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Exploring Urban Compactness and Greenhouse Gas Emissions in the Road Transport Sector: A Case Study of Big Cities in South Korea

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Abstract: This study examined the relationship between urban compactness and greenhouse gas (GHG) emissions in the road transport sector in South Korea, focusing on 84 cities, particularly 27 metropolitan areas with populations of approximately 500,000. We developed an urban compactness index (UCI) using Moran's I, entropy, and the Gini coefficient, integrating city size into the analysis. Cities were categorized into five groups based on their size to analyze GHG emissions and regional variations in compactness comparatively. Our results revealed a significant inverse relationship between UCI and per capita road transport GHG emissions, which was more pronounced in larger cities. Specifically, cities with a population over 1 million displayed reduced per capita road transport GHG emissions in compact urban structures. In conclusion, these findings suggest that larger cities can effectively reduce per capita road transport GHG emissions through urban planning for compact development. Additionally, planners need to consider city size when analyzing the UCI and formulating urban planning strategies aimed at achieving carbon neutrality.

Keywords: carbon neutrality; greenhouse gas emissions; urban compactness index; city size; polycentricity; Korean cities

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1. Introduction

Home to over half the world's population, cities are at the forefront of climate change challenges and solutions. Although cities are significant contributors to greenhouse gas (GHG) emissions, they also play a crucial role in climate change mitigation and efforts toward carbon neutrality [1–6]. A key factor in this urban dynamic is the concept of urban compactness, which influences energy consumption patterns and, consequently, GHG emissions. However, the relationship between urban compactness and GHG emissions remains a subject of debate in current research.

Previous studies have suggested that higher urban compactness, characterized by denser populations and more efficient land use, correlates with lower per capita GHG emissions [7–16]. This is often attributed to reduced vehicle usage in densely populated urban areas, where proximity to public facilities and efficient public transport systems diminish reliance on personal vehicles [17–19].

Contrastingly, some studies found no significant link between urban compactness and GHG emissions, with others arguing that more compact urban forms may increase GHG emissions [14,20,21]. These studies have suggested that factors including city size, policy measures such as fuel taxes, and advanced road transport infrastructure might be more effective in reducing energy use and GHG emissions. Furthermore, several studies have indicated that at the same level of compactness, polycentric cities emit less GHGs than monocentric ones [22–25].

Urban compactness is used to measure urban form and spatial structure, which are concepts that are simultaneously similar and different [12,25–27]. Moreover, urban compactness quantifies population distribution. Other indicators not reliant on population figures, including average floor area ratio, building floor area, and block size, indirectly capture the compactness of the built environment. Nevertheless, the more concentrated the population's spatial distribution, the denser the built environment, and the stronger the correlations among compactness indicators [28]. Thus, urban compactness measures how people cluster within a city and whether the built environment permits economies of scale.

The concept of urban compactness is interpreted differently in various studies, depending on their approach. First, the concept of compact cities, emerging from the urban planning paradigms of new urbanism and smart growth, extends beyond high population densities or floor area ratios [29]. It encompasses compact development patterns, and a city is only considered compact if it fulfills certain requirements, including mixed land use, transit-oriented development (TOD), access to urban services, and street connectivity. Decision-makers can provide incentives to reduce pollution and improve walkability by mixing uses and TOD [30]. This divergence in perspective is exemplified in the contrasting viewpoints of Gordon and Richardson [21] and Ewing [8], who criticized monocentric compact development. Gordon and Richardson [21] critiqued the compact development pattern by focusing on total population density and floor area ratio within a single urban space. In contrast, Ewing [8] contended that a metropolitan area exhibits a compact development pattern if it comprises multiple nuclei rather than a single nucleus, with each nucleus exhibiting autonomy. Furthermore, Ewing [8] argued that addressing overcrowding by organizing spatial structures into compact development patterns with multiple nuclei, rather than allowing cities to expand based on free-market economy principles, is more pragmatic.

Various studies have adopted distinct criteria for constructing urban compactness indicators, leading to differing interpretations of the connection between GHG emissions and urban compactness. For instance, Kang [25] assessed urban compactness by focusing on indicators related to population distribution, including Moran's I, entropy, and the Gini coefficient. In addition, Ha [12] evaluated urban compactness by considering factors such as development density and street connectivity, which are congruent with Ewing's research [27,28]. However, Ha [12] introduced an urban compactness index (UCI) that standardized and combined these individual variables, making it challenging to pinpoint the specific variables that notably impacted GHG emission reduction. In addition to population, various socio-economic variables of a city, such as per capita vehicle registration, proportion of industrial areas, arterial road ratio, and elderly populations, can influence GHG emissions [31–33]. However, identifying the various components of a city for GHG reduction is not the objective of this study.

