This is the Accepted Manuscript version of an article published by Elsevier in the journal *Cities* in 2024, which is available at: https://doi.org/10.1016/j.cities.2024.105252
Cite as: Chen W, Tan Z, Wu Y, Biljecki F, Liao S, Zhou Q, Li H, Zheng Y, Gao F (2024): Decarbonizing megacities: A spatiotemporal analysis considering inter-city travel and the 15-minute city concept. *Cities*, 152: 105252.

Decarbonizing megacities: a spatiotemporal analysis considering inter-city travel and the 15-minute city concept

Wangyang Chen[a,b,c], Ziyi Tan[a,b,c], Yaxin Wu[a,b,c], Filip Biljecki[d,e], Shunyi Liao[a,b,c,*], Qingya Zhou[a,b,c], Hongbao Li[a,b,c], Yuming Zheng[a,b,c], Feng Gao[a,b,c]

[a]*Guangzhou Urban Planning & Design Survey Research Institute Co., Ltd., Guangzhou 510060, China*
[b]*Collaborative Innovation Center for Natural Resources Planning and Marine Technology of Guangzhou, Guangzhou 510060, China*
[c]*Guangdong Enterprise Key Laboratory for Urban Sensing, Monitoring and Early Warning, Guangzhou 510060, China*
[d]*Department of Architecture, National University of Singapore, Singapore*
[e]*Department of Real Estate, National University of Singapore, Singapore*

Abstract

Megacities are major contributors to global road CO2 emissions, highlighting their pivotal role in achieving low-carbon development. However, comprehensive studies on emission patterns and decarbonization strategies in these metropolitan areas remain limited. This study presents a novel and portable big data-based workflow for megacities to reveal their spatiotemporal dynamics of road CO2 emissions and quantify decarbonization potentials associated with inter-city travel and the 15-minute city concept. We take Guangzhou City (China) as a case study. Our results reveal that primary purpose trips produce 17% more CO2 emissions than secondary trips on average. Inter-city trips account for 36.3% of the total emissions in the city, and those for primary purposes exhibit closer spatial distributions with intra-city trips. While providing more 15-minute-walk POIs exhibits a marginally diminishing effect on reducing trip average emissions, comprehensive implementation of the 15-minute city concept in Guangzhou can reduce up to 56.3% of the total emissions from non-home-related passenger trips, with variations observed across different trip purposes (40%-70%). A significant "head effect" of decarbonization potential across communities exists for all trip purposes. Our study highlights the environmental limitations of monocentric urban planning models in megacities and contributes valuable insights for crafting effective strategies for sustainable urban development.

Keywords: Sustainable development, Urban mobility, Road transport, Carbon emission, Trip purpose

1. Introduction

Anthropogenic Carbon Dioxide (CO2) is considered one of the major contributors of climate change, posing a significant threat to the global environment. Human development produces an enormous and continuously growing amount of CO2 emissions from various sectors (Lamb

*Corresponding author. Email: shunyi_liao@163.com

Abbreviations: HDFV: heavy-duty freight vehicle; POI: point-of-interest; EIQ: Emission Intensity Quantile; RMSD: root-mean-square deviation.

et al., 2014), with the transport sector alone responsible for nearly a quarter of the global emissions (Yan et al., 2017; Van Fan et al., 2018). This proportion is not only substantial but also on an upward trend, intensifying global environmental concerns (IEA; Mohsin et al., 2019). In the transportation sector, road CO2 emissions are crucial for effective carbon emissions control. (Axsen et al., 2022; Roca-Puigròs et al., 2023). Road transport accounts for over 70% of the total transportation volume and the majority of transportation-related carbon emissions in China (Zhang et al., 2022). It also accounts for about 95% of transport sector CO2 emissions in Europe (IEA). Geographically, around the world, road CO2 emissions are predominantly concentrated in urban areas (Pachauri et al., 2014), particularly in megacities (Deng et al., 2023). These cities, characterized by dense populations and heavy traffic, are both the most challenging and the most critical areas for implementing low-carbon development strategies (Sun et al., 2021). All these backgrounds underscore the importance of reducing road CO2 emissions in megacities as a key step towards achieving carbon- neutrality worldwide (Mallapaty, 2020).

Megacities, with their diverse services and populations, exhibit a complex interplay of vehicle travel behaviors driven by various purposes. Understanding the road CO2 emissions associated with these different trip purposes is crucial for developing targeted and efficient carbon reduction strategies (O'Riordan et al., 2022). Since it is difficult to investigate the accurate purpose of each vehicle trip, trip purposes are usually inferred based on point-of-interest (POI) data and Bayesian rule (Gong et al., 2016; Kan et al., 2022). Considering that existing studies often rely on trajectory data from a single vehicle type (mostly taxis) and are limited to specific urban areas (Zhao et al., 2017; Xia et al., 2020), their findings cannot be directly applied to megacities, leaving a gap in comprehensive analyses that include a broader spectrum of vehicle types and cover the entire megacity. Moreover, within the context of such cities, the role of inter-city travel in the overall traffic volume is not negligible (Cui et al., 2020; Li et al., 2020). While existing literature predominantly concentrates on emissions generated by different types of intra-city travel (Kan et al., 2022, 2024), emissions from inter-city trips and their distinct patterns compared to intra-city trips are not fully considered and examined. Additionally, established methodologies for illustrating and quantifying such disparities are also scarce. This study aims to provide a deeper understanding of these disparities in megacities with novel methods, and assess the environmental impact of metropolitan planning paradigms.

The spatial configuration of urban areas can significantly influence CO2 emissions (Hong et al., 2022a). Larger urban areas, characterized by increased populations and land use changes, tend to generate more carbon emissions (Yang and Zhao, 2023; Hong et al., 2022b), intensifying the need for carbon reduction strategies in megacities. Studies suggested that higher urban compactness can benefit carbon reduction by improving connectivity through reduced travel distances and times (Harari, 2020; Falahatkar and Rezaei, 2020; Makido et al., 2012). However, excessive compactness in macroscopic urban layouts may not always be conducive to lower emissions. Studies have indicated that such compactness may lead to the urban heat island effect, thereby elevating overall carbon emissions (Giridharan and Emmanuel, 2018; Debbage and Shepherd, 2015). Therefore, polycentric spatial planning emerges as an alternative approach to enhance carbon emission efficiency (Sha et al., 2020). While some studies confirm the positive impact of polycentric development on carbon mitigation through reduced commuting duration and emission concentration (Sun et al., 2020; Muñiz and Garcia-López, 2019), others find no significant connection between polycentricity and a lower carbon footprint (Lo, 2016; Wang et al., 2022). Despite the ongoing debate regarding the optimal planning paradigm for decarbonization, there is a clear consensus that improving connectivity and minimizing travel distances is an effective approach for mitigating CO2 emissions.

The 15-minute city concept, aimed at creating compact and mixed-use neighborhoods where essential amenities are accessible within a 15-minute walk, has garnered considerable attention in global urban development (Allam et al., 2022; Khavarian-Garmsir et al., 2023; Logan et al., 2022), including many megacities worldwide, such as Paris (Moreno et al., 2021), Toronto (Yu, 2023), and Shanghai (Wu et al., 2021). The 15-minute city concept reshapes built environments, urban structures, and travel patterns, and is recognized for its potential to reduce travel distance and reliance on private vehicles, thereby mitigating road transportation emissions (Allam et al., 2022). Although various studies have examined how built environments and urban structures affect road carbon emissions (Yang and Cao, 2018; Sun et al., 2020; Yang, 2023), the direct and quantitative relationship between the 15-minute city concept and emissions remains underexplored. The big data of individual vehicle travels, represented by vehicle trajectory data, provides convenience for evaluating the impact of the 15-minute city concept on road emissions (Guo et al., 2023). However, very few studies have adopted such an approach to quantify the impact and the potential of the 15-minute city concept on road carbon reduction, indicating a notable gap in the literature.

This study takes Guangzhou, a rapidly growing megacity with significant regional influence in south China, as a representative case study. Guangzhou shares the common features found in megacities globally, including intense daily activity and diverse vehicle usage patterns. Insights gained from Guangzhou should have high reference value for other megacities around the world, especially for those rapidly growing ones. Given the opportunities and limitations elaborated above and in Section 2, we leverage a comprehensive vehicle trajectory dataset encompassing a comprehensive range of vehicle types with advanced fleet sampling rates to conduct a transplantable analysis, which involves four major contributions: (1) Unveiling the spatiotemporal patterns of road CO2 emissions for different trip purposes across an entire megacity with advanced representation of vehicle types and on-road fleets; (2) Introducing novel methods to compare emission disparities between intra-city and inter-city trips; (3) Evaluating the impact of the 15-minute city concept on road CO2 emissions and quantifying its decarbonization potential in the megacity context; (4) Providing original policy recommendations and efficient 15-minute city implementation strategies for low-carbon development in megacities. The remainder of this paper is organized as follows: Section 2 reviews the current literature; Section 3 introduces our study area, data, and research methods; Section 4 presents the research results; Section 5 discusses the results, and describes limitations and future studies; Section 6 concludes the paper.

2. Literature review

2.1. Measurement of road CO2 emissions

Road CO2 emissions can be measured in multiple ways. Road CO2 emissions at regional or national scales were usually estimated using summary statistical data and then allocated by top-down methods (Zheng et al., 2014; Gately et al., 2015). However, these methods cannot capture nuanced emission patterns of individual vehicle trips in cities. While monitoring stations can gauge CO2 emissions at fixed locations in cities (Mitchell et al., 2018; Zhu et al., 2022), their limited and uneven distribution is not conducive to build fine-grained emission inventories across expansive urban areas. Trajectory-based bottom-up methods, which leverage vehicle trajectory data to estimate trip-level CO2 emissions, were widely used to measure road CO2 emissions across large urban areas with enhanced spatiotemporal resolutions (Choi and Zhang, 2017; Kan et al., 2018a; Ma et al., 2019). These methods first extract the driving status (e.g. speed and acceleration) of vehicles from the trajectory data, and then use microscopic models to calculate emissions of each trip at different times and locations (Boulter et al., 2009; Ntziachristos et al., 2009). Many urban and regional road CO2 emission inventories have been established through this approach (Huang et al., 2020; Zhao et al., 2022; Patiño-Aroca et al., 2022; Deng et al., 2023). Integrating the trajectory data and POI data, the purpose of vehicle trips can be inferred by Bayesian rule (Gong et al., 2016; Chen et al., 2018; Kan et al., 2022).

Accordingly, disparities of road CO2 emissions from different trip purposes were demonstrated (Zhao et al., 2017; Xia et al., 2020; Kan et al., 2022, 2024). The above studies lay the foundation for measuring refined and diversified road CO2 emissions in urban settings. Nevertheless, two significant limitations still exist, especially in the megacity context. First, most existing studies are confined to trajectory data from a single vehicle type, which may not fully represent the diverse emission patterns across different vehicle types (Huang et al., 2020). For example, some studies exclusively used taxi trajectory data to investigate passenger-related emissions (Zhao et al., 2017; Sui et al., 2019; Li et al., 2019; Kan et al., 2018b), while others focused on emissions from freight transport by analyzing truck trajectory data (Deng et al., 2020; Zhao et al., 2023). The inconsistent data sources also hinder cross-study comparisons. Second, the measurement of road CO2 emissions differentiated by trip purposes is still limited by the amount of trajectory data used and the city coverage. These gaps highlight the need for using a unified trajectory dataset to measure road CO2 emissions for different trip purposes, covering a wide range of vehicle types and across an entire megacity.

2.2. *Patterns of road CO2 emissions*

Road CO2 emissions exhibit spatial heterogeneity across urban areas due to variations in local emission sources (Zhu et al., 2022). Studies indicate that the generation of travel-related CO2 emissions in different urban areas is influenced by the built environment (Zhou et al., 2022; Xia et al., 2020; Wu et al., 2023). Regions characterized by higher land-use diversity (Barla et al., 2011; Cao and Yang, 2017), population density (Gassner et al., 2018; Modarres, 2013), and road network density (Hong et al., 2021) exhibit reduced vehicular travel demands and consequently lower travel-related CO2 emissions, while areas farther from city centers (Cao and Yang, 2017) and transit systems (Barla et al., 2011) experience heightened emissions. Regarding the distribution of CO2 emissions on roads, a highly concentrated pattern is observed in both European and Chinese major cities (Böhm et al., 2022; Deng et al., 2023). Road segments with higher traffic volume, lower speed, and more congestion are prone to higher level of emissions (Chen et al., 2022; Wen et al., 2022). Temporally, existing studies indicate that the diurnal variation of road CO2 emissions is correlated with that of traffic volumes (Gratani and Varone, 2005; Zhao et al., 2017). Typically, hourly aggregated CO2 emissions from passenger trips exhibit elevated levels during 7:00-19:00 (Zhou et al., 2022; Deng et al., 2023), while emissions from freight transport tend to be concentrated outside of peak commuting hours (Deng et al., 2023; Zhao et al., 2023). From a seasonal perspective, road CO2 emissions tend to be higher in winter compared to summer (Mitchell et al., 2018). Moreover, inter-city road transport is an important contributor to urban agglomerations around megacities (Cui et al., 2020), and its emission patterns are worth studying. Ren et al. (2016) suggested that inter-city emissions were closely linked to the economic development of the destination city. Xu et al. (2021) proposed a gravity theory-based model to reveal driving forces of intercity CO2 emission generation. For the management of facilities and carbon emissions in megacities, clarifying CO2 emission disparities between intra-city and inter-city trips within the city should be more instructive. However, such insights and methodologies are still lacking in the current literature.

2.3. *Impact of the 15-minute city concept*

The 15-minute city concept is getting momentum in the post-epidemic era for achieving an inclusive, economic, and resilient urban paradigm, by restructuring the services and amenities in neighborhoods (Allam et al., 2023, 2022; Wang et al., 2024; Murgante et al., 2024). Khavarian-Garmsir et al. (2023) explored seven basic principles of 15-minute city in human-scale, and listed three contributions of this concept in social, economic, and environmental sustainability. Various methods have been proposed to evaluate the accessibility of different amenities at city scales (Willberg et al., 2023; Wu et al., 2021; Jin et al., 2024; Guzman et al., 2024). Willberg et al. (2023) examined walking accessibility across various demographic groups under the 15-minute city context, revealing seasonal, diurnal, and age-related variations. Jin et al. (2024) presented a comprehensive framework to evaluate the 15-minute accessibility using SafeGraph POI check-in data, and delineated catchment areas for different travel modes across 12 major American cities. These studies provide valuable insights into both the theoretical and practical dimensions of the concept. While the influence of built environments (Yang, 2023; Cao and Yang, 2017) and urban structures (Sun et al., 2020; Sha et al., 2020) on emissions have been frequently examined, the impact of the 15-minute city concept on road CO2 emissions remains underexplored. Yang and Cao (2018) used Origin-Destination (OD) pairs and a travel survey to quantify CO2 emissions from residential trip purposes in Guangzhou, and uncovered variations in the influence mechanism of emissions across different trip purposes. Abbiasov et al. (2024) revealed that the accessibility to local amenities is significantly correlated with the proportion of consumption-related trips made within a 15-minute walk from home. However, the impact of the 15-minute city concept on road CO2 emissions under different trip purposes and local facility conditions has not been comprehensively evaluated. Additionally, there is a lack of direct measurements of the concept's decarbonization potential on road transport. This knowledge is especially crucial for megacities to enhance the efficiency of facility allocation under the constraints of limited resources.

