

The Impact of Compact Cities on Carbon Emissions

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Ph.D Thesis

**The Impact of Compact Cities on Carbon
Emissions**

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Abstract

Compact cities, characterized by high density and accessibility with fully developed inner-city public transport, are widely discussed and implemented around the world in response to the challenges of sustainable development and global warming. While compact city policies are widely believed to contribute to urban low-carbon objectives, empirical evidence has been lacking. This thesis focuses on the relationship between compact cities and carbon emissions and examines how key characteristics of compact urban environments impact urban carbon emissions, aiming to provide deeper insights both theoretically and empirically.

Chapter 1 introduces the research background of this thesis and, through a literature review, outlines the definition, development, characteristics, and potential environmental impacts of compact cities. It was found that key indicators related to compactness, including density and accessibility, significantly impacted urban carbon emissions. While public transportation is often strengthened in compact city policies, there is a lack of quantitative evidence on its overall effect on urban CO₂ emissions. Based on the identified research gaps, the research objectives of this study are formally presented, and the research scheme is preliminarily designed.

Chapter 2 addresses how cities with varying urban growth rates adopt different policy practices and whether these practices contribute to building sustainable, low-carbon cities. This chapter summarizes previous research on compact city dimensions and indicators related to urban form and policies. Representative case studies are conducted, comparing strategies from these cases and identifying two types of cities employing compact city

strategies. The first type includes cities with low urban growth that use compact city strategies to counter an aging society and population loss. The second type includes megacities with rapidly increasing populations that employ these strategies to address issues arising from increased population density.

Chapter 3 aims to clarify the impact of different dimensions of compact urban development on CO₂ emissions, providing guidance for the formulation of compact city policies. This chapter focuses on pivotal elements of compact city development, investigating impacts on sectoral urban carbon emissions and uncovering spatial heterogeneity. The research outcomes affirm that density and accessibility indicators significantly reduce carbon intensity in the energy, industrial, household, and transportation sectors. However, public transport, despite its fundamental role in compact city theory, does not show the expected effectiveness in reducing urban carbon emissions. The study highlights the need for a balanced approach in applying compact city development strategies to achieve urban sustainability under climate change adaptation.

Chapter 4 seeks to understand the nuanced, non-linear relationships between compact cities and carbon emissions. The research methodology builds on existing literature and incorporates machine learning and interpretive methodologies to elucidate the nature and trends of the relationships between compact city factors and emissions intensity. By clustering cities by type and growth dynamics, nuanced policymaking toward carbon emission reduction is developed. The findings reveal that these relationships are indeed nonlinear and that urban sustainability dynamics are complex. For example, higher population density and varied land use are beneficial up to a point but may impart

diminishing returns or even negative impacts if overextended. Moreover, the presence of public transport alone does not necessarily reduce carbon emission intensity. To improve public transportation outcomes, progressing the energy transition and the integration of new energy vehicles (NEVs) must be prioritized.

Chapter 5 concludes the thesis by summarizing the important findings:

- ♦ Different emphases in compact city policies across various city types
- ♦ Significant impact of compact city characteristics on urban carbon emissions with spatial heterogeneity
- ♦ Density and accessibility as effective measures for curbing carbon emission growth within optimal ranges
- ♦ Integration of public transportation and the energy transition in compact city policies

Keywords: Compact city, Carbon emissions, Sustainable city, Urban planning

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Important Abbreviations Used

Abbreviation	Full Form
ASI	Avoid- Shift- Improve
AIC	Akaike Information Criterion
BRT	Bus Rapid Transit
FAR	Floor Area Ratio
GWR	Geographically Weighted Regression
GCIP	Global City Indicators Program
GHG	Greenhouse Gas
LRT	Light Rail Transit
MRT	Mass Rapid Transit
MGWR	Multi-scale Geographically Weighted Regression
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
POI	Points of Interest
SHAP	SHapley Additive exPlanations
SE	Spatial Entropy
SEM	Spatial Error Model
SLM	Spatial Lag Model
SI	Sustainability Indicators
TOD	Transit-Oriented Development
UPT	Urban Public Transport
VKT	Vehicle-Kilometres-Travelled
VMT	Vehicle Miles Travelled
XGBoost	eXtreme Gradient Boosting

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Chapter 1. Introduction

1.1 Research Background

Climate change is a pressing issue today, with phenomena such as global warming, rampant storms, escalating droughts, and rising sea levels severely impacting the survival of humans and other animals on Earth (IPCC, 2014). Greenhouse gas (GHG) emissions, primarily driven by human activities such as the increased combustion of fossil fuels, are the main contributors to climate change (United Nations, 2024). Carbon dioxide, a major component of GHG, is predominantly emitted in urban areas, which account for 70% of all carbon emissions (UN-Habitat, 2011). Reducing urban carbon emissions is therefore a critical concern for governments, academia, and society.

In recent years, there has been increased discussion and research devoted to sustainable urban construction. While promoting economic development, efforts are being made to create urban environments that are resource-efficient, environmentally friendly, and socially equitable. Faced with various urban development issues such as urban sprawl, traffic congestion, worsening pollution, and aging populations, concepts for ideal urban construction strategies have been proposed. One such concept is the compact city, first introduced in 1989, which is considered an effective strategy against urban sprawl and aging (P. W. G. Newman & Kenworthy, 1989). By emphasizing compact urban spaces and high accessibility, as well as advocating for the construction and use of public transport (Burton, 2000), compact cities are thought to positively impact the urban environment by improving

building energy efficiency and reducing transportation related energy use (Ahlfeldt & Pietrostefani, 2017).

Although there is no unified definition of a compact city, past studies have detailed the characteristics that a compact city should possess. Research showed that the key features of compact cities mainly focus on three aspects: density, accessibility, and the use of public transport (OECD, 2012). Studies also indicated that compact cities, as ideal urban models, do not form spontaneously and require detailed planning and policy support (Fan & Chapman, 2022). Many cities around the world, such as London, Melbourne, Toyama, and Shenzhen, for example, have implemented compact city policies. However, these cities vary in terms of geography, level of economic development, and population size. The implementation and effects of compact city policies also differ markedly in these cities. For example, in densely populated, rapidly developing megacities like London and Shenzhen, compact city policies focus on establishing urban development boundaries, curbing sprawl, and protecting woodlands and farmland (Mayor of London, 2004). These policies also ensure the provision of sufficient affordable housing to maintain a healthy density (Mayor of London, 2021). In cities facing severe aging problems like Toyama in Japan, or resource-depleted cities like Anshan in China, compact city policies focus on relocating public facilities, revitalizing city centres, and promoting the use of public transport (Toyama City, 2019).

In the context of combating climate change, how compact city policies guide urban compactness to effectively curb the increase in carbon emissions has become a key issue. Past studies have extensively discussed the impact of compact city characteristics on urban

carbon emissions. Some research suggests that compact city strategies can effectively reduce per capita carbon emissions and carbon intensity by increasing population density (Yigitcanlar & Kamruzzaman, 2018). Other studies have found that an increased land-use mix is negatively correlated with urban carbon emissions (Li et al., 2022). Research on the mechanisms by which the use of public transport advocated by compact cities affects carbon emissions is more complex. Some studies indicate that increased bus use can increase carbon intensity and per capita carbon emissions (Fan & Chapman, 2024), while others suggest that compact urban forms can reduce the use of private cars, thereby reducing urban carbon emissions by decreasing vehicle-kilometres-travelled (VKT) (Fu et al., 2024). Regarding the spatial form of compact cities, some research suggests that there is an optimal density distribution that allows cities to achieve an ideal low-carbon mode (Park et al., 2013). However, other theoretical studies indicate that further empirical evidence is needed to explore how compact city development strategies impact carbon emissions comprehensively (Sharifi, 2019a).

With regard to the current focus of sustainable urban development, this thesis is focused on the intricate relationship between policy driven compact urban characteristics and urban CO₂ emissions. The novel contributions of this thesis aim to guide policymakers on how to tailor compact city strategies to achieve their urban planning and carbon emission reduction goals.

1.2 Literature Review

1.2.1 Approach to a sustainable city form: definition and characteristics

The definition of compact city varies and the term ‘compact city’ dates to 1973, initially proposed by Dantzig and Saaty, highlighting a circular city with a special city form of high-density residential areas, low dependency on automobiles and a clear boundary from the surrounding area (Dantzig & Saaty, 1973). The spatial features showed mixed land use, diversity, and a clear identity. The concept also highlights social functions including social equity, self-sufficiency of daily life and independent governance. But this single-centre form has certain limitations, particularly in the event of population growth and effects such as congestion that may occur, as well as unaffordable house prices. Thomas and Cousins suggested a decentralized approach to urban development that maintains core principles of compactness, including small-scale structures, enhanced accessibility without relying on cars, and the expansion of open spaces and green areas (L. & W., 2003). Churchman emphasized that compact city policies aim to optimize urban resources by boosting residential density, promoting mixed land use, and curbing development beyond specified limits (Churchman, 1999). Additionally, various researchers have elaborated on the defining traits of compact cities. For example, Burton points out that high density not only includes high average population and building density, but also high density of building form, which can accommodate such a population. Also, mixed land use should provide various and abundant infrastructure and services both vertically and horizontally (Burton, 2002). Neuman identified a high ratio of open space and sufficient fiscal capacity to finance the

development (Neuman, 2005). The OECD defines compact cities as a spatial form characterized by “compactness” and compact city policies are understood as approaches to achieve a compact city by influencing the ways in which urban space is utilized (OECD, 2012).

There are also some commonly discussed points regarding the important characteristics of compact urban areas. With regard to urban size, differing from shrinking cities or urban decay, becoming more compact does not always equal minification, irrespective of size or population. In fact, many large metropolises are applying compact city strategies to counter urban sprawl. Urban sprawl has been linked to higher energy consumption, increased pollution, traffic congestion, and a reduction in the distinctiveness and cohesiveness of communities (Rafferty, 2021). Compact urban development is thought to be a solution to this disordered situation. Development boundaries are usually set in these cases, however small cities such as Toyama in Japan or Anshan in China also adopt compact city strategies in response to an aging society and industrial restructuring issues. These aspects will be discussed in more detail in the following chapters.

Small cities and mega cities usually differ in their city structure regarding the city centre. When the compact city concept was first proposed, it was idealized as a single centered circular city with explicit tiers. Consequently, the concept is often misconstrued as being contrary to decentralization, focusing on a development pattern that centres around downtown or central city areas rather than a dispersed spatial arrangement, leading to notable effects on density. It has also been argued that efforts in downtown renewal have failed with the process of decentralization (Gordon & Richardson, 1997).

However, from a more practical point of view, many metropolises have a multi-centric structure. That does not preclude them from being compact. The OECD has clarified that the compact city structure does not imply a single urban form, suggesting that different metropolitan areas should adopt varied urban structures to achieve compactness, whether monocentric, polycentric, or otherwise. For instance, in megacities, a monocentric compact city might be impractical due to potential negative externalities such as traffic congestion and air pollution, which could outweigh the benefits. In such scenarios, a polycentric compact city might be a more suitable alternative (OECD, 2012).

Building forms are also important when discussing density issues. To guarantee higher density in metropolitan areas, high-rise buildings are usually promoted, and policies are made to ensure sufficient accommodation and jobs are available in these urban centres. London in Britain utilizes Development Plans to guide the construction of tall buildings as a means of promoting regeneration capacity and administering future growth, fostering new dwellings and economic growth, especially in order to make optimal use of public transport and achieve good connections to services and amenities (Mayor of London, 2021). Nanjing in China has released policies stating that the approval of construction of low-density houses including villa and cottages will be stopped to increase floor area ratio (FAR), the ratio of floor area to land area, indicative of density (*Planning and Management Rules for Low-Rise Residential Building Projects*, 2021). Apart from high-rise buildings, Vancouver in Canada launched the EcoDensity Chapter that allows secondary suites, basement suites and laneway housing to be built on the bases of existing residences to increase accommodation and overall density (Metro Vancouver, 2020). Compactness in

building and urban forms varies economically and geographically, and flexibility should be prioritized in planning compact city policies.

Public transportation and Transit-Oriented Development (TOD) are considered integral components of compact cities. Elkin et al. argued that the spatial scale of compact cities should be conducive to walking, cycling, and efficient public transportation (Mayer Elkin et al., 1991). However, the feasibility of public transportation in compact city development has also been questioned. Frank and Jaap suggested that the success of public transportation under compact city policies depends on urban land use policies (le Clercq & de Vries, 2000). Breheny believes that compact cities should feature a combination of high density and mixed land use function (Breheny, 1997).

Currently, there is no unified concept or set of characteristics defining compact cities, however, scholars generally agree that compact cities are those that efficiently save land resources while providing sustainable benefits to residents. Generally speaking, they possess moderate to high density (including population and buildings), mixed land use, and efficient transportation, among other features (Burton, 2000; Ewing, 1997).

1.2.2 Measurement of urban compactness

Research on the measurement of urban spatial compactness primarily encompasses two aspects: 1) the compactness of urban spatial form and 2) the compactness of urban function units. Lan et al. conducted a knowledge graph analysis of urban spatial compactness research based on literature metrics and found that early research on the measurement of urban spatial form characteristics typically started with the geometric

features of urban spatial form. This included measuring the external contours of the city, assessing the relationship between urban patches and specific locations, and measuring the degree of correlation between internal city blocks (Lan et al., 2022). On the other hand, multi-index compactness measurement methods incorporate measurements of factors such as functionality, population, and economy in addition to urban spatial form, allowing for a better quantification of compact city characteristics (OECD, 2012). Several dimensions, including density, mixed land use, centrality, and road accessibility have been proposed as measures of urban sprawl, and compact cities, as a strategy against urban sprawl, often have quantitative indicators related to these aspects (Ewing & Hamidi, 2014). For instance, Tsai proposed a compactness indicator system at the metropolitan level based on urban scale, density, even distribution, and agglomeration degree (Tsai, 2005). Kotharkar et al. evaluated compact urban form based on six dimensions: overall density, distribution of density, mixed land use, transportation network, accessibility, and urban shape (Kotharkar et al., 2012). Kasanko et al. constructed an indicator system based on the five aspects of urban built-up area, residential land, urban expansion land, population density, and urban density (Kasanko et al., 2006). Several empirical studies use indicators such as population density, land development density, and road density to measure urban compactness (Yao et al., 2022). Mubareka et al. integrated four independent morphological indicators, including core unit coverage rate, core area ratio, connecting area as a percentage of built-up area, and branching area as a percentage of built-up area into a comprehensive index for evaluating urban compactness (Mubareka et al., 2011).

The OECD identifies three core characteristics of 'compactness' in urban development: 1)

dense and proximate development patterns, 2) urban areas integrated with public transport systems, and 3) easy access to local services and employment opportunities (OECD, 2012). This thesis will follow these three key dimensions of compact urban development, to further explore their relationship with urban CO₂ emissions.

1.2.3 Environmental impacts of compact urban form

In order to meet the key aims of this research, I conducted a thorough review of existing literature pertaining to the environmental effects of compact cities, with a specific focus on assessing variations in environmental impact indicators across different levels of compactness.

Density indicators and their associated impacts have been a predominant subject of investigation in the field of compact city studies. An investigation into smart city practices in the UK has revealed that while the relationship between city 'smartness' (which is often associated with technological development) and CO₂ emissions is not linear, and although the impact of city smartness on CO₂ emissions remains consistent over time, there is a significant negative correlation between population density and CO₂ emissions (Yigitcanlar & Kamruzzaman, 2018). Researchers in Japan have discovered that urban compactness and centralization, characterized by higher floor area and population density around transportation hubs, play a significant role in reducing CO₂ emissions. This reduction is achieved through policies promoting increased use of public transportation, conservation of natural environments, green initiatives, the adoption of renewable energy sources, efficient utilization of fossil fuels, and the implementation of measures to reduce CO₂

emissions from buildings and control vehicle emissions (Suzuki et al., 2015). Research has also revealed that maximizing the density and land use mix within urban forms can effectively mitigate carbon emissions. These findings underscore the importance of implementing appropriate urban policies and planning approaches, such as compact cities, green cities, or transit-oriented development, as effective strategies for reducing carbon emissions and working towards the creation of low-carbon cities (Shen et al., 2022).

However, research also exists that draws opposing conclusions. By using a bottom-up approach and combining two unprecedented sets of microscopic data on population and CO₂ emissions, a study in the United States suggested that the high productivity of large cities comes at the cost of proportionally higher emissions compared to small cities. This provides evidence that large cities with higher population density could result in elevated GHG emissions (Oliveira et al., 2014). After the breakout of COVID-19, researchers also looked into the impact of compact urban form on pandemic resilience and found that different measures of density may result in different outcomes when analysing the impacts of urban form on COVID-19 prevalence (Hejazi et al., 2023). Literature indicates that current evidence on urban resilience conflicts primarily pertains to density, but conflicts may also arise from measures related to other elements (Sharifi, 2019b).

From an energy perspective, Pucher and Lefevre conducted a comprehensive study on urban transportation crises in both Europe and North America. Their findings suggest that higher urban density correlates with reduced average travel demand for motor vehicles and shorter average travel distances. This, in turn, leads to significant energy savings (Pucher & Lefèvre, 1996). Newman and Kenworthy undertook a thorough investigation into the

connection between per capita gasoline consumption and population density. Their study yielded the conclusive result that higher population density and increased urban compactness are associated with reduced per capita gasoline consumption (P. W. G. Newman & Kenworthy, 1989). However, researchers in the United States have put forth an argument challenging the cost-effectiveness of compact development in reducing transport emissions. They contend that achieving meaningful reductions in per capita driving requires substantial increases in urban densities, which, in their view, may exacerbate traffic congestion rather than alleviate it (Randal, 2009). Research on the energy consumption of urban construction reveals an interesting trend: as building density increases, energy consumption decreases, both in terms of everyday travel and overall energy use. However, it is worth noting that building density does not appear to have a significant relationship with transport energy consumption (Holden & Norland, 2005).

Studies have also delved into the environmental impacts of urban spatial form. For instance, Jia et al. conducted research on the environmental consequences of urban spatial compactness in China. Their findings indicated that as urban areas become more compact and adopt simpler shapes, resource conservation becomes increasingly pronounced (Jia et al., 2019). Researchers in Korea suggested that a trade-off exists between height intensification and building energy consumption within the context of developing a compact city. Furthermore, they proposed that finding the optimal balance in this trade-off is contingent upon the specific level of population density in a given area (Park et al., 2013). A study conducted in fifty Japanese cities revealed an intriguing pattern, suggesting that cities characterized by lower fragmentation and greater compactness, as measured by

morphological indicators, tend to emit less CO₂ from the passenger transportation sector compared to more sprawled urban areas. However, it is also worth noting that excessively dense settlements following a mono-centric form may result in higher per capita CO₂ emissions (Makido et al., 2012). A study conducted in China identified an optimal development mode for Guangzhou, emphasizing a combination of moderate population and economic growth, increased technological investment, and the promotion of compact urban spatial patterns. This comprehensive approach was found to be the most effective means of achieving a balance between economic growth and CO₂ emission reduction in the region (X. Liu et al., 2019).

Transportation emissions accounted for 29% of total US GHG emissions in 2020 (EPA, 2020). Passenger cars and vans (light commercial vehicles) are respectively responsible for around 12% and 2.5% of total European Union GHG emissions. To meet the urgent need to achieve net-zero carbon emissions, urban transit needs to shift towards low carbon mobility where both passenger and goods transportation emit less GHG than current levels. Academic studies have revealed that public transportation systems, such as mass rapid transit (MRT), light rail transit (LRT), bus rapid transit (BRT), and other lower-capacity variants, play a crucial role in transforming urban transit. They enhance commuting efficiency and support the adoption of low-emission vehicle technologies (Hickman et al., 2011). Previous studies also identified that public transport is a climate change mitigation solution developed through urban experiments (Bulkeley & Castán Broto, 2013; Sethi et al., 2020). However, they do not provide specific details on the types of public transport measures that were considered and tested during their experiments.

In compact city construction, public transit is considered a priority factor, however it is not the only approach to reducing emissions. The 'Avoid- Shift- Improve' (ASI) approach is used by transport scholars and practitioners. This approach aims to achieve substantial reductions in GHG emissions, lower energy consumption, decreased congestion, and ultimately the creation of more liveable cities. 'Avoid' refers to avoiding or reducing travel or the need to travel, 'Shift' means the shift toward more energy efficient modes, while 'Improve' stands for improving efficiency through vehicle technology (Bongardt et al., 2019). Precedential studies identify the difficulty of estimating the exact impact of public transport construction alone on overall city carbon emissions.

While there is a substantial body of research supporting the notion that compact cities can significantly reduce resource and energy consumption while demonstrating strong environmental performance, it is essential to acknowledge that there are also studies which raise questions about the concept of compact cities. Consequently, there exists an ongoing debate and some controversy surrounding the environmental effects of compact city development. More importantly, previous studies focused mainly on one dimension of compact cities (in most cases, density), while there has been discussion undertaken in the literature showing that improving density on its own is not effective enough for creating a sustainable and low-carbon urban area (Sharifi, 2019a).

1.3 Research Objectives

Despite the existence of extensive research on the relationship between compact city

development and carbon emissions, significant academic gaps remain in this field. The varying geographical, economic, and demographic contexts of different cities pose challenges in generalizing the effects of compact city policies. Moreover, existing studies predominantly focus on single characteristics such as population density, often neglecting the combined and interactive effects of various compact city features. Particularly, the comprehensive impact of public transportation usage, land-use mix, and building density on carbon emissions requires further empirical investigation to elucidate their complexity and diversity. Consequently, exploring the multifaceted impacts of compact city strategies on carbon emissions across diverse urban contexts is crucial for future research. This research will provide policymakers with more specific and practical guidance to promote the transition towards low-carbon and sustainable urban development.

Based on the above research background and literature review, this thesis proposes the following research objectives:

- ♦ Clarify the characteristics of compact city development under the guidance of compact city policies to investigate the specific implementation of these policies in different cities, and to discuss their commonalities and differences.
- ♦ Explore the mechanisms by which compact city development characteristics impact urban carbon emissions and analyze their spatial heterogeneity.
- ♦ Investigate the non-linear relationship between compact city development characteristics and urban carbon emissions, and model and predict the temporal trends of carbon emissions in different types of compact cities.

1.4 Research structure

Figure 1.1 shows the overall research framework of this thesis, and the specific contents of each chapter is detailed as follows:

Chapter 1 introduces the research background of this thesis, and through a literature review, outlines the definition, development, characteristics, and potential environmental impacts of compact cities, identifying existing academic gaps. According to the findings of the literature review, the research objectives of this study are formally proposed, and the research scheme is preliminarily designed.

Chapter 2 incorporates a focused literature review using targeted keywords to sort and summarize previous research on compact city dimensions, characteristics, and indicators related to urban form and compact city policies. This chapter also includes case studies investigating key compact city policies from several countries. By comparing strategies from these cases, two types of cities that employ compact city strategies are identified, providing insights into the differences between compact city policies in different types of cities.

Chapter 3 aims to clarify the impact of different dimensions of compact urban development on CO₂ emissions, thereby providing guidance for the formulation of compact city policies. Ordinary Least Squares (OLS) and Multiscale Geographically Weighted Regression (MGWR) models are employed to investigate the intricate relationship between compact city characteristics and urban carbon emissions from various sectors. Additionally, the MGWR model uncovers spatial heterogeneity in the effects of urban compactness indicators on sectoral carbon emissions.

Chapter 4 seeks to understand the nuanced, non-linear relationships between compact

cities and carbon emissions. The research methodology applied in this chapter builds on existing literature and incorporates machine learning and interpretive methodologies to elucidate the nature and trends of the relationships between compact city factors and emissions intensity. Furthermore, by clustering cities by type and growth dynamics, nuanced policymaking guidelines which contribute to carbon emission reduction are elicited.

Chapter 5 summarizes the main findings on the impact of compact cities on carbon emissions. The academic contributions, innovations, and future directions of this study are also discussed.

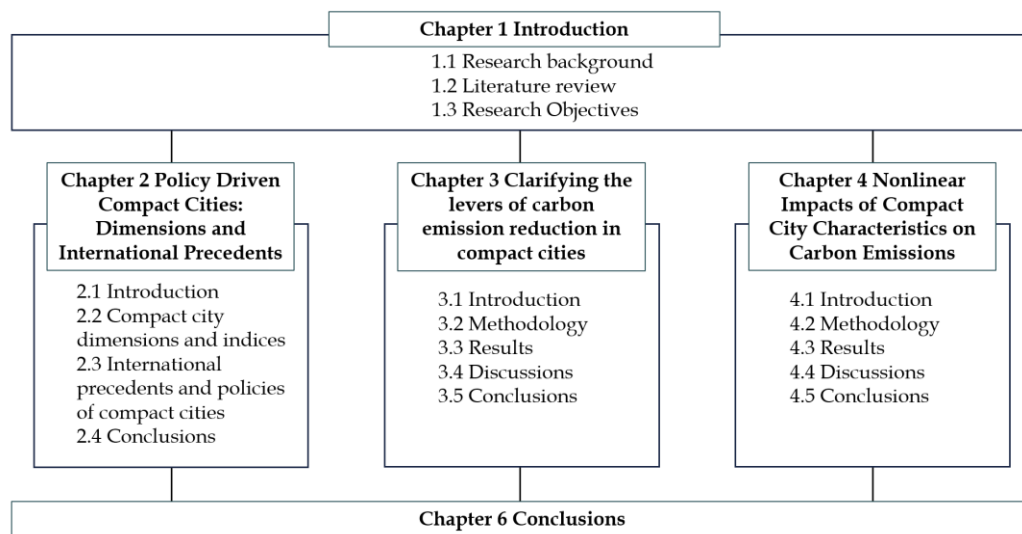


Figure 1.1 Overall research framework of this thesis

Chapter 2. Policy Driven Compact Cities: Dimensions and International Precedents

2.1 Introduction

Compact cities, characterized by high density, mixed land use, and efficient public transportation, have emerged as a key strategy to address sustainable urban development and climate change. These cities aim to reduce urban sprawl, lower carbon emissions, and improve urban quality of life. However, the implementation of compact city principles varies widely across different urban contexts due to geographical, economic, and demographic differences.

