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The effects of commuter travel behavior on transportation heat and pollution emissions

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ABSTRACT

Transportation systems have been identified as significant component of the gross anthropogenic heat emission, which was investigated in cities of America and Australia. Existing empirical studies, however, lack to answer whether individual commute travel behavior influence the UHI effect through affecting anthropogenic heat from transportation. Using Shenzhen as a case, this paper answers this question by: a) estimating how the heat and pollution from transportation changes in different behavioral models; b) identifying factors affecting individual commute travel behavior change; c) finding methods contributing to reducing anthropogenic heat from transportation. Results show that individual commute travel behavior do have a great influence on urban thermal environment and some effective measure can be applied to achieve a lower anthropogenic heat from transportation.

Introduction

Urban heat island (UHI) is becoming one of the biggest environment issues in the 21-century. Anthropogenic heat is one of the three main causes of UHI, which causes higher air temperature in the city central areas of up to 2-3°C at nighttime in winters (Fan & Sailor, 2005). Transportation systems has the dominant effect on the gross anthropogenic heat emission, which was investigated in cities of America and Australia (Khan & Simpson, 2001; Sailor & Lu, 2004).

Generally, anthropogenic heat emission from transportation is calculated as a significant component of anthropogenic heat rather than independently (Sailor & Lu, 2004; Lee et al., 2009; Quah & Roth, 2012). Since the objective of this research are to estimate the total anthropogenic heat of the study area and heat from other transport means is small, heat emission of transportation is usually assumed to equal to heat from vehicular traffic. Furthermore, due to data availability, heat from vehicles is considered an equation of the number of vehicles, energy used by vehicles, and distance travelled by vehicles within the study area. In this research, we focus on the effects of commute travel behavior on urban thermal environment. The detailed commute travel behavior from "Residents' travel survey of Shenzhen" was used for analyzing the current situation in Shenzhen city. A new method is proposed in this paper to estimate the anthropogenic heat emission from transportation.

Individual commute travel in rush hours is potentially affecting the urban heat island phenomenon though influencing transportation heat emissions. However, the relationship between travel behavior and anthropogenic heat of a city has not been proved yet, researchers has proved that reducing the level of urban vehicular passenger travel is one of the efficient approaches for urban energy savings (Kwan & Hashim, 2016; Moriarty, 2016). Meanwhile, some researchers proved that the increase of public transport proportion locally would be helpful in pursuing energy

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savings in Beijing, China (Liu et al., 2015). Hence, it's needed to figure out the effects of commute travel behavior on urban thermal environment.

The analysis of travel mode choice is useful to understand and predict travel demands and considered to be an important tool in transportation planning and policy making (Hagenauer & Helbich, 2017). In this paper, in order to explore factors influencing residents' commute travel mode choice, multinomial logit model (MNL) for mode choice are used. The multinomial logit (MNL) model and its variations, based on random utility theory, with efficient enclosed mathematical structure and explainable model estimation results, become the dominating and most-used travel mode choice model for decades (Wang & Ross, 2018). Some researchers examined whether the construction of flyover infrastructure induces travel mode switch behavior of individuals using a multinomial logistic regression model and found that flyovers have a significant impact on induced travel mode switch behavior of individuals (Rahman & Baker, 2018).

The objective of this paper is to figure out the effects of commute travel behavior on urban thermal environment and the quantitative relationship. Based on resident' commute travel behavior, we proposed a new function to calculate anthropogenic heat emission from transportation. Then we investigated how anthropogenic heat emission from transportation changed within different commute modes using scenario analysis. Furthermore, we analyze factors influencing individual commute travel behavior and hints for future urban island heat effect mitigation will be given to policy makers.

