A TWO-STAGE SIMULATION APPROACH OF URBAN TRANSPORT EMISSION EVALUATION TOWARDS CARBON PEAK: A CASE STUDY IN SUZHOU, CHINA

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Commission IV, WG IV/9

KEY WORDS: Carbon peak, Carbon emission simulation, Automotive travel demand, Multi-scenario analysis, Facility distribution

ABSTRACT:

The ever-increasing automotive travel demand is a major source of urban carbon emissions. Therefore, it could be an effective way for local governments to achieve carbon peak by optimizing facility distribution and transport management strategies, that results in lower automotive demand. This study adopts a two-stage approach to evaluate the carbon emission performance of a representative Chinese megacity, i.e. Suzhou. The first stage is to predict the carbon peak through multi-scenario sensitivity analysis with respect to three essential factors for the whole city. The second stage is to estimate the link-based carbon emissions with given traffic flow and vehicle operating mode indicators during the peak hour, so as to locate urban areas and/or facilities with higher emission intensity. Then a correlation analysis is further conducted to explore the possible connections between the built environment factors and transport-related carbon emissions.

1. INTRODUCTION

China, as the world's largest energy producer and consumer, has made an official commitment that China will “aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060” (IEA, 2021). Carbon peak refers to the point that the total emissions of carbon dioxide reach a historical peak, and after that, the emissions will gradually decrease. Urban land use and transport system are closely related to carbon dioxide emissions emitted through human activities. Especially the development of urbanization and motorization stimulates the ever-increasing energy consumption. In 2019, the transport sector, being the second largest source of carbon emissions in China, was responsible for 9% of the overall emission[1]. Additionally, urban transport-related emissions have grown with a rate of 7.5% from 2007 to 2019 in China, which is significantly higher than the world’s average rate of 2.3% (Wen and Song, 2022).

The level of urban transport-related emissions is correlated with various aspects. It is recognized that energy structure and travel demand characteristics are the two major influencing factors. On one hand, modern transport has been heavily relied on oil products, which was responsible for more than 90% of transport sector energy demands despite inroads from biofuels and electricity in 2020 (Bouckaert et al., 2021). Residents' daily travel demand by private automotive with the highest per-capita emission level, becomes the major contribution of urban transport emissions in Chinese megacities. On the other hand, as the urban growth boundary continues to expand to accommodate more population, both the total number of trip demand and the average travel distance keeps increasing, which in turn further stimulates motorized travel demand and results in severe congestion problems.

To mitigate traffic congestion and to reduce carbon emissions are two related but different planning objectives. Compared with many congestion-release oriented policy instruments, such as road rationing, few have been proposed as targeted emission-reduction approaches from spatial perspective. When the government tries to make a balance between economic development and environmental preservation, it is not enough to simply claim the carbon peak commitment. Exploring the feasible pathway through more accurate problem identification is now essential.

Multi-scenario simulation was usually conducted to accomplish the estimations of carbon dioxide emissions and the trend forecasting under different possible conditions (Özer et al., 2013; Seo et al., 2018; Wang et al., 2022). Seo et al. (2018) applied multi-scenario simulation to estimate the range of available potential emission reduction by technical improvements or the emission regulation of heavy-duty vehicles in Korea. Among existing studies, Long-range Energy Alternatives Planning system (LEAP) is usually incorporated as the simulation tool. Shahid et al. (2021) simulated Pakistan’s electrical system from 2016 to 2040 by LEAP. Handayani et al. (2022) utilized the Next Energy Modelling System for Optimization (NEMO) framework of LEAP to evaluate the pathway of the ASEAN power sector toward net-zero emissions by 2050.

Some studies also tried to estimate carbon emissions from a microscopic perspective, in which high-resolution road network and traffic flow data were usually required. Microscale traffic simulation and emission models were widespread used. Usually, a microscopic traffic flow simulation procedure was conducted using observed data from the real world so as to satisfy the input requirement of any vehicle emission model. Quaassdorff et al. (2016) utilized the VISSIM-VERSIT to estimate scenario-averaged emission factors in a heavily trafficked roundabout. Samaras et al. (2019) combined a microscopic dynamic traffic model (AIMSUN) with an instantaneous emission model (CRUISE) to calculate fuel consumption under congested traffic conditions. Zhou et al. (2019) localized the IVE model to identify characteristics, high-solution spatial and temporal distribution of vehicle emissions in Chengdu, China. Alfaseeh et al. (2020) incorporated both a calibrated traffic microsimulation and Motor

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[1] https://wri.org.cn/en/research/toward-net-zero-emissions-road-transport-sector-china

Vehicle Emission Simulator (MOVES) to predict greenhouse gas emission.