This chapter explores the dimensions of policy-driven compact cities and examines international precedents to understand the adoption and effectiveness of compact city strategies. By analyzing policy frameworks, implementation practices, and outcomes in various case studies, this chapter identifies commonalities and differences in compact city policies and their overall success in achieving low-carbon urban development.

Section 2.2 reviews the dimensions of compact cities, focusing on key characteristics such as density, land use diversity, and transportation accessibility. Various indicators used to measure urban compactness and their impact on carbon emissions are discussed.

Section 2.3 presents case studies of cities implementing compact city strategies, including low-growth cities counteracting population decline and rapidly growing megacities managing increased population density. Case studies from Toyama, Melbourne,

London, and Vancouver provide diverse perspectives on compact city strategies across different contexts.

Section 2.4 synthesizes findings from the case studies, highlighting key lessons and best practices for future compact city initiatives. Critical factors contributing to the success or failure of compact city policies, such as governance structures and stakeholder engagement, are discussed.

Section 2.5 concludes the chapter by summarizing key insights and outlining implications for policymakers and urban planners. Here, I emphasize the need for a context-specific approach to compact city development, considering each urban area's unique challenges and opportunities. These findings lay the groundwork for subsequent chapters, which will further investigate the relationship between compact city characteristics and carbon emissions.

In summary, this chapter aims to provide a clear understanding of the dimensions and international precedents of policy-driven compact cities, contributing to the discourse on sustainable urban development and offering practical insights for creating resilient, low-carbon cities.

2.2 Compact city dimensions and indices

Researchers have consolidated the essential dimensions of compact urban form. Ahlfeldt and Pietrostefani, in their review of 189 studies, identified three primary categories of compact city characteristics: economic density, morphological density, and mixed land

use (Arbury, 2005). Kotharkar et al. assessed compact urban form using six dimensions: overall density, density distribution, mixed land uses, transportation network, accessibility, and urban shape (Kotharkar et al., 2012). Bibri et al. identified four dimensions of compact cities including compactness, high density, land-use mix and sustainable transport (Bibri, 2020). Further, Dempsey highlighted that the characteristics of compact cities are well established within the prevailing theoretical framework of sustainability, which includes high residential density with mixed land use, an efficient public transport system, and low energy consumption (Dempsey, 2010). The OECD outlines three principal characteristics of 'compactness': 1) dense and closely situated development patterns, 2) urban areas interconnected by public transport systems, and 3) accessibility to local services and employment opportunities (OECD, 2012). Some empirical studies, however, utilize indicators such as population density, land development density, and road density to measure urban compactness (Yao et al., 2022).

Most studies share key dimensions with little differences and sometimes overlap with each other. These features all focus on aspects which could improve urban sustainability. For example, high population and residential density improves energy efficiency and further reduces energy consumption per capita. Mixed land used development and high accessibility reduced travelling distance to workplaces, entertainment, and local services. This approach works together with transit-oriented development which enhances public transport connection to reduce the use of private cars and further mitigate air pollution and GHG emissions. Explicit characteristics of compact urban form clarifies the 'causes' in studying compact cities and measurable indicators representing the characteristics that are

the foundation for investigating the effect of compact city strategies in reducing CO₂ emissions. This study will follow the definition of the OECD report which was published in 2012, as it provides a clear classification between indicators relating to compactness and indicators relating to compact city policies for the first time (OECD, 2012), to assess density, accessibility and public transport as three key aspects of compact cities and explore in detail how they are interlinked with compact city policies, and how carbon emissions are ultimately affected.

2.2.1 Indicators related to compactness

2.2.1.1 Density and Proximity

Quantifying compactness usually begins with the consideration of density, which is the most frequently used index and can be measured in a number of different ways. To measure overall urban densities, various population density metrics have been proposed, including persons per hectare, persons per hectare in built-up areas, and jobs per urban hectare (Burton, 2002; Fouchier, 2004). Gross density and net density are distinguished by the number of dwellings on all land use types versus residential building sites, excluding roads, parks, and other non-residential land uses (Roseland, 2005). Additionally, density indicators closely related to urban land use efficiency have been identified. The floor area ratio (FAR), also known as the floor space ratio, is frequently utilized in urban development practices to describe the ratio of total floor space within buildings to the total area of the property (Roseland, 2005), effectively measuring the intensity of urban land use.

The regeneration rate, which indicates the rate at which new development occurs

within already developed parcels or replaces old structures, is also a key factor in compact urban planning (OECD, 2012). Alongside vacancy rates of housing and office buildings, this metric is valuable for assessing the intensity of use of existing urban buildings.

Beyond average urban density, the spatial distribution of density provides insights into the spatial characteristics of urban form. Spatial metrics, or landscape metrics, serve as quantitative measures to describe these characteristics. Makido et al. introduced a 'Compactness Index' that combines the shape and number of settlement patches to represent compactness (Makido et al., 2012). Additionally, proximity is employed to evaluate the morphological aspects of compact cities. Unlike density, proximity focuses on how urban activities are distributed within a metropolitan area. It has predominantly been measured by average travel distance within a given area. Commuting distance, average distance for shopping, leisure and logistics are also measured to assess proximity (OECD, 2012).

2.2.1.2 Accessibility to local businesses and services

Accessibility to local businesses and services refers to the ease with which residents can reach amenities such as grocery stores, clinics, restaurants, and local employment either by walking or taking a short public transport ride (OECD, 2012). This concept is closely tied to population and employment density, as well as the mixed land-use elements of a compact city. Mixed land-use is the most commonly applied approach to enhance accessibility to local businesses and services (Conticelli, 2020). Research found that mixed use of land have a significant impact on the travel pattern and commuting behaviour (Cervero, 1996). The

vehicle miles travelled (VMT) can also be lowered by a higher degree of mixed land-use (Maria Kockelman, 1997).

However, developing indicators for mixed land use is challenging. Current studies reveal that there is no universally accepted definition of mixed land-use, and perspectives on what constitutes mixed land use vary. It can be simply gauged as a binary (0-1) variable such as either non-residential uses exist or not within a defined geographic area (Cervero, 1996). Job-housing balance is another way to indicate the degree of local mixed land use and is used to measure urban sprawl (Ewing et al., 2003; P. Zhao, 2010). Other indicators are also proposed to measure accessibility, for example the ratio of residential area to non-residential area, the percentage of residents who have access to local services within 500 meters, and the number of key facilities per thousand inhabitants (Burton, 2002; Kaido & Kwon, 2013).

2.2.1.3 Public transport systems

When a city becomes compact and population density increases, intra-urban mobility can be influenced in several ways. On one hand, road trips relying on automobiles become increasingly difficult due to congestion caused by rising traffic levels, which in turn exacerbates pollution and GHG emissions. On the other hand, higher accessibility, a key characteristic of compact cities, results in shorter average distances to reach local services. This increased accessibility, coupled with the availability of public transport systems, enhances sustainability by offering affordable travel options (Murray, 2001). Scholars have explored various methods to measure the availability of inner-city public transport systems.

One set of indicators includes the percentage of commuters using public transport and the percentage of commuters walking to work (Ewing et al., 2008). Other common indicators focus on the supply of public transport systems, such as the total length of transport lines, the number of stations, and station density. From a more detailed perspective, transit accessibility, which reflects the concept of transport system availability, can be viewed as both a potential and an activity where individuals consider public transport as a viable option (Kaszczyszyn & Sypion-Dutkowska, 2019). Additionally, walking access to public transportation stops can be measured by indicators such as the maximum walking distance for residents to reach transit stops (Foda & Osman, 2010). Another measure of transit accessibility is spatial coverage, which refers to the area served by transit services (Beimborn et al., 2003). The frequency of service is also a crucial factor to consider alongside these indicators.

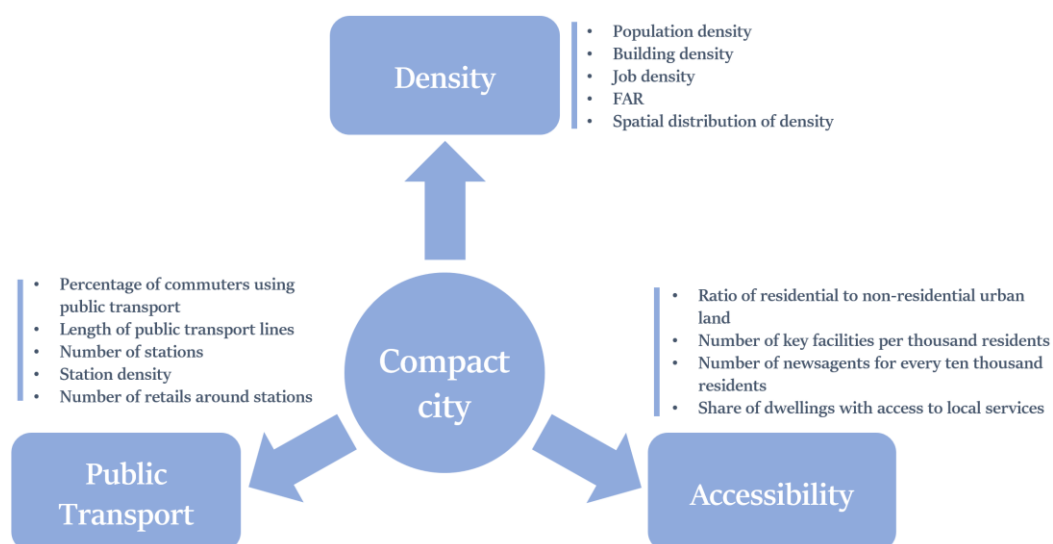


Figure 2.1 Key Indicators measuring compactness.

As shown in Figure 2.1, the three sets of indicators discussed above cover the main

characteristics of compact cities. However, as mentioned in the previous chapter, rather than naturally appearing, a compact city is proposed as an ideal sustainable city form derived consciously from long-term planning and strategic policies. When an evaluation of indicators relating to compactness are not sufficient to clarify the compact city's formation, policies also need to be classified and evaluated to measure their impact.

2.2.2. Indicators related to compact city policies

As is the case with guidelines and ways of implementing compact cities, indicators used to evaluate compact city policies can also be divided into two categories: the first is an indicator used to quantify the thoroughness of compact city policies. For example, the number and variety of policies relating to compactness. The second accounts for the indicators used to quantify the environmental and economic effects of compact city policies.

According to a survey conducted by the OECD in 2010, it was identified that in most OECD countries, the concept of a compact city is an essential part of urban planning policies. In addition to national policies, there are a variety of policies at the metropolitan and local levels including both strategies and instruments. Policy instruments can also be categorized by type of intervention including regulatory, fiscal, partnership approaches etc. (OECD, 2012). Regulatory tools such as urban growth boundary (UGB) and density requirements are commonly used for compact cities to limit urban sprawl and increase efficiency of urban land use. Financial tools such as incentives or subsidies are used to promote transit-oriented development (TOD). When evaluating the intensity or the degree of compact city penetration, the number, scope, and variety of compact city policies can be

considered as indicators.

Regarding the impact of compact city policies, indices are typically linked to the objectives of compact urban design and serve to justify and quantify how these policies contribute to the environmental, economic, and social goals of sustainable development (Bibri, 2020). Various sustainability indicators (SI) have been proposed by international organizations to measure urban sustainability, with some being quantitative and explicit, while others are more qualitative and implicit (Bell & Morse, 2008). The Global City Indicators Program (GCIP), operated by the World Bank, is a decentralized, city-led initiative aimed at developing a standardized system to measure and monitor city performance and urban quality of life (Bhada & Hoornweg, 2009). The OECD highlights that, despite the increasing discussion on environmental sustainability indicators, there are relatively few indicators for social and economic sustainability. They have proposed a set of indicators focusing on three aspects: public open space, transport and household energy use, and affordability and public services (OECD, 2012).

Based on the review of previous literature, this study found that compact city indicators measure two aspects of the development of compact cities. One is to assess the compactness, to quantify different dimensions generated from key characteristics of compact cities including density, public transport and accessibility. The other is to evaluate the intensity and impact of compact city policies on various aspects of city development (environmental, social, economic outcomes etc.). It should be noted that an ideal compact city does not naturally emerge. It requires detailed guidelines and specific policies to construct.

2.3 International precedents and policies of compact cities

In order to achieve a low-carbon urban spatial structure, scholars in the field of urban planning suggest using urban planning methods to undertake a low-carbon reconstruction of urban space. It has been proposed that the system dynamics model could be used as a decision-making tool in the urban planning process to take carbon emissions and global warming into account in the urban planning process, which will help to reduce carbon emissions and contribute to solving the problem of global warming (Kean Fong et al., 2008). This research also identified a relationship between carbon emissions and urban morphology, and advocates for the compact urban space development model. Compact cities can save transportation costs, reduce energy consumption in transportation, and thereby reduce CO₂ emissions (Breheny, 1995).

With regard to precedents, many regions have announced compact city strategies as part of their urban planning, and their experience may help in building sustainable cities in the future. Since compact city policies strengthen various aspects of urban development, in this study we focused on specific policies relating to reducing carbon emissions and achieving sustainable development, targeting the focus of our study. Here, we assess a selection of influential compact cities with a variety of approaches and outcomes based on their specific demographics and needs. These case studies aim to identify the empirically important factors of compact city policies.

2.3.1 Toyama city, Japan

Toyama city has become a global model for compact urban development. Researchers attribute its success to effective governance and dedication (Kriss et al., 2020). As the capital

city of Toyama Prefecture, Toyama, like many other ordinary Japanese cities, was suffering from urban sprawl, an aging society and declining population in the 2000s. In 2005, with the advancement of urbanization, seven municipalities merged, and the urban area expanded fivefold to 1,242 square kilometres, but the population density decreased accordingly (NAKANO et al., 2018). With the declining birthrate and the aging population, the central area of Toyama became empty, and the government had to face a worsening financial situation. To address these problems, the Toyama City government issued the Downtown Revitalization Plan and Public Transport Revitalization Plan in 2007 (Toyama City, 2007; ToyamaCity, 2007). The transition to compact urban development is clearly proposed and policies are introduced to attract residents and businesses to move along transit corridors.

The Downtown Revitalization Plan was carried out in 3 phases. The first stage was from 2007 to 2012, with the ideal of turning the tide of the decentralizing and deteriorating city centre. The most important part of Toyama's success, the light rail transit (LRT) system, was also proposed during this stage. The second stage covered the period from 2012 to 2017, enhancing the quality of urban space. In this stage, partnerships with the private sector, nonprofits, academia, and local communities played an important role in developing social capital. The third phase was enforced from 2017 until 2022, further reinforcing the liability of the city centre. This phase focused specifically on the relocation of public facilities (Kriss et al., 2020).

The performance of Toyama proved to be stunning. The economic value of the LRT project was enhanced by reducing the construction period to three years instead of the

originally estimated nine. The net present value (NPV) of this project also improved by 16.9 billion yen because of the utilization of existing tracks (Kriss et al., 2020). These efforts resulted in a population shift back into the city centre and the utilization of public transportation corridors. It is noted that the behaviour of residents, particularly the elderly, was changed due to the LRT system. There is anecdotal evidence that the LRT triggered a mode shift from cars and buses, which will have an impact on reducing urban carbon emissions. In March 2019, Toyama city announced its 3rd "Toyama City: Environmental Model City Action Plan: CO₂ reduction plan based on compact city strategy" and set the goal of cutting GHG emissions by 30% in 2030 and 80% in 2050 (Toyama City, 2019). Apart from promoting the use of LRT and cycling to cut down emissions from the transport sector, Toyama city proposed "The promotion of eco-life integrated with compact town development", in which low-carbon residences deploying renewable energy such as solar power, along with an awareness of 'eco-life' are promoted to the public.

2.3.2 Melbourne, Australia

Melbourne is the second largest urban area in Australia and is the capital and most important economical centre in the State of Victoria. Unlike Toyama city which faced a severe aging problem, the factor driving compact city policies in Melbourne arose from the challenges brought by the changes in its industrial structure. Melbourne suffered from industrial decline in the 1980s, with recessions in almost all sectors of the economy. Inner Melbourne was "at risk of becoming a 'doughnut' city, with an empty core surrounded by expanding suburban developments" (Center for Public Impact, 2019). The region needed

to deal with its deteriorating urban centres. Rapid population growth also presented a challenge. The uneven distribution of jobs led to the increased use of automobiles, and this kind of commuting pattern had a significant impact on Melbourne's economic and environmental performance. Office and professional jobs were concentrated in urban centres, while retail services, community services and industrial jobs were in the outer fringe (OECD, 2012). As the metropolitan area continues to grow, more and more people in outer areas will need to commute long distances to work. Access to the inner-central area will become increasingly congested (Victoria State Government, 2002), identifying an urgent need for better planning of transport, residences and jobs.

Melbourne began its compact city strategy in 2002, when the State of Victoria released "Melbourne 2030: Planning for sustainable growth" (Victoria State Government, 2021). This long-term plan aims at managing sustainable growth in Melbourne and surrounding regions. The plan outlined the direction towards creating 'a more compact city' for the first time and introduced an urban growth boundary as a tool to curb the sprawl of metropolitan Melbourne. It proposed the establishment of activity centres to serve as hubs for high-quality development, activities, and living for the entire community, while restricting development outside these centres (Victoria State Government, 2002). In 2008, the state government issued "Melbourne @ 5 Million" as a complement to "Melbourne 2030". The plan, in consultation with the Department of Transport, focuses on the construction of a modern integrated transport system in the metropolitan area to achieve the sustainable goals (Victoria State Government, 2008).

Melbourne has undertaken numerous initiatives to become a low-carbon city and

manage urban sprawl. Policies have mandated the intensification of land use within the urban growth boundary, emphasizing areas around activity centres and public transport hubs. However, some critics argue that the policy has not been fully and effectively implemented, leading to substantial expansions of the growth boundary. Woodcock et al. attribute this shortcoming to the government's concern over potential electoral backlash if Melbourne's cherished urban 'character' were to change (Woodcock et al., 2009). In the latest metropolitan planning strategy "Plan Melbourne 2017-2050", which was released by the Victoria State government in 2017, the city no longer emphasizes the word 'compact'. Instead, the concept of the 20-minute neighbourhood is proposed, which also aligns with the high accessibility characteristic of compact cities (Victoria State Government, 2017). Goals regarding a low-carbon city are also mentioned such that Melbourne will reduce GHG emissions to net zero by 2050 (Victoria State Government, n.d.). However, a conclusive evaluation of the environmental effects of Melbourne's compact city construction has not been undertaken and the achievement of a low-carbon city is still under development.

2.3.3 London, Britain

Greater London, with the same extent as the region of London, is an administrative area in England governed by the Greater London Authority. The region covers 1,572 km² and had a population of approximately 9 million by mid-2020. The population has been growing since the 1990s. To effectively manage London's growth within its boundaries and enhance urban living without encroaching on open spaces, the Greater London Authority

published its statutory spatial development strategy, known as The London Plan, in 2004 (Mayor of London, 2004). This plan was revised and republished in February 2008, and a new version was issued by the Greater London Authority in March 2021 (Mayor of London, 2021).

The compact city strategy in London starts from The London Plan 2004, in which Objective 1 states new homes will have to be accommodated within London's existing boundaries without infringe on open spaces. Key policy directions were stated for achieving this objective, which emphasizes higher density and intensification commensurate with public transport capacity, resulting in a high-quality compact city. This objective also incorporates Objective 5 'To improve London's accessibility', in which development of public transport and transport system are aimed at tackling congestion and improving sustainability. The London Plan 2004 also established policy directives aimed at addressing climate change and ensuring that the environmental impact of London's growth does not exacerbate global warming (Mayor of London, 2004). To deal with congestion, financial tools such as the London congestion charge are employed to raise funds for the construction of public transport systems. All motorists driving within London's Congestion Charge zone are required to pay a fee. This congestion charge, one of the largest in the world, serves as a benchmark for other cities considering similar initiatives (OECD, 2012).

London's compact city strategy has been in place for over a decade and has received criticism from urbanists. Some argue that both the scheme and its implementation have failed to provide the housing residents need, have displaced low-income households and contributed to spatial social polarization (Bowie, 2017). Others also suggest that although

increasing population density generates significant economic returns, risks like congestion and increasing house prices exacerbate inequality within cities (Sarah Colenbrander, 2017).

Taking these concerns into account, the Greater London Authority adopted a new London Plan in 2021. In the chapter of 'Design', instead of designing for a compact city as was stated in 2004, a choice was made to strengthen sustainable density which 1) considers, and is linked to the provision of future planned levels of infrastructure and, 2) in proportion to the site's accessibility by walking, cycling, and public transport to jobs and services (Mayor of London, 2021).

2.3.4 Vancouver, Canada

Greater Vancouver, also known as Metro Vancouver, is the metropolitan area located in south-western British Columbia, Canada, with its major urban centre being the city of Vancouver. It covers an area of 2,882 km² with a population of approximately 2.6 million. The population experienced significant growth over the past few decades, increasing more than one million people in a generation. Facing continuing growth in the region, a key challenge is to accommodate growth while promoting liveability and sustainability (Metro Vancouver, 2020).

Unlike the aforementioned examples, Metro Vancouver is not a single city but a federation comprising 21 municipalities, one Electoral Area, and one Treaty First Nation that collectively plan for and deliver regional-scale services. In 2011, a regional growth strategy titled 'Metro Vancouver 2040: Shaping our Future' was issued by the 21 municipalities, TransLink (the statutory authority responsible for the transportation

network in the Metro Vancouver region), and adjacent regional districts. It gives a collective vision for how the region planning to accommodate the increasing population and jobs in the next 25 years. It also provides strategies to achieve five goals related to urban development, including the economy, the environment and climate change, housing and community services, and integrating land use and transportation. One goal is to create a compact urban area (Metro Vancouver, 2020).

To achieve this goal, which makes sure growth and development happens in the right places to increase the efficiency of limited land use and at the same time conserving lands for future generations. Metro Vancouver details 3 strategies: 1) Contain Development: setting an Urban Containment Boundary to constrain development within assigned areas to protect important lands and reduce utility costs; 2) Grow in the Right Places: directing residential and employment growth to Urban Centres (designed as priority locations for employment and services, high-density housing, commercial, cultural, recreational, institutional and mixed-use); 3) Protect Rural Landscapes: urban levels of development are not intended for lands with a Rural designation, and to ensure this, sewer services are not extended into these areas. Metro Vancouver also connects creating a compact urban area with achieving regional GHG emission reduction targets for 2020 and 2050. Construction and automobiles contribute to 65% of the regional GHG emissions. A compact urban area promotes reduced car usage and encourages the development of more energy-efficient buildings, thereby further decreasing per capita emissions of both GHGs and pollutants (Metro Vancouver, 2020).

To enhance growth in Urban Centres, Metro Vancouver promote transit-oriented

communities, where public transit, cycling and walking are preferred. This also integrates with Transport 2050 (Translink's new Regional Transportation Strategy) to achieve Goal 5, supporting sustainable transportation choices (*Transport 2050 Regional Transportation Strategy*, n.d.). Apart from providing convenient, reliable, affordable, safe and comfortable access for everyone, Transport 2050 also highlights a carbon-free goal in creating future transport. The target is to reduce GHG from light-duty vehicles to 65% of 2010 levels by 2030, and to eliminate transportation GHG emissions altogether by 2050. To achieve this, Translink proposes 4 strategies including: 1) reducing the energy requirements of the transport system; 2) transition to zero-emission vehicles; 3) supporting ready access to low-carbon fuels; 4) account for and reduce upstream and downstream emissions in the transportation system.

Vancouver adopted their compact city strategy focusing on the perspectives of urban land use designation and transit-oriented development and directly link their compact development with reducing GHG emissions. However, the regional GHG emissions in Metro Vancouver were 14.7 million tonnes in 2019, reflecting a modest 1% reduction from the 2010 baseline. Further action is required for Metro Vancouver to meet its 2030 target and achieve carbon neutrality by 2050 (MetroVancouver, 2022).

Table 2.1 summarizes the key strategies and policies implemented by the four case study regions.

Table 2.1 Key strategies and policies for case compact cities from the latest plans.