Data and modeling framework

Database

The database used in this research is "Residents' travel survey of Shenzhen" which was funded by Urban Planning, Land & Resources Commission of Shenzhen Municipality, and conducted in November 2016 to January 2017. This database is based on the household travel survey which includes 68,000 families (2% of the total) from the whole household in Shenzhen. In this survey, Shenzhen was divided into 1,114 traffic analysis zones (TAZs). The area of a TAZ is around 1 km^2 in urban areas and around 10 km^2 in green spaces. The survey consists of individual characteristics, household characteristics and all travels of each people in a day.

Another database used in this research is the 2016 Shenzhen building survey which was undertaken by Shenzhen Urban Planning and Land Resource Research Center. This survey obtained information of all 587,843 buildings in Shenzhen, which includes a building's location (longitude and latitude), height, usage, floor area, ownership and structure category.

Modeling framework

Heat and pollution from transportation. Heat from transportation is notoriously difficult to calculate and often evades systematic treatment (Afshari et al., 2018). Usually, a top-down method and a bottom-up method are used to estimate the traffic related anthropogenic heat. The former makes an estimation from large scales to a small scale and requires aggregate data of a large scale to be scaled down to smaller scales of interest (Lee et al., 2009). To the contrary, the latter makes an estimation from small scales to a larger scale (Sailor et al., 2007).

Generally, using a bottom-up method, detailed hourly fractional traffic profiles, hourly population density, energy release per vehicle per meter of travel and per capita daily vehicle distance are needed to estimate heat released from transportation. Specifically, the most challenging aspect is the derivation of a typical daily profile of the anthropogenic heat release rate (Afshari et al., 2018). One of the most challenging data is the hourly distribution of vehicle classes, and to obtain this specific data, some assumptions are needed (Quah & Roth, 2012) and the accuracy of the result greatly reduced.

In this paper, the database from "Residents' travel survey of Shenzhen" will be used. All travels of each people in a day are listed in this survey. As this paper focuses on the heat and pollution emission from commute transportation, we take advantage of these traffic behavior data, a new function is proposed for deriving normalized daily profile(s) of traffic related heat release rates using this detailed travel behavior data as follows:

$$Q_{TR}(\hbar) = [\sum_{ij}(RF_{ij} \cdot N_{ij} \cdot D_{ij} \cdot HE_j)/T_{ij}/3600]/A \tag{1}$$

Where $Q_{TR}(h)$ is the total anthropogenic heat release in any hour from transportation, RF_{ij} is the per capita energy consumption of residents taking class i vehicles consuming fuel type j of a day(*L/km/Person*), N_{ij} is the total number of residents taking vehicle i using fuel j, D_{ij} is the mean commuting distance of residents taking vehicle i using fuel j(k*m/Person*), HE_j is the net heat combustion of fuel type j (*J/ kg*),which is assumed to be 29307.T_{ij} is the mean travel time of residents taking vehicle i using fuel j(h), A is the size of the study area (m^2).

In the above function, the per capita energy consumption of residents taking class i vehicles consuming fuel type j in peak time of a day (RF_{ij}) is used empirical data from Beijing city (Table 1). As this empirical data is from Beijing city rather than Shenzhen city, which has a certain impact on the accuracy of the results. In addition, though electric bus is advocated by the local government, in this research, the number of electric bus is not available. Thus, we assume all buses are diesel ones with 40 seats. This method will greatly simplify the calculation, however may reduce overall accuracy of the results at same time. The total number of residents taking vehicle i using fuel j can be calculated using the total number of employees multiplied by the proportion of a class vehicle used.

Table 1. Energy consumptions of different urban transport modes

Energy consumption	Private cars	Taxi	Diesel buses	Metro
kgce/ km/v[1]	0.012	0.098	0.26	3.416
Occupancy rate	1.5	1.28	40	1440
kgce/ km/p[2]	7.87	8.52	0.85	0.242

1: kilogram standard coal consumption of per vehicle driving one kilometer; 2: kilogram standard coal consumption of per commuter driving one kilometer