After obtaining the emission estimators, researchers are also interested in finding the connection between emissions and any possible influencing factors. Some studies indicated that transport-related carbon emissions are closely related to urban land use and relevant policies (Brownstone and Golob, 2009; Ye et al., 2018; Penazzi et al., 2019; Muto et al., 2022; Wen et al., 2022). Ye et al. (2018) concluded that compact urban form, efficient land use and moderate block size could be the basic structural characteristics towards lower carbon emissions. Wen et al. (2022) made use of high-density traffic monitoring data to estimate link-based emissions and adopted a generalized additive model to identify the nonlinear relationships between population, urban form and emissions. Other studies proposed analytical frameworks to explore the influencing factors of transport-related emissions, such as Sustainable Urban Mobility Plan (Jordová and Brůhová-Foltýnová, 2021), spatial-modal scenarios (Chow, 2016) and compact city policy instruments (Lee and Lim, 2018). However, few studies have established an analytical framework from macroscopic scenario analysis to microscopic carbon emission estimation, so as to find a viable path towards carbon peak.

This study conducted an empirical analysis on carbon emissions associated with residents' daily travel demand, taking Suzhou as an example. The remainder of this paper is organized as follows. Section 2 describes the study area. Section 3 conducts a multi-scenario simulation for the whole area. Section 4 estimates the link-based automotive emissions at the microscopic level, followed by a correlation analysis between automotive emissions and the built environment factors in Section 5. Finally, section 6 summarizes the main findings.

2. STUDY AREA

Suzhou is a modernized and wealthy city. Both the GDP and GDP per capita rank the top ten among all Chinese cities. On the other hand, Suzhou is a 2,500-year-old city, with plenty of inherited historic and cultural heritages. Therefore, the balance between preservation and development is always an inevitable issue during the planning decision making process. As shown in Figure 1, the study area includes five districts, namely Gusu (GS) District, Industrial Park (IP), Huqiu (HQ) District, Wuzhong (WZ) District and Xiangcheng (XC) District.

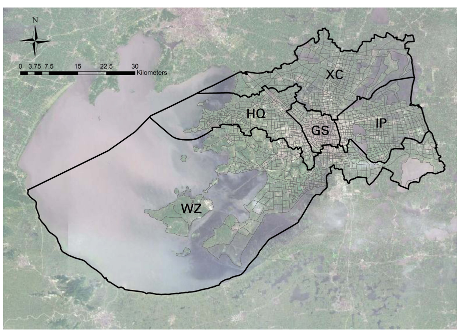

Figure 1. Diagram of the study area

Different development stages and functional orientations make the five districts display different characteristics of urban land use. For example, GS is a historic district with an old city surrounded by canals in the city center. As shown in Table 1, GS has a very high population density. And it is home to an incredible wealth of Suzhou's delicate history dating back thousands of years, focusing on commercial, cultural and tourism industry development. Besides, many municipal level public service facilities, e.g. schools and hospitals, are also located in GS. On the other hand, IP, which have been developed since 1990s, becomes the center of modern Suzhou with the new CBD and urban landmarks. The rest three districts are also newly developed as a result of urbanization and industrialization.

District	Area (km²)	Population (person)	Population Density (person/km²)
Gusu (GS)	83.42	924,083	11,077
Industrial Park (IP)	278.19	1,133,927	4,076
Huqiu (HQ)	332.37	832,499	2,505
Wuzhong (WZ)	2,231.46	1,388,972	622
Xiangcheng (XC)	489.96	891,055	1,819

Table 1. Area, population and population density by district

Travel Mode	2013	2018	2019	2020	2021
Automotive	24.76%	30.42%	31.50%	33.10%	33.20%
Metro	1.07%	5.07%	6.00%	5.60%	6.10%
Bus	17.24%	13.55%	12.10%	9.60%	8.70%
Non-motorized	56.93%	50.96%	50.40%	51.70%	52.00%

Table 2. Changes in travel mode shares from 2013 to 2021

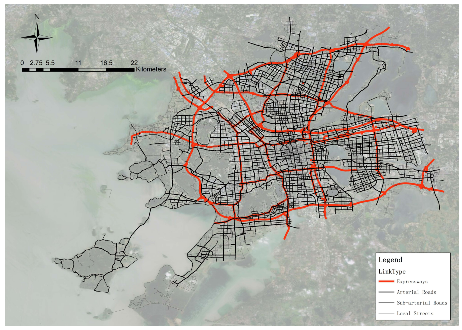

Figure 2. Ring road network of Suzhou

Although polycentric development was already proposed in existing land use plan, as GS and IP possess a large number of attractive commercial areas and high-quality public facilities, there still exists many long-distance travel demand among districts. As shown in Table 2, the share of private automotive mode has increased to 33.20%. With a network of five metro lines established since 2012, the overall public transport share even decreased from 18% to 15%. By looking at the road network, as shown in Figure 2, a clear "ring + radial" expressway structure supports the clustered layout of urban land use, while the planning dense metro network has not been realized When residents are used to auto-dependent lifestyle, it will be harder to shift back to public transport unless the policy is mandatory or the travel time is much shorter. Additionally, this would probably end up with either a more congested old city or a less vital old city. Local government has foreseen the possible scenarios, but most of the resultant management strategies are focused on mitigating traffic congestion. Although reducing carbon emission is related to that, the solutions could be quite different. For example, encouraging electric vehicles (EVs) would not decrease auto demand, while building more roads would not lower down the emissions. In addition, as there is almost no space for new land development in the old city, millions of new population will find their residences in the four new urban districts. Without proper land use plans and urban resources allocation, the overall auto demand will keep increasing.