Compact City	Policies				Reducing GHG/ Mitigating Climate Change
	Density	Public Transport	Accessibility		
Toyama (Toyama City, 2019)	♦ Urban redevelopment projects ♦ Hosting events and festivals to attract residents	♦ LRT development ♦ Community bus service ♦ Pedestrian-friendly passages	♦ Welfare facilities ♦ Promotion of residences around public transport stations	♦ Popularization of low-carbon housing ♦ Raising awareness of eco-life	
Melbourne (Victoria State Government, 2017)	♦ Increase new housing inside the urban growth boundary ♦ Facilitate well-designed, high-density residential developments in the city center	♦ Completion of the Metro Tunnel project ♦ Improve freight efficiency and increase capacity of gateways ♦ Improve outer-suburban public transport	♦ Creating a 20-minute neighborhood ♦ Deliver social infrastructure to support strong communities ♦ Deliver local parks and green neighborhoods	♦ Improve energy performance and efficiency of buildings ♦ Facilitate the uptake of renewable energy technologies	
London (Mayor of London, 2021)	♦ Infrastructure assessment during the planning application process to ensure sustainable density	♦ Increase capacity of public transport services through financial contributions and cooperation with Transport for London	♦ Development proposals in proportion to the site's accessibility to jobs and services ♦ The delivery of the mayor's strategic target of 80 per cent of all trips by foot, cycle or public transport by 2041	♦ Detailed energy strategy is required for major development proposals to demonstrate how the zero-carbon target will be met ♦ Development proposals referable to the mayor should calculate whole life-cycle carbon emissions	

Vancouver (Metro Vancouver, 2020)	♦	Urban Containment Boundary	♦	Frequent Transit Network to increase the proportion of trips made by low-carbon travel methods	♦	Offer diverse and affordable housing options. ♦	Develop healthy and complete communities with access to a variety of services and amenities	♦	Encourage energy-saving and low- carbon land- use and transportation
	♦	Higher density trip- generating development							
	♦	Urban Centers and Frequent Transit Development Areas							

In summary, we identified that Toyama City was a typical example of implementing a compact development strategy from start to finish, combining compact development and emission reduction in its latest development plan, mapping out a clear path for emission reduction, focusing on 1) increasing the proportion of public transportation use, 2) improving energy efficiency in the city centre and housing along the transit route, 3) promoting low-carbon housing and awareness of emission reduction strategies, and 4) promotion of the renewable energy industry. In contrast, Melbourne's compact city strategy, which centred on urban growth boundaries, has not worked as well as it should have due to the mismatch between the distribution of employment and housing opportunities provided. In addition, a soaring population lead the government to abandon the compact city strategy and instead emphasize a polycentric structure, with several assigned activity centres characterized by transit-connectedness and high-accessibility. With regard to carbon emissions, although an ambitious target of zero emissions by 2050 has been set, Melbourne's emissions reduction strategy focuses more on improving energy efficiency in

buildings and the energy transition than on reducing emissions by planning sustainable urban density and spatial structure. London's compact city strategy aims to accommodate growth while protecting the Green Belt, with a core strategy of better land use, which is also associated with its much-criticized high housing prices. The government seeks to achieve industrial and population agglomeration through high-density mixed-use land that will attract investment to support adequate public facilities and transportation infrastructure. Emission reduction goals are focused on improving energy efficiency in buildings and introducing new energy sources, with limited mention of transportation strategies. Vancouver's compact city policy is relatively comprehensive with urban growth boundary at its core, the regional level compact strategy states a focus on growth in Urban Centres and Frequent Transit Development Areas while preserving agricultural land. There are also community-level compact strategies that create compact communities by emphasizing proximity and accessibility, while emphasizing compact transport development to reduce GHG emissions.

2.4 Discussion

Based on the literature review and case studies discussed above, we present a comparative assessment of how cities with varying urban growth rates implement different policy practices and evaluate whether these practices contribute to the goal of building sustainable, low-carbon cities.

The cases assessed have different populations and urban growth rates, thus adopting

their compact city strategies from different starting points. Basically however, they can be divided into two types: 1) aging society, with low urban growth, building a compact city to avoid waste of resources and restimulate urban prosperity, e.g., Toyama city, and 2) fast growing megacity, with high urban growth, aiming to accommodate increasing population levels of sustainably, while limiting urban sprawl, e.g., London.

While having the same goal of achieving higher density, these two types of cities place emphasis on different aspects and select different strategies as a result. Cities like Toyama, with a relatively small population size and low urban growth rate, need to focus carefully on their budget when enhancing public transport, ideally choosing lower-cost projects such as buses and light rail instead of subways, which require a longer time for construction at significantly higher cost. On the other hand, generally more financially capable megacities consider capacity as the most important point in designing urban public transport due to the needs of commuting residents. Their primary aim is to alleviate congestion and increase commuting efficiency and to some extent, to achieve environmental goals of mitigating pollution and carbon emissions. Careful planning of transport systems is required in both types of compact cities.

With regard to urban centres, for cities with low urban growth, prosperity in the urban centre is essential for attracting people living in the suburbs to move into the city centre. Accessibility to local entertainment, medical resources and public services is also important. While for capital cities with a high, ongoing increase in population, there are no concerns about the concentration of density of residents, instead, affordable and sufficient accommodation in the city centre to serve urgent need is critical for the sustainable

development of the compact city. However, open space and green areas in the city centre for leisure are also important. This is further supported by the 'compensatory mechanism hypothesis,' which suggests that residents in high-density areas tend to use significantly more energy for air travel, and that access to private gardens can lead to a reduction in leisure travel (Holden & Norland, 2005). This factor is crucial in compact city design, as compact city theory posits that higher density will result in a more sustainable urban form with lower per capita energy consumption.

Figure 2.2 summarizes the two commonly observed patterns of compact cities.

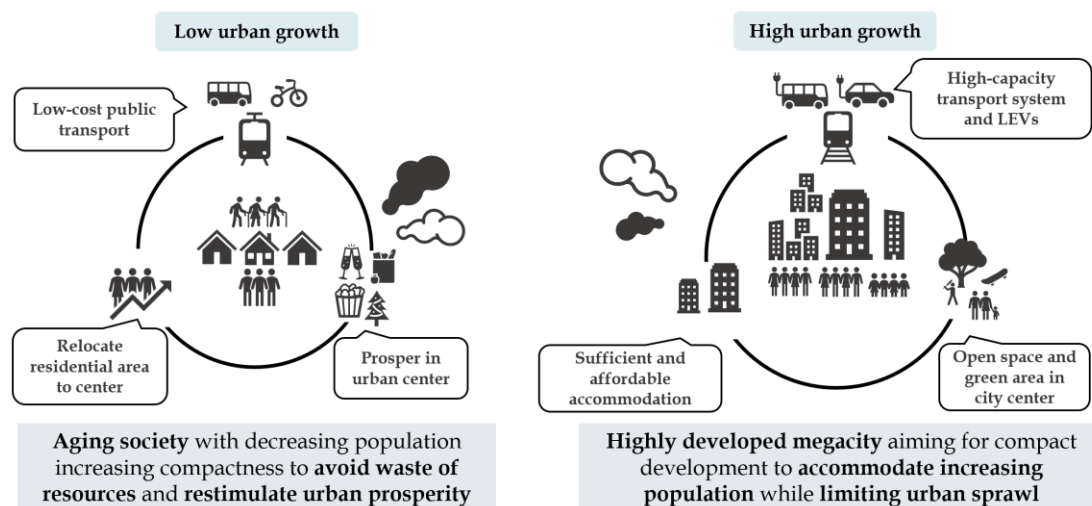


Figure 2.2 Categories of typical characteristics of cities which adopt a compact city strategy depending on urban growth rate.

Overall, when it comes to how compact city policies contribute to the reduction of CO₂ emissions, there is insufficient evidence to draw a clear conclusion. One reason for this is that there is still not a comprehensive and effective evaluation system in quantifying compact city performance. Criticisms have been raised by urbanists pointing out that cities

like Melbourne and London weren't able to follow their compact city strategies or weren't able to deliver what they promised under their proposed policies (Bowie, 2017; Sarah Colenbrander, 2017; Woodcock et al., 2009). In addition, leveraging and co-effects need to be considered when connecting different aspects of compact city characteristics to their impact on urban CO₂ emissions.

2.5 Conclusions

This chapter has examined the dimensions and international precedents of policy-driven compact cities, highlighting how different urban contexts influence the adoption and effectiveness of compact city strategies. The key conclusions drawn from the analysis are as follows:

The core dimensions of compact cities include density, land use diversity, and transportation accessibility. These dimensions are crucial for improving urban sustainability by enhancing energy efficiency, reducing travel distances, and promoting public transportation use.

Compact city strategies vary significantly between cities with different growth rates. Low-growth cities like Toyama focus on revitalizing urban centres and managing population decline, while rapidly growing megacities like London and Melbourne aim to accommodate increasing populations and mitigate urban sprawl. The case studies of Toyama, Melbourne, London, and Vancouver reveal that successful compact city strategies often involve a combination of regulatory measures, public transportation investments, and

incentives for sustainable development. Each city's unique geographical, economic, and demographic context shapes its approach to compact city development.

Effective governance, stakeholder engagement, and the integration of sustainability goals into urban planning are critical factors for the success of compact city policies. Challenges such as financial constraints, political resistance, and the need for comprehensive evaluation systems must be addressed to ensure effective implementation. Policymakers should adopt a context-specific approach to compact city development, considering each city's unique challenges and opportunities. Strategies should balance high-density development with the provision of green spaces and public amenities to enhance urban liveability and sustainability.

These conclusions provide a foundation for further investigation into the relationship between compact city characteristics and carbon emissions, offering empirical evidence to support policy recommendations in subsequent chapters.

Chapter 3. Clarifying the levers of carbon emission reduction in compact cities

3.1 Introduction

Compact cities have been widely recognized as a viable solution to urban sustainability challenges, including the mitigation of carbon emissions. This chapter aims to clarify the mechanisms through which various dimensions of compact urban development influence carbon emissions. Specifically, this section examines how key compact city characteristics—density, accessibility, and public transport—affect urban carbon emission intensity.

Previous chapters have established the theoretical foundations and policy dimensions of compact cities. Building on this, the current chapter focuses on the empirical investigation of these characteristics. Utilizing a robust dataset from 340 prefecture-level cities in China, this study quantifies the impact of compact city indicators on carbon emissions across different sectors: energy, industry, transportation, and households.

To guide this empirical investigation, the following hypotheses are proposed:

- ♦ *Hypothesis 3.1: Higher urban density is associated with lower carbon intensity.*
- ♦ *Hypothesis 3.2: Enhanced accessibility is correlated with reduced carbon intensity.*
- ♦ *Hypothesis 3.3: Increased utilization of public transportation is linked to lower carbon intensity.*

To test these hypotheses, the study employs both traditional Ordinary Least Squares (OLS) regression and Multiscale Geographically Weighted Regression (MGWR) models. These models help uncover the spatial heterogeneity in the relationship between urban

compactness and carbon emissions, providing a nuanced understanding of how compact city strategies can be optimized for carbon reduction.

The analysis begins with a detailed description of the study area and data collection methods, including the calculation of carbon intensity and the selection of compact city indicators such as population density, floor area ratio, public transportation usage, and mixed land-use degree. This is followed by a rigorous examination of the statistical relationships between these indicators and carbon emissions.

By elucidating the specific impacts of compact urban development on carbon emissions, this chapter aims to provide actionable insights for policymakers and urban planners. These insights are crucial for formulating effective compact city policies that not only enhance urban sustainability but also contribute significantly to global efforts in reducing greenhouse gas emissions.

3.2 Methodology

3.2.1 Study area and data

In this study, I aim to explore the impact of three fundamental characteristics of compact cities on urban carbon emission intensity. Figure 3.1 illustrates the research framework of this study.

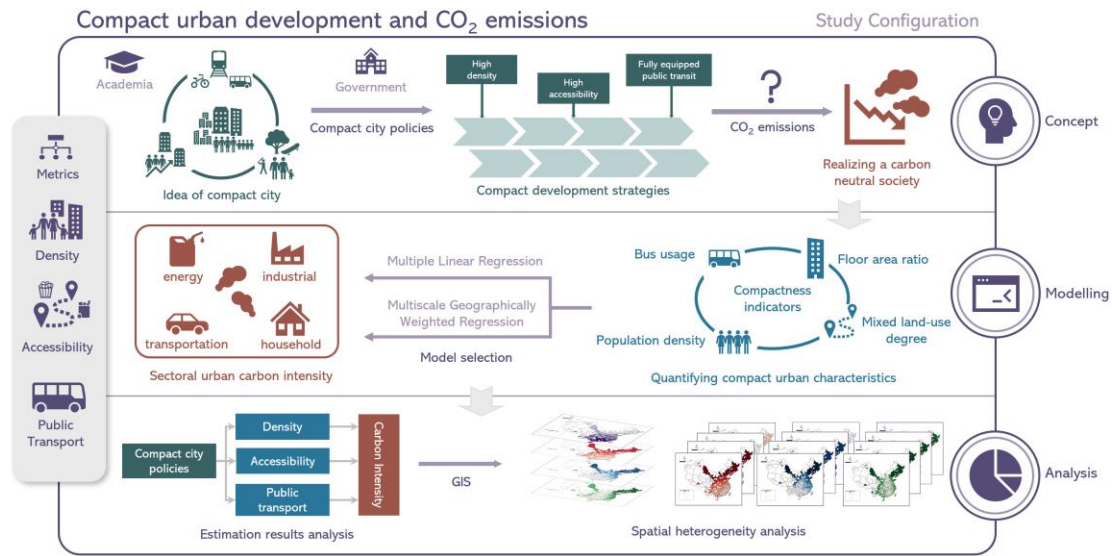


Figure 3.1 Research framework of this study

The most recent, relevant data for the year 2019 was collected for the purposes of this study. The dependent variable in our study, which is urban GHG emissions data, was provided by the China Greenhouse Gas Working Group (CCG). The dataset draws upon internationally established and widely applied methods for calculating urban CO₂ emissions. It calculates both direct emissions which are generated within the administrative boundaries of cities, and indirect emissions resulting from the purchase of electricity from external sources. Indirect emissions are determined by multiplying the externally sourced electricity consumption within the city by the emission factors of the regional power grid in which the city is located. The foundational data for cities integrates information from the China High Resolution Emission Database (CHRED) 3.0, various official datasets at the urban level, as well as findings from on-site investigations, telephone consultations, and data obtained through correspondence with relevant departments facilitated by CCG (China City Greenhouse Gas Working Group, 2022). This dataset encompasses carbon emission information for 340 different prefecture-level cities in China across various sectors,

alongside GDP data.

The four sectors of emissions which have been analysed in this study include energy, industry, transportation and households, which are calculated with sub-sectors and activity data using a bottom-up approach (Y. Gao et al., 2022), which has been widely-used in many studies (Bo et al., 2021). Emissions from the energy sector are based on the power plants with activity data including coal, oil, and gas fuel. The industry sector incorporates emissions from industrial boilers, industrial processes and industrial solvent use. Residential source emissions have three sub-sectors, namely biomass combustion, other residential burning and residential solvent use, while the transportation sector considers on-road and non-road activities consuming oil and gas fuels.

I subsequently calculated carbon intensity based on this dataset. Carbon intensity in this study refers to the amount of carbon emissions divided by unit GDP (kg CO₂ eq/CNY). For urban development-related data, including population, urban area measurements, commercial housing sales area, and commercial housing construction land area, I relied on data sourced from the China Urban Statistical Yearbook (Urban Socio Economic Survey Department of the National Bureau of Statistics, 2020). Information pertaining to urban public transportation was obtained from the China Urban Construction Statistical Yearbook (MOHURD, 2020). The calculation of mixed land-use degree was based on Points of Interest (POI) data extracted from OpenStreetMap (OpenStreetMap contributors, 2015), as detailed in Section 3.2.3 below.

3.2.2 Compact city indicators and variables

As detailed in the previous chapter, within the existing literature, scholars have synthesized the core dimensions of compact urban form. Most studies share key dimensions with minimal variation and often overlap. This study will adhere to the definition outlined in the OECD report of 2012, evaluating density, accessibility, and public transport as the three pivotal aspects of compact cities, and delving into how carbon emissions are influenced in detail (OECD, 2012). Drawing from the comprehensive literature review, four specific indicators have been selected to quantify urban compactness. These include population density and floor area ratio (FAR) to represent horizontal and vertical density, respectively, serving as our density indicators. Additionally, I utilize public transportation utilization as an indicator of public transport development and mixed land-use degree to gauge accessibility. Further, I incorporated a set of control variables associated with compact city development. These control variables encompass aspects such as industrial structure, per capita GDP, urbanization rate, and green area (Fan & Chapman, 2022). Table 3.1 presents the variables and their definition for use in this study.

Table 3.1 Definition of variables used in this study

Variable	Meaning	Definition
PopDEN	population density	urban population/urban area
FAR	floor area ratio	gross floor area/lot area
PTusage	public transportation usage	annual bus passenger volume per capita
RailTrans	railway transport	dummy variable of the presence of railway
MixedLU	mixed land-use degree	spatial entropy value of urban POI data
GDPcap	GDP per capita	urban GDP/ urban population
IndStructure	Industrial structure	GDP of Secondary Industry/ Total GDP
Urbanization	urbanization rate	urban population/total population
GreenArea	urban green space area	area of public recreational green space
CI	carbon intensity	per GDP carbon emission

Before applying regression models, I standardized the variables by performing a z-transformation, ensuring each variable has a mean of 0 and a standard deviation of 1. This standardization facilitates the interpretation and comparison of individual bandwidths. Through standardization, the bandwidths directly indicate the spatial scale at which the conditional relationship between the dependent and independent variables vary (Oshan et al., 2019). Table 3.2 provides a comprehensive overview of the descriptive statistics of variables included in the regression models.

Table 3.2 Descriptive statistics of independent variables

Variable	Mean	STD	Min	Max
PopDEN	460.31	363.39	4.08	2587.54
FAR	12.58	8.47	0.00	44.76
PTusage	108.81	78.83	2.04	489.04
RailTrans	0.09	0.29	0.00	1.00
MixedLU	3.67	0.72	1.00	4.77
GDP/cap	63840	35295	15987	191942
IndStructure	42.85	9.50	15.75	72.90
Urbanization	0.61	0.21	0.14	1.00
GreenArea	10367.10	19699.27	243.20	163905.60

3.2.3 Calculation of the degree of mixed land-use

Access to local businesses and services includes the ease with which residents can reach nearby amenities like grocery stores, medical clinics, restaurants, and local job opportunities, either by walking or taking a short ride on public transport (OECD, 2012). This accessibility is closely linked to population or employment density, as well as the mixed land-use elements found in compact cities. Mixed land-use, the most common method for

representing accessibility to local businesses and services, has been shown to significantly influence travel patterns and commuting behaviours (Cervero, 1996; Conticelli, 2020). Increased mixed land use can also reduce vehicle miles travelled (VMT) (Maria Kockelman, 1997). However, creating indicators for mixed land-use presents challenges, as there is no clear definition, and opinions vary on what constitutes mixed land use. It can be measured as a binary variable indicating the presence or absence of non-residential uses within a defined geographic area (Cervero, 1996). Job-housing balance serves as another indicator of local mixed land use and is used to assess urban sprawl (Ewing et al., 2003; P. Zhao, 2010). Other proposed indicators for measuring accessibility include the ratio of residential to non-residential areas, the percentage of residents with access to local services within a 500-meter radius, and the number of key facilities per thousand inhabitants (Burton, 2002; Kaido & Kwon, 2013).

This study utilizes an approach from within compact city theory and leverages implications for policy formulation, using the spatial entropy (SE) index to calculate the degree of mixed land use, aiming to characterize the dispersion and concentration of land-use types contained within each city (DECRAENE et al., 2013). The model was designed to be suitable for Places of Interest (POI) data types (Xia & Lu, 2023). A total of 193,755 POI data points from 381 cities in China are sorted and 137 land-use types are identified. POI classes are divided into 14 secondary categories: catering, hospitality, retail services, commercial and financial services, life services, entertainment, health care, science and education, sports and cultural facilities, park and green area, communal facilities, religion, tourist attractions, and others, based on the POI original attributes. Table 3.3 gives examples

of key POI classes and their categories. However, industrial activities are not found within the POI data categories extracted from OpenStreetMap, representing a limitation of this study.

Table 3.3 POI classification and land use types

ID	Land use type	POI category	POI classes examples
1	Commercial use	Catering	restaurant, fast food, beverages, cafe, bakery, bar, pub
2	Commercial use	Hospitality	hotel, hostel, guesthouse, alpine hut, motel
3	Commercial use	Retail services	supermarket, shops, market place, mall, convenience
4	Commercial use	Commercial and financial services	department store, travel agent, bank, atm, bicycle rental
5	Commercial use	Life services	hairdresser, pharmacy, car wash, laundry, veterinary
6	Commercial use	Entertainment	cinema, theatre, theme park, dog park
7	Public management and communal service use	Health care	hospital, dentist, doctors
8	Public management and communal service use	Science and education	school, university, college, kindergarten,
9	Public management and communal service use	Sports and cultural facilities	stadium, playground, museum, sports center, library, arts center
10	Public management and communal service use	Park and green area	park, fountain, zoo, garden
11	Public management and communal service use	Communal facilities	town hall, toilet, drinking water, police, fire station, post office
12	Special use	Religion	shrine, wayside cross, church
13	Special use	Tourist attractions	monument, castle, shelter, memorial, ruins, tower, artwork
14	Special use	Others	water tower, water well, lighthouse, embassy, prison, graveyard

The spatial entropy index, used to assess the degree of dispersion in the urban land-use

structure, is defined in equations 1 and 2 as follows:

$$SE_i^x = - \sum_x [p_i^x \ln(p_i^x) + (1 - p_i^x) \ln(1 - p_i^x)] \quad (1)$$

where

$$p_i^x = \frac{x_i}{N_i} \quad (2)$$

Here, SE_i^x is the spatial entropy in the target city, p_i^x is the frequency of POI category x in city i ($x = 1 \dots k, \sum_1^k p_i^x = 1$), x_i is the number of POI category x in each city i , and N_i is the number of all POI categories in the city i . The larger the value of SE_i^x , the greater the entropy of POI categories in the grid, and the higher the degree of mixed land-use. When $SE_i^x = 0$, it indicates that there is only 1 POI category in the city. QGIS version 3.30 was used to extract the POI data for our modelling.

3.2.4 Multiscale geographically weighted regression model

Global regression or ordinary least squares (OLS) regression is the most commonly employed method used to investigate the factors influencing CO₂ emissions in environmental economic research (M. Wang et al., 2022). OLS has been used to assess the linear connection between CO₂ emissions and various influencing factors. However, OLS approaches don't take spatial heterogeneity into account, and estimates parameters in a 'global' and 'average' way (Anselin & Griffith, 1988). Empirical studies have discovered that certain economic behaviours exhibit spatial variability and heterogeneous differences, leading to spatially nonstationary relationships between dependent and explanatory variables (Tenerelli et al., 2016). To address these challenges, the Geographically Weighted Regression (GWR) method was introduced (Brunsdon et al., 1996). GWR is one of the

primary methods for detecting and modelling spatial heterogeneity and is widely used in studying spatial non-stationarity (Brunsdon et al., 2010). This model incorporates the spatial location information of the data as parameters in the coefficient estimation of the model. The model formulation can be expressed as shown in equation 3, assuming that there are n observations, for the observation i at location (u_i, v_i) , the linear regression model is:

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^n \beta_j(u_i, v_i)x_{ij} + \varepsilon_i \quad (3)$$

where $\beta_0(u_i, v_i)$ is the intercept, x_{ij} is the j th predictor variable, $\beta_j(u_i, v_i)$ is the j th coefficient, ε_i is the error term, and y_i is the explained variable (Oshan et al., 2019).

Although classical geographically weighted regression models introduce more variable parameters compared to global regression models, the limitation, in which all local coefficient spatial processes have the same scale remains. Therefore, based on the generalized additive model, multi-scale geographically weighted regression (MGWR) was proposed (Fotheringham et al., 2017). This method allows each covariate to have its own spatial smoothing level, uses its own optimal bandwidth for regression, and customizes the spatial scale of each spatial process, resulting in spatial process models that are closer to reality and more explanatory. In MGWR, the model can use the golden search algorithm to find the most suitable bandwidth for different variables for regression modelling. This avoids mismatches between bandwidth and the scale of variable effects, thereby reducing noise in parameter estimation.

The MWGR model formulation used in this study can be expressed as shown in equation 4:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^p \beta_k(u_i, v_i)x_{ik} + \varepsilon_i \quad (4)$$

where y_i represents the carbon intensity in city i . (u_i, v_i) is the mean coordinate of city i . $\beta_0(u_i, v_i)$ is the intercept term that varies across space. $\beta_k(u_i, v_i)$ are the local regression coefficients for predictor k at location i . x_{ik} are the predictor variables. ε_i stands for the random error (Oshan et al., 2019).

Estimating the coefficients in the MGWR model involves several steps that extend the approach used in traditional GWR model.

(1) Initialization:

Define the spatial coordinates (u_i, v_i) for each city i . And select a set of bandwidths for each predictor variable x_k . The bandwidth determines the spatial scale over which the data points influence the local parameter estimates. In MGWR, different predictors can have different bandwidths.

(2) Weight Calculation:

For each city i , calculate the weights for all other observations j , using a spatial weighting function. Common choices include Gaussian, exponential, or bi-square kernels. In this case, the Gaussian weighting function was used. The weights depend on the distance d_{ij} between locations i and j and the bandwidth b_k for the k -th predictor. The weight w_{ij}^k for predictor k is typically given by:

$$w_{ij}^k = \exp\left(-\frac{d_{ij}^2}{b_k^2}\right) \quad (5)$$

for a Gaussian kernel, where d_{ij} is the distance between observations between locations i and j , and b_k is the bandwidth for the k -th predictor.

(3) Local Regression

For each city i , perform a weighted least squares regression using the weights w_{ij}^k for each predictor. The local regression model for city i is:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^p \beta_k(u_i, v_i)x_{ik} + \varepsilon_i \quad (4)$$

The weighted least squares solution is obtained by minimizing the following objective function:

$$\sum_{j=1}^n w_{ij}^k (y_j - \beta_0(u_i, v_i) - \sum_{k=1}^p \beta_k(u_i, v_i)x_{jk})^2 \quad (6)$$

(4) Bandwidth Optimization

The bandwidth b_k for each predictor are crucial and typically selected through an optimization process, often using cross-validation or Akaike Information Criterion (AIC). The goal is to find the bandwidths that minimize the prediction error or AIC, balancing bias and variance.