Air pollution from transportation is an important research sector of transportation. Generally, CO, NOx and PM_x three main air pollutants in existing studies (Lozhkina & Lozhkin, 2015; Kishimoto et al., 2017). Since metro is powered by electricity that is considered as clean energy, air pollution from metro is not calculated. The occupancy rate of taxi, small passenger vehicles and public bus are 1.28, 1.5 and 40, respectively. They the total emissions of road vehicles can be calculated as follows:

$$E = \sum_i P_i \cdot EF_i \cdot D_i \times 10^{-6} \tag{2}$$

Where E is the total emissions of road vehicles *(t)*, EF_i is the pollution emission factor of vehicle i (*g/km*), P_i is the number of vehicle i, D_i is the average travelled distance of vehicle i *(km)*.

Table 2. Pollution emission factors of different vehicles

(Ministry of environmental protection of the People's Republic of China, 2015)

Vehicle types	Pollution emission factors (g/km)		
	CO	NO_x	$PM_{2.5}$
Small passenger vehicles	0.68	0.032	0.003
Public buses[1]	3.25	9.892	0.252
Taxi	2.45	0.135	0.003

1: As using electricity as power, metro can be regard as a kind of sustainable transportation mode.

Scenario analysis. Generally, the use of technology, infrastructure expansion, and behavioral change by modal shift are three common transport mitigation scenarios analyzed in existing research (Kwan & Hashim, 2016). For behavioral change, behavioral change was the decreased usage of personal car and increased usage of public transportation. The percentage of modal shift to public transportation ranged from 30% to 70%. Besides, two extreme scenarios are also compared. One scenario is 100% usage of public transportation. The proportion of public bus and metro are identified according to the actual research data. The other is 100% usage of private car. Therefore, there are five scenarios assumed as below:

- Scenario 1： 100% usage of personal car
- Scenario 2： 30% usage of public transportation and 70% usage of personal car
- Scenario 3： 50% usage of public transportation and 50% usage of personal car
- Scenario 4： 70% usage of public transportation and 30% usage of personal car
- Scenario 5： 100% usage of public transportation

Multivariate logit analysis. In order to analysis factors influencing commuters' choice between car, metro and bus, a multinomial logit model (MNL) is proposed. Based on the independence of irrelevant alternatives (IIA) hypothesis, the MNL model assumes that the ratio of the choice probabilities of any two alternatives is independent to the attributes and the choice set (Hess, 2005). The utility of each traffic mode is a linear parameter function of the variable we chose. The proposed models were estimated by R (version 3.5.1) with package mlogit (Croissant, 2012) where the reference alternative is car.

$$U_i = \sum_j \beta_{ij} \cdot X_{ij} + \varepsilon_i \tag{3}$$

Where U_i is the travel utility of traffic mode i, X_{ij} is the j^{th} variable of traffic mode i, β_{ij} is the coefficient of X_{ij}, and ε_i is the mode specific constant.

Built environment variables, travelers' socio-demographic attributes as well as traffic mode characteristics go into the model as independent variables. As special institutional population registration system, census register is included.

The Baidu map is used to estimate the in-vehicle travel and access times of metro, bus and car according to trip origin and destination (OD) locations. Since the object of this study is commuter's travel which happened at peak time, commuting trip data is extracted at peak hours in the afternoon when commuters go home from work. The variables contained in the dataset are shown in Table 3.

Table 3. Variables used in the model

	Variables	**Definition**
Mode related variables (3)	TTime	Travel time (h)
	TDistance	Travel distance (km)
	TCost	Travel cost (Yuan)
Individual related variables (2)	Age	-
	Gender	-
Household related variables (5)	HhSize	Household Size
	PCRegister	1= Traveler has Shenzhen census register 2= Other
	HhIncome	1= Household income≤200,000￥/a 2= 200,000￥/a < Household income≤500,000￥/a 3= Household income > 500,000￥/a
	Htype	1= Rental an apartment 2= Owning an apartment
	Owning a car or not	1=yes; 0=no
Land use variables (8)	FZ_PR	Plot ratio of origin TAZ
	FZ_ABH	Average building height of workplace TAZ
	FZ_BSN	Bus stations number of workplace TAZ
	FZ_MSN	Metro stations number of workplace TAZ
	TZ_PR	Plot ratio of home TAZ
	TZ_ABH	Average building height of home TAZ
	TZ_BSN	Bus stations number of home TAZ
	TZ_MSN	Metro stations number of home TAZ

