Long, R., Chen, H., Geng, J., 2019. A review of China's road traffic carbon emissions. J. Clean. Prod. 207, 569–581.
Zhu, P., 2012. Are telecommuting and personal travel complements or substitutes? Ann. Reg. Sci. 48 (2), 619–639.