2.4. *Decarbonization policy and potential estimation*

Policies are widely used to achieve decarbonization goals for the road transport sector(Dong et al., 2022; Stanley et al., 2011). Santos et al. (2010) categorized policy instruments into three types: physical policies (e.g. public transport, land use, and road construction), soft policies (e.g. car sharing, online working, and online shopping), and knowledge policies (e.g. research and development). The policy design can be concluded into three primary directions: (1) Energy solution (e.g. fuel efficiency improvement, vehicle electrification, and biofuel technologies) (Kazancoglu et al., 2021; Duan et al., 2021; Venturini et al., 2019; Hasan et al., 2020; Liaquat et al., 2010; Inkinen and Hämäläinen, 2020); (2) Administrative intervention (e.g. carbon pricing, infrastructure enhancement, and travel demand analysis), (Kazancoglu et al., 2021; Venturini et al., 2019; Hasan et al., 2020); (3) Transport mode optimization (e.g. low-emission mobility investment, active transport promotion, and public transport improvement) (Kazancoglu et al., 2021; Duan et al., 2021; Hasan et al., 2020; Barisa and Rosa, 2018). Crafting hypothetical scenarios based on different aspects of the policy is an essential step in assessing policy's decarbonization potential (Dong et al., 2022; Lu et al., 2020). Dong et al. (2022) evaluated the carbon reduction potential for eight policy scenarios and demonstrated that combining all reduction policies yielded the greatest potential. Lu et al. (2020) established a scenario analysis model to analyze potential energy conservation and CO2 emissions reduction, indicating traffic structure as the most important factor when indirect influences are considered. With the policy scenarios, mathematical models, such as The Integrated MARKAL-EFOM System (TIMES) (Amorim et al., 2014; Jia et al., 2011), and Low Emissions Analysis Platform (LEAP) (Dong et al., 2022; Yan and Crookes, 2009; Duan et al., 2021), are leveraged to quantify the corresponding emission reduction potential. The 15-minute city concept mainly involves replacing vehicle trips by walking and cycling to reduce related CO2 emissions. Although several studies have assessed the carbon reduction potential by substituting short car trips (Neves and Brand, 2019; Keall et al., 2018; Gebhardt et al., 2022), the literature still lacks citywide quantification of decarbonization potential of the 15-minute city concept considering different scenarios. Besides, the distribution patterns of decarbonization potential over urban areas remain unexplored.

To conclude, four major limitations are identified in the existing literature. First, the representation of vehicle types and the coverage of urban areas in measuring road CO2 emissions is insufficient in the context of megacities. Second, previous research lacks insights and methodologies to clarify CO2 emission disparities between intra-city and inter-city trips within urban areas. Third, the impact of the 15-minute city concept on road CO2 emissions across different trip purposes and local facility conditions has not been fully evaluated and quantified. Fourth, the decarbonization potential of the 15-minute city concept on road transport is rarely measured directly, and its distribution patterns over urban areas remain unexplored. This study addresses these limitations and enriches the toolkits to achieve more efficient and sustainable management of facilities and road carbon emissions for megacities, especially for those experiencing rapid growth.

3. Methods

3.1. Study area

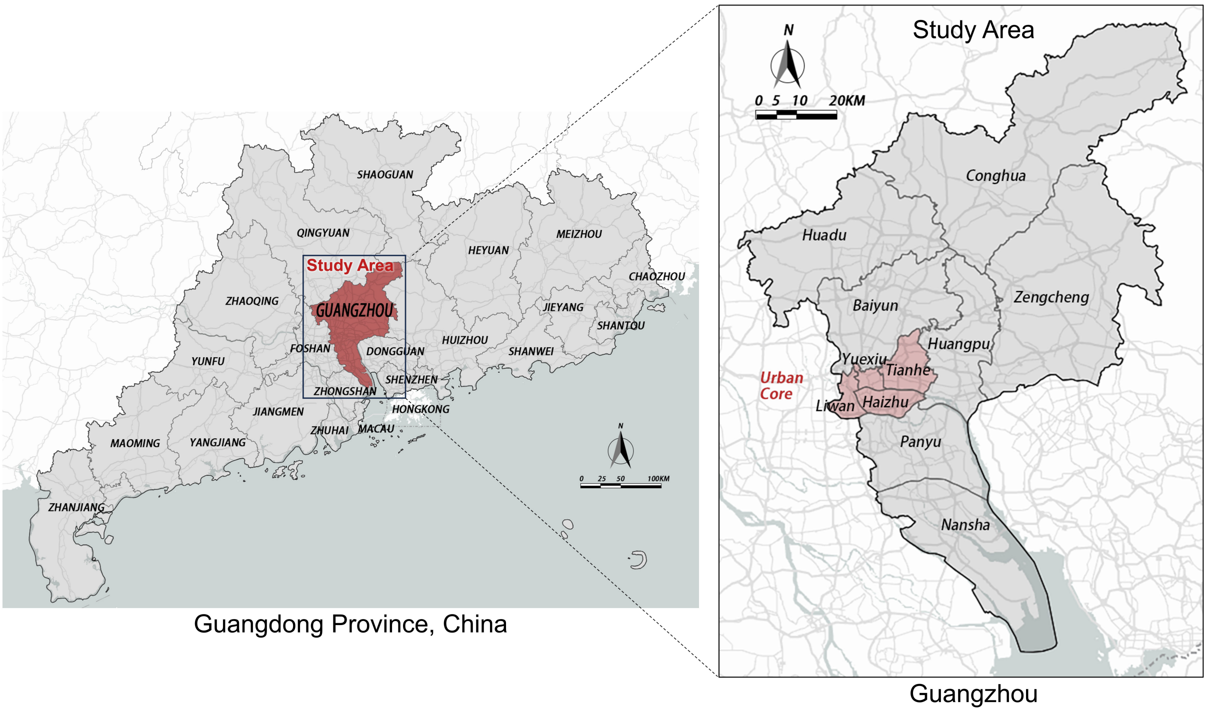

Figure 1: The regional position (in Guangdong Province) and administrative districts of Guangzhou City, China.

Our study area is Guangzhou City, the capital of Guangdong Province, China (Figure 1). Guangzhou is an expansive metropolis with a population of 18.74 million, an area of 7,249.27 square kilometers, a GDP of 2501.9 trillion CNY (equivalent to 362.7 trillion USD) by the end of 2020 (Guangdong Province Statistical Bureau, 2021). It comprises 11 districts, including Liwan, Yuexiu, Haizhu, Tianhe, Baiyun, Huangpu, Panyu, Nansha, Huadu, Conghua, and Zengcheng, which can be further divided into 169 subdistricts and 2,317 communities. The urban core encompasses Liwan, Yuexiu, Haizhu, and Tianhe, characterized by a richer historical legacy, a denser population, and a more vibrant economic landscape.

We provide an overview of urban planning and development history of Guangzhou to help international readers understand the background of the city. With a history of over 2,100 years, Guangzhou is a prominent southern Chinese political center and global trade hub (Xu and Yeh, 2003; Niu and Wu, 2020). During the Qing Dynasty, constrained by city walls, early urban expansion of Guangzhou primarily occurred along the Pearl River, benefiting from foreign trade and proximity to the foreign administration zone (Liu et al., 2022a). These areas, near today's southern Liwan and West Haizhu, gradually evolved into the primary commercial core of Guangzhou. The inner urban area of Guangzhou remained compact before 1949 (Xu and

Yeh, 2003). After that year, as Guangzhou was designated as a national industrial hub, its urban structure was reevaluated (Tian and Shen, 2011). From 1959 to 1977, the city's master plans emphasized urban expansion for accommodating industrialization and diversifying land use by relocating dense industries from the core to the suburbs (Xue et al., 2014). However, those plans failed to materialize (Gong et al., 2014), resulting in slow urban growth. With the Open-door policy in 1978, Guangzhou experienced rapid economic growth alongside a significant influx of population and industries (Cheng et al., 2017). Consequently, the new master plan in 1984 proposed a tri-nuclei urban structure along the Pearl River, incorporating the old core, Tianhe, and Huangpu. Nevertheless, the effort to decentralize the city developed slowly. The 15th master plan implemented between 1987 and 2000, along with the slogan ("Southward expansion, Northward optimization, Eastward extension, Westward combination") proposed in 2000, further emphasized the shift towards a polycentric urban structure (Xu and Yeh, 2003; Wu et al., 2016; Cheng et al., 2017; Meng et al., 2020). From 2001 to 2009, Guangzhou experienced rapid urban expansion in suburban regions such as Nansha, Zengcheng, and Conghua, which are far from the traditional inner core (Wu et al., 2016; Meng et al., 2020).

However, this round of suburban expansion primarily focused on residential projects, the established inner core continued to attract concentrations of employment, commerce, and public services due to its well-developed infrastructure and stronger foundation compared to the suburbs (Gong et al., 2014; Li and Liu, 2017). To accommodate high-tech and high-profit companies, a new Central Business District (CBD) was planned in Tianhe, aiming to alleviate pressure on land use within the existing core (Gaubatz, 1999). However, the success of Tianhe CBD, coupled with its proximity to the old core, stimulated real estate developments along the major connecting roads, resulting in an "enlarged inner city core" (Li and Liu, 2017). The inner ring road, linking seven radial highways extending to suburbs, further reinforced this monocentric pattern. Although it enhanced mobility and accessibility from suburban areas, it encountered heightened congestion with the surge in private car ownership (Feng and Li, 2013). Additionally, the noise, pollution, and visual impact of the viaducts also diminished environmental quality in the inner city core (Tian, 2006), highlighting Guangzhou's drawbacks as a monocentric city.

3.2. Data

3.2.1. Vehicle trajectory data

To characterize vehicle travel behavior and estimate road CO2 emissions associated with various trip purposes, we utilize vehicle trajectory data obtained from PalmGo, a Chinese driving navigation data company. The trajectory dataset comprises anonymized navigation service records from all major navigation platforms in China. This data only preserves relevant vehicle trajectory details, including route trajectory and timestamps. Each trajectory represents a unique vehicle trip and is depicted as a sequence of road segment identifiers with corresponding timestamps, pinpointing the location of the vehicle on the road network at specific times. Leveraging PalmGo's road network data and its associated index system, the trajectories are reconstructed into spatial strings. This comprehensive road network data includes all publicly accessible roadways in Guangdong Province, including highways, provincial & urban expressways, major roads, secondary roads, and branches. The dataset contains around 91.79 million trajectories collected within a single week (19-25 October 2020) across Guangdong Province. We filter the trajectories to include only those with at least one sample located within Guangzhou. We also remove abnormal instances with only one sample location. This process results in around 21.72 million valid trajectories. These refined dataset offers excellent spatial coverage in our study area, covering 99.5% of the road segments and 99.1% of the total road length in Guangzhou.

The dataset captures a diverse range of vehicle types, ranging from mini to large passenger vehicles and from mini to heavy-duty freight vehicles. However, the dataset simplifies this diversity into a dichotomy: heavy-duty freight vehicles (HDFVs) and non-HDFVs. This is because all operational HDFVs in China are legally mandated to install and activate Global Positioning System (GPS) devices, making their trajectories easy to distinguish. Unfortunately, for the other vehicles (non-HDFVs), since reporting detailed vehicle information (e.g. vehicle type, fuel type, and emission standard) is not necessary for navigation services, these factors are not available. Despite this limitation, we incorporate these factors to the best possible extent in our emission estimations (Section 3.3.1). Due to the aforementioned regulation, the trajectory sampling rate for HDFVs nears 100%. The sampling rate for non-HDFVs also approximates to 40%, showcasing a leading sampling rate and comprehensive coverage of vehicle types compared to existing research in the field (Zhao et al., 2017; Xia et al., 2020).

The trajectories are categorized into two trip types, intra-city and inter-city trips, based on the departure and destination locations. Intra-city trips indicate trajectories with both origin and destination situated within the boundary of Guangzhou, while inter-city trips include trajectories where either the departure or destination location falls outside of Guangzhou. Table 1 displays the distribution of valid trajectories across vehicle types and trip types.

Table 1: Distribution of valid trajectories for different vehicle types and trip types.

Vehicle type	**Trip type**	**Num. of valid trajectories**	**Total mileage (million km)**	**Sampling rate (%)**
HDFV	Intra-city	462,169	24.76	100
	Inter-city	358,708	54.12	
Non-HDFV	Intra-city	17,702,932	142.59	40
	Inter-city	3,195,726	86.54	
Total		21,719,535	308.01	-

3.2.2. *POI and place check-in data*

We leverage point-of-interest (POI) and place check-in data to infer the trip purpose of each vehicle trajectory. POIs within the study area are obtained from Amap, a prominent provider of digital maps in China. The initial POI data includes over 20 primary categories with numerous subcategories, which we systematically consolidate into 11 discernible trip purposes (Table 2), including nine well-established trip purposes (i.e. home-related, work-related, passenger transport, shopping, dining, recreation, schooling, lodging, and medical) (Gong et al., 2016; Zhao et al., 2017; Chen et al., 2018; Xia et al., 2020; Kan et al., 2022) and two trip purposes introduced in this study (i.e. life service and freight transport). "Life service" indicates POIs catering to daily necessities not categorized elsewhere, such as courier stations and repair shops. "Freight transport" is further divided into HDFV freight transport and non-HDFV freight transport. HDFV freight trips are directly identified based on the vehicle type in the trajectory data, while non-HDFV freight trips are inferred using the same approach as other trip purposes.

The operating hours of POIs play a crucial role in trip purpose inference. While some POIs directly provide this information, others lack such specifications. To alleviate this issue, we assign default operating hours to each trip purpose, which are drawn from real-life experiences and relevant literature (Zhao et al., 2017; Xia et al., 2020). Recognizing potential limitations in capturing home-related POIs from Amap, we complement the data with house listing data from Lianjia, the largest real estate brokerage company in China. To reflect the temporal variations in POI attractiveness across different trip purposes, we leverage place check-in data from Foursquare (https://foursquare.com). This cloud-based location technology platform provides place check-in times and associated POI categories contributed by anonymous users. Due to data limitations in China, we utilize data from Tokyo, Japan, as an surrogate. This choice is based on the similarity in lifestyle and cultural background between Tokyo and Guangzhou.

Table 2: The primary categories, total quantities, and default operating hours of POIs for each trip purpose.