Results

Heat and pollution from transportation in Shenzhen at 2016

Using data from "Residents' travel survey of Shenzhen", we found that car, bus and metro are three most used vehicles for residents to commute in Shenzhen, which is about 46.96%. The car sector can divide into taxi and small passenger vehicles. The mean commuting distance are 8.79 km and 8.07 km, respectively. The mean commuting distance via bus differs little from that with cars. The commuting distance of residents using metro is 14.14 km, which is the longest in all of the transportation types, about 2.61 times of the average commuting distance.

In 2016, the number of employed population in Shenzhen is 9.26 million, which is used to calculate the number of commuters taking different transportation modes by multiplying the occupancy rate of different vehicles with the total number of employed persons.

As illustrated in table 4, heat from transportation system of Shenzhen in 2016 is 2.57 W/m^2. Heat from cars accounts 87% of the total, which means the usage of car largely influences transportation heat emission in Shenzhen. Heat from bus and metro is small. Especially, heat from metro is only 1%, which means usage of metro should be encouraged.

Table 4. Heat emission from transportation in Shenzhen at 2016

Commuting mode	Heat emission(w/m^2)	Percentage
Bus	0.07	6%
Metro	0.02	1%
Car	1.12	87%
Taxi	0.08	6%
Total	1.29	100%

As illustrated in table 5, pollution from transportation of Shenzhen in 2016 is 28.29t. CO, NO_X and $PM_{2.5}$ are 21.23t, 6.84t and 0.22t, respectively. CO emission from cars dominates the total CO emission while NO_X and $PM_{2.5}$ emission from buses are the most. What should be point out is that as using electricity as power, metro can be regard as a kind of sustainable transportation mode.

Table 5. Pollution from transportation in Shenzhen at 2016

Vehicle types	CO	NO_X	$PM_{2.5}$
Bus	1.94	5.90	0.15
Car	15.17	0.71	0.07
Taxi	4.12	0.23	0.01
Total	21.23	6.84	0.22

Heat and pollution from transportation under different scenarios

Five scenarios are assumed in this paper. The percentage of modal shift to public transport in scenarios ranged from 0% to 100%. The ratio between the usage of bus and metro is 2:1 which is identified according to the actual research data.