This study aimed to clarify the relationship between urban compactness and GHG emissions, considering the nuances and varying interpretations of urban compactness in the existing literature. In addition, the diversity in study scopes, units of analysis, and methodologies employed in previous research were acknowledged. Particular emphasis was placed on the often-overlooked aspect of city size, i.e., population, and its impact on GHG emissions. The distinctiveness of this study lies in proposing a new direction that considers city size in the methods used to determine the UCI, which has been indiscriminately used. UCI components, including Moran's I, entropy, and the Gini coefficient with GHG emissions, were compared, with a specific focus on population distribution, while variables related to the built environment, including access to urban services and street connectivity, were excluded. If demographic indicators do not demonstrate a significant correlation with GHG emissions, it raises questions about the relevance of built environment indicators, which exclude population, in understanding the link between urban compactness and GHG emissions. Ultimately, this study contributes to the ongoing discourse by providing a nuanced understanding of the relationship between urban compactness and GHG emissions, considering different city sizes and contexts. The findings aim to inform urban planning and policy decisions, supporting efforts to mitigate climate change through smarter urban development strategies.

2. Materials and Methods

2.1. Study Location and Emissions Data

The analysis focused on metropolitan areas in South Korea with populations of 500,000 or more. The study's temporal scope covers a single year—2019—encompassing population and road transport emissions data. In 2022, South Korea amended its Local Government Act, designating cities with a population of 500,000 or more as metropolitan areas. By 2023, 27 cities, including those that had already been designated, had earned this recognition. Considering that GHG emission calculations vary by country, this study was limited to Korean cities, preventing cross-country comparisons.

This study primarily focused on observing GHG emissions per capita according to city size to establish a clearer relationship between compactness and GHG emissions. Planners should consider upgrading the thermal efficiency of buildings to reduce both the cost of energy use in residential and commercial sectors and GHG emissions from the construction sector [34]. While residential energy use shows significant variability between temperate and cold climates [35], its correlation with urban compactness is not as strong as with energy use in the road transport sector [17,25,36,37]. Therefore, this study focused its analysis on GHG emissions from the road transport sector. A higher population often correlates with increased energy consumption and, consequently, greater GHG emissions.

This study directly constructed data on per capita GHG emissions in the road transport sector, referencing the guidelines of the Intergovernmental Panel on Climate Change (IPCC). The correlation between urban sprawl, compactness, and gasoline consumption has been extensively explored in prior research [7,8,21,27,28]. This study focused on road transport GHG emissions to investigate the direct association between urban compactness and GHG emissions. These road transport GHG emissions were calculated at the Tier 2 level using conversion Equation (1).

$$E_{i,j} = Q_{i,j,k,l} \times EC_i \times EF_{i,j,k,l} \times 10^{-6} \quad (1)$$

where $E_{i,j}$ represents GHG emissions (j) from the combustion of fuel (i) [in tCO_2eq.]; $Q_{i,j,k,l}$ represents fuel (i) usage according to vehicle type (k) and control technology (l) [in KL]; EC_i represents the calorific value (net calorific value) coefficient of fuel [in MJ/L]; $E_{i,j,k,l}$ is the emission factor of GHG (j) according to fuel (i), vehicle type (k), and control technology (l) [in $kgCO_2$eq./TJ].

GHG emissions in the road transport sector can be calculated differently depending on the level of data granularity, ranging from Tier 1 to Tier 3. Tier 1 estimates emissions based on average emission factors for each fuel type and fuel consumption, and currently, South Korea's GHG emissions statistics are provided at the Tier 1 level. Tier 2 is more detailed, with vehicle and fuel types being further subdivided. Furthermore, emissions are estimated based on the number of vehicles and annual mileage. Tier 3 involves activity data-based analysis, estimating emissions based on detailed emission factors and vehicle mileage, but it includes challenging variables to derive, such as annual vehicle usage time. Owing to limitations in data acquisition, this study constructed and used GHG emissions data for the road transport sector at the Tier 2 level. To address this, the Ministry of Land, Infrastructure and Transport (MLIT) recently developed a Carbon Spatial Map based on these data [38,39].