Trip purpose	**Primary POI categories**	**Num. of POIs**	**Default operating hours**
Home-related	Residential community; Apartment	31,001	0:00-24:00
Work-related	Office; Government; Company	88,380	8:00-22:00
Passenger transport	Railway station; Long-distance bus station; Metro station; Airport	1,378	0:00-24:00
Shopping	Shopping malls; Supermarket	127,528	9:00-22:00
Dining	Restaurant	99,788	11:00-22:00
Recreation	a) Cultural facilities (museum, art gallery, sport hub, etc.); Scenic spot; b) Theater; KTV; Bar	24,729	a) 9:00-17:00 b) 0:00-24:00
Schooling	a) University; b) High school; Middle school; Primary school; Training agency	14,870	a) 0:00-24:00 b) 7:00-18:00
Lodging	Hotel	9,117	0:00-24:00
Medical	Hospital	13,351	0:00-24:00
Life service	Courier station; Repair shop; Salon; Financial service	70,323	8:00-22:00
Freight transport	Factory; Industrial park; Logistics park	16,487	0:00-24:00

3.3. CO2 emission estimation

3.3.1. Trip-level CO2 emissions

This study implements a trajectory-based bottom-up framework to estimate road segment-level CO2 emissions for each trip. By leveraging information from each trajectory, we calculate segment-level speeds based on road length and corresponding travel time. Subsequently, a speed-based microscopic emission model is applied (Boulter et al., 2009). A key parameter in this model is the "emission factor", which represents the amount of CO2 emitted per unit distance traveled by a vehicle. The emission factor is determined by the speed and a series of empirical coefficients varying with vehicle type, fuel type, and emission standard (Supplementary Table S4). Given the absence of these attributes for every single trajectory, we adopt a prevalent approach in the literature (Pla et al., 2021; Zhou et al., 2022). This approach employs average coefficients weighted by urban-level distributions of vehicle types, fuel types, and emission standards. Detailed distributions of the attributes for Guangzhou are collected from official annual reports (Supplementary Table S1-S3). The obtained weighted average coefficients for HDFVs and non-HDFVs are presented in Supplementary Table S5. For each trajectory, the emission factor on each road segment is computed based on the average speed and weighted average coefficients (Boulter et al., 2009). Road segment-level CO2 emissions are determined as the product of the road segment length and the emission factor.

3.3.2. Aggregated CO2 emissions

Given the road segment-level CO2 emissions per vehicle trip (trajectory), these emissions are then aggregated spatially (by road segment) and temporally (by hour of the day) to analyze variations across the city and throughout the day. Our primary objective focuses on evaluating the decarbonization potential of the 15-minute city concept within the megacity context. Therefore, we prioritize distinguishing trip purposes and trip types (i.e. inter-city or intra-city trips) over daily emission fluctuations. As a result, weekday and weekend emissions are merged during this aggregation process to capture overall road CO2 emission patterns for different trip purposes. Trip-level emissions for the entire week are aggregated for each road segment according to the hour of the day. Recognizing that road segments vary in length, we express emission intensity at the road segment level as emissions per unit road length. Additionally, it is important to note that this study only considers emissions generated within the boundary of Guangzhou.

3.4. Trip purpose inference

Trip purpose for each trajectory is inferred using a modified Bayesian rule-based method adapted from Kan et al. (2022). This method assumes that the most likely trip purpose aligns with the POI category exhibiting the highest visit probability. Given the arrival location and time of a trajectory, candidate POIs are identified considering both spatial proximity and operating hours. Spatially, candidate POIs must be within a maximum walking distance threshold (set at 500 meters based on previous studies (Smith and Butcher, 2008; Zhao et al., 2017)). Temporally, the operating hours of POIs must be compatible with the arrival time. The likelihood of a visit decreases as the distance between the arrival location and the POI increases. This spatial attractiveness is modeled using an accessibility-distance decay function with an exponential impedance factor β set to -1.5 (Gong et al., 2016; Chen et al., 2018). For each POI category, the temporal attractiveness during each hour is quantified by the number of check-ins during the hour divided by the average number of check-ins across all hours (Chen et al., 2018; Kan et al., 2022). The overall attractiveness of a candidate POI is then calculated as the product of its spatial and temporal attractiveness. Given the overall attractiveness of all candidate POIs, their visit probabilities are calculated based on Bayesian rules. Traditionally, the trip purpose is determined by the POI category with the highest visit probability (Gong et al., 2016; Zhao et al., 2017; Kan et al., 2022). However, relying solely on the top-ranked POI can lead to inaccuracies. For instance, a shopping trip on a commercial street might be misclassified if the closest POI is a hospital. To address this limitation, our method considers the top N most likely POIs for trip purpose inference (Equation 1). The optimal value of N will be determined by comparing the inference results with survey data.

$$tp_i = \arg\max_{tp}\Big(\sum_{O_j \in TOP(N), TP(O_j)=tp} Pr(O_j|(x_i, y_i), t_i)\Big) \tag{1}$$

where tp_i represents the trip purpose of trajectory i, $TOP(N)$ signifies the set of POIs with the top N visit probabilities, $TP(O_j)$ yields the corresponding trip purpose of POI O_j, tp denotes a trip purpose, and $Pr(O_j|(x_i, y_i), t_i)$ refers to the visit probability of POI O_j given the arrival coordinates (x_i, y_i) and time t_i.

3.5. Comparison between intra-city and inter-city trips

This study proposes a novel method to compare road-level emissions between intra-city and inter-city trips. While intra-city trips are inclined to contribute more CO2 emissions than inter-city trips due to their higher volume, this approach focuses on the relative emission intensity for each trip type on road networks. We use a quantile transform to standardize emission intensities for each trip type independently. This transform effectively converts emission intensities into a uniform distribution between 0 and 100. We denote this normalized value as "Emission Intensity Quantile" (EIQ). The EIQ effectively captures the relative emission intensity of a specific trip type on a given road segment. Based on the EIQs of intra-city trips, all road segments are divided into 100 groups corresponding to the 100 quantiles. To visualize the spatial disparities in road-level emission distributions between intra-city and inter-city trips, we construct an diagram that presents the average EIQ of road segments within each quantile for both trip types, which is named as "EIQ diagram". It includes a red line representing the average EIQ for intra-city trips and a blue curve depicting the average EIQ for inter-city trips. A wider separation between the curve and the line indicates a more pronounced difference in the spatial distribution of relative emission intensity between the two trip types. This disparity can be quantified using the root-mean-square deviation (RMSD) calculated through Equation 2. The RMSD provides an overall measurement of the difference in road-level emission distributions between intra-city and inter-city trips. A higher RMSD signifies a more substantial difference.

$$RMSD = \sqrt{\frac{\sum_{s=1}^{N} (EIQ_s^{intra} - EIQ_s^{inter})^2}{N_s}} \tag{2}$$

where EIQ_s^{intra} and EIQ_s^{intra} denote the Emission Intensity Quantile of intra-city and inter-city trips at road segment s, respectively. N_s represents the total number of road segments.

3.6. 15-minute city concept

3.6.1. Definition and settings

This study adheres to the definition of the 15-minute city prevalent in Chinese urban settings (Wu et al., 2021; Weng et al., 2019). This definition proposes that residents should have access to a variety of essential amenities within a 15-minute walking radius. We translate this concept into the context of vehicle trajectories. Given the departure location and time of a trajectory, we designate POIs that are operating at that time and lie within a 15-minute walking distance from the departure location as "15-minute-walk POIs". In our calculations, a walking speed of 72 m/min is used for a holistic consideration of pedestrian mobility across all age groups (Schimpl et al., 2011). Walking times between two given locations are calculated using the shortest path in the road network. Our analysis of the 15-minute city concept's impact on road CO2 emissions focuses on non-home-related passenger trips, which exclude trips categorized as home-related, HDFV freight transport, and non-HDFV freight transport.

3.6.2. Evaluation of decarbonization potential

This study posits that the 15-minute city concept influences road CO2 emissions through two primary mechanisms: 1) altering vehicle travel demands and 2) reducing trip average emissions. For the first mechanism, we assume that achieving the concept will cut vehicle travel demands within a 15-minute walking or driving radius. For the second mechanism, we assess how trip average emissions vary with the number and proximity of 15-minute-walk POIs from departure locations. This analysis will yield corresponding reduction rates in trip average emissions for different trip purposes and 15-minute-walk POI configurations (number and proximity). We particularly outline two situations regarding the number of 15-minute-walk POIs. The first situation is when there is at least one 15-minute walk POI matching the trip purpose. This situation investigates the decarbonization effect of the minimum supply of 15-minute walkable facilities. The other situation is when there are abundant 15-minute walk POIs matching the trip purpose. The specific threshold for "abundant" POIs varies for different trip purposes and will be determined based on subsequent data analysis.

Incorporating the mechanisms above, we establish five distinct decarbonization scenarios for comprehensive analysis. For vehicle travel demand, Scenario 1 envisions eliminating all vehicle trips within a 15-minute drive, while Scenario 2 considers eliminating all vehicle trips within a 15-minute walk. For trip average emissions, Scenario 3 depicts the situation where abundant 15-minute-walk POIs are available citywide, whereas Scenario 4 examines the effect of at least minimal POIs accessible within a 15-minute walk across the city. Scenario 5 evaluates the combined impact of Scenario 1 and 3. In Scenarios 1 and 2, the decarbonization potential is calculated as the cumulative CO2 emissions for vehicle trips within a 15-minute driving and walking radius, respectively. For Scenario 3 and 4, the decarbonization potential is the sum of reduction in emissions per trip, which is the product of trip-level emissions and the reduction rate determined by the trip purpose and the 15-minute-walk POI configurations.

The decarbonization potential of Scenario 5 is the integration of those of Scenarios 1 and 3, excluding overlapping reductions. It is important to note that these scenarios represent theoretical extremes. While the 15-minute city concept may reduce vehicle travel, it cannot completely eradicate it. Thus, the decarbonization potential obtained in this analysis reflect the feasible limits under each scenario.

4. Results

4.1. Validation of trip purpose inference

A comprehensive validation process is conducted to identify the optimal number of top candidate POIs to consider for trip purpose inference. We conduct multiple inference iterations, evaluating the impact of including the top 1, top 5, top 10, and all candidate POIs most likely to be visited. The results are then compared with a survey dataset (Zhao et al., 2017). As the survey data only distinguishes between three types of trip purposes (shopping, dining, and recreation), we recalibrate the corresponding proportions in our results for a fair comparison (Table 3). The findings reveal that using the top 10 most likely POIs yields inferred results closest to the survey data. In comparison, inferences based on the top 1 and top 5 likely POIs tend to overstate visits to recreational POIs, while using all candidate POIs introduces noise due to variations in the total number of POIs among the trip purposes. For a more comprehensive perspective, we compare our results with those from previous inference studies encompassing nine commonly used trip purposes (Table 4). Notably, our inference relying solely on the top 1 most likely POI significantly exaggerates the proportion of passenger transport trips while underestimating work-related trips. In contrast, inferences based on the top 5 and 10 likely POIs produce trip purpose distributions that are more consistent with the outcomes of these previous studies. Considering a better alignment with the survey data, we choose the inference using top 10 most likely POIs as the foundation for subsequent analyses.

Table 3: Comparison of the distribution of inferred trip purposes with survey data.

Trip purpose	**This study**				**Survey(%)**
	Top 1 (%)	Top 5 (%)	Top 10 (%)	All (%)	
Shopping	38.5	39.4	40.7	61.4	41.2
Dining	22.3	32.6	39.1	36.3	37.1
Recreation	39.3	28	20.2	2.3	21.7

[1] The proportions of shopping, dining and recreation trips obtained by this study are renormalized to fit the categorization of the survey data (Zhao et al., 2017).

4.2. Spatial patterns of road CO2 emissions

The spatial patterns of road CO2 emissions associated with different trip purposes are firstly demonstrated. We define primary trip purposes as those representing a significant portion of daily activities. These include home-related, work-related, shopping, dining, life service, and recreation. All other trip purposes, such as passenger transport, schooling, lodging, medical, non-HDFV freight transport, and HDFV freight transport, are categorized as secondary trip purposes.

Figure 2 illustrates the road segment-level distribution of daily average emission intensities for each primary trip purpose, with inset maps magnifying four areas of interest. To explore the relationship between road CO2 emissions and trip destinations for each trip purpose, we overlay a grey gradient heatmap representing the spatial distribution of trip destinations onto the emission maps. Home-related and work-related trips emerge as two dominant contributors

Table 4: Comparison of the distribution of inferred trip purposes with previous studies.

Trip purpose	**This study**				**Study 1 (%)**	**Study 2 (%)**
	Top 1 (%)	Top 5 (%)	Top 10 (%)	All (%)		
Home-related	22.4 (19.4)	23.6 (21.2)	24.7 (22.1)	14.8 (12.6)	29.4	25.4
Work-related	14.4 (12.5)	22.6 (20.3)	23.4 (20.9)	24.7 (21.1)	25.6	21.4
Passenger transport	12.9 (11.2)	4.9 (4.4)	2.9 (2.6)	1.1 (0.9)	3.5	1.5
Shopping	11.0 (9.5)	12.2 (11.0)	13.8 (12.3)	34.1 (29.1)	12.2	10.8
Dining	6.3 (5.5)	10.1 (9.1)	13.2 (11.8)	20.2 (17.2)	10.6	7.2
Recreation	11.2 (9.7)	8.7 (7.8)	6.8 (6.1)	1.3 (1.1)	7.8	7
Schooling	5.1 (4.4)	5.1 (4.6)	4.5 (4.0)	1.9 (1.6)	3	5.1
Lodging	12.5 (10.8)	10.2 (9.2)	8.3 (7.4)	0.9 (0.8)	5.4	17.3
Medical	4.3 (3.7)	2.4 (2.2)	2.4 (2.1)	1.1 (0.9)	2.5	4.3
Life service	- (6.7)	- (9.4)	- (10.2)	- (14.5)	-	-
Freight transport (Non-HDFV)	- (6.6)	- (0.9)	- (0.5)	- (0.3)	-	-

[1] The proportions outside the brackets represent the renormalized proportions obtained by this study after excluding the trip purposes we add (i.e. life service and freight transport) to maintain consistency with the previous studies. The proportions in the brackets indicate the original percentages without the exclusion. Study 1 and 2 refer to the work of Gong et al. (2016) and Zhao et al. (2017), respectively.

to CO2 emission among primary trip purposes, accounting for 15.5% and 13.6% of total emissions, respectively. CO2 emissions from home-related trips are predominantly concentrated along major roads in the urban core and express corridors leading to suburban residential areas in Baiyun, Panyu, and Huangpu Districts. These high-emission roads spatially coincide with corresponding destinations. Destinations for work-related trips are concentrated in Yuexiu and southwest Tianhe Districts, which are the employment hub of Guangzhou with dense clusters of government agencies, companies, and institutes. However, the corresponding road CO2 emissions exhibit a more dispersed pattern, encompassing a broader area across the entire city. Elevated emissions are observed on major roads and express corridors similar to home-related trips, along with express corridors linking southward and suburban ring expressways. Most spatial characteristics observed for work-related emissions extend to shopping, dining, and life service trips. However, these trip purposes exhibit a less pronounced concentration of arrival locations and a weaker peripheral extension of high-emission roads. Recreation presents the lowest overall emission intensity in primary trip purposes. Areas with higher emissions from recreational trips are mainly distributed along major roads encircling recreational venues in the urban core, Baiyun Mountain in the north of the urban core, and Chimelong Tourist Resort in Panyu District.