Therefore, under the target of carbon peak, relevant strategies need to be re-evaluated.

3. MULTI-SCENARIO SIMULATION

At the macroscopic level, a multi-scenario simulation approach is conducted to find the contributions of four influencing factors, e.g. population, technological development, land use and transport management strategies, through which the possible peak future could be revealed.

In comparison with other existing simulation tools, Long-range Energy Alternatives Planning system (LEAP) integrates energy planning and climate change mitigation assessment [2], and contains a complete energy system accounting framework, including transportation. Specifically, population, travel characteristics, energy consumption indicators, and other environmental parameters can be considered in LEAP. The main output of LEAP includes 100-year global warming potential (GWP) in terms of carbon dioxide equivalent.

3.1 Scenario settings

27 scenarios are built with regard to different levels of technological development, travel modal splits and average travel distances, as shown in Table 3. The development of technology is an external influencing factor, which can be expected, but not under the control of the local government. Land use can be adjusted by the local government. The degree of land use's impact could be simulated, but in this study, it is only estimated. The transport management strategies are controllable decision-making variables by the government. Note that, owing to the impact of the COVID-19 on traffic demands since 2020, the base simulation year is 2018.

Influencing Factors	Indicators	Scenario Variables
Population	Population	Number of residents
	Average trip rates	Number of trips per person
Technological Development	Energy structure	Percentage of coal bituminous
		Percentage of crude oil
		Percentage of natural gas
		Percentage of clean energy
	Vehicle categorization and fuel consumptions	Proportion of electric automotives
		Fuel automotive consumption
		Electric automotive consumption
		Diesel bus consumption
		Electric bus consumption
Transport Management Strategies	Travel modal split	Metro share
		Bus share
		Automotive share
		Non-motorized travel mode share
Land use	Average travel distances	Metro average travel distance
		Bus average travel distance
		Automotive average travel distance

Table 3. Scenario settings

3.1.1 Scenario setting of population

The population of the study area in 2018 is 5.15 million[3]. The future population and annual growth rate are set according to "Suzhou Master Plan 2020-2035". The total population will reach 6.9 million by 2035.

3.1.2 Scenario setting of technological development

The development of technology includes progress in energy and improvement of vehicle efficiency (the distance travelled per use of a quantified energy). To be more specific, progresses in energy (such as adjustment of energy structure and development of clean energy) affect the emissions of electricity generation to a great extent. Electric vehicles (EVs) and metro all use electricity. If more clean energy and fewer fossil fuels are used to generate electricity, the average emission intensity of electricity generation can be reduced, so that indirect emissions of EVs and metro will decline. Additionally, increasing vehicle efficiency can be achieved by improving the design and technology used in automotives and buses.

National Energy Board states that 59% of the electricity in China in 2018 is generated by coal. The remaining is from crude oil (18.9%), natural gas (7.6%) and clean energy (14.5%). The three groups of variables are defined according to "China Southern Power Grid New Energy Research", as shown in Table 4.

Energy Structure	2018	2035		
		Low	Medium	High
Coal Bituminous	59.00%	56.80%	40.00%	30.00%
Crude Oil	18.90%	18.90%	17.00%	10.00%
Natural Gas	7.60%	8.40%	18.00%	22.00%
Zero Carbon Energy	14.50%	15.90%	25.00%	38.00%

Table 4. Scenario setting of energy structure

In 2018, the fuel consumption per hundred kilometers of fuel automotives and buses was 10 liters of gasoline and 33 liters of diesel, while electric automotives use 20 kilowatt-hours and electric buses use 75 kilowatt-hours per hundred kilometers. This study assumes fuel automotives consume 5 liters of gasoline and electric ones consume 12 kilowatt-hours per hundred kilometers[4], which is set as the upper bound. Lower and medium values are reduced by 10% and 20% respectively. All the operating buses in the study area have been electric since 2020. This study assumes electric buses maintain the current energy consumption level, i.e. 62.5 kilowatt-hours per hundred kilometers.

Suzhou's electric automotives accounted for 0.87% in 2018[5]. In reference to "New Energy Vehicle Industry Development Plan (2021-2035)", electric automotives will make up from "Low" to "High", are 5.18%, 20%, 40%, respectively. The lower bound, 5.18%, is estimated through linear regression.

