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Uncovering the spatiotemporal patterns of CO_2 emissions by taxis based on Individuals' daily travel

Pengxiang Zhao[a], Mei-Po Kwan[b,*], Kun Qin[c,d]

[a] Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, PR China
[b] Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, 255 Computing Applications Building, MC-150, 605 E Springfield Ave., Champaign, IL 61820, USA
[c] School of Remote Sensing and Information Engineering, Wuhan University, 129 Luoyu Road, Wuhan, Hubei 430079, China
[d] Collaborative Innovation Center of Geospatial Technology, 129 Luoyu Road, Wuhan, Hubei 430079, China

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ABSTRACT

Traffic-related carbon dioxide (CO_2) emissions have become a major problem in cities. Especially, the CO_2 emissions induced by taxis account for a high proportion in total CO_2 emissions. The availability of taxi trajectory data presents new opportunities for addressing CO_2 emissions induced by taxis. Few previous studies have analyzed the impact of human trips on CO_2 emissions. This paper investigates trip-related CO_2 emission patterns based on individuals' travel behavior using taxi trajectory data. First, we propose a trip purpose inference method that takes into account the spatiotemporal attractiveness of POIs to divide human trips into different types. Further, we reveal the spatiotemporal patterns of CO_2 emissions from various types of trips, including temporal regularity and periodicity as well as spatial distribution of "black areas". Finally, comparative analysis of CO_2 emissions for different kinds of trips based on trip behavior is conducted using three variables, namely trip distance, trip duration and trip speed. This study is helpful for us to understand how to make travel and cities more sustainable through modifying people's trip behaviors or taxi trips.

1. Introduction

As a major cause of global warming, the continuous increase of atmospheric carbon dioxide (CO_2) poses a great threat to the global ecological environment. The growth rate of global CO_2 emissions remained at 4% on average in the last decade and reached the lowest growth rate in 2014 (0.5%). However, the volume of global CO_2 emissions reached 35.7 billion tones in the same year. Therefore, how to maintain economic growth while reducing CO_2 emissions and constructing "green cities" has become a major theme in recent scientific research (Ma et al., 2011).

Traffic-related CO_2 emissions are one of the main sources of carbon emissions. Previous studies on traffic-related CO_2 emissions largely used data collected through travel surveys, questionnaires or interviews. In recent years, with the rapid development and widespread use of global positioning systems (GPS), the Internet, and communication technology, massive amounts of GPS trajectory data that record human travel have been collected from GPS-equipped mobile devices or vehicles and widely used to analyze human trips (González et al., 2008; Song et al., 2010; Liu et al., 2012; Liu et al., 2014; Gong et al., 2016; Alexander et al., 2015; Liu et al., 2015). Compared to traditional methods based on travel surveys or questionnaires, the advantages of using vehicles' GPS trajectories, including taxi trajectory data, to estimate CO_2 emissions mainly include the following three aspects. First, travel surveys that collected detailed activity-travel data from participants are very costly and time-consuming to collect. Obtaining a sample with a few thousands of subjects can easily cost over half a million US dollars and usually take several months or even longer to complete. Real-time taxi GPS trajectory data are collected for fleet management or dispatching purposes and can often be acquired by researchers at low costs. Data can be collected by tens of thousands of taxis simultaneously. In addition, each taxi carries many different passengers every day. Hence, taxi GPS trajectory data can reflect the travel of millions of taxi passengers. Further, CO_2 emissions information obtained from survey data is often obtained from several typical communities in a city. However, GPS trajectory data can be used to investigate CO_2 emission of people's daily travel across the whole city since they cover broad areas of a city. Second, travel survey data are utilized to estimate CO_2 emissions based on respondents' transportation mode and travel distance, which neglects traffic conditions (e.g., traffic congestion) and the actual footprint of vehicles. For instance, vehicle-based travel distance in conventional surveys is often less than the distance between people's

* Corresponding author.
E-mail address: mpk654@gmail.com (M.-P. Kwan).

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residence and workplace due to the neglect of the distance between home/workplace to public transit stations that is covered by walking. Taxi GPS trajectory data accurately record the entire vehicle-based travel distance. In addition, carbon emission characteristics derived from GPS trajectory data can indicate complex spatiotemporal patterns of carbon emission due to real-time data collection. Third, urban transportation is extremely complicated, as it often involves many route choices, accelerations and decelerations due to traffic congestion, traffic signals, stop signs, and intersections. On the one hand, complex route choices make it difficult to accurately assess travel distance. On the other hand, previous studies indicate that vehicle emissions are closely related to vehicle acceleration and deceleration. Taxi GPS trajectory data record vehicles' travel speed at each sampling timestamp. Therefore, taxi GPS trajectory data can be used to more accurately estimate CO_2 emissions when compared to traditional travel survey data. In light of these relative advantages, GPS vehicle trajectory data offer new opportunities for analyzing the CO_2 emissions associated with human trips. In addition, to reduce traffic-related CO_2 emissions, much of past research mainly concentrated on improving energy efficiency and analyzing how urban form, travel behavior and socio-economic factors influence CO_2 emissions. However, few studies have systematically analyzed how human trips influenced CO_2 emissions. There is thus an urgent need to investigate the relationship between the patterns of traffic-related CO_2 emissions and individuals' daily activity-travel patterns.