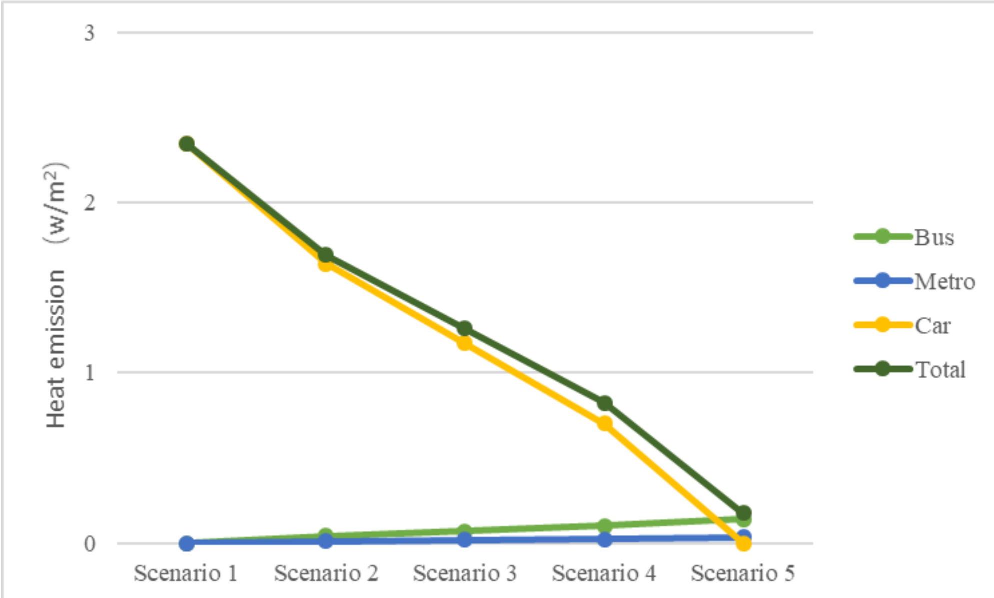

Fig.1 Heat emission of transportation at different scenarios

Heat emission at five different scenarios is showed in figure 1, with the decrease (from 100% to 0) of car usage and the increase (from 0 to 100%) of public transportation, the overall heat emission is decreasing sharply from 2.35 W/m^2 to 0.17 W/m^2. The decrease of heat from car is most significant, which shows a steep descent from 2.35 W/m^2 to 0. Oppositely, increase of heat from bus and metro is slowly. Heat from bus increases from 0 to 0.14 W/m^2 while heat from metro from 0 to 0.03W/m^2, which are much smaller than the reduction of heat from car. In conclusion, the most heat from transportation comes from car and as a result, the improvement of traffic structure contributes to the reduction of heat emission.

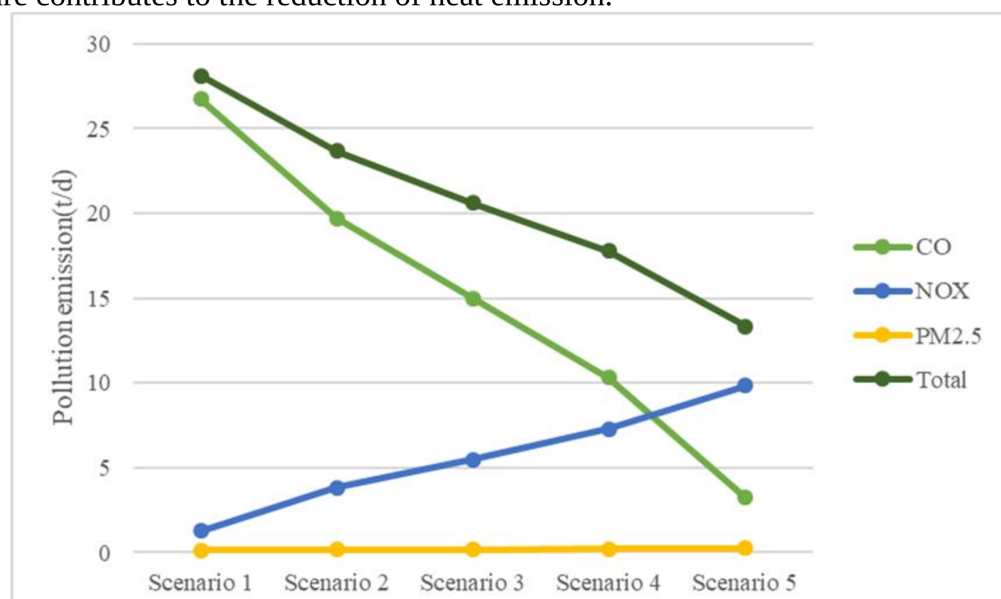

Fig.2 Pollution emission of transportation at different scenarios

Pollution emission at five different scenarios is showed in figure 2, with the decrease (from 100% to 0) of car usage and the increase (from 0 to 100%) of public transportation, the overall heat emission is decreasing from 28.13t/d to 13.32t/d. For different pollutants, the changing situation is different. The CO emission decreases greatly while the NO_X emission increases slightly. The emission of PM2.5 doesn't change much. In a long term, the pollution emission reduction will be more noticeable. If the usage of public transportation adds up from 30% to 70%, the total pollution emission will reduce as much as 2,148t in a year. That is to say, the improvement of traffic structure also contributes to the reduction of pollution emission.