(5) Iterative Estimation:

The estimation of $\beta_k(u_i, v_i)$ is iterative. Start with initial bandwidth estimates and perform the local regressions to obtain initial coefficient estimates. Update the bandwidths based on the residuals from the initial regression and repeat the process until convergence, where changes in the coefficients and bandwidths become negligible. The weighted least squares problem is to be solved to estimate $\beta_k(u_i, v_i)$:

$$\hat{\beta}(u_i, v_i) = (X^T W_i X)^{-1} X^T W_i y \quad (7)$$

where X is the matrix of predictor variables, W_i is the diagonal matrix of weights w_{ij}^k for each predictor, and y is the vector of observed responses.

In this study, I employ both traditional multiple linear regression models and the

multiscale geographically weighted regression (MGWR) model. This comprehensive framework enables us to examine how various features of compact city development influence urban carbon emission intensity and its spatial heterogeneity. In this study, I use the software StataSE 17 and MGWR version 2.0 (Oshan et al., 2019) to apply OLS and MGWR in order to investigate the impact and spatial heterogeneity of compact urban characteristics on carbon intensity.

3.3 Results

3.3.1 General impact of urban compactness on CO₂ intensity

Table 3.4 illustrates the estimated results from the regression analysis, which demonstrate a clear relationship between CO₂ emissions and compact urban characteristics under both the OLS and MGWR models.

Table 3.4 Estimation results of MGWR model for urban compactness influencing CO₂ intensities

Variable	OLS			MGWR		
	Coefficient	Std.Error	P-value	Coefficient	Std.Error	P-value
CONSTANT	4.513	0.791	0.000	-0.130	0.057	0.190
PopDEN	-0.001	0.000	0.004	-0.154	0.074	0.028
FAR	-0.060	0.013	0.000	-0.175	0.087	0.000
PTusage	0.000	0.002	0.998	-0.019	0.080	0.791
MixedLU	-0.590	0.151	0.000	-0.158	0.064	0.016
GDPcap	0.000	0.000	0.004	-0.223	0.129	0.083
IndStructure	0.022	0.012	0.068	0.199	0.121	0.197
Urbanization	0.842	0.632	0.185	0.054	0.076	0.144
GreenArea	0.000	0.000	0.455	0.068	0.077	0.805

Number of observations	223	223
Adjust R square	0.298	0.480

Results show that density represented by population density (PopDEN, $p < 0.05$) and floor area ratio (FAR, $p < 0.01$) are negatively correlated with carbon emissions, consistent with previous studies (Suzuki et al., 2015; Yigitcanlar & Kamruzzaman, 2018). The coefficients are -0.154 and -0.175 respectively. At the heart of compact city development lies the belief that increasing the availability of affordable housing in the city centre and constructing taller buildings to boost population density can help reduce wastage of public resources, decrease per capita building energy consumption, and consequently, mitigate carbon emissions (Park et al., 2013). Many countries and regions have implemented specific density policies to enhance urban sustainability (Mayor of London, 2004; Toyama City, 2019). In addition to acknowledging the positive environmental impacts, it is also crucial to recognize that in developing countries like China, as income levels increase, residents are increasingly seeking higher-quality and more diverse services. Simultaneously, it's worth noting that a significant portion of service products pose logistical challenges for transportation, cannot be stored, and necessitate face-to-face interaction for production and consumption. Higher population density is associated with reduced costs for both the production and consumption of such services. Therefore, in the construction of compact cities, increasing density, both horizontally and vertically, appears to be an essential component.

Accessibility represented by the degree of mixed land-use (MixedLU) shows a significant negative relationship with urban CO₂ emissions ($p < 0.01$), with a coefficient of -

0.158. Previous research found that mixed use of land had a significant impact on travel patterns and commuting behaviour (Maria Kockelman, 1997). While many studies employ POI data to calculate mixed land-use degree, there remains a paucity of research exploring its connection with urban carbon emissions. High accessibility is also frequently linked with elevated employment density and can also play a role in enhancing social equity (Zhu & Yang, 2014).

Surprisingly, the estimated results of the MGWR model show that the public transportation indicator is unrelated to carbon emissions, which is contrary to our common understanding. In the theoretical framework of compact cities, public transportation is considered a crucial component. It is considered that transit-oriented development which enhances public transport connection could reduce the use of private cars and further mitigate air pollution and GHG emissions (Dempsey, 2010). Nevertheless, several studies have also underscored the fact that achieving a reduction in carbon emissions from urban transportation relies not only on the restructuring of public transportation but also significantly on renewable energy transition and the advancement of intelligent transportation systems (Ferreira & D'Orey, 2012; Gomi et al., 2010). Our research findings corroborate this perspective. In the pursuit of compact city development, it is imperative that the design of public transportation systems goes hand in hand with the promotion of clean energy. This symbiotic approach is essential for establishing a genuinely sustainable, low-carbon urban transportation environment.

Figure 3.2 illustrates the distribution of regression coefficients for various indicators.

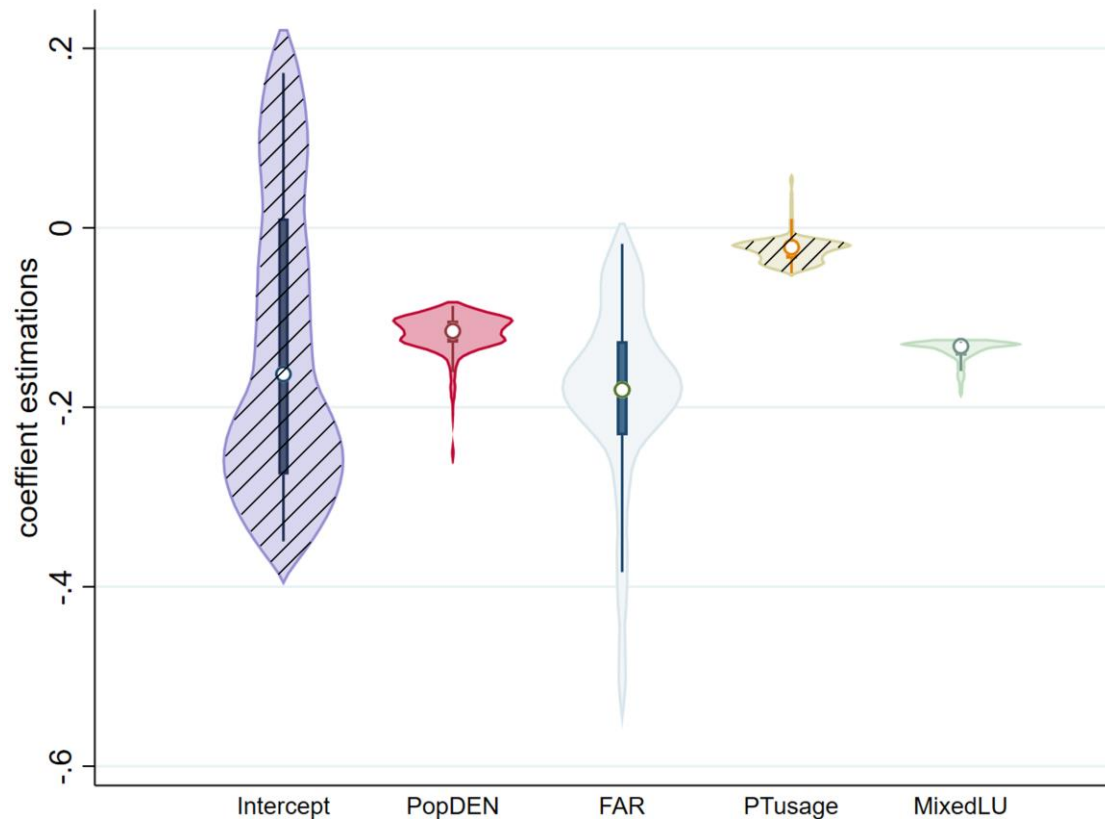


Figure 3.2 Violin diagram of regression coefficient distribution of the MGWR model results

Note: The graph marked with oblique lines represents output results of regression coefficients in the regression model with a p-value greater than 0.1.

The constant variable (Intercept) exhibits both positive and negative effects on carbon intensity. The coefficient of the constant variable represents the influence of geographical location variations on carbon intensity when all other variables remain constant. This can be interpreted as the inherent impact of location itself on carbon intensity. Consequently, the change in geographic location alters the direction of the impact on carbon intensity accordingly.

The violin diagram reveals that FAR has the lowest median point among all independent variables, suggesting the strongest negative impact on total carbon intensity. Following FAR, population density ranks second, followed by mixed land-use, all of which

exert a negative impact on total carbon intensity. Additionally, the distribution range of coefficients for FAR is notably larger compared to that of other indicators. In contrast, public transport, despite its insignificance in relation to carbon intensity ($p\text{-value} > 0.1$), displays a coefficient distribution pattern that is almost zero.

In addition to examining the total carbon intensity of each city in our study, we have also applied our model to assess the impact of urban compactness on carbon intensity within four distinct sectors: energy, industrial, transportation, and household. The coefficients estimated from the regression are presented in Table 3.5.

Table 3.5 Estimation results of the MGWR model for urban compactness influencing sectoral CO₂ intensities

Variable	Energy Sector Carbon Intensity	Industrial Carbon Intensity	Transportation Carbon Intensity	Household Carbon Intensity
PopDEN	-0.216 ***	-0.225***	-0.103	-0.133 *
FAR	-0.293 ***	-0.273***	-0.184 **	-0.13 *
PTusage	-0.009	-0.014	-0.101	0.034
MixedLU	-0.265 ***	-0.261***	-0.153 *	-0.329 ***
No. of observations	223	223	223	223
Adjust R square	0.403	0.385	0.591	0.422

Note: ***, **, and * denote the significance levels of the 0.01, 0.05, and 0.1, respectively.

It is evident that density and accessibility indicators exhibit significant negative correlations with total carbon intensity. Specifically, an increase in FAR (density indicator) and MixedLU (accessibility indicator) are both associated with a reduction in carbon intensity across all four sectors. PopDEN (density indicator) is found to be significant in reducing carbon intensity in the energy, industrial, and household sectors, but it does not exhibit a correlation with carbon intensity reduction in the transportation sector. This observation may be attributed to the common phenomenon of traffic congestion often associated with high-density city centres.

Notably, PTusage (public transportation indicator) does not demonstrate statistical significance in its relationship with carbon intensity within each sector, even within the transport sector. This discovery represents a pivotal finding in our study. Previous researchers have raised criticisms and objections against the compact city development model, contending that mass transportation may not be a sufficient replacement for automobility, as it often suffers from issues of slowness and limited flexibility in serving people's travel needs precisely when and where they require them (Hassan & Lee, 2015). It

is noteworthy that compact development, in some cases, can lead to increased traffic congestion due to the necessity of achieving substantial increases in urban densities to attain only marginal reductions in per capita driving. In the United States, the implementation of compact city policies has faced criticism, with arguments suggesting that a significant portion of the reductions in driving results from policies that raise the cost of driving rather than from the actual promotion of compact development (Randal, 2009).

From the results, it can be observed that higher density and accessibility have negative impacts on urban carbon intensities which validates hypotheses 3.1 and 3.2. However, the impact of public transport usage on carbon intensities is not significant in all four sectors, contrary to hypothesis 3.3. In the discussion section, we further explore the complex interplay between the development of urban public transportation, economic growth, the promotion of social equity, and the pursuit of carbon neutrality objectives.

3.3.2 Spatial heterogeneity of the effects of urban compactness on CO₂ intensity

Our findings also reveal that the MGWR model proves to be more robust in explaining the spatial patterns of carbon emissions influenced by urban compactness, as evidenced by the higher adjusted R^2 value (0.456) compared to that of the global regression model (0.296). We have also identified the substantial impact of specific compactness indicators on urban CO₂ emissions. However, it is worth noting that further analysis is required to further clarify the spatial heterogeneity of the compact city's effect on carbon emissions. The spatial

distribution of the regression coefficients are detailed below.

Figure 3.3 depicts the spatial variation of the effect of the constant variable on urban total CO₂ intensity.

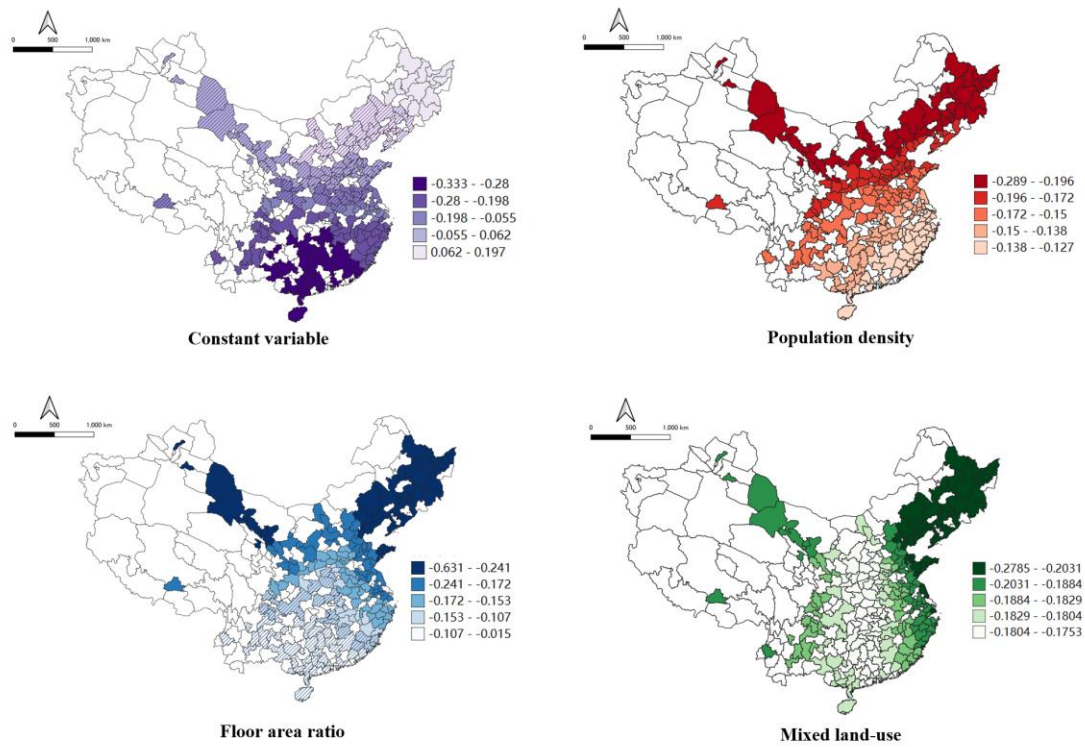


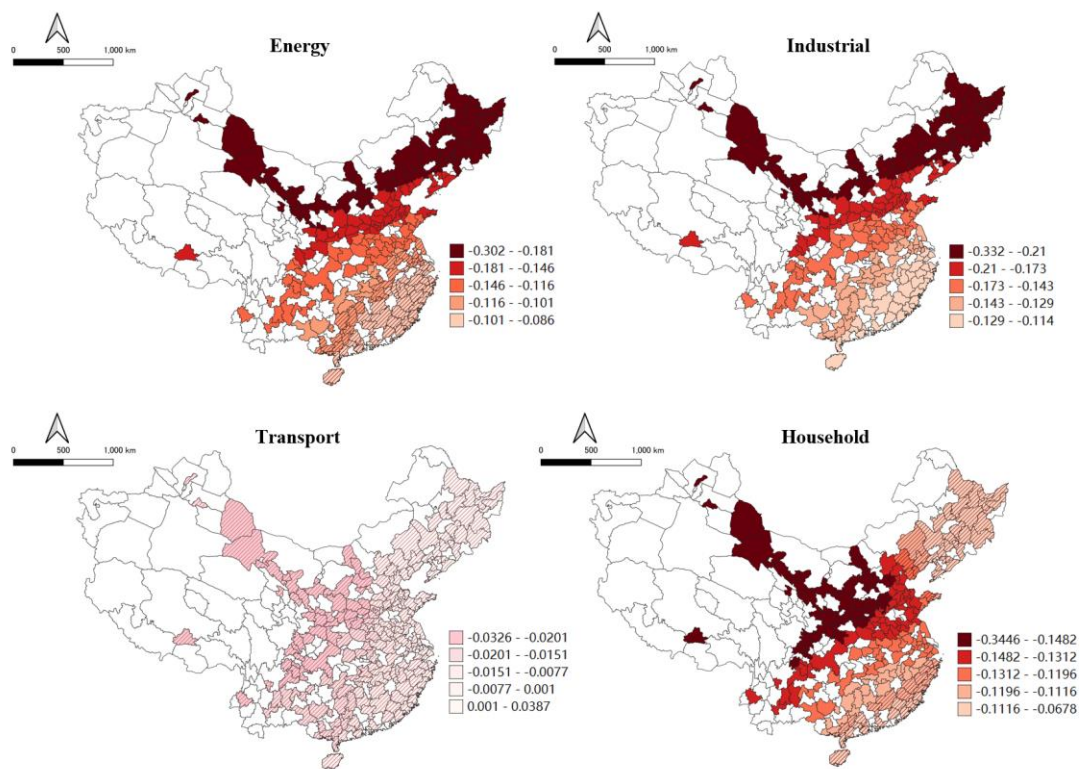
Figure 3.3 Spatial heterogeneity of the effect of urban compactness on total CO₂ intensity

Note: The graph marked with oblique lines represents output results of regression coefficients in the regression model with a p-value greater than 0.1.

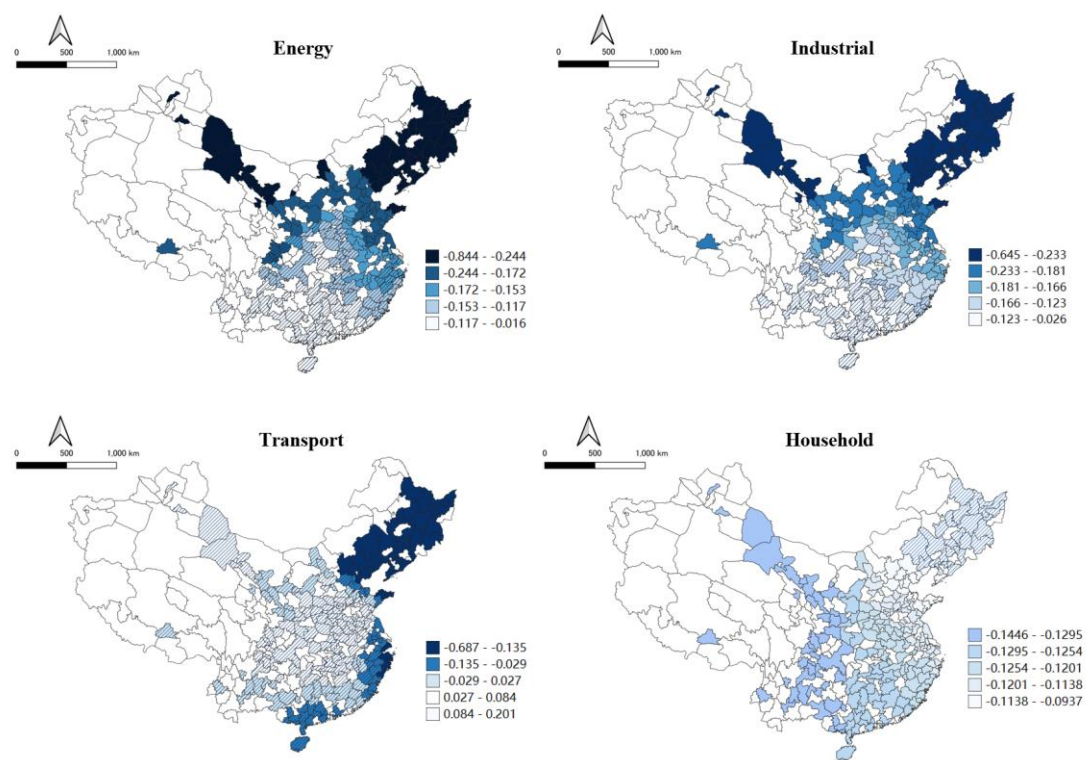
Figure 3.3 illustrates that in the southern regions of China, there is a higher likelihood of experiencing lower carbon intensity. China's heavy industry is predominantly located in the northern regions, especially in the northeast. Meanwhile, light industry and other high-value-added industries are concentrated in the southern regions, aligning with our estimation results. Figure 3 also provides an insight into the spatial distribution of

regression coefficients pertaining to the impact of population density, floor area ratio, and the degree of mixed land-use on overall urban carbon intensity. This visualization demonstrates that, across the entire nation, both population density and floor area ratio exhibit substantial and negative correlations with carbon emissions. Notably, the regression coefficients exhibit a gradual increase from the densely populated southern regions to the sparsely populated western and northeastern regions. This observation suggests that northern China possesses more potential for achieving carbon emissions reduction by enhancing urban density. Furthermore, the land mixed-use intensity indicator exhibits a robust negative correlation with carbon emissions, particularly in the eastern regions, with a notable emphasis on the northeast. Consequently, implementing compact city strategies in the northeast region could prove to be especially effective in advancing the pursuit of carbon neutrality goals.

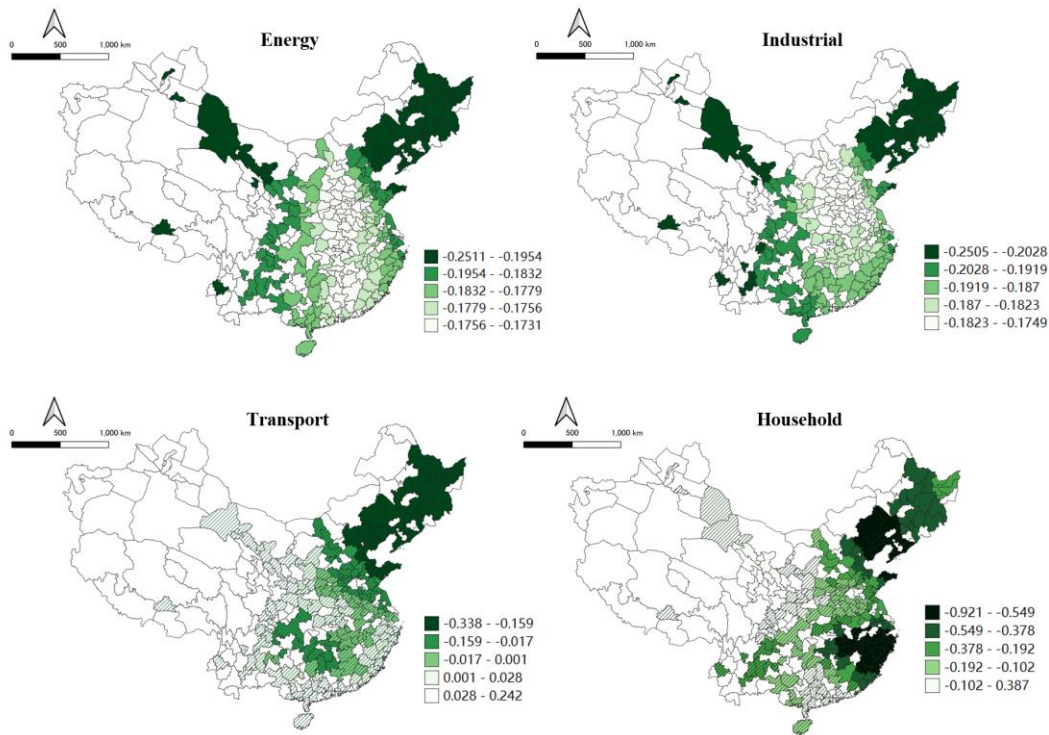
Figure 3.4 illustrates the spatial heterogeneity of the impact of population density on cross-sectoral CO₂ intensity.



(a) population density



(b) floor area ratio



(c) Mixed land-use

Figure 3.4 Spatial heterogeneity of the effect of urban compactness on sectoral CO₂ intensity

Note: The graph marked with oblique lines represents output results of regression coefficients in the regression model with a p-value greater than 0.1.

Here, our results show that in the energy and industrial sectors, the northern regions of China exhibit a more pronounced potential for reducing carbon emissions per unit of GDP when population density increases. This observation is particularly significant given the current demographic trend where young individuals are increasingly relocating to the southeastern part of China in search of better opportunities. Consequently, there has been an urgent call for the adoption of compact city strategies in the northern part of China in recent years. The floor area ratio, serving as another density indicator, exhibits a notable impact on carbon intensity in each sector. Interestingly, it follows a similar pattern in the

energy and industrial sectors as population density, highlighting the higher potential for reducing carbon intensity in the northern regions. However, it is worth noting that the coefficients in the household CO₂ intensity sector are comparatively lower. This discrepancy may be attributed to the fact that an increase in floor area ratio often involves taller buildings equipped with elevators, resulting in greater vertical energy consumption. Additionally, higher buildings tend to consume more energy for temperature control, which could account for the observed variations (Ratti et al., 2005). Indeed, based on the observed patterns, it appears that an increase in floor area ratio may not result in a significant reduction in household CO₂ intensity. Other factors related to building design and energy consumption within households may play a more influential role in this specific sector. Mixed land use, serving as the indicator for accessibility, has a consistently negative impact on CO₂ intensity across all four sectors. This suggests that promoting increased mixed land use through the implementation of compact city policies could indeed be one of the most effective strategies for advancing China's carbon neutrality goals.

3.3.3 Robustness tests

In order to mitigate the potential issue of correlation among the independent variables in our regression model, we conducted a variance inflation factor (VIF) analysis on our dataset. VIF quantifies how much the variance of an estimated regression coefficient is influenced by multicollinearity. Typically, a high VIF, exceeding 10, signals the presence of multicollinearity. The results, as displayed in Table 3.6, confirm that multicollinearity is not present among the analysed variables.