3.1.3 Scenario setting of modal splits

In addition to the increase of total OD (origin-destination) demand caused by population growth, the auto mode share is directly related to whether the carbon peak can be achieved. It is generally considered that shifting individual motorized travel to public transit and non-motorized transportation (NMT) can

[2] https://www.sei.org/projects-and-tools/tools/leap-long-range-energy-alternatives-planning-system/
[3] Suzhou Statistical Yearbook-2019: http://tjj.suzhou.gov.cn/sztjj/tjnj/2019/indexce.htm
[4] http://csae.sae-china.org/
[5] 2018 Suzhou Transportation Development Annual Report

reduce carbon emissions. As claimed by OD Survey, over the last five years, the automotive trip (including private automotives, taxis and business automotives) has increased from 24.76% to 30.42%. On the contrary, the bus trip has dropped dramatically, from 17.24% to 13.55%. Thanks to the construction of metro infrastructure, total green transportation had increased by 0.31%. However, it is worth noting that without strong, deliberate policy intervention, the trend of individual motorized travel will continue, leading to carbon emissions increasing rapidly. Therefore, three groups of variables are defined in combination of mode share trends and "Suzhou Master Plan 2020-2035".

Travel mode	2018	2035		
		Low	Medium	High
Metro	5.07%	15.00%	17.00%	20.00%
Bus	13.55%	8.00%	12.00%	15.00%
Automotive	30.42%	37.00%	31.00%	25.00%

Table 5. Scenario setting of travel mode split

Current metro development gives a strong vision, so the three levels of metro's share are set to 15%, 16% and 20% in 2035, as shown in Table 5. According to "2018 Urban Metro Transit Statistical and Analysis Report", the energy consumption per passenger-kilometer of metro transit is 0.139 kilowatt-hours in Suzhou. In addition, considering the current metro patronage will increase to a higher level with better metro operational performance, e.g. reduced headway and more dense stations, the energy consumption per passenger-kilometer of metro transit is set to 0.06-0.08 kilowatt-hours.

3.1.4 Scenario setting of travel distance

Average travel distances are closely related to the land use, e.g. residence and workplace distribution. Normally, urban sprawl results in increased travel distance. As shown in Figure 1, the land use intensity of GS is highly limited, so the future increased population will live in new districts. Even though polycentric development is encouraged in the land use plan, which could help to reduce the average travel distances, in the scenario setting, this study has to consider every possibility. Therefore, the variations of average travel distances for each travel mode are defined according to 2018 OD survey (Table 6).

Average Travel Distance (km)	2018	2035		
		Low	Medium	High
Metro	12.2	14	12.2	10
Bus	6.5	8.5	6.5	4.5
Automotive	9	11	9	7

Table 6. Scenario setting of average travel distance

3.1.5 Scenario formation

With a fixed population growth, this study alters the future scenarios with respect to 27 combinations of technological development, transport management strategies and land use indicators, i.e. LLL, LLM, LLH, LML, LMM, LMH, LHL, LHM, LHH, MLL, MLM, MLH, MML, MM, MMH, MHL, MHM, MHH, HLL, HLM, HLH, HML, HMM, HMH, HHL, HHM, HHH. The first letter represents the level of technological development including low (L), medium (M), high (H). The second letter represents the level of travel modal splits, and the third letter represents the level of average travel distances.

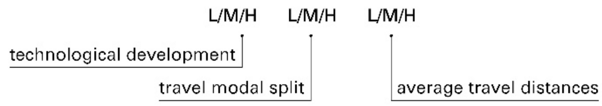

Figure 3. Combined scenario setting

3.2 Impact of influencing factors on carbon peak

As shown in Figure 4, the curves show emission trends of 27 scenarios from 2018 to 2035. There are 9 scenarios in which transport-related carbon emissions keep declining or reach the peak value before 2035, i.e. HLH, HMM, HMH, HHM, HHH, MMH, MHM, MHH, LHH.

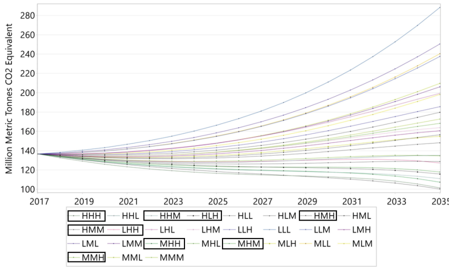

Figure 4. 100-Year GWP: Direct (Demand) plus Indirect (Transformation) Emissions Allocated to Demands

3.2.1 Impact of technological development

When technological development reaches the highest level, there are 5 scenarios (HLH, HMM, HMH, HHM, HHH) under which carbon emissions can reach the peak or keep declining, showing the importance of developing clean energy. Encouraging the adoption of electric vehicles also plays a crucial role. If technology develops normally as predicted before 2035, and the proportion of electric automotives reaches 20% in 2035, land use and transport management strategies shall meet the requirement: one reaches the upper bound and the other reaches the median value in order to reach carbon peak. In the worst case, the technological development is far from satisfactory, so it requires the transport management strategies and land use to reach the upper bound.

3.2.2 Impact of travel modal splits

When travel modal splits reach the highest level, there are 5 scenarios (HHM, HHH, MHM, MHH, LHH) meeting the demand of carbon peak. It demonstrates that encouraging public transport and restricting automotives are effective. If local government is not able to successfully shift the demand from automotive to public transport (L), then both technological development and polycentric development shall reach the higher performance level, i.e. HH.