Factors influencing residents' commuting mode choice

The impacts of individual related variables on mode choice. Both age and gender are significant variables (Table 6). The younger the commuter, the more metro and bus trips. The relationship between gender and the probability of choosing public transit is negative, which means female has more car trips comparing with male. From the perspective of operation, improving the carriage environment is useful measures.

The impacts of household related variables on mode choice. Three of five household related variables are statistically significant (Table 6). On the whole, the impacts of household related variables on mode choice is internal consistent. Commuters who have Shenzhen census register, commodity housing purchased and cars are more likely to choose car rather than bus and metro.

Statistically, the coefficients of census register and housing type variables are significant. This can be explained by the fact that these two variables are important aspects of economic capability. The ownership of car significantly impacts the commuters' mode choice. As expected, a commuter owning a car has considerably more car trips than a carless commuter. It suggests that increasing the cost of using cars, such as raising the fuel price and parking fee, are useful to the reduction of car usage.

The impacts of land use variables on mode choice. Six variables of eight land use variables are significant ones and five of them are significant the usage of metro (Table 6). This can be explain that the usage of metro are more impacted by building environment as the number of metro stations are much less than bus stations. Besides, four of the six significant variables are building environment of home. This suggests that the impacts of home area land use on mode choice are more significant than the impacts of workplace land use. As the number of stations influencing the choice of public transit, improving the coverage of public transport and operating extra public transport at rush hours are effective methods to the reduction of car usage.

Table 6. Parameter estimation results for multinomial logit (MNL) model

Variable	Traffic mode	Coeff.	Z-value	
Mode related variables				
Bus (intercept)		3.009	-3.039	***
Individual related variables				
Age	bus	-0.0192	-2.6732	**
	metro	-0.0291	-3.7737	***
Gender	bus	-0.7042	-7.4373	***
	metro	-0.4888	-4.7739	***
Household related variables				

PCRegister_1	bus	-0.4256	-3.7692	***
	metro	-0.3570	-2.8843	**
HType_1	bus	0.2477	2.0148	*
	metro	0.3728	2.7420	**
Hcarornot	bus	-3.524	-29.8894	***
	metro	-3.271	-25.1537	***
Land use variables				
FZ_ABH	metro	0.0117	2.6857	**
FZ_MSN	metro	0.1712	2.9635	**
TZ_PR	bus	-0.446	-5.6953	***
TZ_ABH	metro	0.0567	4.2914	***
TZ_BSN	bus	0.0129	2.8210	**
	metro	0.0082	1.6534	.
TZ_MSN	metro	0.7238	8.9321	***
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 1				
Log-Likelihood	-3841.8			
McFadden R^2	0.29247			
Likelihood ratio test	chisq = 3176.1 (p.value = < 2.22e-16)			

Conclusion

Commuter behavior influences heat and pollution from transportation. We found that the dominant factor is the usage of car. With the decrease of car usage and the increase of public transportation, the overall heat and pollution emissions decrease greatly. Thus, less use of cars and more use of public transportation, especially metro help to create a cleaner and more comfortable urban environment. In addition, as electrification of buses and cars (both taxi and private car) are useful method to reduce heat and pollution from transportation, commuters should choose greener means of transport.

Then factors influencing residents’ commuting mode choice have been analyzed. Results showed that less travel time and travel cost increase the probability of choosing public transit. Younger male commuters who earn low household income, rent an apartment, have large household size and do not have Shenzhen household registration as well as cars are more likely to choose public transit. In addition, dense and diverse development of workplace help to enhance the ratio of public transit.

Therefore, some effective methods both from planning and operation aspect are given for policy makers to reducing heat and pollution from transportation. Improving the carriage environment increasing the cost of using cars, such as raising the fuel price and parking fee and improving the coverage of public transport and operating extra public transport at rush hours are all effective methods to the reduction of car usage.

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