The spatial patterns of road CO2 emissions for secondary trip purposes manifest distinct characteristics compared with primary trip purposes, as illustrated in Figure 3. Secondary trip purposes, except for freight transport, exhibit a stronger spatial correlation between road segment-level emission intensity and destination density. Passenger transport trips show four distinct clusters of high emissions and destination density, precisely corresponding to the four major transportation hubs: Baiyun International Airport, Guangzhou Railway Station, Guangzhou East Railway Station, and Guangzhou South Railway Station. Elevated emission intensities are also observed on major routes connecting these hubs to the urban core. Education trips concentrate around the Wushan-Huashi education cluster, while lodging and medical trips cluster within the urban core where is rich in relevant facilities. Freight transport is not a direct trip purpose for most residents but significantly contributes to road CO2 emissions. Together, HDFV and non-HDFV transport constitute 31.9% of the total emissions, with the highest trip average

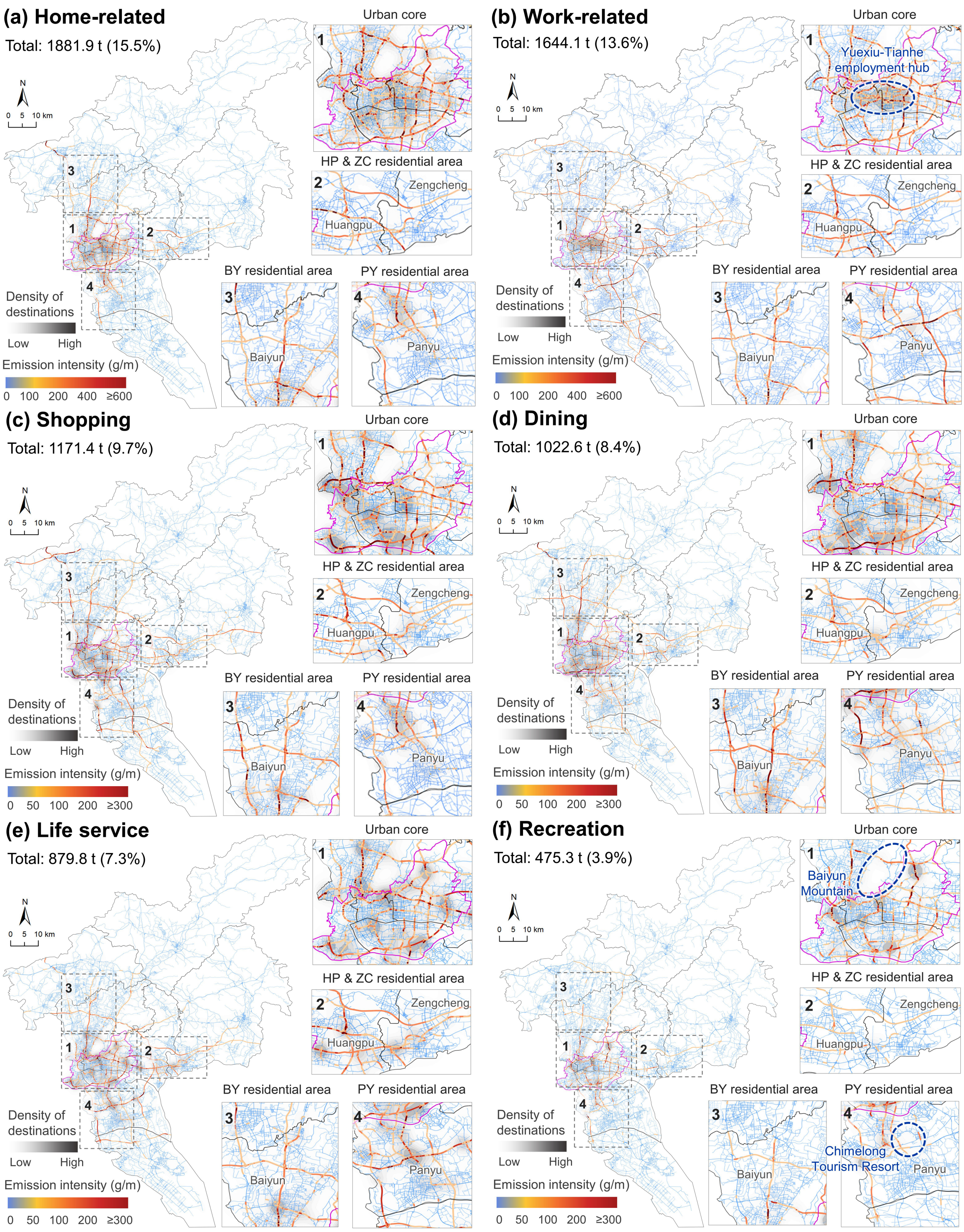

Figure 2: Spatial distributions of daily average emission intensities (g CO2/m) from primary trip purposes at road segment level. The gray lines represent administrative district boundaries, while the rose-colored boundary highlights the urban core. The destinations of trips are visualized using a gray gradient heatmap derived through kernel density estimation. Four areas of interest are magnified in inset maps: (1) urban core, (2) Huangpu and Zengcheng (HP & ZC) residential area, (3) Baiyun (BY) residential area, and (4) Panyu (PY) residential area.

emissions. However, the emission patterns of non-HDFVs and HDFVs is different. Freight transport non-HDFVs primarily operate on intra-city routes along expressways near the periphery of the urban core, exhibiting lower emission intensities on roads leading outside the city.

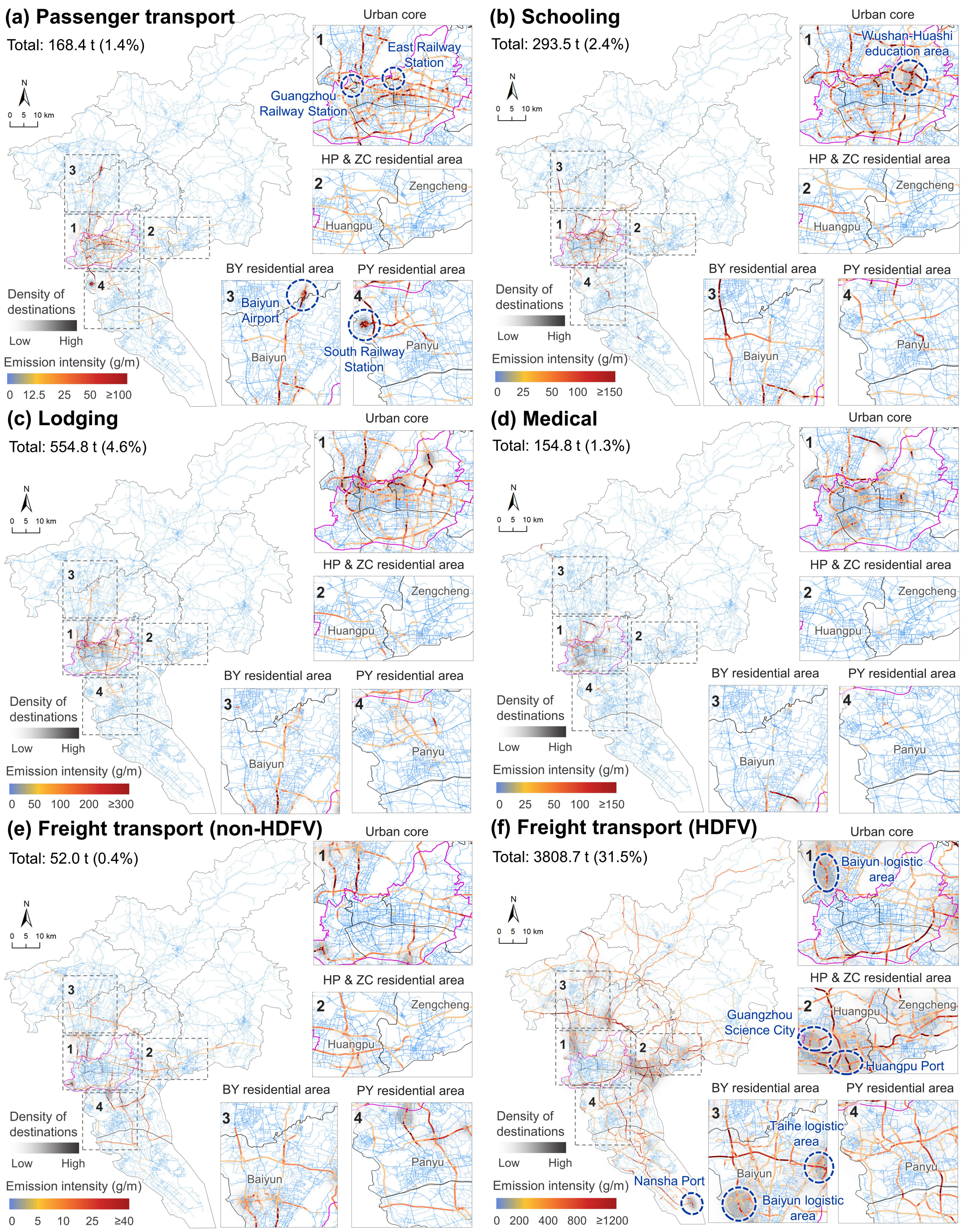

Figure 3: Spatial distributions of daily average emission intensities (g CO2/m) from secondary trip purposes at road segment level. The gray lines represent administrative district boundaries, while the rose-colored boundary highlights the urban core. The destinations of trips are visualized using a gray gradient heatmap derived through kernel density estimation. Four areas of interest are magnified in inset maps: (1) urban core, (2) Huangpu and Zengcheng (HP & ZC) residential area, (3) Baiyun (BY) residential area, and (4) Panyu (PY) residential area.

Their destinations tend to cluster in light industry-dominated areas in Baiyun and Panyu Districts. In contrast, HDFVs travel to locations with heavy freight transportation demand, such as large industry parks (e.g. Guangzhou Science City in Huangpu), logistic clusters (e.g. Taihe logistic area in Baiyun), and cargo port zones (e.g. Huangpu Port in Huangpu and Nansha Port in Nansha). Operating on regional expressways, including those connecting to outer suburbs and other cities, HDFVs contribute the largest share of total emissions (31.5%) and display an exceptionally high trip average emission (42.17 kg per trip), significantly exceeding the average of other trip purposes (1.20 kg per trip).

4.3. *Temporal patterns of road CO2 emissions*

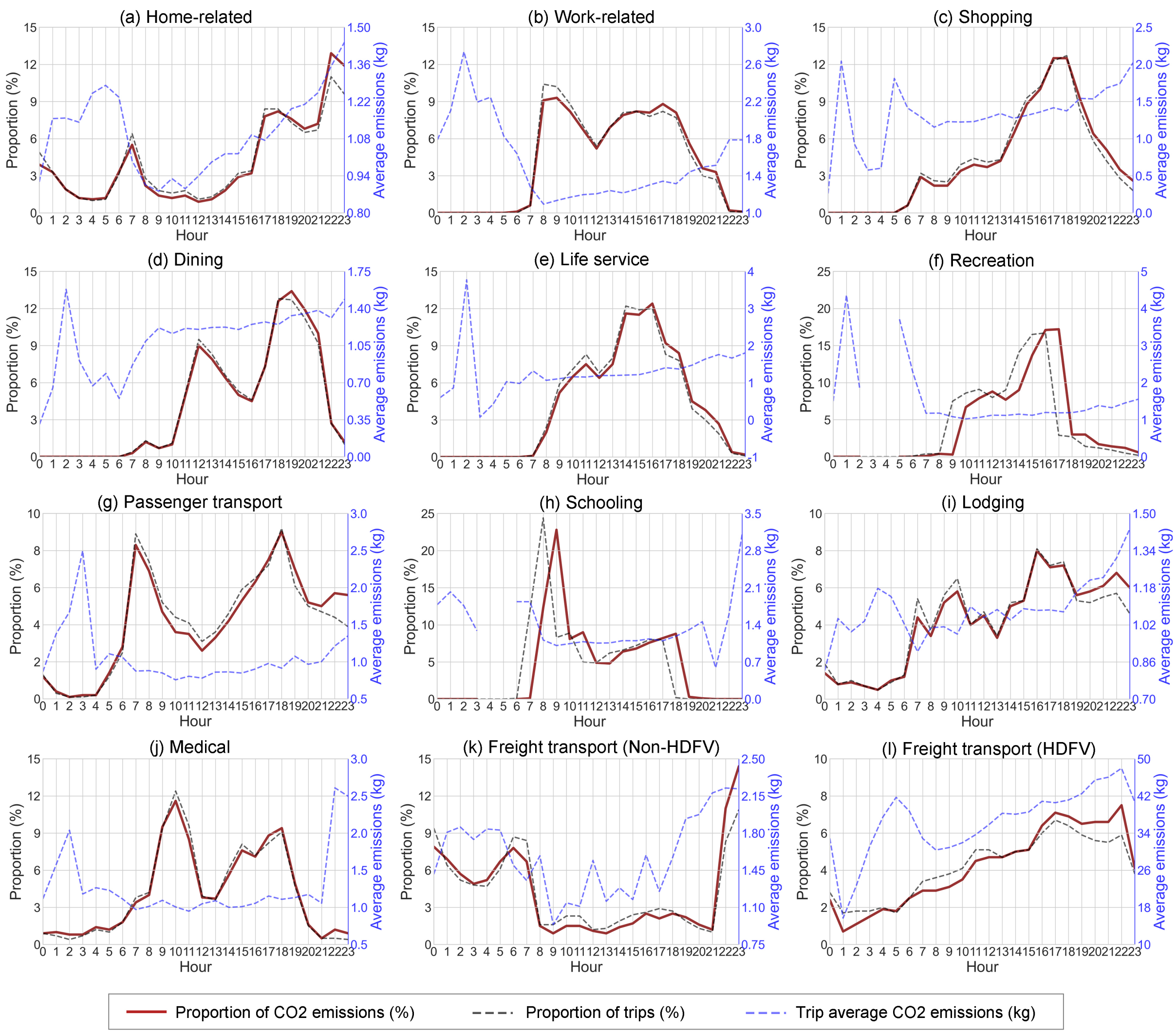

Figure 4: Temporal variation of road CO2 emissions from each trip purpose.

Figure 4 illustrates the temporal patterns of road CO2 emissions. Most home-related trip emissions occur after 16:00, while work-related trip emissions remain consistently elevated during working hours, exhibiting a slight decline at noon, reflecting the typical commuting patterns of urban workers. Shopping emissions gradually rise in the morning, increase more quickly in the afternoon and peaking at around 19:00 before gradually diminishing. Dining-related emissions exhibit two clear peaks, aligning with customary meal times at noon and dusk. Emissions from trips associated with life service and recreation concentrate during working hours, particularly in the afternoon (14:00-17:00), potentially influenced by the opening hours of the facilities related to life services and recreational activities, such as financial outlets, cultural facilities, and scenic spots. Passenger transport trips reveal bimodal peaks during the morning and evening rush hours. During these periods, individuals residing or working in areas beyond subway services may resort to taxis or online ride-hailings services for commuting to and from subway stations. Emissions from schooling trips follow a unimodal distribution, peaking in the morning when students attend schools. Lodging emissions rise as the evening approaches, reflecting the check-in and check-out times at hotels and accommodations. Emissions from medical trips are most concentrated in the morning and afternoon, corresponding to hospital service hours. In contrast to the patterns for most trip purposes, non-HDFV freight transport exhibits lower emission intensity during the daytime compared to nighttime. This observation can be attributed to the reduced temporal and financial expenses associated with nocturnal transportation, which allows freight vehicles to circumvent traffic control and congestion. However, this characteristic is not evident in HDFV freight transport, which displays a gradual increase in CO2 emissions from the early hours to the end of the day.