3.2.3 Impact of average travel distance

When land use is reasonably planned, there are 6 scenarios (HLH, HMH, HHH, MMH, MHH, LHH) meeting the demand of carbon peak. It is noteworthy that scenario HHL cannot reach carbon peak before 2035. It demonstrates that if Suzhou plans to expand on a large scale to accommodate a larger population, i.e. the average travel distance is 14km from metro transit, bus 8.5km, automotive 11km, no matter how much progress is made in the other two aspects, carbon peak would not be achieved before 2035.

https://doi.org/10.5194/isprs-annals-X-4-W3-2022-285-2022

According to the above scenario simulation, it can be predicted that Suzhou can achieve the transport-related carbon peak in the domain of residents' daily travel before 2035 with the reasonable strategies of technology, transport management and land use. All three aspects of strategies are effective, but carbon peak cannot be achieved only by developing one of them. As is known, national technological development cannot be controlled by the local government. The above analysis has already obtained the enhanced travel mode share. Furthermore, scenario HHL verifies that optimization of land use plays an indispensable role in reducing emissions. As shown in Figure 5, automotives are responsible for a large proportion of emissions in scenario HHL.

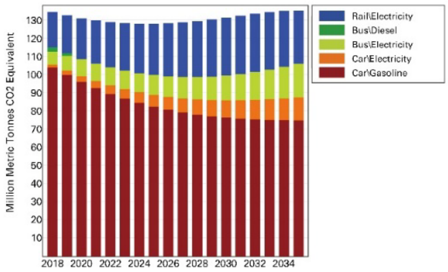

Figure 5. Scenario HHL's 100-Year GWP: Direct (Demand) plus Indirect (Transformation) Emissions Allocated to Demands

4. LINK-BASED CARBON EMISSION EVALUATION

The multi-scenario simulation demonstrates the importance of land use optimization in achieving carbon peak. And automotive emissions make up the largest share. Therefore, in order to find a viable path, it is of interest to further identify the current automotive emission hotspots.

At microscopic level, the unit carbon emission intensity is related to vehicular operating mode, e.g. start/stop, speed. Therefore, this study includes simulation data such as road network structure, traffic flow and vehicle speed, which helps to make a more accurate estimate at regional level.

EPA's Motor Vehicle Emission Simulator (MOVES) [6] is a recognized emission modelling system in various researches. It provides a link-based emission module with the above given data.

In this section, MOVES is applied to simulate 2018 carbon emission level during the peak hour in a typical weekday in Suzhou. The results are analysed and evaluated at both link and traffic analysis zone (TAZ) level.

4.1 Parameter settings

The road network consists of 21,879 links [7] with four types, including expressway, arterial road, sub-arterial road, and local street. The other link-based attributes include free flow speed (FFS), road capacity, traffic flow, and intersection signal control settings.

4.1.1 Average Link Speed

The average link speed is estimated by the vehicle link travel time and link length. In this study, BPR function [8] is applied to calculate the link travel time, as shown in Eqn.(1):

$$t = t_0 \times [1 + \alpha \cdot (q / c)^{\beta}] \tag{1}$$

Where t_0 is the free flow travel time; q is the traffic flow and c is the link capacity; α and β are parameters, which are defined according to the empirical studies of Chinese megacities (Wang et al., 2006).

4.1.2 Intersection Delay

Existing studies proves idling fuel vehicles generate more carbon dioxide and volatile organic compounds (Shancita et al., 2014). Therefore, it is essential to estimate the vehicle delay at signalized intersections at microscopic level.

In this study, the HCM delay formula for signalized intersections [9] is adopted as shown in Eqn. (2):

$$d = \frac{0.5C(1-\lambda)^2}{1-[\min(1,x)\lambda]} + 900T\left[(x-1) + \sqrt{(x-1)^2 + \frac{1.2x}{cT}}\right] \tag{2}$$

Where C is the cycle length (s); λ is the green ratio; x is the degree of saturation; c is the capacity of the link. T is the analysis time, while in this study, the value is set to 0.25, which means that traffic peak duration is 15 minutes.

4.2 Link-based emissions

Figure 6 shows the link-based emissions. The darker the colour, the higher the emissions. In general, the links with high emissions are mostly expressways and arterial roads with heavy traffic flow. Also, extreme values are observed at bottlenecks in/out the old city, West Hill Island and East Hill Island because of traffic congestion. Besides, as shown in Table 7, the average emission intensity in the old city is higher due to the combined impact of both dense intersections and relatively lower road capacities, although there are no heavy loaded expressways in it.

It can safely be concluded that the degree of traffic congestion and traffic flow are the direct influencing factors of transport-related carbon emissions.

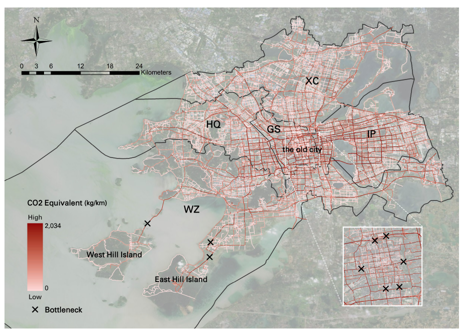

Figure 6. Total emissions of each link

[6] https://www.epa.gov/moves
[7] provided by Suzhou Planning & design research institute co., LTD
[8] Bureau of Public Roads (1964). Traffic Assignment Manual. U.S. Department of Commerce, Urban Planning Division, Washington D. C.
[9] Highway Capacity Manual (HCM) 2010. National Research Council, Transportation Research Board. Washington, D.C.