Table 3.6 Results of variance inflation factor

Variable	VIF	1/VIF
GreenArea	2.23	0.449164
GDPcap	2.14	0.466736
RailTrans	2.07	0.483502
PTusage	1.71	0.583187
PopDEN	1.57	0.63608
Urbanization	1.56	0.639636
IndStructure	1.42	0.702838
MixedLU	1.29	0.77512
FAR	1.25	0.797355
Mean VIF	1.69	/

After collinearity checks were completed, adjustments were made to the original model presented above, including both its structure and variables, in order to validate the robustness of our compactness index identification results concerning the impacts of urban carbon emissions. Specifically, several variables that were not statistically significant were excluded, and the regression model was reconstructed. The results of the new model indicate that population density (PopDEN), floor area ratio (FAR), and mixed land use (MixedLU) remain critical factors influencing urban carbon emissions. This finding further corroborates the robustness of the MGWR model regression results. Detailed outputs of the validation models regarding the related robustness checks can be found in Table 3.7.

Table 3.7 Estimation results for robustness check 1

Variable	OLS			MGWR		
	Coefficient	Std.Error	P-value	Coefficient	Std.Error	P-value
CONSTANT	5.834	0.524	0.000	-0.132	0.091	0.210
PopDEN	-0.001	0.000	0.005	-0.179	0.063	0.004
FAR	-0.063	0.012	0.000	-0.308	0.059	0.000
MixedLU	-0.608	0.147	0.000	-0.254	0.062	0.000
GDPcap	0.000	0.000	0.027	-0.143	0.064	0.026
Number of observations	223			223		
Adjust R square	0.298			0.381		

In our research, we employ carbon intensity as the dependent variable to represent urban carbon emissions, a measure that accounts for economic growth. It is worth noting that other studies have utilized CO₂ equivalent per capita as the dependent variable when examining the impact of compact urban form on CO₂ emissions (Makido et al., 2012; Park et al., 2013). Additionally, it is important to mention that in our analysis, we utilize bus passenger volume as a metric to assess the development and utilization of inner-city public transport. We did not incorporate the presence of railways, including subways and light rail, into our study. Building upon previous research, we have identified two distinct types of compact city development modes: the fast-growing type and the decreasing population type. It is worth noting that the presence and scale of public mass-transport systems play a pivotal role in distinguishing between these two categories of compact cities (Fan & Chapman, 2022). We introduced an additional dummy variable into our model, which represents the presence of inner-city rail systems, as part of our robustness checks. The results of these robustness checks are presented in Table 3.8.

Table 3.8 Estimation results for robustness check 2

Variable	Carbon Intensity			CO ₂ per capita		
	Coefficient	Std.error	P-value	Coefficient	Std.error	P-value
CONSTANT	4.364	0.794	0.000	9.720	5.298	0.068
PopDEN	-0.001	0.000	0.008	-0.008	0.002	0.000
FAR	-0.060	0.013	0.000	-0.256	0.086	0.003
PTusage	0.000	0.002	0.899	0.002	0.011	0.856
RailTrans	-0.625	0.402	0.121	-6.491	2.678	0.016
MixedLU	-0.552	0.152	0.000	-3.278	1.015	0.001
GDPcap	0.000	0.000	0.025	0.000	0.000	0.000
IndStructure	0.018	0.012	0.144	0.227	0.082	0.006
Urbanization	0.900	0.631	0.156	3.768	4.212	0.372
GreenArea	0.000	0.000	0.233	0.000	0.000	0.101
No. of observations	223					
Adjusted R square	0.303			0.318		

It is noteworthy that the indicators related to density and accessibility continue to exhibit a robust and negative correlation with urban carbon emissions, whether measured by CO₂ per capita or carbon intensity. Even with the inclusion of the RailTrans dummy variable in the model, PTusage still does not demonstrate statistical significance in its relationship with carbon emissions. It is important to highlight that the mere presence of a rail system could potentially lead to a reduction in CO₂ per capita emissions. This observation aligns with the understanding that only large to mega cities typically possess the resources and demand necessary to establish inner-city rail systems to facilitate extensive commuting. Furthermore, it is noteworthy that the relationship with carbon intensity remains statistically insignificant. These outcomes affirm the robustness of our baseline regression results.

3.4 Discussion

First, it is essential to clarify that the development of compact cities, as advocated by many governments today, encompasses multidimensional aspects such as urban planning, upgrading transportation systems, comprehensive land use changes, and the redevelopment of residential and commercial buildings. It is not solely concerned with making the physical layout of cities more compact. The goals set by compact city policies go beyond simply increasing population density by setting urban boundaries, as this can lead to congestion issues and hinder urban development. Compact city policy instruments emphasize functional compactness and their role in urban sustainability, particularly in carbon reduction, is not isolated. They require synergy with economic, energy, and social welfare policies to truly achieve urban sustainability.

In our study, we chose to utilize carbon intensity as our dependent variable. This choice aligns with our research focus on developing countries, such as the case study nation of China, where there is a prominent emphasis on economic development in tandem with the pursuit of carbon neutrality. This aspect holds particular significance for numerous second-tier Chinese cities as they strive to shift from traditional industrial centres towards more compact development (Z. Wang et al., 2016). Within this evolving context, the concept of a low-carbon economy and the pursuit of a low-carbon development path become paramount. Carbon intensity, as a metric, proves to be apt for measuring and addressing this demand.

3.4.1 Enhancing urban density and accessibility to build a low-carbon urban form

Our study's primary objective was to discern the optimal allocation of limited resources among the three pivotal dimensions of compact city development: density, accessibility, and public transportation. We seek to enhance urban sustainability and foster low-carbon transformation through this allocation. Our research outcomes affirm the conclusions drawn from previous studies, emphasizing the role of density indicators in facilitating carbon reduction in urban areas (M. Tan et al., 2008). While the majority of previous research has focused on the relationship between population density and carbon emissions, our study suggests that, in comparison to population density, an increase in floor area ratio may prove to be a more effective strategy for reducing urban carbon intensity. This observation aligns with the vertical compact development component inherent in compact city strategies. Corroboratively, a study in China showed that building area and number of storeys affect residential carbon emissions, while building area, shape coefficient, and floor area ratio impact public land emissions (Xu et al., 2023). Nevertheless, the proposition of elevating the floor area ratio necessitates a simultaneous increase in the availability of affordable residences, particularly within the city centre. Moreover, the elevation of FAR typically entails the construction of taller buildings. In densely populated metropolises such as Guangzhou and Nanjing, the imposition of restrictions on villa development can, to some extent, be seen as an implementation of the government's compact city construction policy. However, in certain shrinking cities located in the northeastern part of the country, where population outflows are being experienced, the task of increasing floor area ratio poses primarily economic and financial challenges. The critical question is whether real estate developers will exhibit the confidence to enter such markets. For investors, concerns

like population aging, the prevalence of state-owned enterprises, or industrial overcapacity in the northeast may take a backseat to other formidable challenges, such as bureaucracy and issues related to data accuracy and reliability. While the vision of augmenting urban density to promote sustainability and curtail carbon emissions is indeed laudable, its practical implementation may encounter substantial challenges. Moreover, the significance of the vertical dimension of energy consumption should not be underestimated in this pursuit. In this regard, policies aimed at increasing density for compact cities must be customized to suit the unique urban contexts and characteristics present in diverse regions, rather than relying on a uniform, one-size-fits-all approach.

In comparison to the intricate challenges associated with increasing urban density, the prospect of enhancing accessibility to bolster environmental performance appears more attainable. Our research findings also lend credence to this perspective. The theoretical foundation of low-carbon compact cities centres on the concept of diminishing travel demand to curtail energy consumption. Elevating mixed land-use degree enables residents to access a diverse range of resources and services within the same vicinity. Instead of solely emphasizing the construction of tall buildings, augmenting or relocating social and commercial services to integrate with residential areas offers a twofold advantage. Not only does it cultivate a more vibrant and appealing city centre, but it also effectively reduces urban carbon emissions. This approach to compact development holds promise and can be effectively applied in both large and small cities alike.

Drawn from the discussion above, I propose a number of specific policy recommendations as follows:

- ♦ Increase urban density: conducting infrastructure assessment during the planning application process to ensure sustainable density; increasing new housing inside the urban growth boundary; conducting urban redevelopment projects under the base of existing low FAR constructions.
- ♦ Increasing urban accessibility: delivering social infrastructure to support strong communities; developing healthy and complete communities with access to a range of services and amenities

It is hoped that the results of the present study will enable policy makers to optimize the performance of compact cities regarding GHG emissions without jeopardizing agricultural lands and open space in urban areas, and effectively stem urban sprawl.

3.4.2 Public transport and the 'double carbon' goal dilemma in China

An intriguing aspect of this study is its utilization of public transportation data from the year 2020, prior to the onset of the COVID-19 pandemic. The findings indicate that increased usage of public buses may potentially exacerbate urban carbon emissions. However, in the current landscape of China, third-tier cities have witnessed a remarkable decline in public transportation services. The primary factor behind this decline is the 'zero-COVID' approach mandated by the central government, which has strained local government finances and led to a significant reduction in subsidies for public transportation systems following the conclusion of the pandemic. Consequently, public

transportation companies find themselves unable to sustain their operations (New Tang Dynasty Television, 2023; Red star news, 2023).

Furthermore, the widespread adoption of shared bicycles in China has further diminished the demand for public buses among citizens. In a sense, third-tier cities in China are achieving carbon emission reductions in urban road transport passively. However, this passive reduction in public services undoubtedly impacts local economic activity, thereby influencing carbon intensity. It is important to recognize that public transportation, alongside other public services that have been curtailed due to financial constraints, play a pivotal role in promoting social equity, enhancing daily life convenience, and serving as a lifeline for low-income individuals. The duration of this situation remains uncertain, but it is evident that it is not a sustainable one (The Paper.cn, n.d.). Previous research considering urban public transport and its impact on GHG emissions have drawn similar conclusions. For example, a study in China found that total carbon emissions from urban public transport (UPT) in Shenzhen have risen sharply due to the rapid growth in transport turnover. However, the current low-carbon UPT model has only reduced CO₂ emissions by 0.21 Mt (cumulative value from 2005 to 2015), which is insufficient to significantly contribute to the city's overall emission reduction targets (Dong et al., 2018). There are also studies showing different conclusions on the proportion of public transport methods in achieving the urban carbon-neutral goal. Research in Shanghai found that rail transit is the predominant mode of transportation, and by optimizing the urban traffic structure, 47.62% of the carbon emissions reduction target can be achieved (L. Zhang et al., 2020). But Shanghai, as one of the biggest mega cities in the world, cannot be considered representative

due to the nature of its large population size, urban area and high level of development. Additional research suggests that the promotion of carbon emission reduction through public transportation requires the widespread introduction of new energy vehicles to achieve the desired effects (Kolbe, 2019)(Ercan et al., 2016).

More importantly, the research outcomes in the present study provide valuable theoretical underpinnings for the development of public transportation policy within the context of compact cities. Simply increasing public transportation usage does not automatically contribute to the achievement of carbon neutrality goals. However, public transportation remains an indispensable service for urban residents. Consequently, future research pertaining to compact cities will need to focus on devising strategies for aligning public transportation with increased density and accessibility, while also orchestrating a transition toward cleaner energy sources. This will be a central area of inquiry in the years to come and may include the 'greening' of public transportation options, i.e., electric or hydrogen-based vehicles alongside a reduction in the carbon intensity of the electrical grid.

3.4.3 A-S-I or total electrification?

In the context of compact city construction, public transit is often regarded as a crucial factor, but it does not stand alone in the quest to reduce emissions. Transport scholars and practitioners frequently employ the 'Avoid-Shift-Improve' (ASI) approach, which is designed to make substantial reductions in GHG emissions, energy consumption, and congestion, all while striving to create more liveable cities (Bongardt et al., 2019). 'Avoid' emphasizes the need to prevent or diminish travel or the necessity to travel altogether. 'Shift'

pertains to shifting towards modes of transportation characterized by higher energy efficiency. 'Improve' underscores the enhancement of efficiency through advancements in vehicle technology. This approach has attracted scholarly attention, leading to investigations into economic and environmental impacts within urban transportation. Hampus et al., employed a system dynamics approach to operationalize the ASI framework. Their work has shed light on the endogenous effects embedded within urban systems (Mårtensson et al., 2023). In Paris, France, research findings indicated that even a daily travel time increase of fewer than 10 minutes could prompt 46% of drivers to make a modal shift to e-bikes, with some opting for public transit. Such a modal shift holds the potential to slash daily mobility emissions by 15% and yield annual climate and health benefits valued at € 125 million (Leroutier & Quirion, 2023). Furthermore, research conducted in China adopts a bottom-up energy system optimization model to explore CO₂ emission trends comparing the ASI approach and collaboration between the transportation, power, and hydrogen sectors. The outcomes highlight the formidable challenge of attaining carbon neutrality solely through improvements in the transportation sector. However, when integrating negative emission technologies from the power and hydrogen sectors, it becomes feasible for the transportation sector to achieve carbon neutrality (Fang et al., 2023). Studies collectively underscore the importance of electrification alongside compact city development to effectively limit global temperature rise to 1.5 degrees Celsius, in line with climate goals (Fulton & Reich, 2021). This research aligns with these findings, emphasizing the significance of behaviour change while highlighting the critical importance of designing public transportation systems that are in harmony with the ongoing transition

to cleaner energy sources in order to curb urban carbon emissions.

3.4.4 Limitations and future perspectives

This study, while providing valuable insights, is not without limitations.

Firstly, with respect to the data concerning compact city characteristics, the absence of comprehensive statistical data compelled us to exclude certain indicators of compactness from our sample of Chinese cities (e.g., number of shared bicycles to quantify public transport degree, national-scale data of average distance to public transport stations to quantify accessibility etc.). Our selection of indicators for compact development was influenced by our review of previous research. We chose one to two representative indicators to quantify each of the three dimensions of compact development. Specifically, in the realm of public transportation, we focused on two indicators: bus usage and the presence of rail transit. Future research could delve further into these indicators and explore the nuanced impact of various dimensions of public transportation on urban carbon intensities.

Secondly, the regression analysis of this study is based on a cross-sectional dataset rather than panel data, which doesn't provide insight into changes over time. And the POI data collected for calculating the degree of mixed land-use is not synchronized with the year of other indicators due to difficulty in data collection. Future research using panel data to investigate the relationship between compact cities and urban carbon intensity could aid in drawing more robust conclusions.

Moreover, prior studies have proposed the existence of two distinct types of compact city development: one characterized by rapid population growth and development, and the

other typified by declining population and slow development, which is often observed in second-tier cities of developed countries (Fan & Chapman, 2022). This study, however, primarily concentrates on investigating the overall impact of compact characteristics on carbon emissions and the spatial distribution disparities, without specific differentiation between these two distinct types of compact city development. Future research could undertake the modelling of different types of compact city developments to dissect the environmental differences between them.

Lastly, the COVID-19 pandemic significantly influenced the 3 years following 2020, serving as a notable time point for numerous studies. The pandemic had a protracted impact on compact city development in China, as it necessitated prolonged measures for epidemic control. The post-pandemic situation remains dynamic and may warrant further research and exploration.

3.5 Conclusions

This chapter sought to clarify the impact of different dimensions of compact urban development on CO₂ emissions, thereby providing guidance for the formulation of compact city policies. We employed OLS and MGWR models to investigate the intricate relationship between compact city characteristics and urban carbon emissions from various sectors. The study's results revealed that density indicators, exemplified by population density and floor area ratio, exert a notable negative influence on urban carbon emissions. Furthermore, accessibility indicators, as represented by degree of mixed land-use, also

exhibit a negative correlation with carbon emissions. However, it was notable that the public transportation indicator failed to demonstrate a significant impact on the attainment of urban carbon reduction objectives.

Additionally, the MGWR model unearthed spatial heterogeneity in the effects of urban compactness indicators on sectoral carbon emissions. The negative impact of density indicators on overall carbon emissions diminishes as one moves from northern to southern Chinese cities. This indicates that northern Chinese cities hold greater potential for achieving their low-carbon goals through the implementation of compact city policies. Accessibility indicators exert a negative influence on carbon emissions from all sectors, encompassing energy, industrial, transportation, and household. This impact is most pronounced in the northeastern and western regions of China.

In summation, this study underscores the positive role of increasing urban compactness through the enactment of compact city policies in reducing urban carbon emissions. Nevertheless, it dispels the notion that achieving carbon reduction objectives can be solely realized through heightened public transportation usage. Rather, to align with energy policies to propel low-carbon development within urban transportation comprehensively may be a better implementation approach for compact city policies, providing an intriguing avenue for future investigative efforts in this field.

Chapter 4. Nonlinear Impacts of Compact City Characteristics on Carbon Emissions

4.1 Introduction

The relationship between compact city characteristics and carbon emissions is complex and often nonlinear. While previous chapters have explored the theoretical foundations and linear impacts of compact urban development, this chapter delves into the nonlinear effects of these characteristics on carbon emissions. Specifically, it examines how population density, land-use mix, and public transportation usage influence urban carbon intensity in ways that are not adequately captured by linear models.

Given the limitations of traditional regression approaches in addressing these nonlinear relationships, this chapter employs advanced machine learning techniques, particularly the eXtreme Gradient Boosting (XGBoost) algorithm, to provide a more nuanced analysis. Additionally, the SHapley Additive exPlanations (SHAP) method is used to interpret the results, offering insights into the importance and interaction of various features in the model. This approach allows for a deeper understanding of the mechanisms through which compact urban development affects carbon emissions.

The study area encompasses 340 prefecture-level cities in mainland China, with data collected on urban construction, socio-economic indicators, and carbon emissions for the years 2005, 2010, 2015, and 2020. This extensive dataset provides a robust foundation for analysing the temporal and spatial dynamics of urban carbon emissions.

To guide this empirical investigation, the following hypotheses are proposed:

- ♦ *Hypothesis 4.1: An increase in population density will be associated with a reduction in urban carbon intensity.*
- ♦ *Hypothesis 4.2: Improved accessibility within urban areas will correlate with decreased urban carbon intensity.*
- ♦ *Hypothesis 4.3: Greater utilization of public transportation will lead to lower urban carbon intensity.*

The objectives of this chapter are threefold: 1) to identify the nonlinear relationships between key compact city characteristics (density, accessibility, and public transportation usage) and carbon intensity; 2) to interpret the results using the SHAP method, thereby elucidating the importance and interactions of these characteristics; 3) to conduct clustering analysis and simulate temporal trends in carbon emissions for different city clusters, providing insights into the effectiveness of compact city policies in various urban contexts.

By addressing these objectives, this chapter aims to contribute to the existing body of knowledge on urban sustainability and provide actionable insights for policymakers and urban planners. The findings will highlight the critical factors that influence carbon emissions in compact cities and suggest optimal strategies for achieving sustainable urban development.

4.2 Methodology

4.2.1 Research design and study area

This study encompasses four primary stages. Firstly, prefecture-level cities in mainland

China were selected as the study area and data was collected on urban construction, socio-economic indicators, and carbon emissions for the years 2005, 2010, 2015, and 2020. The collected data underwent thorough preprocessing to ensure accuracy and consistency.

Figure 4.1 illustrates the study area and the distribution of city-level CO₂ emissions.

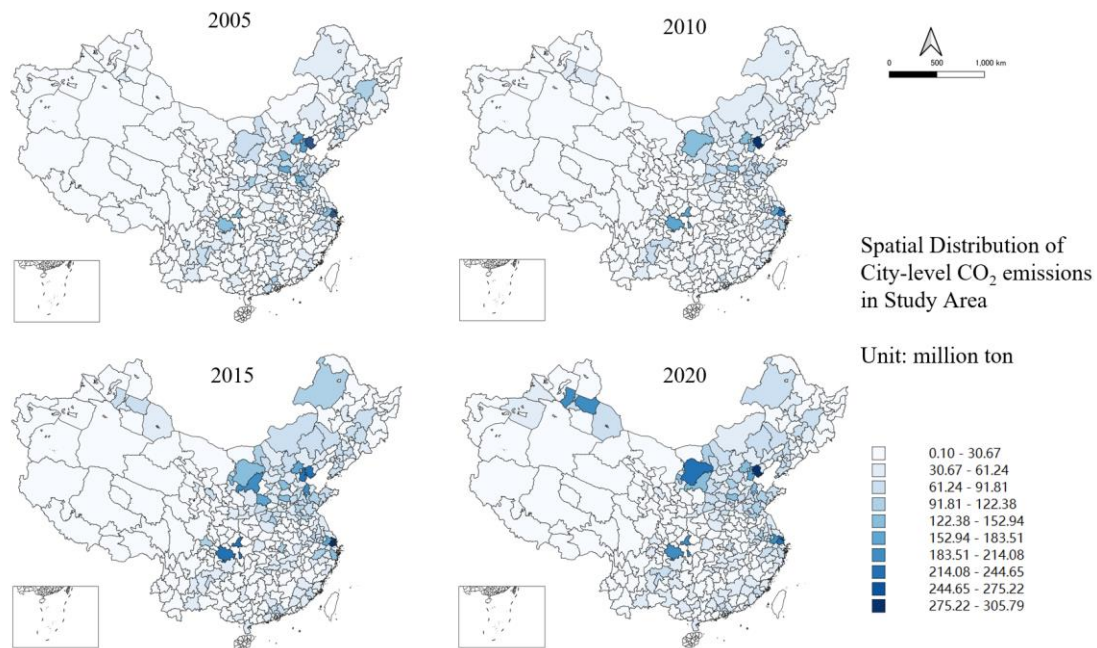


Figure 4.1 Study area and spatial distribution of city-level CO₂ emissions

Secondly, to examine the nonlinear relationships between compact urban development characteristics and carbon emissions, machine learning models were utilized, specifically XGBoost, and the elicited results were then compared with traditional linear regression and spatial regression models. Thirdly, the SHAP method was used to interpret the results of the machine learning models, providing insights into feature importance and the nature of the nonlinear relationships. Lastly, a clustering analysis was conducted on the compact development indicators of the sample cities, followed by a simulation of the temporal trends in carbon emissions for different city clusters. Figure 4.2 presents the comprehensive

research framework of this study.

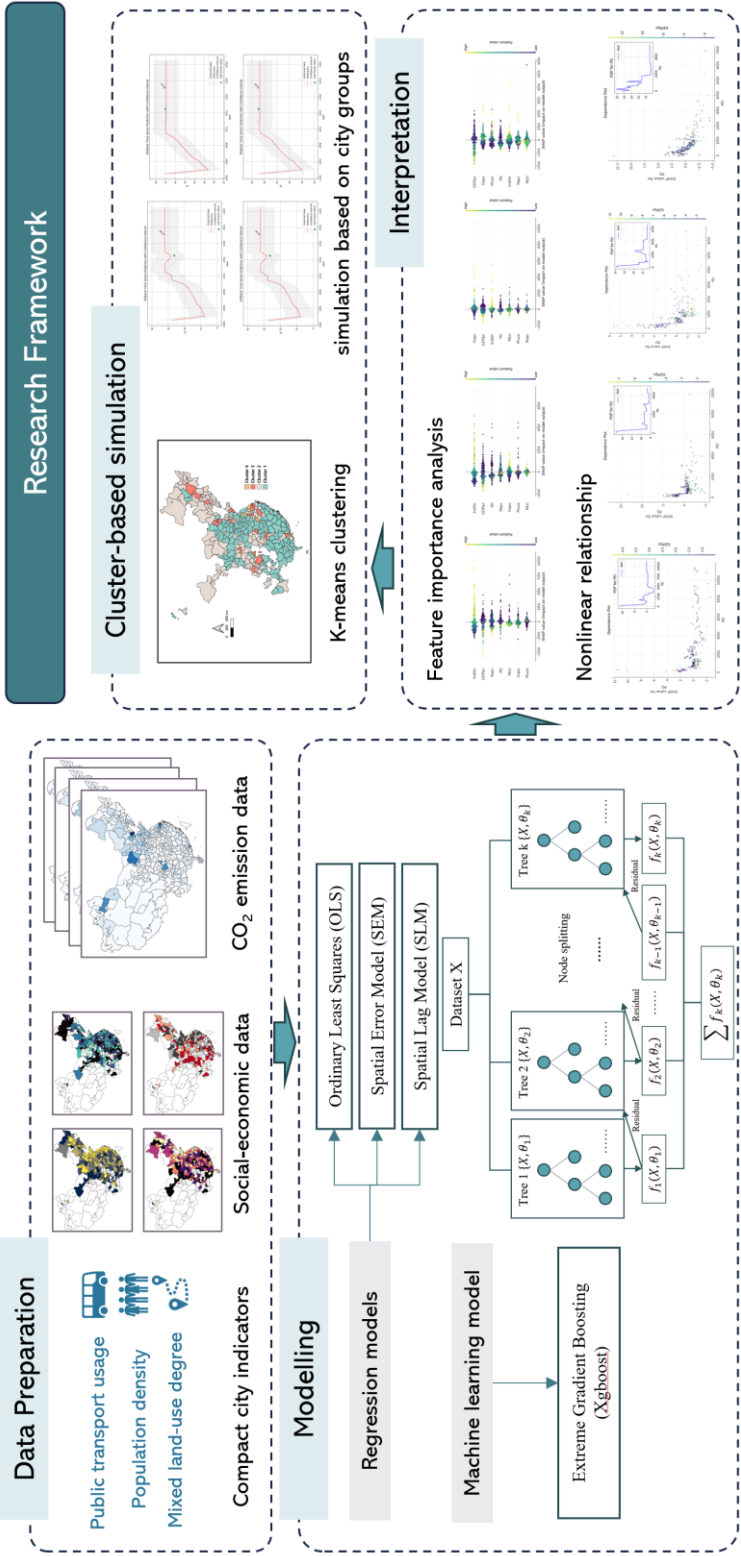


Figure 4.2 Research framework of this study

4.2.2 Data and variables

The dependent variable in this study, city-level CO₂ emissions, was also provided by the China Greenhouse Gas Working Group (CCG) (China City Greenhouse Gas Working Group, 2022). This dataset employs internationally established and widely applied methodologies for calculating urban CO₂ emissions, including both direct emissions generated within the administrative boundaries of cities and indirect emissions resulting from the purchase of electricity from external sources. Indirect emissions are calculated by multiplying the city's externally sourced electricity consumption by the emission factor of the regional power grid where the city is located. The foundational data for cities integrates information from the CHRED 3.0 database, various official urban-level datasets, as well as findings from on-site investigations, telephone consultations, and data obtained through correspondence with relevant departments facilitated by the CCG (Y. Gao et al., 2022). This dataset encompasses carbon emission information for 340 different prefecture-level cities in China across various sectors. Carbon intensities were calculated based on this dataset, with carbon intensity defined as the amount of carbon emissions divided by unit GDP (kg CO₂ eq/CNY).