2.2. Determination of UCIs

Moran's I, entropy index, and Gini coefficient are UCIs based on population distribution and were computed for each city. The unit of analysis for these calculations was a grid cell measuring 500 m × 500 m. The equations for each indicator have been published by Tsai and Lai et al. [26,40] and are as follows:

$$\text{Entropy index} = \ln n - \sum_{i=1}^{n} P_i \ln\left(\frac{1}{P_i}\right) \quad (2)$$

where n, is the number of sub-areas; P_i is the population ratio of the sub-area of the ith jurisdiction.

$$\text{Gini Coefficient} = 0.5\sum_{i=1}^{n}|X_i - Y_i| \tag{3}$$

where n is the number of sub-areas; X_i is the proportion of land area in sub-area i; Y_i is the proportion of the population in sub-area i.

$$\text{Global Moran's I index} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}\left[\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2\right]} \tag{4}$$

where n is the number of sub-areas; W_{ij} is the weight of I in sub-area j; X_i is the population of sub-area j; X_j is the population of sub-area j; $\overline{X}$ is the average population.

When analyzing these indicators, the sub-area under consideration is an individual grid cell. For instance, if the city of Seoul has an area of 600 km^2, there would be approximately 1200 grid cells of 500 m × 500 m each. When analyzing the UCI of Seoul, each of these 1200 grid cells become a sub-area of Seoul.

This study constructed the UCI (entropy, Gini coefficient, and Moran's I) for the 84 cities under study and presented the relationship between each index and per capita road transport GHG emissions in scatter plots. Among the UCIs, the one that best represented compactness was selected, and a correlation analysis was conducted to assess the relationship between this selected index and GHG emissions. After examining the relationship between each UCI indicator and per capita GHG emissions in the road transport sector, the UCI was reconstructed by multiplying it with the min–max normalized city size, allowing the relative size of each city to act as a weighted factor. This enabled a re-exploration of the relationship between the original and improved UCIs and per capita GHG emissions in the road transport sector.

Subsequently, this study categorized 84 cities into ordinal ranks using natural breaks by city size in GIS for comparative analysis. During this process, the average per capita GHG emissions in the road transport sector for each city size category were calculated, and the standard deviation for each group was determined. This comprehensive approach allowed for a thorough examination of the relationship between urban compactness and GHG emissions in the context of South Korean metropolitan areas.

3. Results

3.1. Relationship between UCI and GHG Emissions According to City Size

Among the three UCIs, only Moran's I significantly correlated with GHG emissions per capita in the road transport sector. Specifically, a negative correlation was observed between them. In addition, the entropy index and Gini coefficient positively and negatively correlated with GHG emissions, respectively, (Figure 1; Table 1), albeit non-significantly.

When evaluating urban compactness, both the entropy index and Gini coefficient are suitable when considering city size. Figure 1 demonstrates that no clear linear relationship exists between these two indicators when city groups are not separated by size. However, when large- and medium-sized cities are segregated, large cities, such as Seoul and Busan, tend to have lower values of both the entropy index and Gini coefficient. This pattern is due to the inherent characteristics of these indices, where larger cities tend to yield smaller values. Since these indices assess population distribution, larger cities, such as Seoul, with approximately 10 million people and with most of their areas inhabited, result in smaller values compared with those of smaller- and medium-sized cities. While using administrative district boundaries instead of grid cells can partially mitigate this effect, it may not facilitate a comparative analysis between large and small cities because of the hierarchical nature of regional boundaries.

Table 1. Correlation between urban compactness index and greenhouse gas emissions per capita in the road transport sector.