District	Link-based Average Emission (kg/km)	Zonal-based Average Emission (kg/km^2)
GS	284.03	1980.53
The Old City*	231.09	2502.95
IP	245.61	1074.01
HQ	177.66	388.60
WZ	150.46	98.07
XC	91.19	266.74

*The old city is located in the central of Gusu District.

Table 7. Link-based and zonal-based average emission by district

4.3 Zonal-based emissions

Figure 7 summarizes the estimation results in terms of carbon emission per square kilometer, using TAZ as the basic analytic zone. The darker the colour, the higher the emission intensity. In general, locational variations are noticeable among districts. And the emissions are considerably accumulated in the central area. For example, GS and IP have higher emission than those in the other three districts, which are probably associated with highly dense population and concentrated activity destinations. On the other hand, as shown in Figure 7 and Table 7, the average emission intensity of the four new development districts, i.e. HQ, WZ, XC and IP, varies. Being the more developed districts, IP and HQ contain a large proportion of high emission areas. However, as the increased population would be more distributed in the new districts, the overall emission level could hardly reach carbon peak, unless ideal jobs-housing balance and polycentric development are highlighted in the land use plan and achieved in the future.

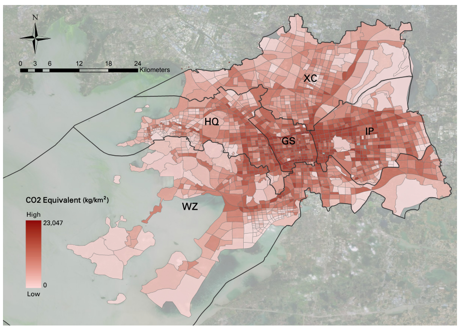

Figure 7. Zonal-based emissions per square kilometer of TAZ

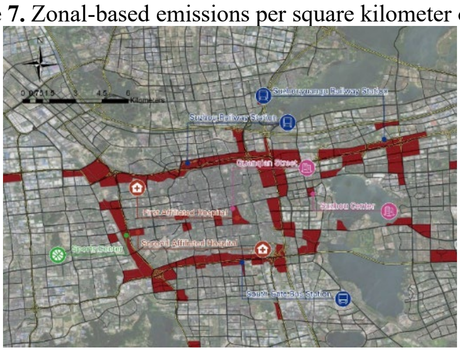

Figure 8. Areas with higher carbon emission intensities

Other than areas along expressways, the top-100 higher emission areas out of 1627 TAZs are mainly commercial centers, railway stations and important public facilities, such as hospitals. Several examples can be found in the old city in GS and the new CBD in IP, as shown in Figure 8. The underlying reason can be derived by examining both the location and OD demand from 2018 survey. For one, they are located in the city central along arterial roads with heavy traffic flow. For another, these facilities attract residents from all over the city, which means more long-distance automotive trips. Besides, since the land use intensity is highly limited in the old city due to heritage preservation purpose, the road capacity is relatively low, and most parking lots are over-loaded during the peak hour. Both the slow speed traffic flow and the queue of idling vehicles make the emission problem more severe.

A series of road rationing policies are introduced in the old city to mitigate traffic congestion. For instance, only local residents' or registered vehicles can drive in the core area. The objective was to mitigate traffic congestion and the effects are getting weaker. On one hand, local government has to enlarge the restriction area. On the other hand, they are also worried if it would cause the loss of urban vitality. When carbon peak is now another issue of concern, things become more complicated. It is of interest to come up with more feasible solutions, not just targeted at auto demand itself, but also the origin of demand, i.e. land use and facility distribution. As observed from the emission results, hospitals are the "pain point". But the solution is definitely not relocation, since most public facilities have to serve a designated area of population. Improvements should be made to have a more balanced facility and medical resource distribution. And of course, transport supply and management strategies can be employed to encourage the activity demand more evenly generated in both spatial and temporal dimensions, e.g. off-peak travel and shared parking.

5. CORRELATION ANALYSIS

Based on the zonal-based emission estimation, correlation analysis is conducted intended for figuring out the main sources of emissions in different regions, so that effective strategies can be proposed through further investigation.

Influencing factors that may affect transport-related carbon emissions include percentage share of each category of road, traffic infrastructure, floor area ratio (FAR), urban land-use ratios, land use mix and point of interest (POIs). After quality assessment and data cleaning, a total of 37 potential factors are mapped and visualized in ArcMap. Subsequently, statistical analysis is carried out at the TAZ level (per square kilometer).