Considering that taxi trips are a major contributor to traffic-related CO_2 emissions and can be used to reflect people's daily travel to some extent, this paper uses taxi trajectory data collected in Wuhan, China to explore the patterns of taxi trip-related CO_2 emissions based on individuals' daily travel. The uniqueness of this study is that CO_2 emission patterns associated with various types of human trips are explored. This enhances our understanding of how different trips contribute to CO_2 emissions. Using taxi trajectory data, we first propose an inferential method that considers the spatiotemporal attractiveness of pertinent points of interest (POIs) for inferring trip purposes based on Bayesian rules and the enhanced two-step floating catchment area (E2SFCA) method. We then divide the trips into different categories. Further, the spatiotemporal patterns of CO_2 emissions from different kinds of trips are examined. Finally, the impact of trip behavior on CO_2 emissions is quantitatively analyzed. The results will help us better understand how to make travel and cities more sustainable through modifying people's trip behaviors or taxi trips. In addition, this study contributes to advancing analytical methods for using GPS trajectory data to address issues associated with traffic-related CO_2 emissions.

The remainder of this paper is structured as follows. Related work is discussed in Section 2. The methodology of this study is presented in Section 3, including study area, data preprocessing, as well as the methods for inferring trip purposes and for measuring CO_2 emissions. In Section 4, the results are reported, including the validation of the trip inference method, the exploration of the spatiotemporal patterns of CO_2 emissions, and the impact of trip behavior on CO_2 emissions. Section 5 summarizes the main contributions of the study and suggests directions for future research.

2. Related work

Numerous studies have indicated that traffic-related carbon dioxide emission is one of the primary sources of CO_2 emissions (Christen et al., 2011; Franco et al., 2013; Darido et al., 2014). With the rapid growth in the ownership and use of motor vehicles in countries like China, traffic-related CO_2 emission is becoming a major social and environmental concern. According to the latest estimates of the International Energy Agency, the total CO_2 emissions from the transport sector accounted for 23% of total emissions in the world (Schipper et al., 2009). Another study indicated that motor vehicles contributed to almost 70% of the total CO_2 emissions in large Chinese cities (Darido et al., 2014). Taxis, which play an important role in urban public transportation systems, are responsible for a large share of urban traffic flows. Previous studies have found that air pollution emissions from taxis are higher than cars, buses, and subways (An et al., 2011). For instance, Stead (1999) demonstrated that taxis' emissions are higher than that of private cars under the same speed. Wang et al. (2008) studied the emission contribution of each type of vehicle in Shanghai and found that taxis accounted for 16.3% of the total CO_2 emissions. Oliver et al. (2008) observed that taxis accounted for 18% of the total distance traveled by all vehicles in Tianjing and 12% of the CO_2 emissions from all vehicle types. Hence, more attention should be paid to the CO_2 emissions that taxis contribute to the urban environment.

In this context, many studies have examined traffic-related CO_2 emissions and low-carbon transport. Specifically, the development of new energy vehicles (Bose, 2008), improvement in energy efficiency (Gomi et al., 2010), mitigation of traffic congestion and enhancement of road traffic efficiency (Lu et al., 2007; Hickman et al., 2011) were introduced to reduce CO_2 emissions and fuel consumption. There are also studies that examined how urban form, travel behavior and socio-economic factors influence CO_2 emissions (Grazi et al., 2008; Yang et al., 2015; Liu et al., 2017; Xiao et al., 2016). However, these studies ignored one important factor in low-carbon transport, namely human trips.

Some studies have been carried out to examine CO_2 emissions generated by personal travel based on human trips. For instance, Stead (1999) explored the relationship between transport emissions and travel patterns using National Travel Survey data of Britain and found that travel distance is the most representative measure of travel patterns that are closely related to traffic-related emissions. However, this study merely selected travel distance and travel time to measure travel patterns and thus did not consider other aspects of human travel that may be closely related to traffic-related emissions. Carling et al. (2013) evaluated CO_2 emissions generated by consumers' cars travel to shopping centers located in downtown, edge-of-town or out-of-town locations. The results showed that out-of-town shopping centers increase CO_2 emissions. Jia et al. (2013) studied people's trips to and from a shopping center and the CO_2 emissions of these trips using GPS trajectory data. The study revealed the space-time patterns of CO_2 emissions and provides a new perspective for investigating issues related to the dynamics of traffic-related CO_2 emissions. Jia and Håkansson (2016) estimated CO_2 emissions induced by intra-urban cars travel to a retail destination from the perspective of travel behavior and store location. The study found that behavioral change and store relocation have a large potential to reduce CO_2 emissions.

However, these studies on CO_2 emissions largely focused on people's intra-urban shopping trips and overlooked human trips for other purposes. Li et al. (2015) studied China's low-carbon transportation from two aspects, namely, private cars and public transport. The quantitative comparison of CO_2 emissions for shopping trips showed that emissions produced by private cars are five times higher than those by public transport and emissions on weekends are higher than emissions on weekdays. Ma et al. (2011) utilized Beijing residents' activity survey data to evaluate CO_2 emissions based on individuals' travel behavior. The study found that the impact of travel mode on CO_2 emissions is far greater than that of daily total travel. Chai et al. (2012) examined low-carbon strategies using household travel survey data in Beijing and found that the main factors that affect the daily trip-related CO_2 emissions of residents are travel distance and travel mode. Ma et al. (2015) investigated the impact of urban form on CO_2 emission from work and non-work trips using an activity diary survey data. The results showed that their CO_2 emissions differ greatly.

In summary, traffic-related CO_2 emissions from cars are closely associated with human daily travel. Nevertheless, previous studies that seek to reduce CO_2 emissions tend to ignore the in-depth and systematic analysis of the impact of human trips. The current study explores the patterns of transport CO_2 emissions induced by taxis from different