Urban Compactness Index	Correlation Coefficient	*p*-Value
Entropy	0.201	0.066
Moran's I	−0.321	0.003
Gini coefficient	−0.055	0.619

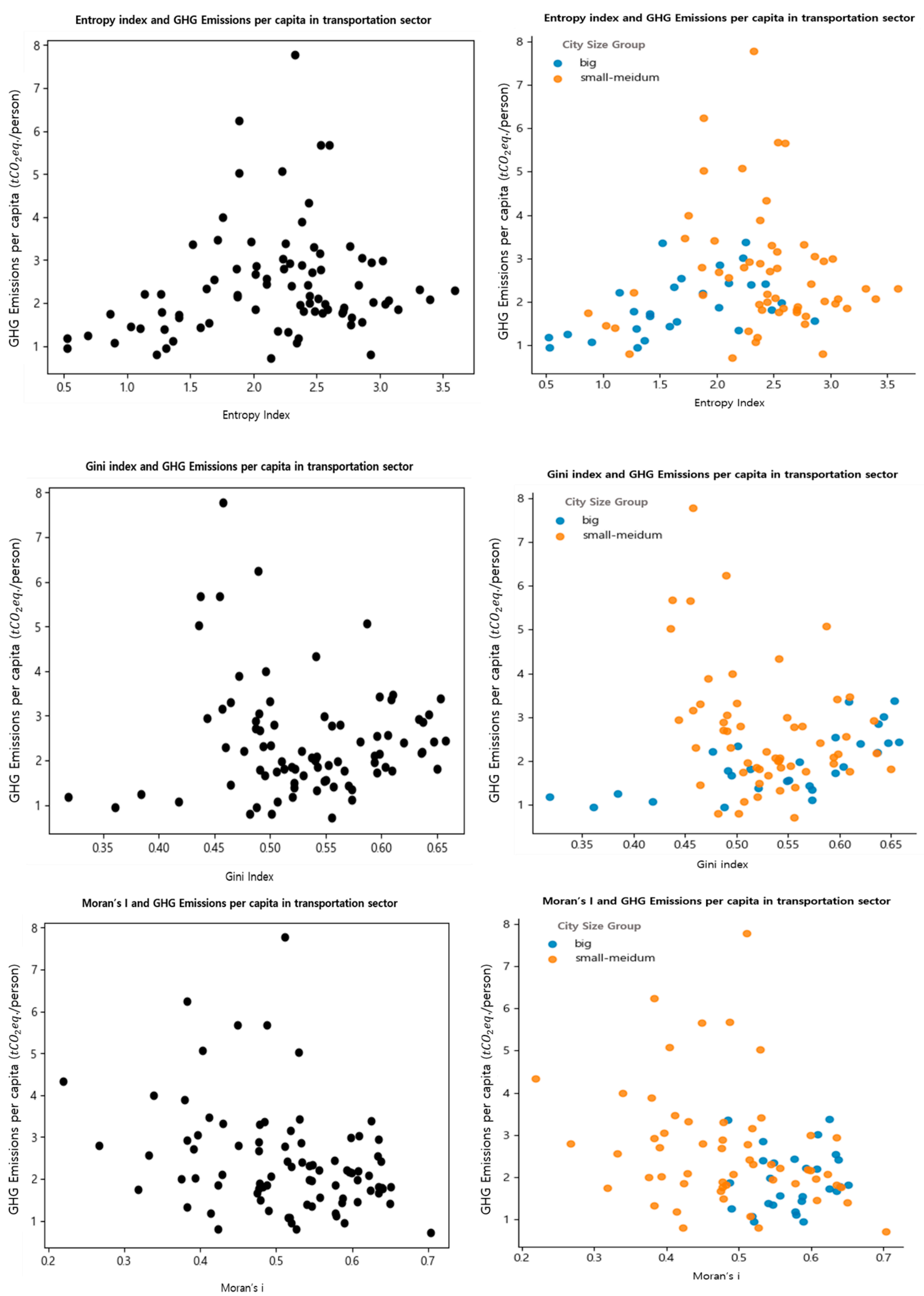

Figure 1. Urban compactness index and greenhouse gas emissions.

The relationship between the UCI and GHG emissions per capita in the road transport sector becomes increasingly evident when the indicators are adjusted for city size. This adjustment is achieved by min–max normalizing the city's population, effectively accounting for city size, and then multiplying it by the UCI (Formula (5), Figure 2). Moran's I theoretically ranges between −1 and 1; in this study, all 84 cities had positive values, indicating the suitability of this reconfiguration. However, as observed in the scatter plot (Figure 1), Moran's I and the Gini coefficient generally represented poor compactness, except in a few regions. To analyze this correlation, taking the inverse of these values is necessary.

$$\text{The adjusted UCI}_{i,k} = \text{UCI}_{i,k} \times \frac{city\ size_i - city\ size_{min}}{city\ size_{max} - city\ size_{min}} \tag{5}$$

where $city\ size_i$ is the city size (population) of the ith jurisdiction; $UCI_{i,k}$ is the kth urban compactness index (Entropy, Moran's I, Gini coefficient) of the ith jurisdiction.