The choice of carbon intensity as the dependent variable, rather than total carbon emissions or per capita carbon emissions, is based on several considerations. Carbon intensity provides a more nuanced measure of the efficiency of economic activities in terms of their carbon output. It accounts for the economic productivity of cities, thereby allowing for a fairer comparison across cities with different economic scales and structures (Hong et

al., 2021). This measure is particularly relevant in the context of urban sustainability and policy evaluation, as it highlights the decoupling of economic growth from carbon emissions, which is a critical goal for sustainable urban development (S. Tan et al., 2017).

The explanatory variables in this study still focus on three key dimensions of compact development: density, accessibility, and public transportation (OECD, 2012). Due to data availability, in this chapter population density, land-use mix, and bus usage are selected to quantify the compact development characteristics of cities. The control variables are also slightly different to those used in the previous chapters. These control variables encompass aspects such as industrial structure, per capita GDP, road area per capita, and green area per capita [50]. Table 4.1 presents the variables used in this study and the definition of each variable. Table 4.2 shows the descriptive statistics of the variables. For urban development-related data, including population and urban area measurements, we relied on data sourced from the China City Statistical Yearbook (National Bureau of Statistics of China, 2005, 2010, 2015, 2020). Information pertaining to urban public transportation and land-use types was obtained from the China Urban Construction Statistical Yearbook (Ministry of Housing and Construction of China, 2005, 2010, 2015, 2020).

Table 4.1 Variable definitions

Variable Type		Variable	Definition	
Dependent variable	Carbon emissions	CI	Carbon intensity	CO ₂ emissions/GDP
Independent variable	Compact city characteristics	PD	Population density	Population/Area
		Ptuse	Public transport usage	Bus usage per capita per year

	MLU	Mixed land-use degree	Spatial entropy index of land-use types
Controls	Gapc	Green area per capita	Green area/population
	Rapc	Road area per capita	Road area/population
	GDPpc	GDP per capita	GDP/population
	InStr	Industrial structure	percentage of GDP from second industry

Table 4.2 Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
CI	1137	2958.38	2955.79	52.36	27382.72
PD	1137	1262.43	1617.15	3.68	11344.20
Ptuse	1137	38.43	66.06	0.00	877.58
MLU	1137	0.83	0.06	0.49	1.00
Gapc	1137	9.11	6.32	0.35	73.31
Rapc	1137	11.66	8.00	0.33	94.10
GDPpc	1137	4.16	3.21	0.24	23.37
InStr	1137	45.28	11.79	0.00	89.75

4.2.3 Analytical methods

4.2.3.1 Traditional regression models

To address potential multicollinearity among the independent variables in our models, we performed a variance inflation factor (VIF) analysis on our dataset. VIF measures the degree to which the variance of an estimated regression coefficient is increased due to multicollinearity. Generally, a VIF value exceeding 10 indicates significant multicollinearity. The results, as shown in Table 4.3, indicate that multicollinearity is not an issue among the variables analysed.

Table 4.3 Results of variance inflation factor

Variable	VIF	1/VIF
Rapc	2.53	0.3960

Gapc	2.32	0.4303
GDPpc	1.74	0.5748
Ptuse	1.18	0.8449
PD	1.05	0.9516
IndStr	1.05	0.9532
MLU	1.03	0.9715
Mean VIF	1.56	/

With the VIF test confirming the absence of multicollinearity, we proceeded to use traditional regression models to explore the relationships between compact urban characteristics and city-level carbon emissions. A simple specification was applied without incorporating variable interactions or transformations. While nonlinearity can be addressed within traditional regression frameworks through transformations, polynomial terms, or nonlinear combinations of coefficients, these approaches necessitate prior assumptions about the relationship being modelled (Montgomery et al., 2021). Despite their typically lower explanatory power relative to machine learning models, traditional regression methods were employed in this study for two main reasons: (1) to establish a baseline comparison for the nonlinearity detected by machine learning models, given the widespread use of linear methods in previous research; and (2) to assess the significance levels of compact urban characteristic variables (Bansal & Quan, 2024).

Three sets of traditional regression models were utilized for each year: ordinary least squares (OLS) models, spatial lag models (SLM), and spatial error models (SEM).

Ordinary Least Squares (OLS) Model: The OLS model was used to establish any linear relationships between the compact urban characteristics and carbon emission intensity. This model serves as a benchmark for evaluating more complex models.

The OLS model formulation used in this study can be expressed as shown in equation 5:

$$\begin{aligned}
CI_i = & \beta_0 + \beta_1 PD_i + \beta_2 Ptuse_i + \beta_3 MLU_i + \beta_4 Gapc_i \\
& + \beta_5 Rapc_i + \beta_6 GDPpc_i + \beta_7 InStr_i \\
& + \varepsilon_i
\end{aligned} \tag{5}$$

Spatial Lag Model (SLM): To account for spatial dependencies where the carbon emissions of a city might be influenced by those of its neighbouring cities, we employed the spatial lag model. This model includes a spatially lagged dependent variable to capture these potential spillover effects.

The SLM model formulation used in this study can be expressed as shown in equation 6:

$$\begin{aligned}
CI_i = & \rho WCI_i + \beta_0 + \beta_1 PD_i + \beta_2 Ptuse_i + \beta_3 MLU_i \\
& + \beta_4 Gapc_i + \beta_5 Rapc_i + \beta_6 GDPpc_i \\
& + \beta_7 InStr_i + \varepsilon_i
\end{aligned} \tag{6}$$

where ρ represents spatial lag coefficient, representing the influence of neighbouring cities' carbon intensities. WCI_i represents weighted sum of neighbouring cities' carbon intensities, where W is the spatial weights matrix (Seya et al., 2020).

Spatial Error Model (SEM): The spatial error model was applied to address spatial autocorrelation in the error terms, which could arise from unobserved spatially structured factors. This model helps to correct for biases in parameter estimates that can occur due to such spatial autocorrelation.

The SEM model formulation used in this study can be expressed as shown in equation 7:

$$\begin{aligned}
CI_i = & \beta_0 + \beta_1 PD_i + \beta_2 Ptuse_i + \beta_3 MLU_i + \beta_4 Gapc_i \\
& + \beta_5 Rapc_i + \beta_6 GDPpc_i + \beta_7 InStr_i \\
& + \lambda W_{u_i} + \varepsilon_i
\end{aligned} \tag{7}$$

where λ is the spatial error coefficient, representing the spatially correlated error term. W_{u_i} is the weighted sum of the error terms from neighbouring cities, where W is the

spatial weights matrix (Seya et al., 2020).

Each model was estimated using data for the years 2005, 2010, 2015, and 2020 to analyse the temporal dynamics and robustness of the relationships between compact urban development indicators and carbon emissions. The results from these traditional regression models provide a foundation for understanding any basic linear relationships and serve as a point of comparison for the more advanced machine learning models.

4.2.3.2 Machine learning model and Shapley value

To further explore the nonlinear relationships between compact urban development indicators and carbon emissions, we utilized the XGBoost (eXtreme Gradient Boosting) algorithm and employed SHAP (SHapley Additive exPlanations) to visualize and interpret the results. XGBoost, an advanced machine learning technique, enhances the traditional Gradient Boosting Decision Trees (GBDT) by incorporating regularization terms into the loss function, thereby improving its robustness against overfitting. Additionally, XGBoost uses a second-order Taylor expansion of the loss function to handle situations where the derivatives of the loss function are complex to compute.

For a dataset with n observations and m features, the XGBoost model can be expressed as follows (Parsa et al., 2020):

$$\widehat{CI}_i = \sum_{k=1}^K f_k(x_i), f_k \in F \ (i = 1, 2, \dots, n)$$

In this expression, $F = \{f(x) = w_{q(x)}\}$ where $q: \mathbb{R}^m \rightarrow \{1, 2, \dots, T\}$ and $w \in \mathbb{R}^T$. Here,

F represents the collection of decision tree structures, q is the mapping function that assigns samples to leaf nodes, T denotes the number of leaf nodes, and w is the set of weights for the leaf nodes. $\widehat{CI}_i$ is the predicted carbon intensity for the i th observation. x_i is Feature vector for the i th observation, which includes PD_i , $Ptuse_i$, MLU_i , $Gapc_i$, $Rapc_i$, $GDPpc_i$ and $InStr_i$. f_k is the k th regression tree in the ensemble. K is the total number of trees in the model.

The objective of constructing an XGBoost model involves optimizing the parameters to minimize the objective function, which includes both the training loss and a regularization term. The objective function can be written as:

$$Obj = \sum_{j=1}^T (G_j w_j + \frac{1}{2} H_j w_j^2) + \lambda \sum_{j=1}^T w_j^2 + \gamma T$$

In this equation, G_j and H_j are the first-order and second-order gradient statistics on the loss function for the samples in leaf node j , respectively. λ is the regularization parameter to control overfitting, γ is the complexity cost for adding a new leaf node, and w_j is the weight for leaf node j . The optimization results of XGBoost model hyperparameters is shown in Table 4.4.

Table 4.4 Optimization results of XGBoost model hyperparameters

Hyperparameter	Optimal value
learning_rate	0.1
max_depth	5
n_estimators	100
random_state	42

After training and optimizing the XGBoost model, Shapley values were used to interpret the model's results. Shapley value is based on cooperative game theory and is used to explain the output of machine learning models by assigning each feature an importance value for a particular prediction. This method provides insights at both the global and local levels by quantifying the contribution of each feature to the model's predictions.

The SHAP value for a feature i is calculated as:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! (|N| - |S| - 1)!}{|N|!} [v(S \cup \{i\}) - v(S)]$$

In this formula, ϕ_i represents the Shapley value for feature i ; N is the set of all features; S is a subset of N not containing feature i ; and $v(S \cup \{i\})$ and $v(S)$ are the model outputs with and without feature i , respectively.

Using Shapley value, we can visually and quantitatively interpret the influence of each compact urban development indicator on carbon emissions, thereby uncovering any underlying nonlinear relationships.

4.2.3.3 Clustering analysis and carbon emissions simulation

To simulate the temporal variation in carbon emissions across cities with different compact urban characteristics, we first conducted a clustering analysis. This analysis aimed to categorize cities based on their economic and spatial development levels. We selected the GDP, population, and constructed area of each city in 2020 as scale indicators. Additionally, we included the average annual growth rates of GDP, population density, and constructed

area over the past decade as compact development indicators (Wu & Zhang, 2024). Using these six variables, we performed K-means clustering on 283 prefecture-level cities in China.

K-means clustering is an unsupervised machine learning algorithm that partitions a dataset into K distinct, non-overlapping clusters. Each data point is assigned to the cluster with the nearest mean, serving as the cluster centroid. The algorithm iteratively refines the cluster centroids to minimize the within-cluster sum of squares (WCSS), ensuring that data points within each cluster are as similar as possible. This clustering approach enabled us to group cities with similar development trajectories and compactness characteristics.

Building on this clustering foundation, we employed the XGBoost model to simulate and predict carbon emissions for cities within each of the four clusters. This model allowed us to capture nonlinear relationships between compact urban development indicators and carbon emissions, providing insights into how these relationships evolve over time.

4.3 Results

4.3.1 Impact of compact urban characteristics on urban carbon intensities

To evaluate the impact of compact urban characteristics on urban carbon intensities, traditional regression models were employed, including OLS, SLM, and SEM, as detailed in the previous section. Table 4.5 presents the performance metrics for these models across the years 2005, 2010, 2015, and 2020.

Table 4.5 Performance metrics for traditional regression models

Metric	Model type	2005	2010	2015	2020
R square	OLS	0.14	0.16	0.17	0.21
	SLM	0.30	0.30	0.26	0.46
	SEM	0.32	0.30	0.25	0.46
Obs		276	282	283	296

Notes: A higher R square value indicates a better fit of the model

The R^2 values indicate that SEM generally provides the best fit, particularly in the later years, suggesting spatial dependencies are significant in modelling urban carbon intensities.

Table 4.6 details the estimation results for the traditional regression models.

Table 4.6 Estimation results for traditional regression models

Variable	2005					
	OLS		SLM		SEM	
PD	-0.20	**	-0.24	***	-0.30	***
MLU	-9168.84	**	-8572.51	**	-9156.96	***
Ptuse	-0.06		0.00		0.16	
GDPpc	-638.12	**	-661.41	***	-680.34	***
IndStr	117.48	***	108.98	***	118.05	***
Gapc	-12.98		42.21		64.56	
Rapc	-159.06	***	-129.78	**	-143.06	**
Variable	2010					
	OLS		SLM		SEM	
PD	-0.39	***	-0.29	**	-0.18	
MLU	-2577.94		-1620.56		-1628.73	
Ptuse	0.48		-0.07		0.28	
GDPpc	-257.45	***	-224.79	***	-254.09	***
IndStr	81.05	***	74.01	***	79.99	***
Gapc	121.06	***	99.96	***	95.19	**
Rapc	-72.28	**	-52.89	*	-52.95	
Variable	2015					
	OLS		SLM		SEM	
PD	-0.33	**	-0.28	**	-0.27	*
MLU	-3326.14		-2265.87		-1565.81	
Ptuse	-0.65		-1.47		-1.71	
GDPpc	-138.28	**	-98.76	*	-78.79	
IndStr	42.50	***	42.16	***	46.78	***
Gapc	170.64	***	148.44	***	145.83	***
Rapc	-57.73	**	-55.63	***	-58.56	***
Variable	2020					
	OLS		SLM		SEM	
PD	-0.36	***	-0.27	***	-0.17	
MLU	-5646.65	***	-4756.10	***	-4337.23	***
Ptuse	16.55	***	7.01		5.62	
GDPpc	-237.04	***	-159.88	***	-154.67	***
IndStr	40.30	***	47.54	***	57.78	***
Gapc	43.92	**	27.60	*	23.25	
Rapc	22.93		10.61		2.00	

Notes: Significant at *0.10, **0.05 and *** 0.01 levels

The results in Table 4.5 reveal several key insights into the impact of compact urban characteristics on urban carbon intensities:

Population Density (PD): Population density consistently shows a negative relationship with carbon intensity across all models and years. For instance, in 2020, the coefficients for PD are -0.36 (OLS), -0.27 (SLM), and -0.17 (SEM), significant at the 0.01 level in some cases. This indicates that higher population density is associated with lower carbon intensity, suggesting that more densely populated cities tend to have lower carbon emissions per unit of GDP. The negative relationship is strongest in the OLS model, implying that densification might reduce carbon emissions through increased efficiency in resource use and transportation.

Land-Use Mix (MLU): The coefficient for land-use mix is significant and negative in several models, particularly in the SEM model for 2020, where it is -4337.23 and significant at the 0.01 level. This suggests that better land-use mix, which implies a higher degree of land-use diversity, contributes to lower carbon intensity. The impact of land-use mix appears to be more pronounced in later time periods, indicating an increasing recognition of its importance in urban planning.

Public Transport Usage (Ptuse): The coefficients for public transport usage are generally not significant in most models and years, with the exception of 2020 in the OLS model where it is positive (16.55) and significant at the 0.01 level. This suggests that the effect of public transport usage on carbon intensity is less clear and may depend on other contextual factors such as the quality and coverage of the public transport network.

For the control variables, GDP per Capita (GDPpc) shows a consistently negative relationship with carbon intensity, with significant coefficients across all models and years, indicating higher economic productivity per capita is associated with lower carbon intensity.

Industrial Structure (IndStr) shows positive and significant coefficients, suggesting cities with a higher proportion of industrial activities tend to have higher carbon intensities. Green Area per Capita (Gapc) and Road Area per Capita (Rapc) have mixed results, with coefficients varying across models and years, reflecting complex interactions with carbon emissions.

From the results, it was clarified that higher density and accessibility are generally negatively related to urban carbon intensities which validates hypothesis 4.1 and 4.2. And consistent with the results of previous chapter, the impact of public transport usage on carbon intensities is insignificant almost all models with positive coefficients, contrary to hypothesis 4.3.

While traditional regression models provide valuable insights, they may not fully capture the complex mechanisms through which certain compact urban development indicators affect urban carbon intensities. These models are limited in their ability to account for nonlinear interactions and dependencies among variables. Therefore, in the next section, we detail results from machine learning models, specifically XGBoost, to further explore the nonlinear relationships between compact urban characteristics and carbon emissions, providing a more comprehensive understanding of these dynamics.

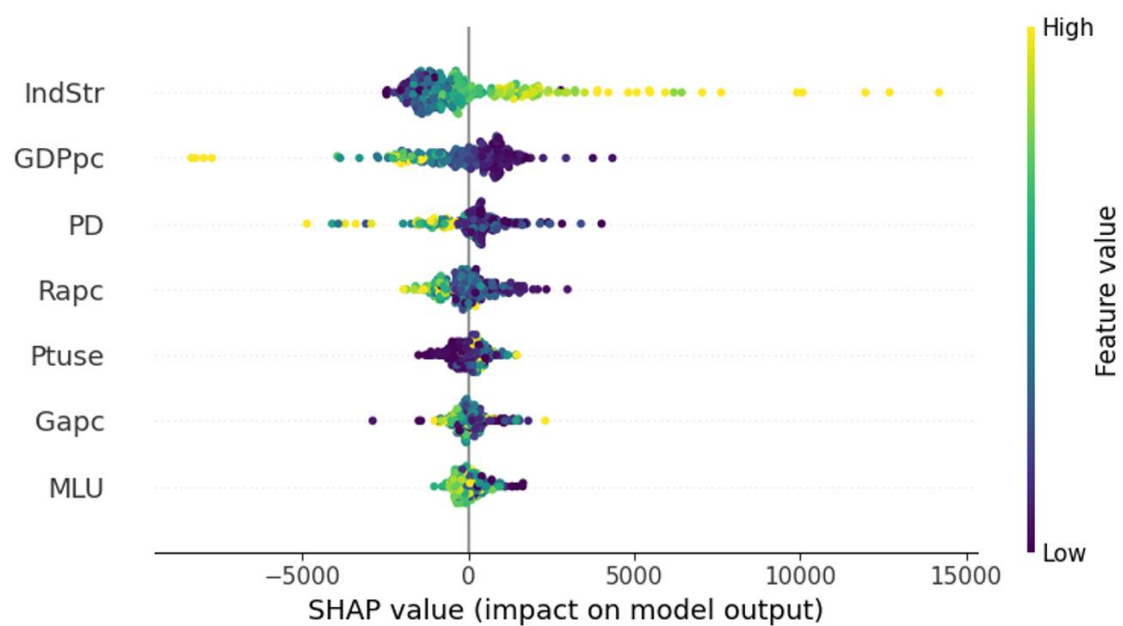
4.3.2 Nonlinear relations between compact urban characteristics and urban carbon intensities

4.3.2.1 Feature importance analysis

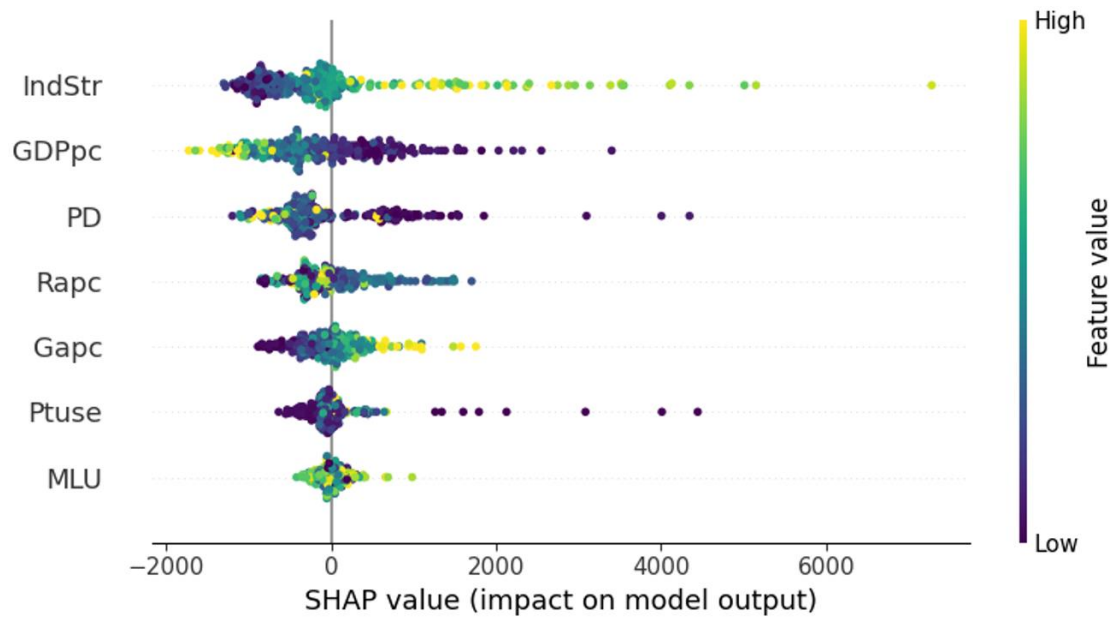
To delve deeper into the nonlinear relationships between compact urban

characteristics and carbon emissions, we employed the SHAP method to interpret the XGBoost model. SHAP values provide a unified measure of feature importance, helping to explain the contribution of each feature to the model's predictions. This method allows us to understand which compact urban development indicators have the most significant impact on urban carbon intensities.

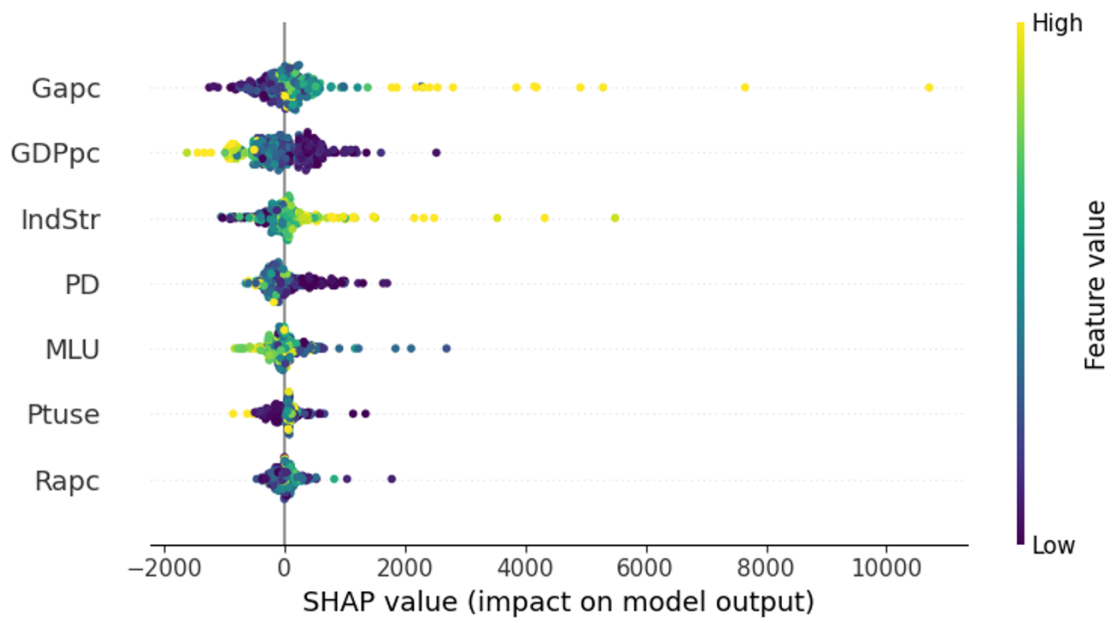
Figure 4.3 shows the feature importance plot of the model. The horizontal axis represents the SHAP value, which quantifies the impact of each feature on the model's output. Positive SHAP values indicate that the feature increases the predicted carbon intensity, while negative SHAP values indicate a reduction in carbon intensity. Each dot represents a data point, with colour gradients indicating the GDP per capita value from low (purple) to high (yellow). The vertical axis lists the features, ranked by their average importance across all data points.