To investigate the mechanisms behind the temporal emission patterns, we compare the hourly variations of emissions with those of the corresponding proportions of trips and trip average emissions for each trip purpose (Figure 4). Our initial observation shows a close synchronization between emissions and the number of trips (trip frequency) across all trip purposes. This indicates that the temporal patterns of emissions are primarily driven by trip frequency. However, when examining the relationship between trip average emissions and emissions, we see differences among the trip purposes. For home-related, lodging, and freight transport (non-HDFV and HDFV), trip average emissions exhibit a positive correlation with overall emissions. This suggests that for these trip purposes, high emission periods are associated with both a high number of trips and high trip average emissions. These two factors jointly contribute to the overall increase in emissions for these trip purposes. In contrast, for the remaining trip purposes, trip average emissions are not significantly associated with changes in the overall emissions. In conclusion, our analysis reveals that the temporal patterns of road CO2 emissions are primarily determined by trip frequency for most trip purposes. However, for home-related, lodging, and freight transport, both trip frequency and trip average emissions influence overall emissions during the period.

4.4. Emission patterns of intra-city and inter-city trips

Urban road transport in Guangzhou holds a significant portion of inter-city trips, which contribute to 36.3% of total road CO2 emissions within the city. Inter-city trips are characterized by an average distance of 40.1 km, which is approximately fourfold greater than the average distance of intra-city trips (9.2 km). Trip distances of both trip types follow a log-normal distribution, as illustrated in Figure 5a. CO2 emissions from both trip types align with a log-normal distribution as well (Figure 5b). Notably, inter-city trip average CO2 emissions (7.5 kg) are 6.7 times larger than their intra-city counterparts (1.7 kg), indicating an even more pronounced amplification than travel distance. However, when we examine trip average emissions by purpose, the difference between inter-city and intra-city trips becomes less dramatic, averaging around 3.4 across trip purposes. Figure 5c demonstrates the magnitude of road CO2 emissions categorized by trip purpose and trip type. On average, inter-city vehicle trips emanate 4,635.7 t CO2 per day in Guangzhou. HDFV freight transport, as the foremost contributor, contributes 43.2% of the total inter-city emissions. Home-related, work-related and shopping merge as the primary contributors among passenger trips, accounting for 15.4%, 10.1% and 9.3% of the total inter-city emissions, respectively. Furthermore, HDFV freight transport holds the highest proportion (52.6%) of inter-city emissions to total emissions among all trip purposes again, followed by non-HDFV freight transport at 46.9%. Additionally, shopping and home-related trips also have over 30% of emissions from inter-city trips. Conversely, schooling, passenger transport and lodging are the trip purposes with the lowest share (around 22%) of inter-city emissions, indicating a more localized emission pattern.

In Figure 6 illustrates disparities in road segment-level distributions of CO2 emissions between intra-city and inter-city trips with EIQ diagrams. Generally, the red line representing

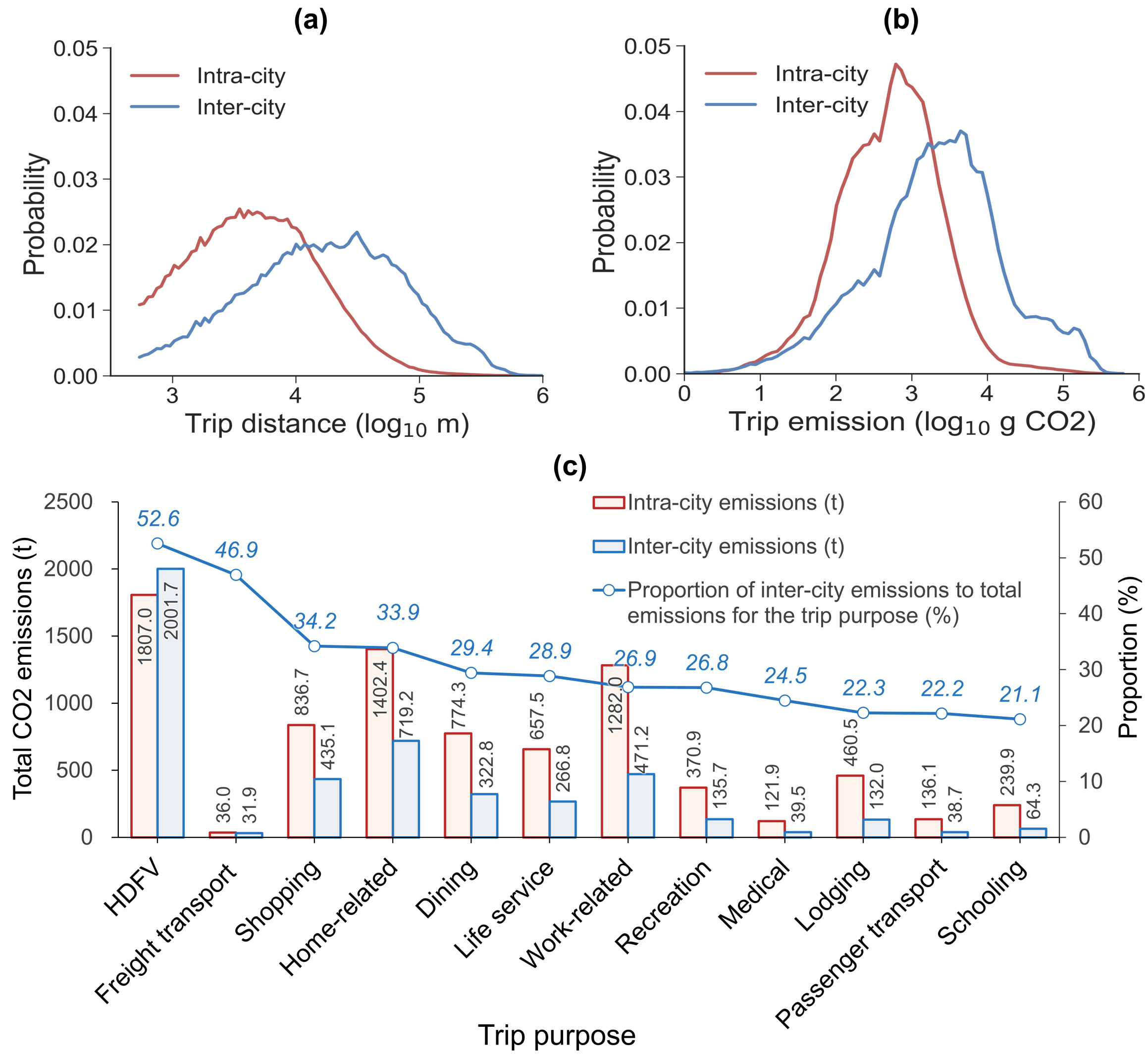

Figure 5: Statistics of road CO2 emissions from intra-city and inter-city trips. (**a**) Probability distribution of trip distances (logarithmic scale) for intra-city and inter-city trips. (**b**) Probability distribution of CO2 emissions (logarithmic scale) for intra-city and inter-city trips. (**c**) Total road CO2 emissions of intra-city and inter-city trips and the proportion of inter-city emissions to total emissions for each trip purpose.

intra-city EIQ remains above the blue curve representing inter-city EIQ, indicating that most roads experience higher relative emission intensity from intra-city trips than inter-city trips. However, a distinct pattern emerges near the 0th quantile, where the inter-city EIQ curves for all trip purposes rise sharply above the intra-city EIQ line. This indicates that roads with the least intra-city EIQ tend to have higher inter-city EIQ. This phenomenon is particularly evident for secondary trip purposes. Geographically, these roads mainly correspond to the major inter-city connectors near the city's boundary, functioning as entry or exit points of the city with minimal intra-city traffic flow. Finally, all the inter-city EIQ curves converge towards the intra-city EIQ lines near the 100th quantile, suggesting that the roads with the most significant emissions from both trip types overlap.

RMSD serves as a quantitative metric to assess the disparities in spatial distributions between intra-city and inter-city trips. A higher RMSD value indicates a larger difference. Primary trip purposes generally have lower disparities (average RMSD of 0.123), compared to secondary trip purposes (average RMSD of 0.263). Home-related and HDFV freight transport exhibit the most similar spatial distribution of relative emission intensities between intra-city and inter-city trips, while non-HDFV freight transport (RMSD = 0.424) and medical trips (RMSD = 0.319)

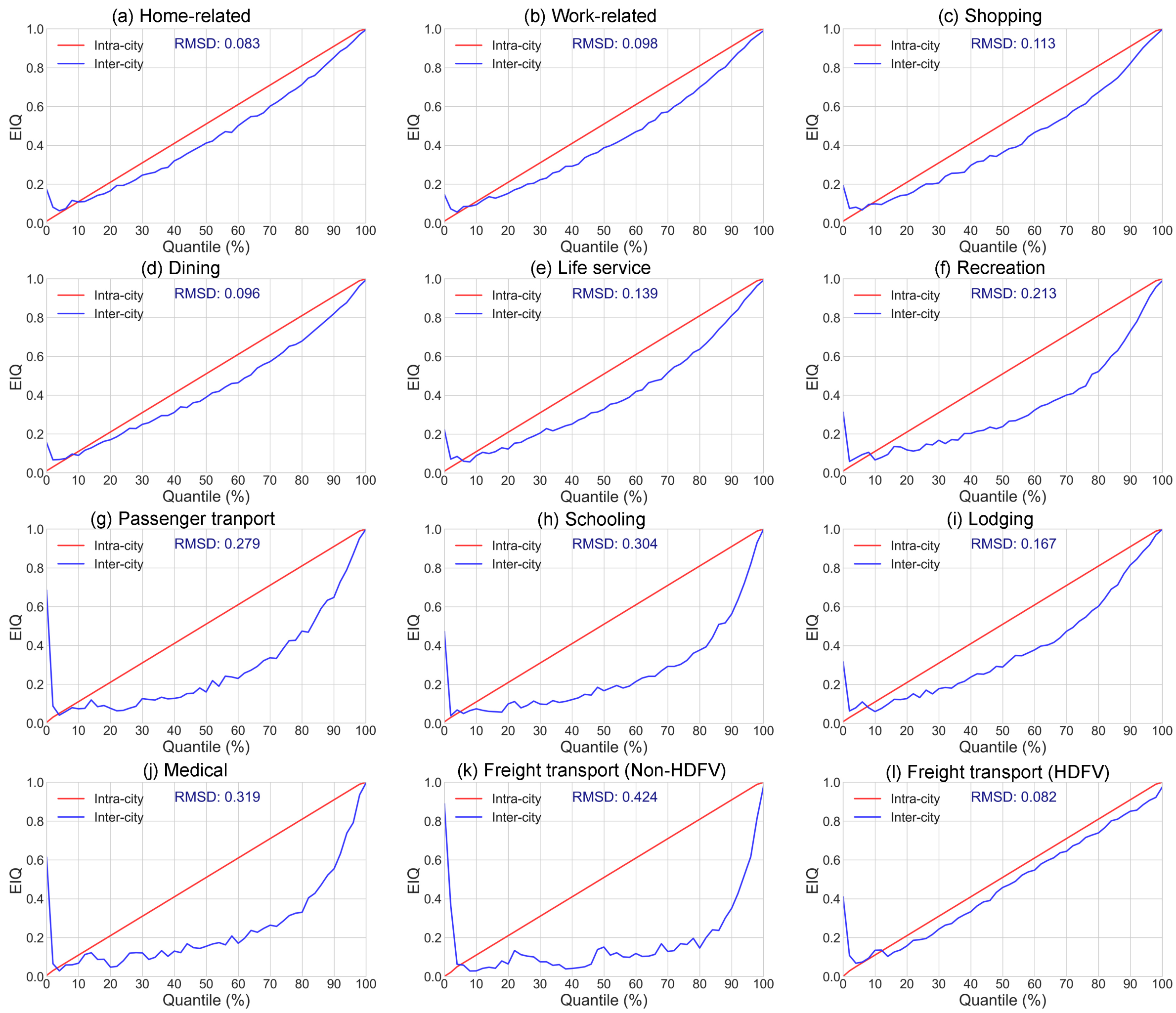

Figure 6: Distribution of Emission Intensity Quantile (EIQ) for intra-city and inter-city trips for each trip purpose.

show the greatest disparities. Moreover, the relationship between total emissions and RMSDs for trip purposes can be well fitted by a descending logarithmic function. This indicates that trip purposes with higher overall emissions tend to have more similar spatial distributions of intra-city and inter-city emissions.

4.5. *Potential impact of the 15-minute city concept*

Leveraging the estimated CO2 emissions and the inferred trip purposes of trajectories, we assess the impact of the 15-minute city concept on road CO2 emissions. First, we investigate how trip average emissions are affected by the number of POIs within a 15-minute walking distance from the departure location (15-minute-walk POIs). Figure 7a shows how trip average emissions vary with the number of 15-minute-walk POIs for different trip purposes. A general trend emerges: vehicle trips departing from places with more 15-minute-walk POIs tend to have less intensive trip average emissions. This observation is statistically significant, with an overall Pearson coefficient of -0.068 ($p < 0.01$). This negative correlation persists for all trip purposes and districts (see Supplementary Table S6-7), suggesting a universal pattern across various trip purposes and locations. Vehicle trips departing from locations with no 15-minute-walk POIs exhibit considerably elevated emissions for all trip purposes. Conversely, trips departing from locations with a minimal POI density (1 to 20 15-minute-walk POIs) experience a substantial reduction in trip average emissions by 32.6% compared with those with no 15-minute-walk POIs. This none-to-minimal reduction rate is consistent across all trip purposes, ranging from 29.4%