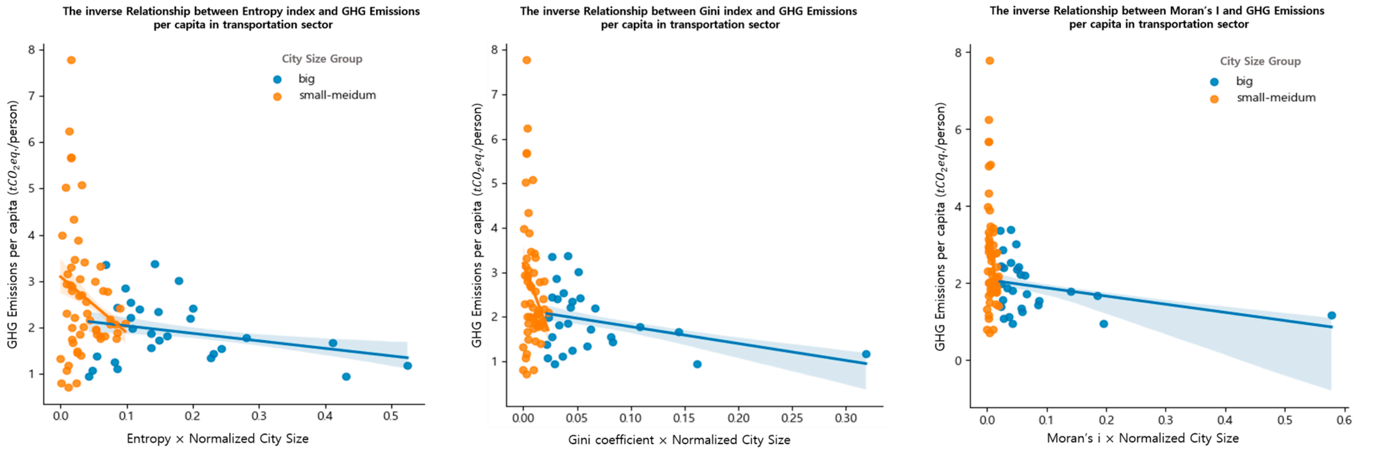

Figure 2. Inverse relationship between the urban compactness index and greenhouse gas emissions.

Each indicator demonstrated an inverse relationship with GHG emissions. The results of the correlation analysis between the inverse of emissions and each indicator's relationship are summarized in Table 2. Unlike the correlation results shown in Table 1, the inverse relationship reveals that all correlation coefficients are positive and statistically significant. In essence, when considering the 84 Korean cities with populations ranging from 40,000 to 10 million, GHG emissions tend to decrease as urban compactness increases.

Table 2. Results of the correlation analysis between the urban compactness index and the reciprocal of GHG emissions per capita in the road transport sector.

Adjusted Urban Compactness Index	Correlation Coefficient	*p*-Value
Entropy × City Size (normalized)	0.217	0.048
Moran's i × City Size (normalized)	0.254	0.020
Gini coefficient × City Size (normalized)	0.262	0.016

3.2. Examining the Relationship between the UCI and GHG Emissions within Cities of the Same Size

Next, we aimed to determine whether greater urban compactness in cities of the same size leads to lower GHG emissions. In our 84 cities, we observed an inverse relationship between urban compactness and GHG emissions. To verify this relationship, groups of cities with similar or identical sizes should exhibit an inverse or negative linear relationship within each group. To this end, the 84 cities under study were categorized into five hierarchical groups—from largest to smallest—using the ArcGIS natural breaks function

(Figure 3). However, because Seoul's population was significantly higher than that of the other cities (exceeding 9 million people), it was not analyzed individually. Instead, it was grouped with Daegu and Incheon, both having populations exceeding 2 million, and with Busan, having a population of over 3 million people.