2005



2010



2015

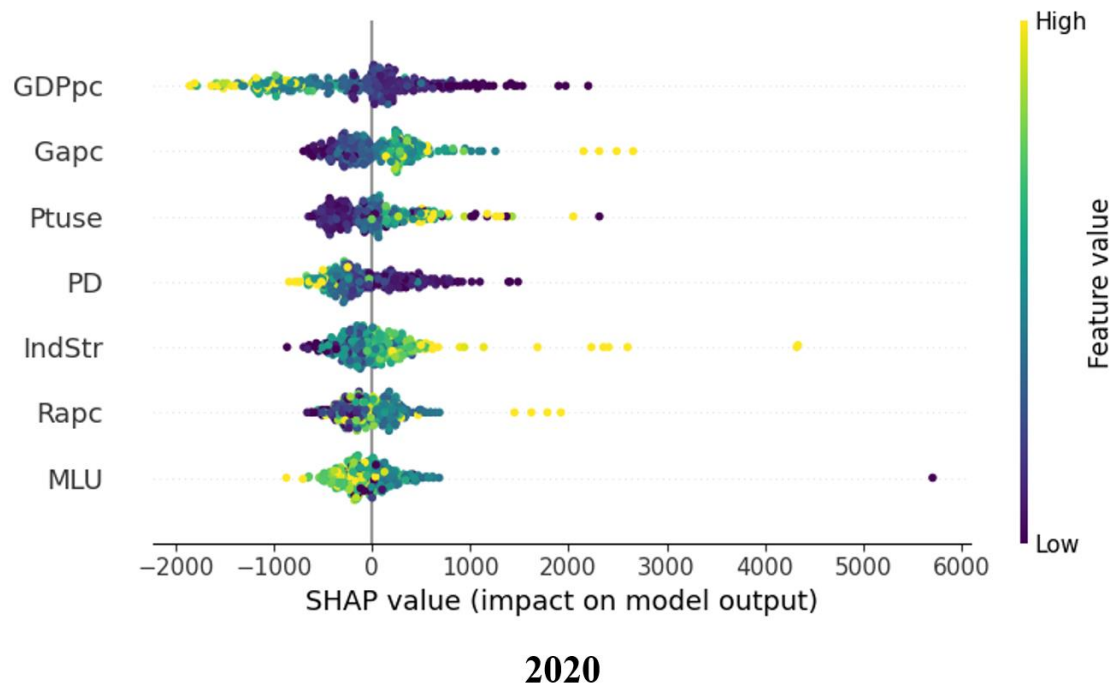


Figure 4.3 Importance of SHAP values regarding urban compact development indicators

The SHAP analysis reveals that the importance of various urban compact development indicators in predicting carbon intensity varies across the years. GDP per capita (GDPpc) is a significant factor throughout the years, with its importance increasing from 2005 to 2015. By 2020, GDP per capita becomes the most important factor, highlighting the growing influence of economic productivity on carbon intensity. Similarly, green area per capita (Gapc) shows moderate importance in 2010 but becomes the most critical factor in 2015, indicating a complex impact on carbon emissions. In 2020, it remains a significant factor, ranking second in importance and showing varied effects.

Public transport usage (Ptuse) initially had less importance in 2005 and 2010, but its significance increases markedly in 2015 and 2020. Population density (PD) is highly important with negative SHAP values in 2005 and 2010, suggesting that higher density

reduces carbon intensity. Although its importance slightly decreases in 2015 and 2020, it remains a significant factor.

Industrial structure (IndStr) consistently shows significant importance from 2005 to 2020, with mixed SHAP values indicating varied impacts on emissions. In contrast, land-use mix (MLU) and road area per capita (Rapc) are generally less important compared to other factors, with mixed SHAP values throughout the years.

Overall, the SHAP analysis indicates that GDP per capita and green area per capita have become increasingly important in recent years, while population density and public transport usage continue to play significant roles in reducing carbon emissions. These findings underscore the dynamic nature of urban development and the need for adaptive strategies in urban planning and policymaking to effectively mitigate carbon emissions. In the following section, summary plots and dependence plots are detailed to further explore and visualize the nonlinear relationships between these key urban characteristics and carbon emissions.

4.3.2.2 Nonlinear mechanism of key compact urban characteristics' impact on carbon intensities

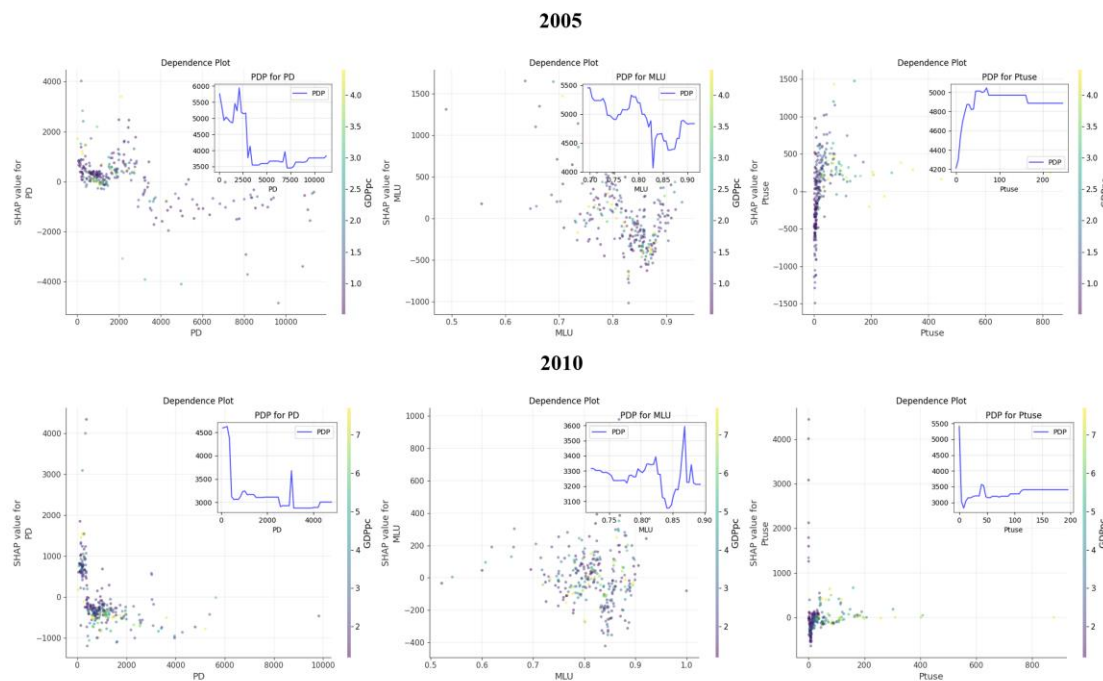
In this section, we explore the nonlinear relationships between compact urban characteristics and carbon emissions using summary plots and dependence plots.

Summary plots provide a comprehensive overview of the feature importance and their effects on the model's predictions. Each dot represents a data point, with the horizontal axis showing the SHAP value, which indicates the impact of the feature on the predicted

outcome. Positive SHAP values mean that the feature increases the predicted carbon intensity, while negative SHAP values indicate a reduction. The colour gradient of the dots represents the value of the feature, ranging from low (purple) to high (yellow).

Dependence plots show the relationship between a single feature and the predicted outcome, while accounting for the average effects of all other features. The horizontal axis represents the value of the feature, and the vertical axis represents the SHAP value. This plot helps to visualize how changes in the feature value influence the prediction, illustrating nonlinear effects.

The following analysis delves into the trends and insights from these plots for three key variables: population density (PD), mixed land-use (MLU), and public transport usage (Ptuse) across the years 2005, 2010, 2015, and 2020. Figure 4.4 presents the summary plots and dependence plots for the impact of these variables on urban carbon intensities.



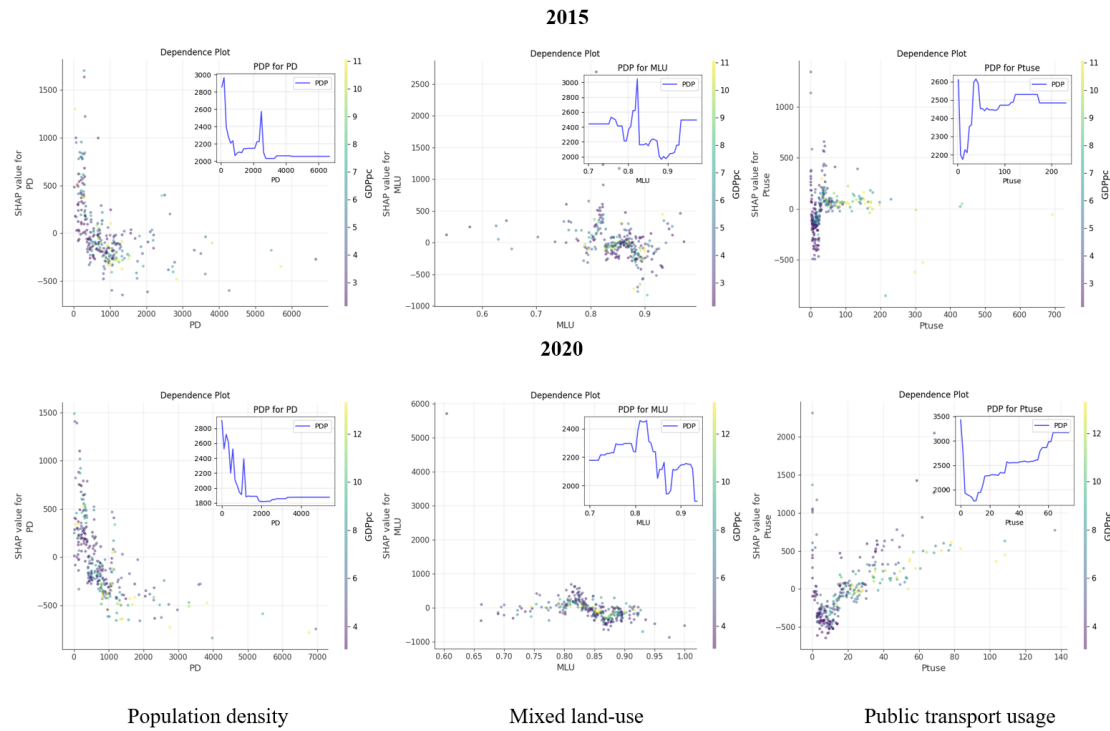


Figure 4.4 Partial dependence analysis of compact urban characteristics

Population Density (PD): The dependence plots for population density consistently show a nonlinear relationship with carbon intensity across all years. Higher population densities are generally associated with lower carbon intensities, particularly evident in 2005 and 2010. As density increases, the SHAP values decrease, indicating that densification effectively reduces carbon emissions. However, the marginal benefits of increased density diminish beyond certain thresholds, suggesting an optimal range for population density that maximizes carbon reduction benefits.

Mixed Land-Use (MLU): The relationship between mixed land-use and carbon intensity is more complex. In the early years (2005 and 2010), the SHAP values show significant variation, with a general trend indicating that moderate levels of land-use mix are beneficial for reducing carbon intensity. By 2015 and 2020, the plots reveal a clearer pattern where a balanced mix of land use significantly lowers carbon emissions. However, extremely high

or low levels of land-use mix do not provide additional benefits, indicating the importance of achieving an optimal balance in urban planning.

Public Transport Usage (Ptuse): Public transport usage also exhibits a nonlinear relationship with carbon intensity. In 2005 and 2010, the dependence plots show that increased public transport usage initially leads to a substantial decrease in carbon intensity, with the effect plateauing at higher usage levels. This trend continues in 2015 and 2020, where the initial increases in public transport usage significantly reduce carbon emissions, but further increases beyond a certain point offer diminishing returns. This highlights the critical role of public transport in mitigating emissions, while also suggesting that complementary measures may be necessary to sustain long-term reductions.

These findings underscore the importance of considering nonlinear effects in urban planning and policymaking. While population density, mixed land-use, and public transport usage are crucial for reducing carbon emissions, their impacts are not linear and require careful optimization. In the following section, these insights and their implications for urban sustainability strategies are further discussed via clustering and forecasting.

4.3.3 Cluster-based simulation and forecasting of city-level CO₂ emissions

4.3.3.1 Clustering results

As mentioned in the methodology section, we first classified Chinese prefecture-level cities based on their scale and development rates. Following previous literature, we selected six indicators: population density, urban area, GDP, and the growth rates of population

density, urban built-up area, and GDP (Wu & Zhang, 2024). Due to data availability, we ultimately classified 283 cities using the K-means clustering method. Table 4.7 presents the results of the clustering analysis.

Table 4.7 Results of K-means clustering

(a) Clustering centres

Cluster Centres	PD	Area	GDP	PD _r	CA _r	GDP _r	Amount
C1	508.32	116.92	1031.73	8.09	9.41	11.83	142
C2	303.51	102.31	988.63	2.92	7.26	12.93	118
C3	1028.06	759.33	10855.70	3.65	7.47	12.46	18
C4	366.00	113.00	1178.70	3.69	67.04	12.28	5

(b) Classification of clustering results

Clusters	Amount	Classification	Examples
C1	142	Moderately Developing City	Shijiazhuang, Xuzhou, Xiamen
C2	118	Slowly Developing City	Baoji, Anshan, Wulumuqi
C3	18	Mega City	Beijing, Shanghai, Nanjing
C4	5	Rapidly Developing City	Dongguan, Nantong, Huai'an

The clustering centres highlight distinct characteristics of each cluster. For instance, Cluster C1, representing moderately developing cities, has a population density (PD) of 508.32 and an average GDP of 1031.73 billion CNY. In contrast, Cluster C3, representing mega cities, exhibits significantly higher values, with a PD of 1028.06 and an average GDP of 10855.70 billion CNY. These differences underscore the varying levels of urban development and economic activity across the clusters, providing a nuanced understanding of the development patterns in Chinese cities.

The cities are then categorized into four groups: moderately developing cities, slowly developing cities, mega cities, and rapidly developing cities. Cluster C1 includes moderately developing cities such as Shijiazhuang, Xuzhou, and Xiamen. Cluster C2 comprises slowly

developing cities such as Baoji, Anshan, and Urumqi. Cluster C3 consists of mega cities including Beijing, Shanghai, and Nanjing. Cluster C4 encompasses rapidly developing cities such as Dongguan, Nantong, and Huai'an. Figure 4.5 shows the spatial distribution of our clustering results.

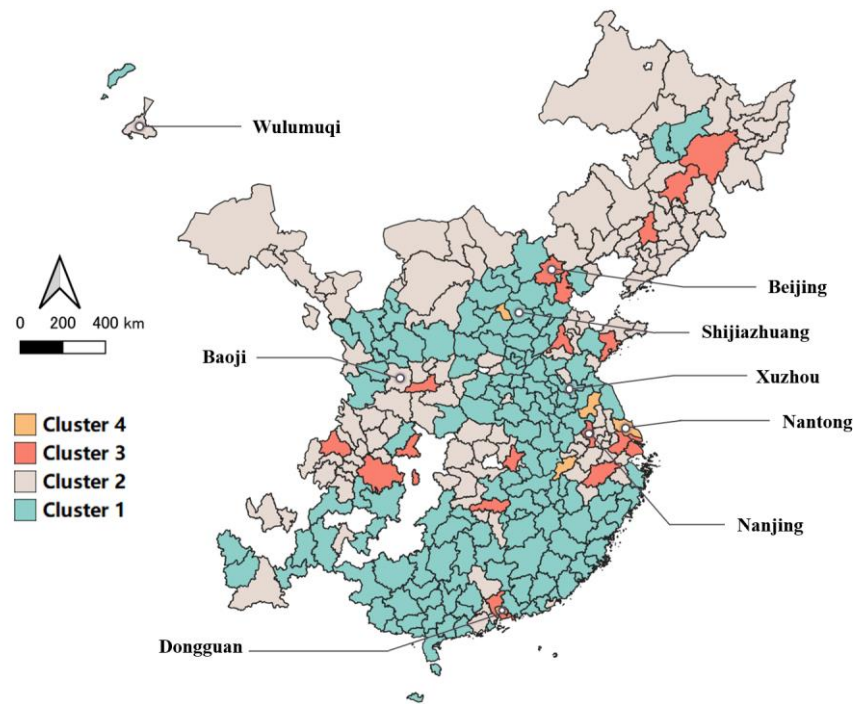
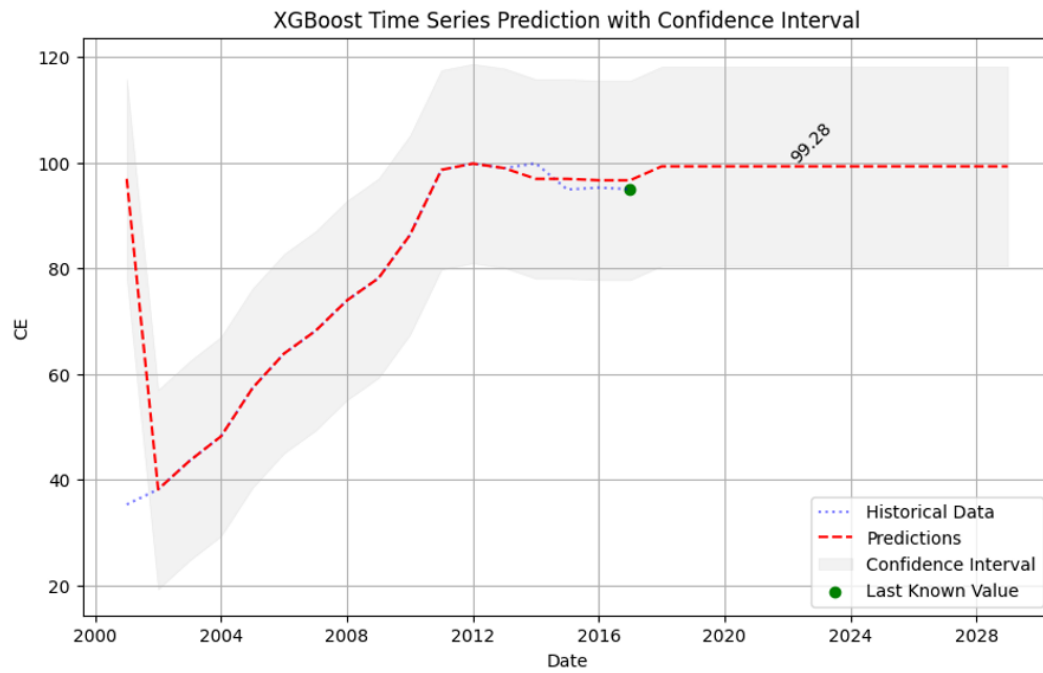


Figure 4.5 Spatial distribution of clustering results

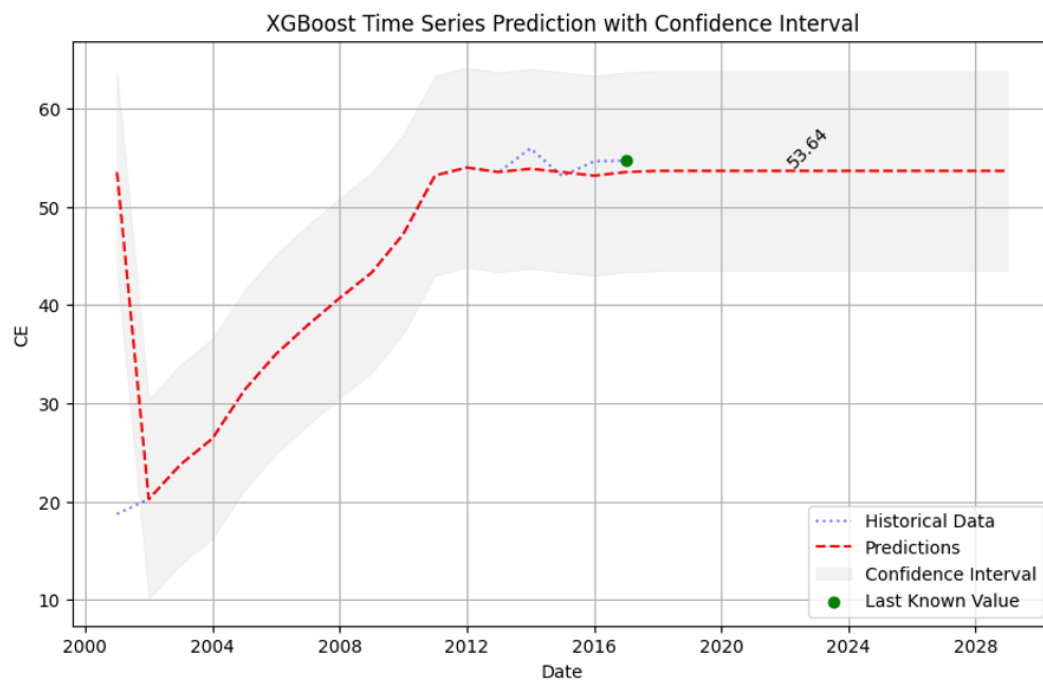
4.3.3.2 CO₂ emissions simulation and forecasting

In this section, we utilize the XGBoost model to simulate and forecast the changes in CO₂ emissions over time. Based on the clustering results, we selected two representative cities from each cluster to demonstrate trends. These eight cities were chosen for their diverse geographical locations, population, cultural backgrounds, and levels of economic development. Additionally, all these cities have implemented compact development policies or strategies (Baoji City natural resources and planning Bureau, 2021; China City

News, 2016, 2021; China State Council, 2017; Dongguan Natural Resources Bureau, 2020; H. Liu & Ji, 2022; Nantong Development & Reform Commission, 2021). Figure 4.6 presents the results of our simulation and forecasting.