The correlation analysis based on spearman's rank correlation coefficient and random forest regression is divided into two parts: the whole area and five districts separately for more targeted strategies. A spearman correlation coefficient greater than 0.6 is considered to be a strong correlation, while less than 0.2 is considered a weak correlation. The random forest models are trained using the scikit-learn package[10].

The separated correlation analysis reflects the characteristics of districts at different stages of development. Several conclusions can be drawn as follows:

In general, zones with high land use and transport intensities, as well as major public facilities, are easily inducing higher emissions.

[10] https://scikit-learn.org/stable/

https://doi.org/10.5194/isprs-annals-X-4-W3-2022-285-2022

As expected, with regard to transport-related factors, road density, intersection density, and parking density are the three most correlated factors. It is worth noting that the density of bus stations and public bicycle stations also have positive correlations with the emission level. The possible reason is that these facilities are mainly distributed along arterial and sub-arterial roads, where public transport, slow traffic and auto travel demand share the same road space, which is common in Chinese cities. As shown in Figure 9, these phenomena are particularly obvious in the old city and well-developed districts since 1990s, such as GS and IP.

	GS	IP	HQ	WZ	XC	The Whole
Expressway_Share	0.422	0.326 ***	0.349	0.482 ***	0.252 ***	0.306 ***
Arterial_Road_Share	0.102 ***	0.229 ***	0.420 **	0.280 ***	0.104 ***	0.184 ***
Sub-Arterial_Road_Share	-0.107 ***	-0.112 ***	0.107 ***	0.035 ***	-0.069	0.022 ***
Local_Street_Share	-0.256	-0.411	-0.504	-0.443 ***	-0.244 ***	-0.321
Road_Density	0.704 **	0.649	0.430	0.557	0.478 ***	0.596 *
Intersection_Density	0.564 ***	0.602	0.453	0.500	0.449 ***	0.572 **
FAR	0.422	0.600	0.696	0.642	0.445 **	0.695 *
SubwayStop_Density	0.065 *	0.139	0.262	0.201	0.059 ***	0.197 **
Busstop_Density	0.320 *	0.516 *	0.396	0.443	0.296 ***	0.468 ***
Bicycle_Density	0.458	0.417	0.454	0.341	0.352 **	0.468
Parking_Density	0.332 **	0.297	0.317	0.523 **	0.272 ***	0.450
Mixuse	0.125	0.187	0.095 *	0.014	0.263 ***	0.114 **
Residential_Area	0.018 ***	0.393	0.370 **	0.408	0.300	0.410 **
Public_Service_Area	0.147 ***	0.132	0.213 *	0.212	0.042 ***	0.238 ***
Business_Area	0.236	0.086 *	0.393 **	0.410 *	0.340	0.346 ***
Industrial_Area	-0.162	-0.164	0.241 *	0.247	0.002	-0.047 *
Logistics_Area	-0.100	-0.199	0.131	0.124	0.043	-0.018
Transportation_Area	0.163	0.076	0.103	0.069	-0.037	0.098
Utilities_Area	-0.003 *	0.009	0.289	0.210 ***	0.007	0.175 ***
Green_Space_Area	-0.118 **	0.278	0.277	0.420 *	0.426 ***	0.360
Other_Area	-0.075 ***	-0.344 **	-0.590 **	-0.599 ***	-0.426 ***	-0.549 ***
PoiHotel	0.165 ***	0.217	0.339	0.222	0.198 ***	0.320 **
PoiGovernment	0.257 ***	0.361	0.371 **	0.462	0.283 ***	0.409 ***
PoiEdu	0.276 ***	0.391 *	0.466	0.474	0.360 ***	0.496 ***
PoiLife	0.301 ***	0.386	0.576 **	0.536 *	0.399 ***	0.532 ***
PoiCatering	0.227 **	0.342	0.494	0.380 *	0.267 *	0.424
PoiCompany	0.298	0.098	0.467	0.501	0.273 *	0.371
PoiIndoorFacilities	0.070 **	0.174	0.213 *	0.200 **	0.197 ***	0.181 ***
PoiSportRecreation	0.304 ***	0.294	0.395	0.318	0.228 ***	0.402 ***
PoiPublicFacilities	0.210 ***	0.305	0.319 **	0.303 **	0.150 ***	0.400 ***
PoiMedical	0.274	0.350 ***	0.394 ***	0.372 ***	0.261 ***	0.394 ***
PoiTrafficAffiliatedFacilities	-0.090 ***	0.045	0.038	0.076	0.049 ***	-0.001 ***
PoiServicedApartment	0.253 ***	0.365	0.541	0.539	0.367 ***	0.532 ***
PoiTraffic	0.363 ***	0.502	0.636	0.558	0.428 ***	0.632 ***
PoiShopping	0.297 ***	0.406	0.575 **	0.476	0.393 **	0.474 ***
PoiScenicSpot	0.103 ***	0.052	0.027 *	0.003	0.018 **	0.125 ***
PoiFinancialInsurance	0.248 ***	0.276 ***	0.408 ***	0.374 ***	0.252 ***	0.370 ***

"***", "**", "*" represents p-value < 0.001, 0.01 and 0.05.