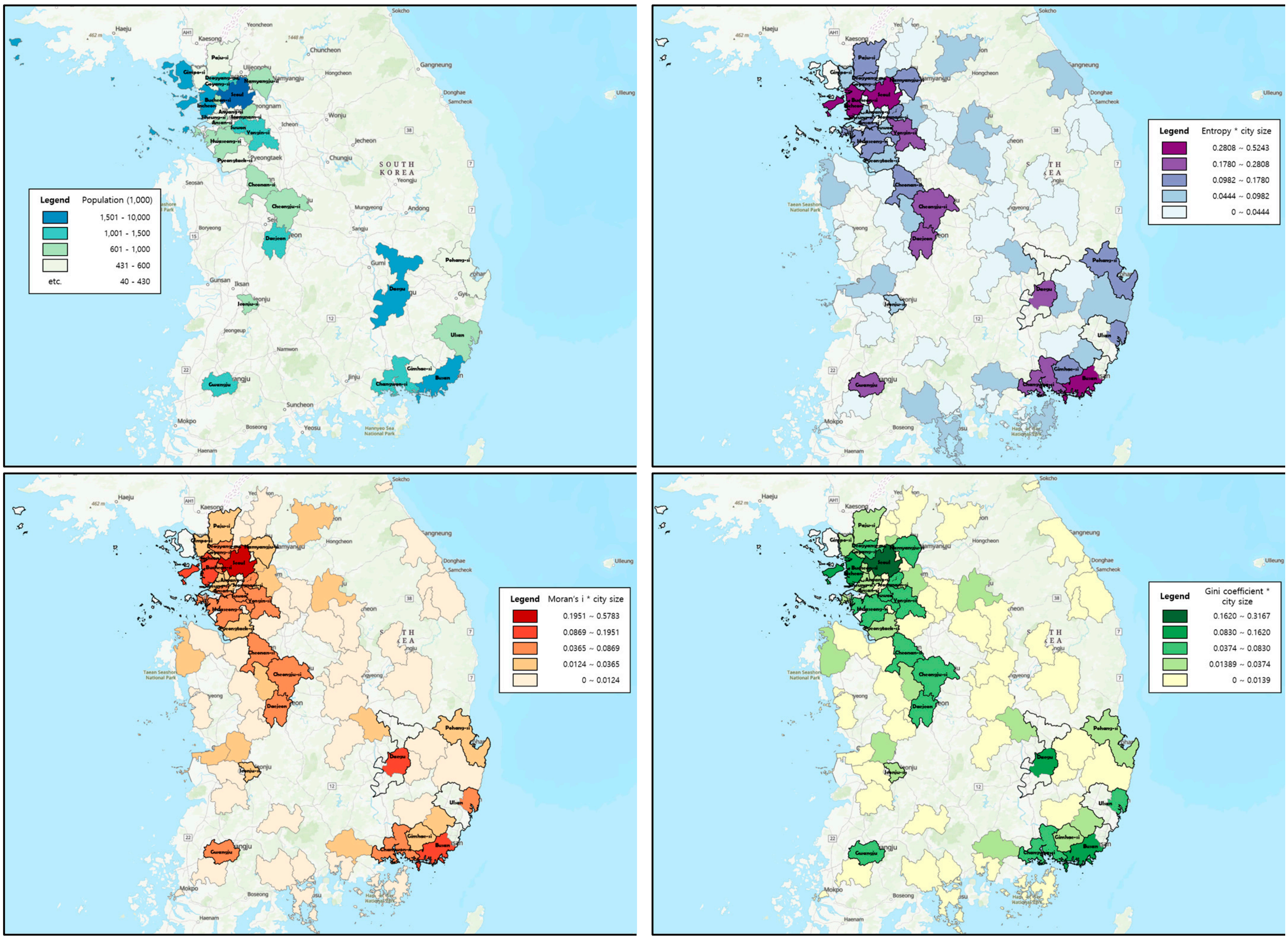

Figure 3. Twenty-seven large cities and urban compactness index multiplied by city size.

When cities of comparable size were grouped, a consistent association between urban compactness and GHG emissions across all groups was not observed. The largest cities, such as Seoul and Busan, were generally associated with lower per capita GHG emissions; however, in other regions, where compactness did not significantly differ nor increase, the opposite trend was observed (Figure 4). However, when examining the group of cities with a population above 1 million, road transport GHG emissions per capita were slightly reduced with greater urban compactness, while no significant linear relationship was evident in other regions.