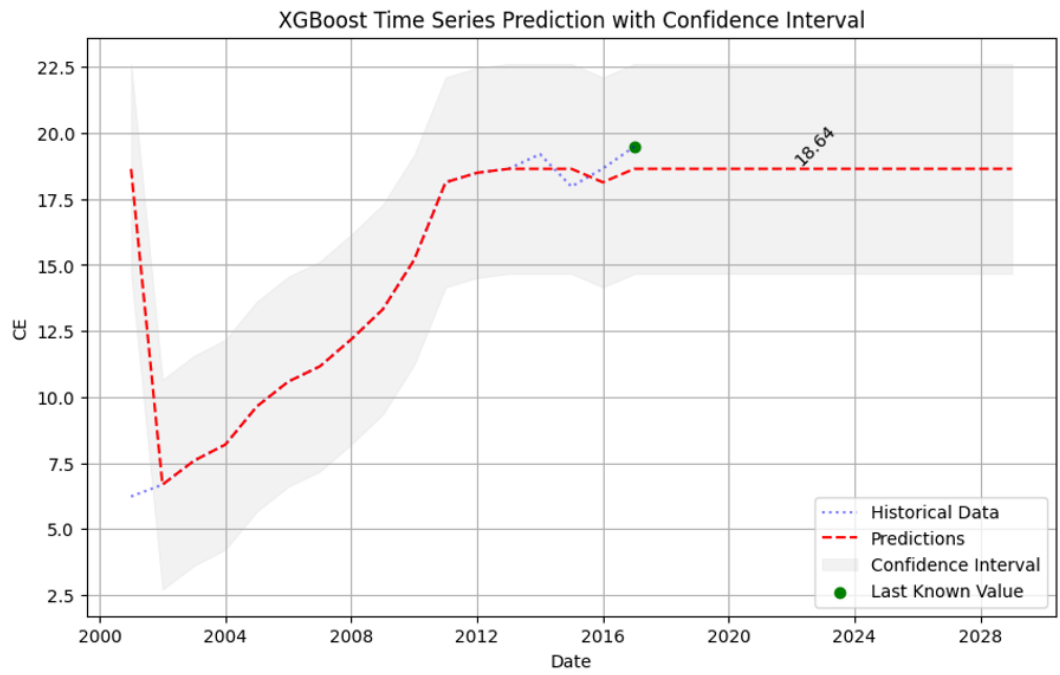


Shijiazhuang

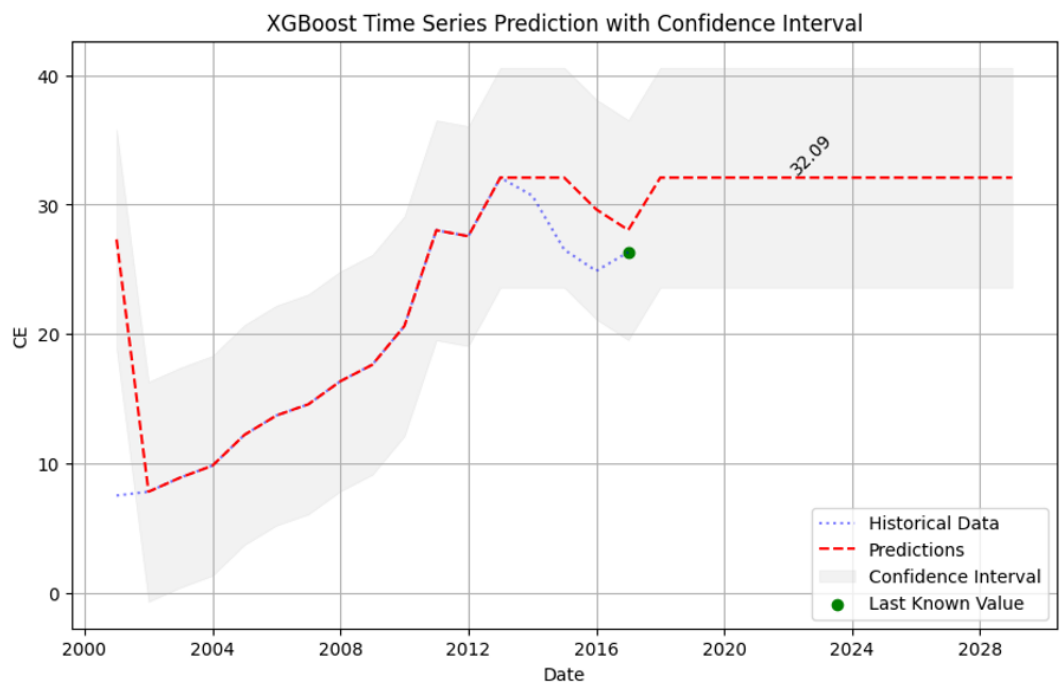


Xuzhou

C1

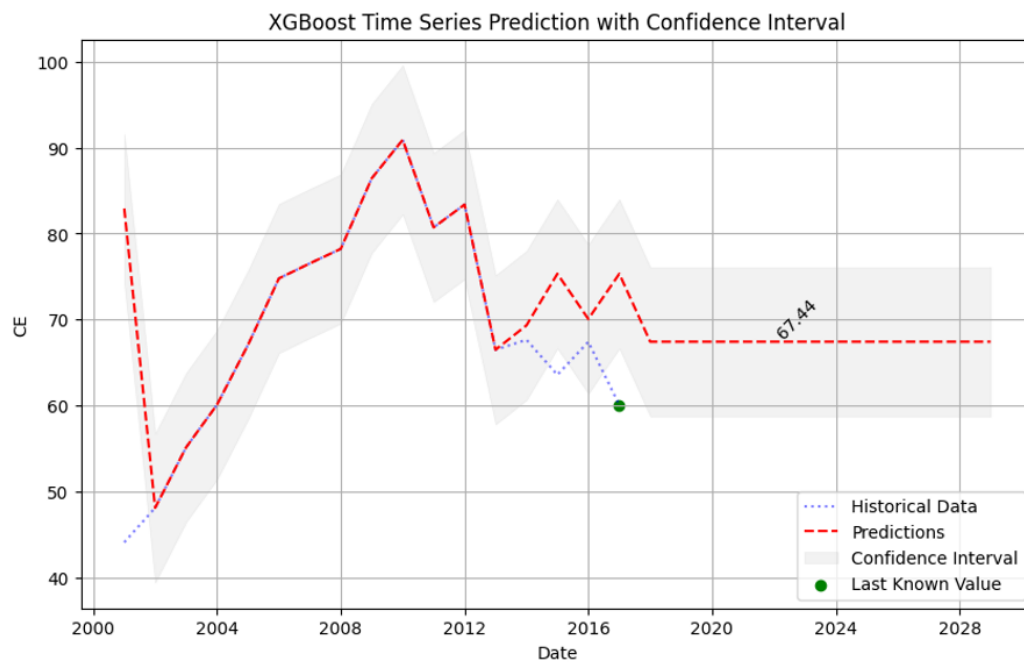


Baoji

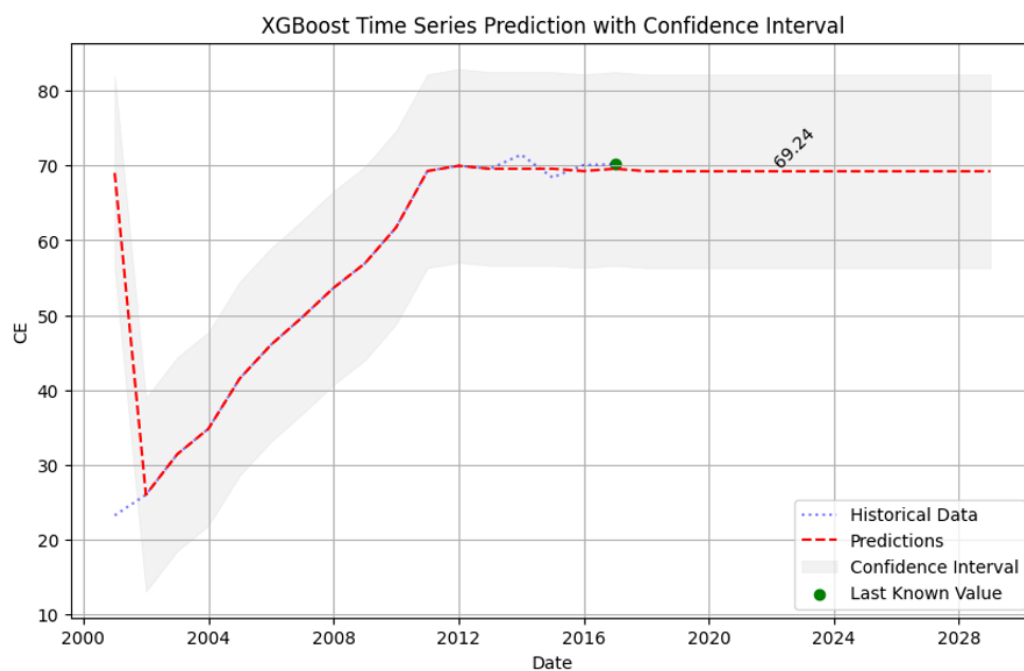


Wulumuqi

C2

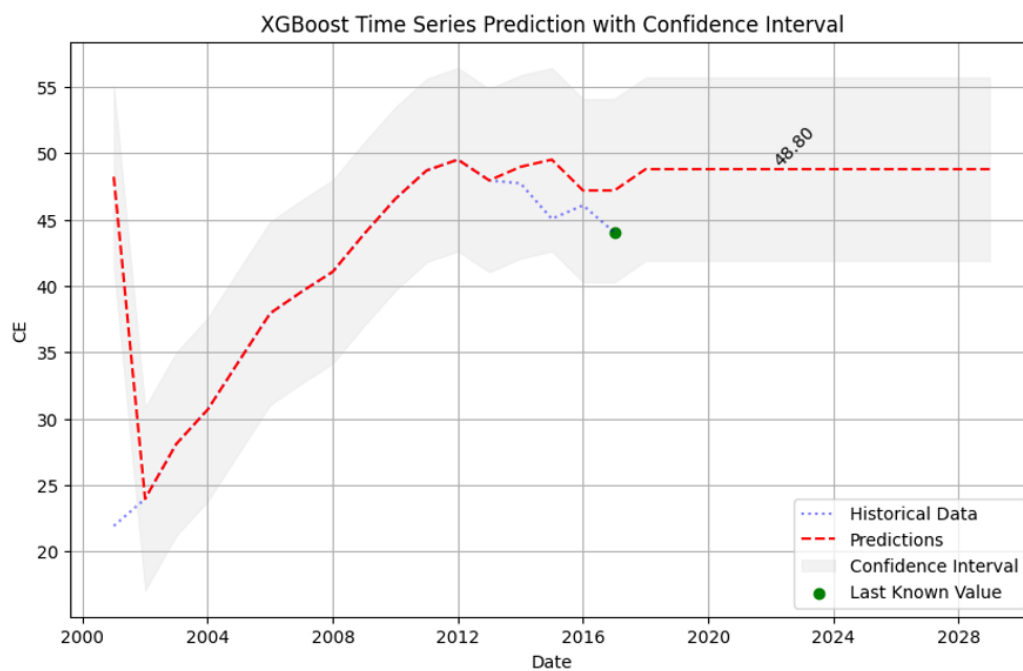


Beijing

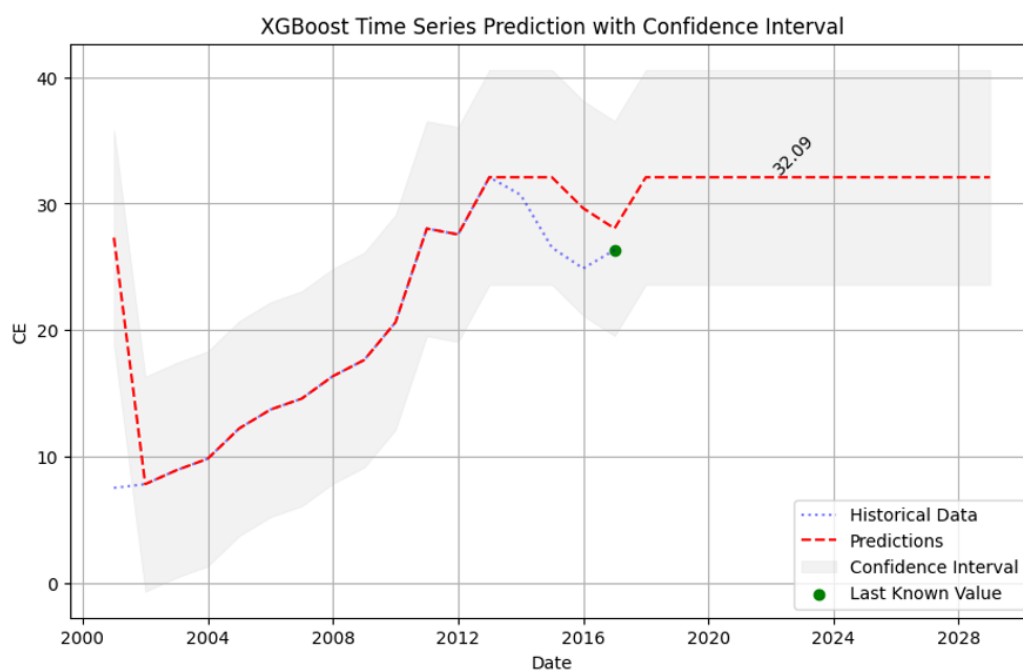


Nanjing

C3



Dongguan



Nantong

C4

Figure 4.6 CO₂ emissions simulation and forecasting based on results of clustering analysis

The simulation results reveal distinct trends in CO₂ emissions for the selected cities within each cluster:

Cluster C1 (Moderately Developing Cities): Shijiazhuang and Xuzhou show a steady increase in CO₂ emissions over the years. The XGBoost model predicts a gradual rise in emissions, reflecting balanced development with moderate economic and population growth. The emissions growth is consistent with the cities' expansion of industrial activities and urban infrastructure. For instance, Shijiazhuang's emissions are projected to increase from approximately 15 MtCO₂ in 2005 to around 30 MtCO₂ by 2025.

Cluster C2 (Slowly Developing Cities): Baoji and Wulumuqi exhibit the slowest increase in CO₂ emissions among the clusters. The model forecasts a relatively low emissions growth rate, indicating limited industrial and economic activities. Baoji, for example, shows an increase from about 10 MtCO₂ in 2005 to just under 20 MtCO₂ by 2025. These cities are characterized by slow urbanization and stable population growth, resulting in a more controlled increase in emissions.

Cluster C3 (Mega Cities): Beijing and Shanghai experience the most significant rise in CO₂ emissions. This increase is attributed to their large populations and extensive economic activities. The model predicts substantial energy consumption and industrial output. For example, Beijing's emissions are forecasted to rise from approximately 70 MtCO₂ in 2005 to nearly 150 MtCO₂ by 2025. The high emissions growth rate in these cities underscores the challenges of managing sustainability in rapidly developing urban centres.

Cluster C4 (Rapidly Developing Cities): Dongguan and Nantong show a notable increase in CO₂ emissions, though not as high as mega cities. These rapidly developing cities are

undergoing fast urbanization and industrialization, leading to increased energy demands and emissions. The model forecasts Dongguan's emissions to rise from around 25 MtCO₂ in 2005 to about 50 MtCO₂ by 2025. The emissions growth in these cities highlights the challenges of managing sustainability in the face of rapid development.

The model's simulation results provide valuable insights into the distinct emissions trends and highlight the need for tailored strategies for CO₂ emissions reduction in different types of cities. While mega cities and rapidly developing cities face significant challenges due to their high growth rates, moderately and slowly developing cities have opportunities to implement sustainable practices more gradually. The XGBoost model's ability to capture these nuances and project future emissions trends underscores its utility in urban sustainability planning.

4.4 Discussion

In summary, this study's analysis revealed that compact urban characteristics significantly impact urban carbon intensities, with population density, land-use mix, and public transport usage playing critical roles. The XGBoost model and SHAP analysis further uncover nonlinear relationships, emphasizing the complexity of urban sustainability dynamics. The cluster-based simulation highlights varying emissions trends across different types of cities, suggesting the need for tailored strategies to effectively mitigate CO₂ emissions.

In this discussion, we delve deeper into these findings, exploring their implications for

urban planning and policymaking to enhance sustainable development in diverse urban contexts.

4.4.1 Optimal and sustainable density

Our findings indicate that population density and mixed land-use have significant negative impacts on carbon intensities, consistent with previous studies (Suzuki et al., 2015; Yigitcanlar & Kamruzzaman, 2018). However, our machine learning model results provide deeper insights into these relationships.

Firstly, for population density, the nonlinear results reveal that urban carbon intensity decreases with increasing population density up to approximately 2000 to 2500 people per square kilometre. Beyond this threshold, the carbon intensity ceases to decrease significantly and may even slightly increase as density continues to rise. This suggests the existence of an optimal density for emission reduction, a concept supported by previous research (Shen et al., 2022). In the early stages of urbanization, increased population density brings numerous benefits such as economies of scale (Cervero & Kockelman, 1997), more efficient resource utilization (P. Newman & Kenworthy, 2013), and lower living costs (Zhou et al., 2021). However, when density surpasses a certain level, issues such as traffic congestions (Randal, 2009), air pollution (Mayer, 1999), high housing prices (Glaeser et al., 2005), and overconsumption of living and public resources emerge (Boyko & Cooper, 2011). Policymakers have recognized these challenges in sustainable urban planning. For instance, the London Plan emphasizes the goal of achieving 'sustainable density', to ensure affordable accommodation and life quality for a smart increase (Mayor of London, 2021). In mega

cities like London, Beijing, and Melbourne, which do not face the threat of population decline, managing density effectively should be a top priority.

Secondly, regarding land-use mix, our nonlinear results indicate an optimal range between 0.8 and 0.9 for achieving the lowest carbon intensity. The land-use mix in this study is calculated based on nine categories of urban land use (residential, public administration, commercial services, industrial, logistics and warehousing, roads and transportation, public utilities, green spaces, and special use areas), using spatial entropy methods with values ranging from 0 to 1. Higher entropy values indicate a greater degree of land-use mix. The theory of compact cities emphasizes that mixed land use is a crucial component of compact development, bringing various benefits. One of the primary benefits of a higher land-use mix is the reduction in travel distances for residents, as diverse land uses are located closer to each other (Ewing & Cervero, 2010). This proximity can lead to a decrease in vehicle miles travelled (VMT), thereby reducing emissions from the transportation sector (Fu et al., 2024). Additionally, mixed-use developments can enhance the vibrancy and economic resilience of urban areas, creating more opportunities for walking and cycling, which further contribute to emission reductions (Li et al., 2022). By integrating residential, commercial, and recreational spaces, mixed-use areas can foster a more dynamic and sustainable urban environment (Frank et al., 2003). However, high levels of land-use mix can also bring about certain challenges. For instance, conflicts between different functional areas can arise, such as noise from commercial activities disturbing the tranquillity of residential neighbourhoods. Implementing effective mixed land-use strategies requires intricate planning and policy support, necessitating coordination among multiple

stakeholders. Ensuring an optimal range of land-use mix might be more complex than controlling population density, but the environmental, social, and economic benefits it offers make it a worthwhile endeavour for urban planners to pursue.

4.4.2 Public transportation and energy transition

Despite the initial emphasis of compact city theory on reducing travel demand through dense urban spaces and resource layouts that promote the use of public transportation over private car usage, our empirical results indicate otherwise. Our findings show that there is no significant relationship between the frequency of bus usage per capita and carbon intensity; in fact, the coefficient is positive. Furthermore, the nonlinear relationships uncovered by our machine learning model suggest that increased bus usage often correlates with higher carbon intensity. This observation is also supported by previous empirical studies (Fan & Chapman, 2024).

This leads us to reconsider the nature of bus usage. In a rapidly developing country like China, which has experienced significant economic growth over the past two decades, public transportation often does not provide a pleasant experience. Specifically, public buses are frequently overcrowded, unreliable, and lack adequate facilities for the elderly and disabled patrons (CHINANEWS, 2020). This is particularly evident when compared to highly developed countries like Japan, which also advocate for compact urban development. The vast urban areas, high population densities, and poorly serviced public transportation systems in Chinese cities do not naturally encourage bus ridership. Instead, people often resort to public transportation out of necessity—due to financial constraints, time

limitations, or severe traffic congestion that makes driving impractical. In megacities like Nanjing, which spans 6,596 square kilometres with multiple urban centres, intra-center travel might involve buses, shared bicycles, or walking. However, for inter-centre travel, private cars are often preferred for their superior convenience and comfort (W. Zhang & He, 2014). Economic growth, rising incomes, improved living standards, or even the rapid expansion of membership-based warehouse clubs in China have all contributed to the increase in private car usage (Lim et al., 2021; Paulley et al., 2006).

For cities in developing countries where the population continues to grow, merely advocating for or increasing the use of public transportation does not effectively reduce carbon emissions in the transportation sector. As long as travel demand continues to rise, alternative approaches must be explored to combat climate change. One such approach, due to its significant impact on climate goals and relative feasibility, is the promotion of new energy vehicles (NEVs) (Yuan et al., 2015). Studies on the deployment of NEVs, such as electric vehicles (EVs) and fuel cell electric vehicles (FCEVs), in both private and public transportation have consistently highlighted the critical role of the energy transition in reducing carbon emissions in the transportation sector (M. Zhao et al., 2021).

As compact cities emphasize density and accessibility, transportation planning should integrate energy transition strategies. This includes the coordinated development of charging and hydrogen refuelling stations alongside bus route planning to support the widespread adoption of NEVs.

4.4.3 What comes after the carbon peak?

In 2020, China announced its ambitious "dual carbon" goals, aiming to peak carbon emissions before 2030 and achieve carbon neutrality by 2060. This strategic decision is set to drive a comprehensive green transformation of China's economic and social development, while also contributing significantly to global climate change mitigation efforts.

Using machine learning models, our study predicted and simulated trends in carbon emissions over time for city clusters in China with varying levels of economic and spatial development, based on compactness indicators and control variables. We found that under the compact development strategy, the growth of carbon emissions in many Chinese cities has already slowed and even shows signs of decline. This finding aligns with the *2021-2022 Chinese Cities Carbon Peak & Carbon Neutrality Index Report*, which shows that from 2016 to 2020, the average annual growth rate of carbon emissions in 110 cities was 0.58%, with 48 cities experiencing a downward trend in emissions, averaging an annual reduction of about 5% (Chinese Academy of Environmental Sciences, 2023).

Furthermore, studies have shown that 43% of cities exhibit a strong decoupling between carbon emissions and economic growth, and 31% show a weak decoupling (C. Gao et al., 2021). This indicates that the relationship between economic growth patterns and carbon emissions in a number of cities is changing, with improving development quality. This group includes economically developed first- and second-tier cities such as Shanghai, Shenzhen, Wuhan, and Zhengzhou, as well as several industrial and resource-based cities like Zibo, Sanmenxia, Panjin, Yulin, and Yan'an (Chinese Academy of Environmental Sciences, 2023).

The presence of decoupling underscores the importance of emission reduction measures beyond industrial structure upgrades and energy structure optimization. The urban spatial structure optimization brought about by compact development, the optimal density and accessibility discussed in the previous sections, and the greening of the transportation sector further highlight the advantages of compact development strategies in reducing carbon emissions.

As cities progress towards their carbon peaks and beyond, these findings suggest that a nuanced approach is necessary. Urban planners and policymakers should consider integrating advanced technologies, promoting clean energy, and enhancing public transportation infrastructure to sustain the momentum of emission reductions. Tailored strategies that reflect the unique characteristics and developmental stages of different city clusters will be crucial in achieving sustainable urban development and contributing to global climate goals.

4.5 Conclusions

This study sought to identify the nonlinear impacts of compact city characteristics on urban carbon intensity. Key factors considered include population density, mixed land use, and public transportation.

First, we identified that these relationships are nonlinear in nature and that urban sustainability dynamics are complex. For example, higher population density and varied land use appear beneficial to a point, but may reach a point of diminishing returns or even

negative impacts if taken too far. Optimal points for both population density (2000 to 2500 people per square km) and land use (entropy values between 0.8 and 0.9) were identified in terms of carbon intensity reduction, however the existence of public transport in a city alone did not necessarily engender carbon emission intensity reduction. In order to improve public transportation outcomes, the energy transition needs to be progressed and NEVs integrated as a priority.

Due to the implementation of compact development strategies, the growth of carbon emissions in many Chinese cities is slowing or declining. Decoupling economic growth from carbon emissions is becoming more common, especially in economically developed and industrial cities. Based on this studies' findings, policymakers should adopt tailored strategies reflecting the unique characteristics and developmental stages of different city clusters in order to derive optimal carbon reduction strategies.

Chapter 5. Conclusions and future work

5.1 Main findings

This thesis has explored the impacts of compact city characteristics on urban carbon emissions through a comprehensive analysis that integrates theoretical frameworks, empirical data, and advanced modelling techniques. The research is structured across several chapters, each contributing to a deeper understanding of how compact city policies and characteristics influence carbon emissions.

In Chapter 1, the research background is introduced and a literature review on the definition, development, and environmental impacts of compact cities is provided. Significant academic gaps were identified, particularly in the empirical evidence linking compact city characteristics to carbon emissions.

Chapter 2 focused on the policy dimensions of compact cities, examining international precedents and case studies to understand how different cities have adopted and implemented compact city strategies. Varying emphases of these policies based on the specific needs and developmental stages of different urban areas are highlighted.

Chapter 3 presented an empirical investigation using data from 340 prefecture-level cities in China. By employing OLS and MGWR models, we examined the linear relationships between compact city characteristics (density, accessibility, and public transport) and urban carbon emissions. This chapter underscored the significance of these characteristics in influencing carbon intensity and revealed spatial heterogeneity in their impacts.

In Chapter 4, the nonlinear relationships between compact city characteristics and carbon emissions were delved into using advanced machine learning techniques, specifically the XGBoost algorithm. The SHAP method was used to interpret the results, providing a nuanced understanding of the complex interactions between various features and their effects on carbon emissions. This chapter also included clustering analysis to simulate and forecast carbon emission trends for different types of cities.

Building on these detailed analyses, the main findings of this study are summarized as follows:

(1) Different Emphases in Compact City Policies Across Various City Types:

Compact city policies vary significantly based on the specific characteristics and developmental stages of different cities. In cities with low urban growth, policies often focus on countering population decline and managing aging populations by revitalizing urban centres and enhancing land-use efficiency. Conversely, rapidly growing megacities prioritize managing increased population density and mitigating urban sprawl through strategic densification and the development of efficient public transportation systems. These differing emphases highlight the necessity of tailoring compact city strategies to the unique needs and challenges of each urban context.

(2) Significant Impact of Compact City Characteristics on Urban Carbon Emissions with Spatial Heterogeneity:

The analysis revealed that compact city characteristics, such as population density, land-

use mix, and public transportation usage, significantly influence urban carbon emissions. However, the impact of these characteristics exhibits spatial heterogeneity, meaning that the effects vary across different regions and urban contexts. This spatial variability underscores the importance of considering local geographic, economic, and social factors when designing and implementing compact city policies to ensure their effectiveness in reducing carbon emissions.

(3) Density and Accessibility as Effective Measures for Curbing Carbon Emission Growth Within Optimal Ranges:

Higher population density and improved accessibility are found to effectively curb the growth of carbon emissions, but these benefits are most pronounced within specific optimal ranges. The study identifies that a population density of approximately 2000 to 2500 people per square kilometre and a balanced land-use mix (entropy values between 0.8 and 0.9) are associated with the lowest carbon intensity. Beyond these thresholds, the marginal benefits of increased density and accessibility diminish, and in some cases, can even lead to adverse effects. This finding suggests that urban planners should aim to achieve and maintain these optimal levels to maximize the environmental benefits of compact city development.

(4) Integration of Public Transportation and Energy Transition in Compact City Policies:

While compact city policies traditionally emphasize spatial compactness, this study highlights the critical importance of integrating public transportation with energy

transition efforts. The empirical results indicate that simply increasing public transportation usage does not necessarily reduce carbon emissions unless it is accompanied by a transition to cleaner energy sources. The promotion of new energy vehicles (NEVs), such as electric and hydrogen-powered buses, alongside the development of supporting infrastructure like charging and refuelling stations, is essential for achieving significant carbon reductions in the transportation sector. This integrated approach ensures that compact city policies contribute holistically to urban sustainability and carbon neutrality goals.

These main findings provide a comprehensive understanding of the complex interactions between compact urban development and carbon emissions. They offer valuable insights for policymakers and urban planners seeking to design effective strategies for sustainable urban development. Future research should continue to explore these dynamics, considering additional variables and employing advanced analytical methods to further refine our understanding of the optimal conditions for compact city success.

5.2 Limitations and future perspectives

While this study provides valuable insights into the relationship between compact urban development and carbon emissions, several limitations need to be acknowledged. These limitations also suggest potential directions for future research.

First, this study focused on the compactness of entire urban areas. However, compact

city theory does not necessarily imply a monocentric city structure; polycentric compact development is also significant. Future research should explore how compact development strategies can be effectively designed for polycentric large cities. Investigating the optimal spatial organization of multiple urban centers could provide deeper insights into how these configurations can contribute to carbon emission reductions. Understanding the dynamics of polycentric urban forms can help policymakers design more efficient and sustainable urban layouts that leverage the benefits of multiple interconnected centers.

Secondly, the data used in this study is current only up to 2020. However, significant socio-economic changes have occurred in China since the COVID-19 pandemic, including the explosive growth of NEVs which has notably impacted the transportation sector. Future research should incorporate more recent data as it becomes available, to capture these developments and their effects on urban carbon emissions. By analyzing data from the past few years, researchers can gain updated insights into the evolving relationship between urban compactness, transportation dynamics, and carbon emissions in the post-COVID era. This approach will ensure that the findings remain relevant and reflect the latest trends and innovations in urban development.

Finally, this study uses mainland China as the target research area in the empirical chapters. The results may differ significantly for developed countries with aging populations and different urban dynamics. Studies conducted on a global scale could provide a more comprehensive understanding of the relationships examined. Future research should consider expanding the study area to include a broader range of regions and cities worldwide. This broader scope would help validate and extend the findings

presented here, offering a more diverse perspective on the impact of compact city characteristics on carbon emissions.

By addressing these limitations, future research can build on the foundations laid by this study and contribute to a more nuanced and comprehensive understanding of how compact urban development strategies can effectively reduce carbon emissions and promote sustainable urban growth.

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