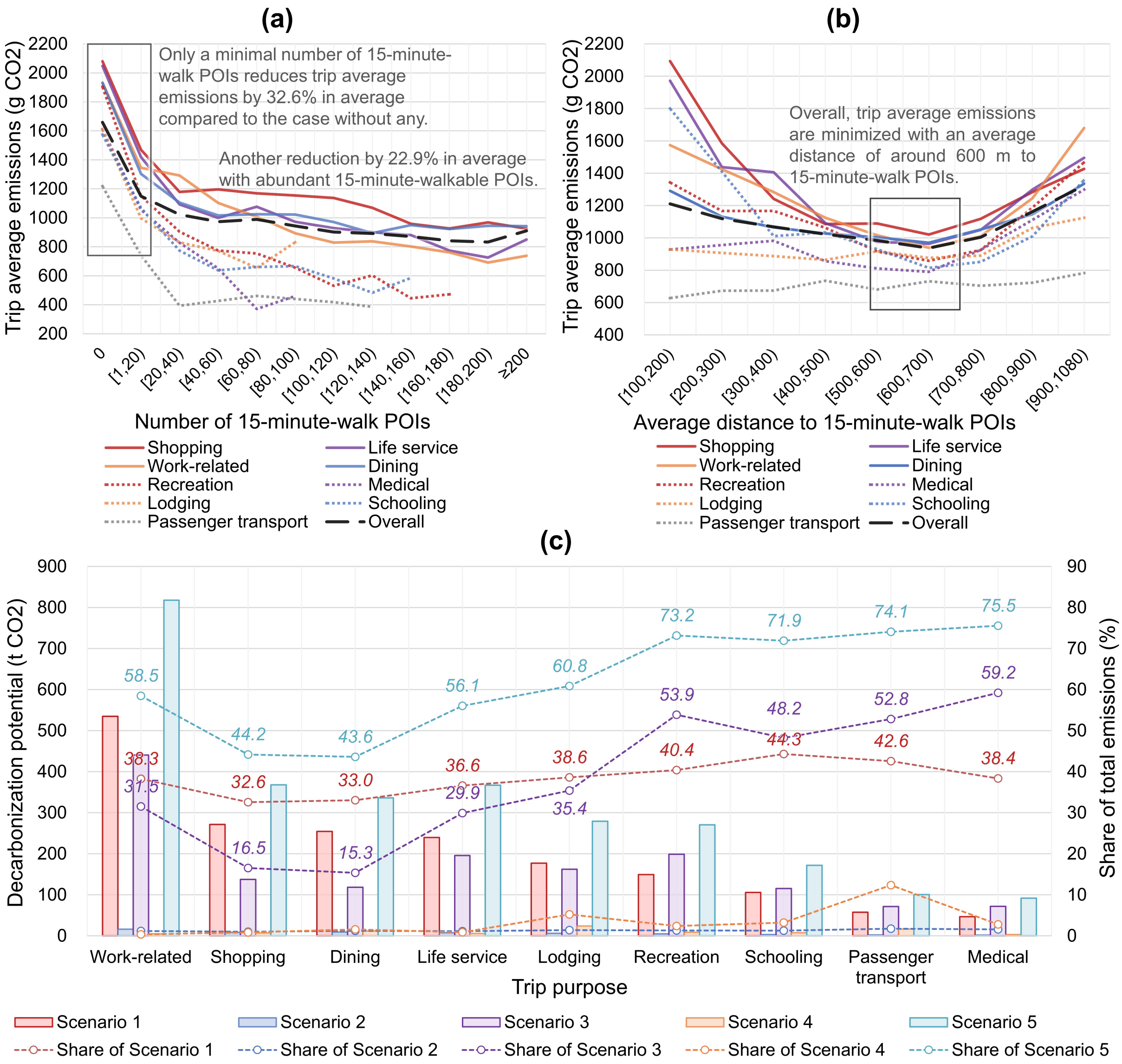

Figure 7: Potential impact of the 15-minute city concept on road CO2 emissions. (**a**) The variation in trip average emissions (g CO2) for different trip purposes over the number of 15-minute-walk POIs related to the purpose. Results obtained with insufficient samples (less than 100) are excluded. The continuous lines, dot lines, and dash line represent the primary trip purposes, secondary trip purposes, and the overall situation, respectively. (**b**) The variation in trip average emissions (g CO2) for different trip purposes over the average distance from the departure plocation to the 15-minute-walk POIs related to the purpose. (**c**) The decarbonization potential and the corresponding share of total emissions for non-home-related passenger trip purposes in five scenarios.

for shopping to 39.6% for recreation (Table 5). The impact on the reduction of trip average emissions gradually diminishes as the number of 15-minute-walk POIs increases. Overall, there is another marginal reduction in trip average emissions by 22.9% when 15-minute-walk POIs become abundant (considered abundant when trip average emissions reach the minimum value for the trip purpose). The minimum-to-abundance reduction rate varies significantly across trip purposes. Dining, lodging, and shopping are associated with a relatively smaller reduction rate (below 27%). Conversely, for some secondary trip purposes such as medical, recreation, and schooling, while rising the number of 15-minute-walk POIs from a minimum to abundance shows greater effectiveness in reducing trip average emissions, with a reduction rate exceeding 37%.

Furthermore, we investigate how the average distance from the departure location to 15-

Table 5: Reduction rates for each trip purpose in trip average CO2 emissions as the number of 15-minute-walk POIs increases from none to minimum, none to abundance, and minimum to abundance, respectively.

	Reduction rate (none-to-minimum)	**Reduction rate (none-to-abundance)**	**Reduction rate (minimum-to-abundance)**
Recreation	39.6%	76.6%	37.1%
Passenger transport	39.2%	68.3%	29.1%
Lodging	38.1%	61.0%	22.9%
Medical	34.5%	76.9%	42.4%
Dining	32.5%	53.7%	21.1%
Schooling	32.1%	69.3%	37.2%
Life service	30.7%	64.5%	33.8%
Work-related	30.4%	64.2%	33.8%
Shopping	29.4%	55.5%	26.1%
Overall	32.6%	55.4%	22.9%

minute-walk POIs affects trip average emissions for different trip purposes (Figure. 7b). Interestingly, the results reveal a U-shape pattern for most trip purposes. When the average distance is short (under 600 m), a closer proximity between the departure location and 15-minute-walk POIs is associated with higher trip average emissions. This pattern is particularly evident for shopping, life service, and schooling trips. For most trip purposes, trip average emissions reach a minimum around an average distance of 600m from 15-minute-walk POIs. As the distance increases from this point, emissions start to rise again. Passenger transport and lodging trips, however, deviate from this pattern, exhibit a consistent positive correlation between trip average emissions and the distance to 15-minute-walk POIs.

The decarbonization potential and share of total emissions from non-home-related passenger trips under five scenarios (defined in Section 3.6.2) are illustrated in Figure 7c. Our results suggest that eliminating vehicle trips within a 15-minute drive (Scenario 1) and providing abundant 15-minute-walk POIs (Scenario 3) present substantial decarbonization potential, reducing total emissions from non-home-related passenger trips by 36.9% and 30.4%, respectively. Notably, Scenario 1 exhibits a consistent reduction rate of around 35% across all trip purposes. In contrast, Scenario 3 demonstrates a more targeted effect on secondary trip purposes, such as schooling, passenger transport, and medical services, potentially reducing their total emissions by around 50%. However, the impact on shopping and dining trips is less significant, with reductions remaining below 20%. Scenario 5 offers a holistic evaluation of the 15-minute city concept's decarbonization potential by considering both reduced vehicle travel demand and lower trip average emissions. This scenario achieves a remarkable 56.3% reduction in the total emissions from non-home-related passenger trips. Road CO2 emissions from recreation, schooling, passenger transport, and medical trips can be curtailed by over 70%, while other trip purposes can also exhibit reduction rates ranging from 40% to 60%. Conversely, the impact of eliminating vehicle trips within a 15-minute walk (Scenario 2) and providing minimal 15-minute-walk POIs (Scenario 4) is relatively modest, mitigating the total CO2 emissions from non-home-related passenger trips by only 1.2% and 1.8%, respectively.

Spatial analysis of decarbonization potential is crucial for developing targeted policy implications. We focus on Scenario 5 to reflect the maximum reduction potential. Since the 15-minute city concept primarily cuts emissions at trip origins, we allocate the decarbonization potential of each vehicle trip to its originating community. Figure 8a shows the spatial distribution of the overall decarbonization potential. The urban core holds 32.8% of the total potential, with variations within its districts. Yuexiu District, with its well-developed infrastructure and compact size, has less potential for further reduction, while central and northern Tianhe, south-

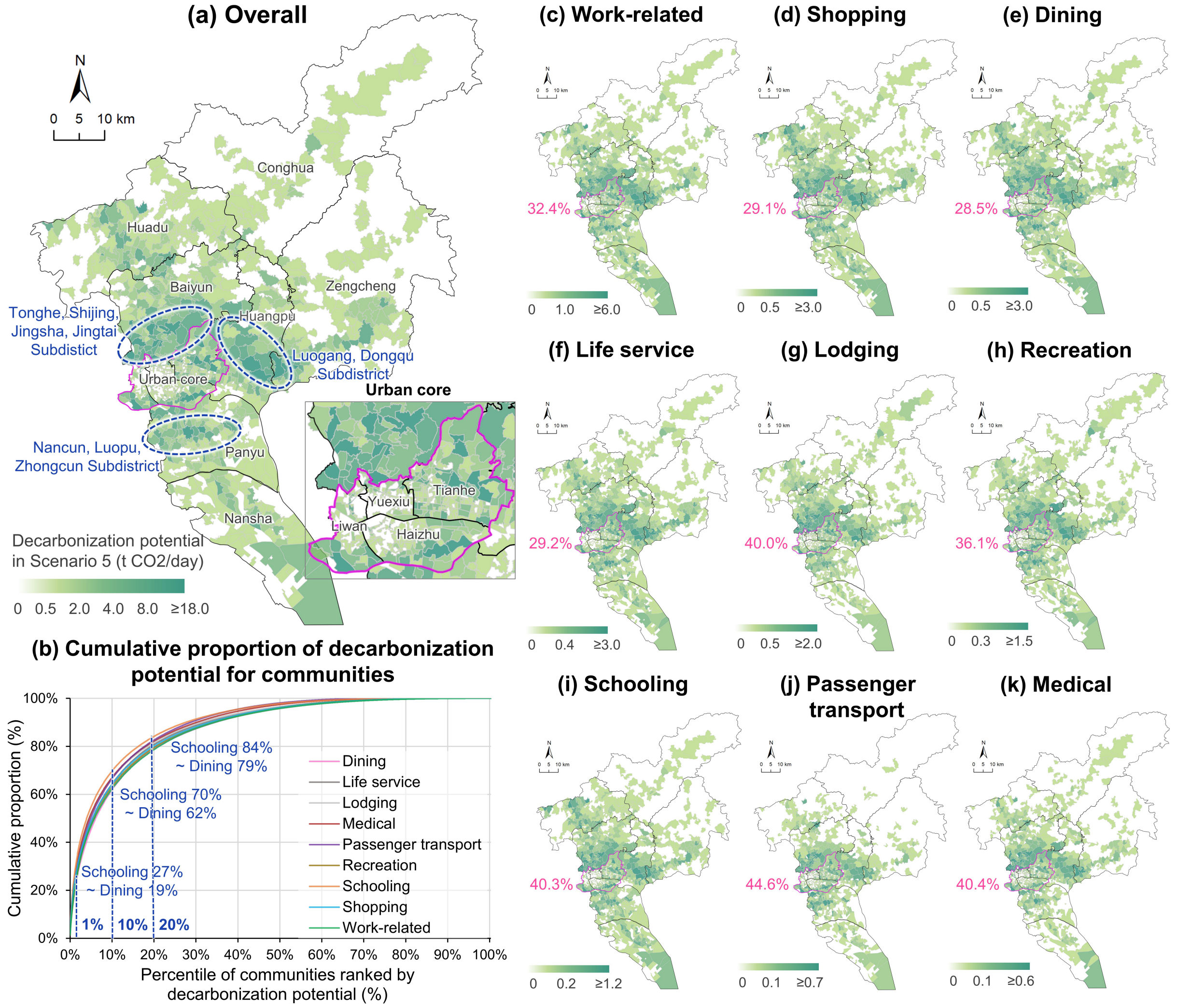

Figure 8: Decarbonization potential of the 15-minute city concept on road CO2 emissions (Scenario 5) in Guangzhou communities. (**a**) Spatial distribution of the overall decarbonization potential (t CO2/day) across communities. Zoom-in for the urban core is provided. (**b**) Cumulative proportions of the decarbonization potential by trip purpose across communities. Horizontal axis: percentile of communities ranked by their total reduction potential. Vertical axis: ratio of total decarbonization potential for the corresponding communities to overall potential. The upper and lower limits of the cumulative proportions and the corresponding trip purposes for the top 1%, 10%, 20% of communities are highlighted. (**c-k**) Spatial distribution of the decarbonization potential (t CO2/day) for non-home-related trip purposes across communities. The share of the potential for the urban core is presented.

western Haizhu, and southern Liwan still preserve significant opportunities for developing the 15-minute city. Three notable high-potential clusters (circled in blue) indicate the residential areas of Baiyun, Panyu and Huangpu Districts adjacent to the urban core, respectively. Together, these areas account for approximately 30.5% of the total potential, despite comprising only around 8.7% of the area of Guangzhou. Some communities in the urban center of peripheral districts (i.e. Huadu, Zengcheng, Nansha, and Conghua Districts) also exhibit moderate decarbonization potential, although they only contribute to less than 5% of the total potential. When categorized by trip purpose, the spatial patterns of decarbonization potential align closely with the overall trends (Figure 8c-k). However, the shares of the potential within the urban core for dining, shopping, life service, and work-related trips (28.5%-32.4%) are lower than those of other trip purposes (36.1%-44.6%). This indicates greater potential for carbon reduction in these frequently occurring trips by enhancing their 15-minute accessibility in residential areas beyond the urban core. Furthermore, the cumulative curves in Figure 8b highlight a significant “head effect” of the decarbonization potential across communities for all trip purposes. Communities within the top 1% of decarbonization potential are associated with a cumulative proportion ranging from 19% (dining) to 27% (schooling). This range expands to 62%-70% for the top 10% of communities and further increases to 79%-84% for the top 20% communities.

5. Discussion

Our findings invite a reassessment of the environmental implications of monocentric urban planning paradigms in megacities, exemplified by Guangzhou. Passenger trip analysis reveals that primary trip purposes, such as commuting and shopping, often involve longer travel distances, resulting in 17% higher trip average emissions than secondary trips. This disparity might be linked to the centralized allocation of primary functional facilities, such as workplaces and shopping centers in Guangzhou. This spatial concentration of major functional facilities around the urban core intensifies the unequal access to these essential resources, compelling suburban inhabitants to travel longer distances. The observed intensive emissions on express corridors between the urban core and suburban areas highlight the potential benefits of a more even distribution of primary functional facilities across peripheral areas. Our findings support developing suburban regional-level employment and commercial subcenters, thereby reducing long-distance vehicle commutes and associated emissions (Sha et al., 2020). This argument is supported by empirical studies for global megacities with more advanced development stage. Jun (2020) revealed that the development of subcenters in Seoul, South Korea, between 2000 and 2015 reduce significantly reduced commute times of subcenter commuters. Sultana (2000) found that dispersed subcenters led to a shorter commute than subcenters closer to the CBD in the Atlanta metropolitan area, USA. Despite the advantages, the potential shortcomings revealed in Hong Kong and Seoul should also be considered for subcenters, including higher housing prices (Huai et al., 2021) and longer commute times for new workers from a wider job market Jun (2020). The study also suggests that the concentration of critical urban functions within a megacity can escalate regional inter-city emissions, with inter-city trips accounting for 36.3% of the total road CO2 emissions in Guangzhou. Passenger trips with primary trip purposes, such as work-related, home-related, and shopping, are major contributors to these inter-city emissions. Besides, trip purposes with higher emissions tend to present a more consistent spatial distribution of between intra-city and inter-city emissions. This suggests that road networks catering to primary trip purposes may experience elevated emissions due to a combined burden of local and non-local traffics, which may lead to increased emissions caused by traffic congestion (Grote et al., 2016). These observations suggest that regions pursuing low-carbon development objectives, such as the Guangdong–Hong Kong–Macao Greater Bay Area (GBA) where Guangzhou is located in (Chinese State Council, 2019), should consider a more balanced regional urban planning paradigm. This could involve a more even distribution of essential functions and resources within megacities and across the broader region.