Figure 9. Spearman's rank correlation coefficient by district

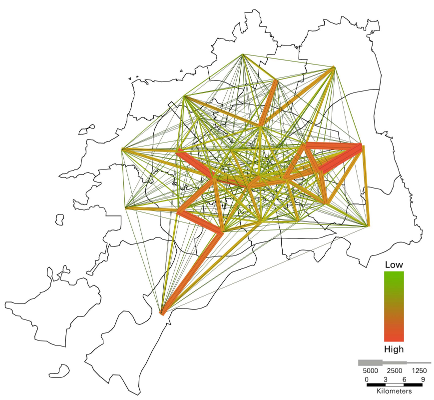

Figure 10. Desire-lines among 24 aggregated analysis zones

In terms of land use-related factors, FAR and major public facilities, such as administrative offices, schools, hospitals, transport stations, and commercial facilities, are mostly associated with carbon emissions, which is more visible in HQ and WZ, two districts developed since 2000s. In contrast, the connection between land use type, POIs and carbon emission are relatively week in GS. To some extent, it implies that popular public facilities in the new towns are more concentrated, locating in areas with high traffic demand. In addition, a large number of activities are associated with public facilities. Take seeking medical advices as an instance. Residents are attracted to municipal-level comprehensive hospitals with good reputations, which are mostly located in the central areas. And this inference can be verified by observing the desire-lines among 24 aggregated analysis zones generated from 2018 OD survey, as shown in Figure 10.

In fact, more regional disparities are noticed among districts. To clearly elaborate the differences, a multiple regression analysis is conducted with Random Forest (RF) method.

	The Whole Area		GS		IP	
R^2	0.71		0.74		0.58	
1	FAR	0.326	Road Density	0.368	Road Density	0.207
2	Expressway Share	0.181	Expressway Share	0.359	FAR	0.206
3	Intersection Density	0.083	Intersection Density	0.029	Expressway Share	0.092
4	Road Density	0.081	Transportation Area	0.026	Sub-arterial Road Share	0.080
5	Poi Traffic	0.028	Poi Traffic	0.025	Local Street Share	0.060

Table 8 R^2 and feature importance ranking according to RF

Table 8 shows the top 5 out of 37 output factors result from several RF procedures. Although FAR, percentage of expressways, intersection and road density are listed in all feature rankings, the sequences are quite different among districts. Road density and percentage of expressways are the two dominant factors in GS. It could be reasonable since GS contains most of the city center with higher road density but relatively narrow roads. Moreover, interzonal long distance auto demand leads to heavy traffic passing through the inner-ring expressway. Both are the probable causes of traffic congestion which could generate extra emissions due to frequent vehicle acceleration and deceleration at low speeds. On the contrary, FAR becomes the one dominant factor in HQ, implying that most emissions are produced by traffic demand within the district. And there exists less-congested zones. As for the developed new town, i.e. IP, road density, FAR, percentage of expressways, sub-arterial roads and local streets rank the top five. Owing to the progressive land use and transport plan, both job-housing balance and grade proportion of road network are properly designed. Therefore, the traffic demand is more evenly loaded. However, because the overall travel demand in IP is very high, a higher level of average carbon emission still inevitable, which could be the warning message for the new districts, and municipal decision makers. If targeted solutions are not proposed, it would be harder to achieve the carbon peak objective, as the private automotive demand will continue to explode in the new towns.

6. CONCLUSIONS

When carbon peak becomes Chinese official commitment to the world, local governments are seeking feasible solutions without compromising economic competitiveness. Traditionally, urban transport, especially private automotive demand, is a major source of urban carbon emissions. This study develops a two-stage approach to evaluate current carbon emission performance of Suzhou, China, which helps the decision-makers opt the more targeted way towards carbon peak. The first stage is to predict the carbon peak through multi-scenario sensitivity analysis with respect to technology development, transport management and land use change at macroscopic level. The results indicate that it is not enough to only rely on uncertain change of energy structure and EVs, because the total private automotive demand will keep increasing as a result of population growth and urban sprawl. Consequently, it is crucial to examine the connection between carbon emission and land use, as well as transport structure. In the second stage, a link-based carbon emission estimation is conducted using traffic demand data generated from 2018 OD survey. As for the major influencing factors, regional disparities have been observed among the old city, newly developed areas and new towns. Public facilities, such as famous hospitals, are identified as the "pain point" due to their locations and strong attractiveness of auto travels. Therefore, polycentric development is encouraged in terms of both facility distribution and related resources. Public transport service should also be improved with targeted OD and demand characteristics analysis.

This study can be extended in two aspects. Firstly, because of limited microscopic traffic data, some simplistic assumptions have been made during the study, such as dynamic vehicle speed and actual intersection delay. Secondly, the ongoing studies are extended to involve the microscopic estimation of more motorized transport modes, such as metro and bus. Then researchers are able to compare the per-capita emission level and to propose more effective transport management strategies. Eventually, more simulations can be conducted with different combinations of land use optimization and transport policy instruments.

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