Notably, the larger the city, the smaller the average value of road transport GHG emissions per capita. When cities of comparable size were clustered, this relationship did not exhibit the same pattern in all groups. However, upon averaging the GHG emissions per capita for each group, larger cities displayed lower emissions. Large cities with more than 1 million inhabitants, including Seoul, Busan, and Goyang, displayed an average per capita GHG emission of 1.6 tons CO_2 eq. or less. In contrast, city-scale groups with populations of 600,000 or more exhibited an average per capita GHG emission of more than 2.2 tons CO_2 eq. or more.

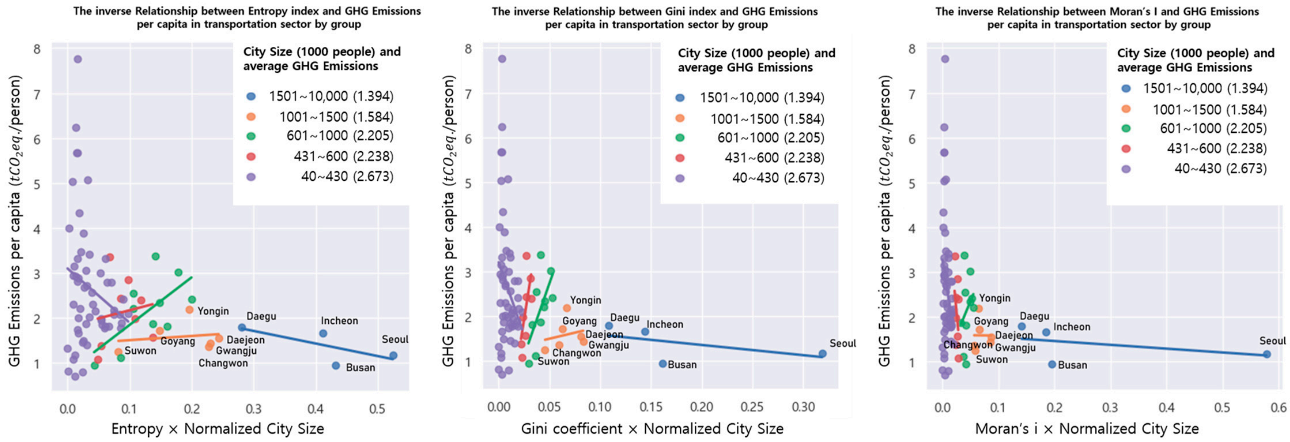

Figure 4. Relationship between urban compact index and greenhouse gas emissions in cities of the same size.

Larger cities tend to exhibit smaller deviations in GHG emissions. To obtain cluster centers for each of the previously classified groups, the K-means clustering method can be utilized in reverse. The distances from the center of each cluster to the emissions of other cities within the same cluster are presented in Table 3. Additionally, a box plot depicting road transport GHG emissions per capita by city size is illustrated in Figure 5. Despite the substantial differences in the number of observations in each group, the deviation in GHG emissions increased as the city size decreased.

Table 3. Average distance of greenhouse emissions by city size.

City Size	The Average Emissions Distance (Each Point–Cluster Center)	Average Values of Carbon Emissions per Capita
Group 1	0.332	1.394
Group 2	0.249	1.584
Group 3	0.597	2.205
Group 4	0.600	2.238

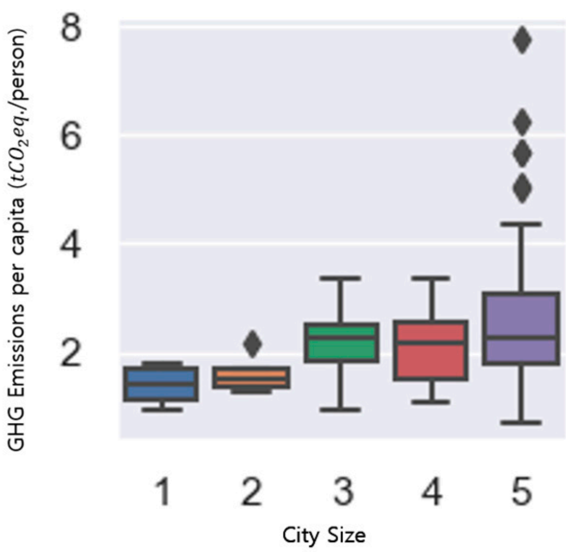

Figure 5. Box plot of greenhouse gas emissions per capita by city size.