Our analysis verifies the beneficial effect of the 15-minute city concept on mitigating road CO2 emissions. Increasing the number of 15-minute-walk facilities has a marginally diminishing effect on reducing trip average emissions, which coincides with the nonlinear relationship between urban form and travel-related emissions observed in previous studies (Yang, 2023). For a neighborhood or community without certain services, the most significant decarbonization effect occurs when the first related facility is introduced. However, in the case of Guangzhou, this approach alone appears to have a limited capacity for further emission reduction. A more impactful strategy involves providing abundant facilities in communities and promoting walking for trips within a 15-minute radius. Moreover, our study reveals varying degrees of remained decarbonization potential across different trip purposes. Our proposed method can capture the specific types of facilities with higher potential in megacities and facilitate targeted efforts to enhance the availability to these facilities. In Guangzhou case, recreation, schooling, and medical facilities have highest carbon reduction potential, with up to 70% of the related emissions that can be potentially reduced. When the number of facilities in the community approaches saturation, increasing the number of facilities is marginal uneconomical. Strategies should shift towards qualitative improvement, such as upgrading the quality and functionality of existing facilities, thereby reducing the necessity for longer vehile trips. Behavioral intervention and improvement of urban cycling and walking infrastructure can also increase walking and cycling travel and reduce carbon emissions (Keall et al., 2018).

This study reveals spatial variations in suitability for implementing the 15-minute city concept, and provides transplantable tools to identify priority areas for implementing the concept. Three high-potential clusters are detected in areas bordering the urban core. These areas are characterized by a proximity to the city center and relatively affordable land prices, accommodating a substantial residential population. However, our results reveal a sluggish development of essential functional facilities in these areas as well, indicating them the most cost-effective areas for targeted interventions. In contrast, regions beyond the urban core and the three identified clusters account for 86% of the land area but only preserve less than 40% of the total potential. The research reveals a notable "head effect" in the distribution of decarbonization potential of the 15-minute city concept across communities. Therefore, focusing policy interventions and investments on high-potential communities can significantly enhance carbon reduction efficiency. To facilitate local policy implementation, we provide tables listing the top 10% of communities with the highest overall and trip-purpose-specific decarbonization potential in Supplementary Table S8-S17. Our big data-based approach enables dynamic evaluation of decarbonization potential across communities in megacities, helping the government adjust its strategies in a timely manner to maintain high marginal returns per unit of investment.

It is necessary to acknowledge some limitations that offer opportunities for further exploration. First, we call for using vehicle trajectory dataset including more details in vehicle type, fuel type, and emission standard to verify our assumptions of on-road fleets during the emission estimation process. Second, incorporating a broader range of indicators, such as urban vitality (Chen et al., 2021; Liu et al., 2022b), could benefit the measurement of POI attractiveness. The study is also limited by the scope of available survey data. The incorporation of a more diverse trip purpose dataset would significantly strengthen the validation process for trip purpose inference models. In conclusion, recognizing these limitations encourages refining the methods and exploring new research lines.

6. Conclusion

This study utilizes a massive vehicle trajectory dataset to reveal multifaceted spatiotemporal patterns and decarbonization potentials of road CO2 emissions in a megacity — Guangzhou, deriving results that may be applicable to other similar regions around the world. Significant spatial disparities in emissions are revealed across various trip purposes. Diurnal variations in road CO2 emissions strongly correlate with trip frequencies for all trip purposes. Emissions from commuting and freight transport trips are influenced by both trip frequency and trip average distance, presenting combined effects on overall emissions. Inter-city trips make a considerable contribution (36.3%) to the total emissions. Our innovative comparison between intra-city and inter-city emissions distributions unveils the potential for reducing inter-city emissions. Increasing the number of POIs within a 15-minute walk from departure locations presents a marginally diminishing effect on reducing trip average emissions. The 15-minute city concept has the potential of reducing up to 56.3% of the total emissions associated with non-home-related passenger trips. Targeted improvements to recreation, schooling, passenger transport, and medical facilities citywide can mitigate up to 70% of the associated road CO2 emissions. Our analysis suggests a significant "head effect" of the decarbonization potential across communities for all trip purposes. Accordingly, priority areas for promoting the 15-minute city concept are identified. By revealing the multifaceted patterns of road CO2 emissions and the decarbonization potential of the 15-minute city concept, this study contributes valuable knowledge to the field of urban sustainability, informing strategies to reduce traffic emissions and promote sustainable megacities globally.

CRediT authorship contribution statement

Wangyang Chen: Conceptualization, Formal analysis, Methodology, Visualization, Writing-Original draft preparation, Writing - Review & Editing, Software. **Ziyi Tan:** Writing - Review & Editing, Formal analysis, Methodology. **Yaxin Wu:** Writing - Review & Editing, Visualization, Formal analysis, Validation. **Filip Biljecki:** Conceptualization, Supervision, Writing - Review & Editing. **Shunyi Liao:** Conceptualization, Methodology, Supervision, Resources, Project administration, Funding acquisition, Writing - Review & Editing. **Qingya Zhou:** Writing- Original draft preparation, Investigation, Validation. **Hongbao Li:** Funding acquisition, Resources, Supervision. **Yuming Zheng:** Data curation, Investigation, Validation. **Feng Gao:** Data curation, Investigation, Validation.

Declarations of interest

None

Acknowledgments

The completion of this work was supported by National Key R&D Program of China (2022YFC3800704-2).

References

Abbiasov, T., Heine, C., Sabouri, S., Salazar-Miranda, A., Santi, P., Glaeser, E., Ratti, C., 2024. The 15-minute city quantified using human mobility data. Nature Human Behaviour , 1–11.

Allam, Z., Bibri, S.E., Chabaud, D., Moreno, C., 2022. The '15-Minute City'concept can shape a net-zero urban future. Humanities and Social Sciences Communications 9, 1–5.

Allam, Z., Moreno, C., Chabaud, D., Pratlong, F., 2023. Proximity-Based Planning and the "15-Minute City": A Sustainable Model for the City of the Future, in: The Palgrave handbook of global sustainability. Springer, pp. 1523–1542.

Amorim, F., Pina, A., Gerbelová, H., da Silva, P.P., Vasconcelos, J., Martins, V., 2014. Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. Energy 69, 104–112.

Axsen, J., Bhardwaj, C., Crawford, C., 2022. Comparing policy pathways to achieve 100% zero-emissions vehicle sales by 2035. Transportation Research Part D: Transport and Environment 112, 103488.

Barisa, A., Rosa, M., 2018. Scenario analysis of CO2 emission reduction potential in road transport sector in Latvia. Energy Procedia 147, 86–95.

Barla, P., Miranda-Moreno, L.F., Lee-Gosselin, M., 2011. Urban travel CO2 emissions and land use: A case study for Quebec City. Transportation Research Part D: Transport and Environment 16, 423–428.

Böhm, M., Nanni, M., Pappalardo, L., 2022. Gross polluters and vehicle emissions reduction. Nature Sustainability 5, 699–707.

Boulter, P., Barlow, T., McCrae, I., Latham, S., 2009. Emission factors 2009: Final summary report. TRL Published Project Report .

Cao, X., Yang, W., 2017. Examining the effects of the built environment and residential self-selection on commuting trips and the related CO2 emissions: An empirical study in Guangzhou, China. Transportation Research Part D: Transport and Environment 52, 480–494.

Chen, C., Jiao, S., Zhang, S., Liu, W., Feng, L., Wang, Y., 2018. TripImputor: Real-time imputing taxi trip purpose leveraging multi-sourced urban data. IEEE Transactions on Intelligent Transportation Systems 19, 3292–3304.

Chen, W., Wu, A.N., Biljecki, F., 2021. Classification of urban morphology with deep learning: Application on urban vitality. Computers, Environment and Urban Systems 90, 101706.

Chen, X., Jiang, L., Xia, Y., Wang, L., Ye, J., Hou, T., Zhang, Y., Li, M., Li, Z., Song, Z., et al., 2022. Quantifying on-road vehicle emissions during traffic congestion using updated emission factors of light-duty gasoline vehicles and real-world traffic monitoring big data. Science of The Total Environment 847, 157581.

Cheng, H., Liu, Y., He, S., Shaw, D., 2017. From development zones to edge urban areas in China: A case study of Nansha, Guangzhou City. Cities 71, 110–122.

Chinese State Council, 2019. Outline Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area.

Choi, K., Zhang, M., 2017. The net effects of the built environment on household vehicle emissions: A case study of Austin, TX. Transportation Research Part D: Transport and Environment 50, 254–268.

Cui, C., Wu, X., Liu, L., Zhang, W., 2020. The spatial-temporal dynamics of daily intercity mobility in the Yangtze River Delta: An analysis using big data. Habitat International 106, 102174.

Debbage, N., Shepherd, J.M., 2015. The urban heat island effect and city contiguity. Computers, Environment and Urban Systems 54, 181–194.

Deng, F., Lv, Z., Qi, L., Wang, X., Shi, M., Liu, H., 2020. A big data approach to improving the vehicle emission inventory in China. Nature communications 11, 1–12.

Deng, X., Chen, W., Zhou, Q., Zheng, Y., Li, H., Liao, S., Biljecki, F., 2023. Exploring spatiotemporal pattern and agglomeration of road CO2 emissions in Guangdong, China. Science of The Total Environment 871, 162134.

Dong, J., Li, Y., Li, W., Liu, S., 2022. CO2 emission reduction potential of road transport to achieve carbon neutrality in China. Sustainability 14, 5454.

Duan, L., Hu, W., Deng, D., Fang, W., Xiong, M., Lu, P., Li, Z., Zhai, C., 2021. Impacts of reducing air pollutants and CO2 emissions in urban road transport through 2035 in Chongqing, China. Environmental science and ecotechnology 8, 100125.

Falahatkar, S., Rezaei, F., 2020. Towards low carbon cities: Spatio-temporal dynamics of urban form and carbon dioxide emissions. Remote Sensing Applications: Society and Environment 18, 100317.

Feng, S., Li, Q., 2013. Car ownership control in Chinese mega cities: Shanghai, Beijing and Guangzhou. Journeys (LTA Academy Singapore) .

Gassner, A., Lederer, J., Kanitschar, G., Ossberger, M., Fellner, J., 2018. Extended ecological footprint for different modes of urban public transport: The case of Vienna, Austria. Land Use Policy 72, 85–99.

Gately, C.K., Hutyra, L.R., Wing, I.S., 2015. Cities, traffic, and CO2: A multidecadal assessment of trends, drivers, and scaling relationships. Proceedings of the National Academy of Sciences 112, 4999–5004.

Gaubatz, P., 1999. China's urban transformation: patterns and processes of morphological change in Beijing, Shanghai and Guangzhou. Urban studies 36, 1495–1521.

Gebhardt, L., Ehrenberger, S., Wolf, C., Cyganski, R., 2022. Can shared E-scooters reduce CO2 emissions by substituting car trips in Germany? Transportation Research Part D: Transport and Environment 109, 103328. URL: https://www.sciencedirect.com/science/article/pii/S1361920922001560, doi:https://doi.org/10.1016/j.trd.2022.103328.

Giridharan, R., Emmanuel, R., 2018. The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. Sustainable cities and society 40, 677–687.

Gong, J., Chen, W., Liu, Y., Wang, J., 2014. The intensity change of urban development land: Implications for the city master plan of Guangzhou, China. Land Use Policy 40, 91–100.

Gong, L., Liu, X., Wu, L., Liu, Y., 2016. Inferring trip purposes and uncovering travel patterns from taxi trajectory data. Cartography and Geographic Information Science 43, 103–114.

Gratani, L., Varone, L., 2005. Daily and seasonal variation of CO2 in the city of Rome in relationship with the traffic volume. Atmospheric Environment 39, 2619–2624.

Grote, M., Williams, I., Preston, J., Kemp, S., 2016. Including congestion effects in urban road traffic CO2 emissions modelling: Do Local Government Authorities have the right options? Transportation Research Part D: Transport and Environment 43, 95–106.

Guangdong Province Statistical Bureau, 2021. Guangdong Statistical Yearbook: 2021. China Statistics Publishers.

Guo, L., Cheng, W., Liu, C., Zhang, Q., Yang, S., 2023. Exploring the Spatial Heterogeneity and Influence Factors of Daily Travel Carbon Emissions in Metropolitan Areas: From the Perspective of the 15-min City. Land 12, 299.

Guzman, L.A., Oviedo, D., Cantillo-Garcia, V.A., 2024. Is proximity enough? A critical analysis of a 15-minute city considering individual perceptions. Cities 148, 104882.

Harari, M., 2020. Cities in bad shape: Urban geometry in India. American Economic Review 110, 2377–2421.

Hasan, M., Chapman, R., Frame, D., 2020. Acceptability of transport emissions reduction policies: A multi-criteria analysis. Renewable and Sustainable Energy Reviews 133, 110298.

Hong, C., Burney, J.A., Pongratz, J., Nabel, J.E., Mueller, N.D., Jackson, R.B., Davis, S.J., 2021. Global and regional drivers of land-use emissions in 1961–2017. Nature 589, 554–561.

Hong, S., Hui, E.C.m., Lin, Y., 2022a. Relationship between urban spatial structure and carbon emissions: A literature review. Ecological Indicators 144, 109456.

Hong, S., Hui, E.C.M., Lin, Y., 2022b. Relationships between carbon emissions and urban population size and density, based on geo-urban scaling analysis: A multi-carbon source empirical study. Urban Climate 46, 101337.

Huai, Y., Lo, H.K., Ng, K.F., 2021. Monocentric versus polycentric urban structure: Case study in Hong Kong. Transportation Research Part A: Policy and Practice 151, 99–118.

Huang, W., Guo, Y., Xu, X., 2020. Evaluation of real-time vehicle energy consumption and related emissions in China: A case study of the Guangdong–Hong Kong–Macao greater Bay Area. Journal of Cleaner Production 263, 121583.

IEA, G.E., . CO2 emissions from fuel combustion. International Energy Agency, Paris .

Inkinen, T., Hämäläinen, E., 2020. Reviewing truck logistics: Solutions for achieving low emission road freight transport. Sustainability 12, 6714.

Jia, L., Wenying, C., Deshun, L., 2011. Scenario analysis of China's future energy demand based on TIMES model system. Energy procedia 5, 1803–1808.

Jin, T., Wang, K., Xin, Y., Shi, J., Hong, Y., Witlox, F., 2024. Is a 15-Minute City Within Reach? Measuring Multimodal Accessibility and Carbon Footprint in 12 Major American Cities. Land Use Policy 142, 107180.

Jun, M.J., 2020. The effects of polycentric evolution on commute times in a polycentric compact city: A case of the Seoul Metropolitan Area. Cities 98, 102587.

Kan, Z., Kwan, M.P., Liu, D., Tang, L., Chen, Y., Fang, M., 2022. Assessing individual activity-related exposures to traffic congestion using GPS trajectory data. Journal of transport geography 98, 103240.

Kan, Z., Liu, D., Yang, X., Lee, J., 2024. Measuring exposure and contribution of different types of activity travels to traffic congestion using GPS trajectory data. Journal of Transport Geography 117, 103896.

Kan, Z., Tang, L., Kwan, M.P., Ren, C., Liu, D., Pei, T., Liu, Y., Deng, M., Li, Q., 2018a. Fine-grained analysis on fuel-consumption and emission from vehicles trace. Journal of cleaner production 203, 340–352.

Kan, Z., Tang, L., Kwan, M.P., Zhang, X., 2018b. Estimating vehicle fuel consumption and emissions using GPS big data. International journal of environmental research and public health 15, 566.

Kazancoglu, Y., Ozbiltekin-Pala, M., Ozkan-Ozen, Y.D., 2021. Prediction and evaluation of greenhouse gas emissions for sustainable road transport within Europe. Sustainable Cities and Society 70, 102924.

Keall, M.D., Shaw, C., Chapman, R., Howden-Chapman, P., 2018. Reductions in carbon dioxide emissions from an intervention to promote cycling and walking: A case study from New Zealand. Transportation Research Part D: Transport and Environment 65, 687–696. URL: https://www.sciencedirect.com/science/article/pii/S136192091830419X, doi:https://doi.org/10.1016/j.trd.2018.10.004.

Khavarian-Garmsir, A.R., Sharifi, A., Sadeghi, A., 2023. The 15-minute city: Urban planning and design efforts toward creating sustainable neighborhoods. Cities 132, 104101.

Lamb, W.F., Steinberger, J.K., Bows-Larkin, A., Peters, G.P., Roberts, J.T., Wood, F.R., 2014. Transitions in pathways of human development and carbon emissions. Environmental Research Letters 9, 014011.

Li, S.m., Liu, Y., 2017. Land use, mobility and accessibility in dualistic urban China: A case study of Guangzhou. Cities 71, 59–69.

Li, T., Wang, J., Huang, J., Gao, X., 2020. Exploring temporal heterogeneity in an intercity travel network: A comparative study between weekdays and holidays in China. Journal of Geographical Sciences 30, 1943–1962.

Li, T., Wu, J., Dang, A., Liao, L., Xu, M., 2019. Emission pattern mining based on taxi trajectory data in Beijing. Journal of cleaner production 206, 688–700.

Liaquat, A., Kalam, M., Masjuki, H., Jayed, M., 2010. Potential emissions reduction in road transport sector using biofuel in developing countries. Atmospheric Environment 44, 3869–3877.

Liu, G., Li, J., Nie, P., 2022a. Tracking the history of urban expansion in Guangzhou (China) during 1665–2017: Evidence from historical maps and remote sensing images. Land Use Policy 112, 105773.

Liu, H., Gou, P., Xiong, J., 2022b. Vital triangle: A new concept to evaluate urban vitality. Computers, Environment and Urban Systems 98, 101886.

Lo, A.Y., 2016. Small is green? Urban form and sustainable consumption in selected OECD metropolitan areas. Land use policy 54, 212–220.

Logan, T., Hobbs, M., Conrow, L., Reid, N., Young, R., Anderson, M., 2022. The x-minute city: Measuring the 10, 15, 20-minute city and an evaluation of its use for sustainable urban design. Cities 131, 103924.

Lu, Q., Chai, J., Wang, S., Zhang, Z.G., Sun, X.C., 2020. Potential energy conservation and CO2 emissions reduction related to China's road transportation. Journal of Cleaner Production 245, 118892.

Ma, R., He, X., Zheng, Y., Zhou, B., Lu, S., Wu, Y., 2019. Real-world driving cycles and energy consumption informed by large-sized vehicle trajectory data. Journal of cleaner production 223, 564–574.

Makido, Y., Dhakal, S., Yamagata, Y., 2012. Relationship between urban form and CO2 emissions: Evidence from fifty Japanese cities. Urban Climate 2, 55–67.

Mallapaty, S., 2020. How China could be carbon neutral by mid-century., volume = 586. Nature , 482–484.

Meng, L., Sun, Y., Zhao, S., 2020. Comparing the spatial and temporal dynamics of urban expansion in Guangzhou and Shenzhen from 1975 to 2015: A case study of pioneer cities in China's rapid urbanization. Land Use Policy 97, 104753.

Mitchell, L.E., Lin, J.C., Bowling, D.R., Pataki, D.E., Strong, C., Schauer, A.J., Bares, R., Bush, S.E., Stephens, B.B., Mendoza, D., et al., 2018. Long-term urban carbon dioxide observations reveal spatial and temporal dynamics related to urban characteristics and growth. Proceedings of the National Academy of Sciences 115, 2912–2917.

Modarres, A., 2013. Commuting and energy consumption: toward an equitable transportation policy. Journal of Transport Geography 33, 240–249.

Mohsin, M., Abbas, Q., Zhang, J., Ikram, M., Iqbal, N., 2019. Integrated effect of energy consumption, economic development, and population growth on CO2 based environmental degradation: a case of transport sector. Environmental Science and Pollution Research 26, 32824–32835.

Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F., 2021. Introducing the "15-Minute City": Sustainability, resilience and place identity in future post-pandemic cities. Smart cities 4, 93–111.

Muñiz, I., Garcia-López, M.À., 2019. Urban form and spatial structure as determinants of the ecological footprint of commuting. Transportation research part D: transport and environment 67, 334–350.

Murgante, B., Patimisco, L., Annunziata, A., 2024. Developing a 15-minute city: A comparative study of four Italian Cities-Cagliari, Perugia, Pisa, and Trieste. Cities 146, 104765.

Neves, A., Brand, C., 2019. Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach. Transportation Research Part A: Policy and Practice 123, 130–146.

Niu, M., Wu, Y., 2020. Financing urban growth in China: A case study of Guangzhou. Australian Journal of Social Issues 55, 141–161.

Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. COPERT: a European road transport emission inventory model, in: Information Technologies in Environmental Engineering: Proceedings of the 4th International ICSC Symposium Thessaloniki, Greece, May 28-29, 2009, Springer. pp. 491–504.

O'Riordan, V., Rogan, F., Gallachóir, B.Ó., Mac Uidhir, T., Daly, H., 2022. How and why we travel–mobility demand and emissions from passenger transport. Transportation Research Part D: Transport and Environment 104, 103195.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., et al., 2014. Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. Ipcc.

Patiño-Aroca, M., Parra, A., Borge, R., 2022. On-road vehicle emission inventory and its spatial and temporal distribution in the city of Guayaquil, Ecuador. Science of The Total Environment 848, 157664.

Pla, M.A.M., Lorenzo-Sáez, E., Luzuriaga, J.E., Prats, S.M., Moreno-Pérez, J.A., Urchueguía, J.F., Oliver-Villanueva, J.V., Lemus, L.G., 2021. From traffic data to GHG emissions: A novel bottom-up methodology and its application to Valencia city. Sustainable Cities and Society 66, 102643.

Ren, W., Xue, B., Geng, Y., Lu, C., Zhang, Y., Zhang, L., Fujita, T., Hao, H., 2016. Inter-city passenger transport in larger urban agglomeration area: emissions and health impacts. Journal of cleaner production 114, 412–419.

Roca-Puigròs, M., Marmy, C., Wäger, P., Müller, D.B., 2023. Modeling the transition toward a zero emission car fleet: Integrating electrification, shared mobility, and automation. Transportation Research Part D: Transport and Environment 115, 103576.

Santos, G., Behrendt, H., Teytelboym, A., 2010. Part II: Policy instruments for sustainable road transport. Research in transportation economics 28, 46–91.

Schimpl, M., Moore, C., Lederer, C., Neuhaus, A., Sambrook, J., Danesh, J., Ouwehand, W., Daumer, M., 2011. Association between walking speed and age in healthy, free-living individuals using mobile accelerometry—a cross-sectional study. PloS one 6, e23299.

Sha, W., Chen, Y., Wu, J., Wang, Z., 2020. Will polycentric cities cause more CO2 emissions? A case study of 232 Chinese cities. Journal of Environmental Sciences 96, 33–43.

Smith, M.S., Butcher, T.A., 2008. How far should parkers have to walk? Parking 47.

Stanley, J.K., Hensher, D.A., Loader, C., 2011. Road transport and climate change: Stepping off the greenhouse gas. Transportation Research Part A: Policy and Practice 45, 1020–1030.

Sui, Y., Zhang, H., Song, X., Shao, F., Yu, X., Shibasaki, R., Sun, R., Yuan, M., Wang, C., Li, S., et al., 2019. GPS data in urban online ride-hailing: A comparative analysis on fuel consumption and emissions. Journal of Cleaner Production 227, 495–505.

Sultana, S., 2000. Some effects of employment centers on commuting times in the Atlanta metropolitan area, 1990. Southeastern Geographer 40, 225–233.

Sun, B., Han, S., Li, W., 2020. Effects of the polycentric spatial structures of Chinese city regions on CO2 concentrations. Transportation Research Part D: Transport and Environment 82, 102333.

Sun, L., Liu, W., Li, Z., Cai, B., Fujii, M., Luo, X., Chen, W., Geng, Y., Fujita, T., Le, Y., 2021. Spatial and structural characteristics of CO2 emissions in East Asian megacities and its indication for low-carbon city development. Applied Energy 284, 116400.

Tian, L., 2006. Impacts of transport projects on residential property values in China: Evidence from two projects in Guangzhou. Journal of Property Research 23, 347–365.

Tian, L., Shen, T., 2011. Evaluation of plan implementation in the transitional China: A case of Guangzhou city master plan. Cities 28, 11–27.

Van Fan, Y., Perry, S., Klemeš, J.J., Lee, C.T., 2018. A review on air emissions assessment: Transportation. Journal of cleaner production 194, 673–684.

Venturini, G., Karlsson, K., Münster, M., 2019. Impact and effectiveness of transport policy measures for a renewable-based energy system. Energy Policy 133, 110900.

Wang, T., Li, Y., Chuang, I.T., Qiao, W., Jiang, J., Beattie, L., 2024. Evaluating the 15-minute city paradigm across urban districts: A mobility-based approach in Hamilton, New Zealand. Cities 151, 105147.

Wang, Y., Niu, Y., Li, M., Yu, Q., Chen, W., 2022. Spatial structure and carbon emission of urban agglomerations: Spatiotemporal characteristics and driving forces. Sustainable Cities and Society 78, 103600.

Wen, Y., Wu, R., Zhou, Z., Zhang, S., Yang, S., Wallington, T.J., Shen, W., Tan, Q., Deng, Y., Wu, Y., 2022. A data-driven method of traffic emissions mapping with land use random forest models. Applied Energy 305, 117916.

Weng, M., Ding, N., Li, J., Jin, X., Xiao, H., He, Z., Su, S., 2019. The 15-minute walkable neighborhoods: Measurement, social inequalities and implications for building healthy communities in urban China. Journal of Transport & Health 13, 259–273.

Willberg, E., Fink, C., Toivonen, T., 2023. The 15-minute city for all?–Measuring individual and temporal variations in walking accessibility. Journal of transport geography 106, 103521.

Wu, H., Wang, L., Zhang, Z., Gao, J., 2021. Analysis and optimization of 15-minute community life circle based on supply and demand matching: A case study of Shanghai. Plos one 16, e0256904.

Wu, J., Jia, P., Feng, T., Li, H., Kuang, H., Zhang, J., 2023. Uncovering the spatiotemporal impacts of built environment on traffic carbon emissions using multi-source big data. Land Use Policy 129, 106621.

Wu, Y., Li, S., Yu, S., 2016. Monitoring urban expansion and its effects on land use and land cover changes in Guangzhou city, China. Environmental monitoring and assessment 188, 1–15.

Xia, C., Xiang, M., Fang, K., Li, Y., Ye, Y., Shi, Z., Liu, J., 2020. Spatial-temporal distribution of carbon emissions by daily travel and its response to urban form: A case study of Hangzhou, China. Journal of Cleaner Production 257, 120797.

Xu, G., Lv, Y., Sun, H., Wu, J., Yang, Z., 2021. Mobility and evaluation of intercity freight CO2 emissions in an urban agglomeration. Transportation Research Part D: Transport and Environment 91, 102674.

Xu, J., Yeh, A.G., 2003. Guangzhou. Cities 20, 361–374.

Xue, D., Huang, G., Guan, J., Lin, J., 2014. Changing concepts of city and urban planning practices in Guangzhou (1949–2010): An approach to sustainable urban development. Chinese geographical science 24, 607–619.

Yan, D., Lei, Y., Li, L., Song, W., 2017. Carbon emission efficiency and spatial clustering analyses in China's thermal power industry: Evidence from the provincial level. Journal of Cleaner Production 156, 518–527.

Yan, X., Crookes, R.J., 2009. Reduction potentials of energy demand and GHG emissions in China's road transport sector. Energy Policy 37, 658–668.

Yang, C., Zhao, S., 2023. Scaling of Chinese urban CO2 emissions and multiple dimensions of city size. Science of The Total Environment 857, 159502.

Yang, W., 2023. The nonlinear effects of multi-scale built environments on CO2 emissions from commuting. Transportation Research Part D: Transport and Environment 118, 103736.

Yang, W., Cao, X., 2018. Examining the effects of the neighborhood built environment on CO2 emissions from different residential trip purposes: A case study in Guangzhou, China. Cities 81, 24–34.

Yu, A., 2023. Exploring the 15-minute City: Access Sufficiency, Travel Behaviour, and Perceptions of Accessibility in the City of Toronto. Ph.D. thesis. University of Toronto (Canada).

Zhang, X., Shao, C., Wang, B., Huang, S., Mi, X., Zhuang, Y., 2022. Exploring the Role of Shared Mobility in Alleviating Private Car Dependence and On-Road Carbon Emissions in the Context of COVID-19. Frontiers in Environmental Science .

Zhao, D., Lei, Y., Zhang, Y., Shi, X., Liu, X., Xu, Y., Xue, W., 2022. Analysis of vehicular CO2 emission in the Central Plains of China and its driving forces. Science of the Total Environment 814, 152758.

Zhao, P., Kwan, M.P., Qin, K., 2017. Uncovering the spatiotemporal patterns of CO2 emissions by taxis based on Individuals' daily travel. Journal of Transport Geography 62, 122–135.

Zhao, P., Li, Z., Xiao, Z., Jiang, S., He, Z., Zhang, M., 2023. Spatiotemporal characteristics and driving factors of CO2 emissions from road freight transportation. Transportation Research Part D: Transport and Environment 125, 103983.

Zheng, B., Huo, H., Zhang, Q., Yao, Z., Wang, X., Yang, X., Liu, H., He, K., 2014. High-resolution mapping of vehicle emissions in China in 2008. Atmospheric Chemistry and Physics 14, 9787–9805.

Zhou, X., Wang, H., Huang, Z., Bao, Y., Zhou, G., Liu, Y., 2022. Identifying spatiotemporal characteristics and driving factors for road traffic CO2 emissions. Science of The Total Environment 834, 155270.

Zhu, X.H., Lu, K.F., Peng, Z.R., He, H.D., Xu, S.Q., 2022. Spatiotemporal variations of carbon dioxide (CO2) at Urban neighborhood scale: Characterization of distribution patterns and contributions of emission sources.

Sustainable Cities and Society 78, 103646.