4. Discussion

The UCI, which assesses a city's physical form, should be adjusted to account for city size. Failing to consider city size poses the risk of comparing cities with vastly different population sizes on the same scale. This may lead to unrealistic interpretations and overlook the true level of compactness. Particularly, owing to the mathematical characteristics of entropy and the Gini coefficient, smaller cities often appear more compact because they have more sparsely populated areas. Initially, the concept of compact cities emerged as a response to urban sprawl, driven by the increasing size of cities. However, imposing skyscrapers and public transit-oriented land use plans in a city such as Taebaek (with a population of approximately 44,000), whose urban area is mostly covered by mountains, would be impractical. Therefore, considering city size is essential.

Above a certain scale, a more compact urban spatial structure tends to be associated with lower GHG emissions. Low-density cities have been proposed to be developed as a sustainable development strategy for a low-carbon society [41], but this is considered inappropriate when considering GHG emissions per capita. The specific threshold for a 'certain scale' may vary by country, and in Korea, this appears to be approximately 1 million in terms of city population. Accordingly, when examining the 27 major cities with a population of at least 670,000, excluding Jeju Island, observing the linear relationship between compactness and emissions becomes challenging. This trend suggests that in this group, the more compact the city, the higher the emissions. As populations grow to a range of 1–1.5 million people, emissions tend to increase. However, the UCIs of the 10 cities with populations ranging from 1 to 10 million indicated that a city's per capita emissions tend to decrease as its physical form becomes increasingly compact. Wang et al. [42] analyzed the relationship between urban size and per capita GHG emissions across 259 cities in China. They found that in small- and medium-sized cities (with populations under 1 million), the relationship between city size and per capita GHG emissions formed an inverse U-shape, while in larger cities (with populations over 1 million), it exhibited a U-shape [43]. Because they did not consider the compactness of the cities, caution should be exercised when directly comparing their findings with those of the present study. Nevertheless, they suggested that in large cities that are not overpopulated, per capita GHG emissions tend to decrease as the city size increases, consistent with the findings of the current study.

Large- and small-to-medium-sized cities differ in their GHG emission mechanisms [19]. Larger cities tend to use energy more efficiently, resulting in lower per capita transport GHG emissions. This becomes observable only when cities are categorized by size, owing to the presence of spatial structure factors such as urban railway systems, which directly impact energy use. Thus, merely assessing the population and cohabitation patterns within a city does not indirectly indicate the efficient utilization of energy. Therefore, we categorized cities by size rather than treating them as a continuous variable and verified that increased city compactness does not translate to higher GHG emissions.

5. Conclusions

Cities should aim to adopt a compact urban form and spatial structure to achieve carbon neutrality effectively [12,17–19,25]. Several cities worldwide are aiming for carbon neutrality, but transforming cities while addressing the substantial burden of energy costs and improving local government capacity has not been discussed [44,45]. In this context, planners need to establish future-oriented urban planning for carbon-neutral sustainable development [46]. Long-term strategies for reducing GHG emissions can be implemented through rational land use planning and spatial structuring [3,47]. However, the higher the UCI in smaller metropolitan cities, the higher the probability for GHG emissions to be higher. This may be attributed to the absence of urban railway systems in cities within this group. Small populations tend to have higher reliance on cars since urban railway construction is deemed inefficient. In such cases, although the spatial structure of the city is compact, GHG emissions increase with the population.

This study has some limitations, particularly related to explaining the entire urban spatial structure. We explored the relationship between the UCI and GHG emissions by emphasizing city size rather than addressing various components of the spatial structure. Consequently, insights into the specific influence of each spatial structure element are lacking. This study directly derived more sophisticated emission data at a resolution of 500 × 500. Due to constraints in obtaining data on energy consumption in South Korea, there was only constructed a dataset for the year 2019, which is a limitation. Additionally, owing to significant differences in the sample sizes of city size groupings, linear regression and multi-level analyses could not be conducted, limiting the ability to test for a clear causal relationship. Finally, the study was constrained in its capacity to track changes in compactness over time because of its inability to calculate historical estimates of transport sector GHG emissions for individual cities.

Future studies can focus on gaining a clearer understanding of this relationship. Based on various urban factors that can influence GHG emissions, categorizing cities and determining the optimal model for a carbon-neutral city within the context of the relationship between these factors and urban compactness is required. Longitudinal data analyses that track changes in the spatial structure of cities served by urban rail and changes in GHG emissions may provide a more comprehensive explanation of the relationship between GHG emissions and urban compactness across different city sizes.

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