

Article

Decoupling Urban Development and Transport Carbon Emissions: A Hierarchical Regression of the TOD 7D Framework in the Seoul Metropolitan Area

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Abstract

Given the huge contribution of the transportation sector to CO₂ emissions in metropolitan areas, urgent countermeasures are needed to achieve carbon neutrality. In this study of 66 administrative units (cities, counties, and districts) in the Seoul metropolitan area, we applied cluster analysis and a hierarchical regression model to analyze the impact of the 7D factors of Transit-Oriented Development (TOD) on CO₂ emissions from road transportation. The effects of TOD factors were found to vary in diverse contexts. A higher concentration of employment intensified regional travel demand, thereby increasing emissions—a phenomenon referred to as the Paradox of Concentration. In contrast, the expansion of urban rail and bicycle infrastructure facilitated modal shift toward sustainable transport but simultaneously stimulated commercial and logistics activities, leading to elevated overall emissions. Thus, a ‘two-faced infrastructure’ pattern is evident in the Seoul metropolitan area. Conversely, strengthened local self-containment by destination accessibility promoted short-distance travel, curbing emissions. These outcomes empirically exhibit that the low-carbon effect of TOD is contingent, implying that urban structure and policy context are key factors in determining emission pathways. The impacts of the TOD 7D factors are discussed in terms of emission effects, and differentiated policy directions reflecting inter-city heterogeneity are suggested. In particular, the results of our analysis emphasize the need for comprehensive TOD strategies that combine transportation infrastructure, demand management, local self-containment, and zero-emission logistics systems, beyond simple compact development strategies. The policy implications described here are applicable in other countries experiencing rapid urbanization.



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Keywords: transit-oriented development (TOD); transport carbon emissions; hierarchical regression; sustainable transport policy; transport carbon decoupling

1. Introduction

The transport sector, one of the main contributors to global CO₂ emissions, accounting for approximately 23% [1], has been identified as a key research area for developing sustainable urban growth strategies in rapidly urbanizing metropolitan regions with high traffic volumes. In particular, because road transport contributes substantially to emissions in metropolitan areas where population and economic activity are concentrated, reducing emissions from this sector is an urgent priority for achieving sustainable urban growth. Globally, emphasis has been placed on simultaneously achieving economic growth

and environmental protection under the green growth paradigm, in which the transition of the transport sector to a low-carbon system and the decoupling of economic growth from environmental burden are regarded as key objectives. In several developed countries, successful decoupling through energy efficiency improvements and decarbonization policies has been reported. Conversely, in many emerging economies, including South Korea, a simultaneous upward tendency of economic growth and CO₂ emissions is still the case [2], which further highlights the need for effective policies to reduce emissions in the transport sector.

In this context, transit-oriented development (TOD) has gained attention as a core strategy for achieving the transition to low-carbon cities. The goal of TOD is to reduce vehicle dependency and to curb emissions by promoting non-motorized modes of transport such as walking and cycling, as well as public transit use, through high-density, mixed-use land development around transit hubs [3]. The analytical framework of TOD originated from the 3D approach—Density, Diversity, and Design—proposed by Cervero and Kockelman (1997) [4]; it was later extended to the 5D model by Ewing and Cervero (2010) [5] through the inclusion of Destination Accessibility and Distance to Transit, and subsequently to the comprehensive 7D framework by Ewing and Cervero (2017) [6], which further integrates Demand Management and Demographic factors.

Previous studies on the relationship between TOD and the level of CO₂ emissions have mainly focused on how high-density, mixed-use development promotes public transit use and reduces vehicle dependence [4,5]. However, these effects may vary in diverse contexts, and the possibility that high-density development could, in fact, expand total transport demand, thereby increasing absolute emissions, has not been sufficiently verified. Furthermore, in previous studies, the interactive effects of TOD density and accessibility on CO₂ emissions have not been sufficiently addressed [4–6].

Accordingly, the focus of the present study was the examination of these potential dual effects; that is, increased mobility activity through improved accessibility. The Seoul metropolitan, although characterized by a particularly high-density, public transit-oriented structure that is rare globally, exhibits various levels of development and distinct transport characteristics across different areas within the metropolitan region. Previous studies conducted in South Korea have mainly focused on a limited set of TOD attributes—such as residential density and mixed land use—while analyses were often confined to individual administrative units, overlooking the metropolitan-scale heterogeneity of the Seoul Capital Region [7]. Moreover, in some studies, trends were presented as average values without reflecting inter-city heterogeneity, which impedes the development of urban type-specific response strategies needed for policy setting and urban planning.

Thus, the aim of this study is to examine the relationship between the 7D factors of TOD and CO₂ emissions from the road transport sector across 66 administrative units—cities, counties, and districts—within the Seoul Metropolitan Area. Specifically, cluster analysis was employed to identify emission characteristics by urban type, and hierarchical regression analysis was used to verify the stepwise explanatory power of the TOD 3D–5D–7D factors as well as the effects of individual variables. The results demonstrate that the low-carbon effects of TOD do not always operate positively; rather, TOD can produce contradictory outcomes across different contexts. Based on these findings, differentiated policy implications are derived according to the heterogeneity among metropolitan units, offering a new analytical perspective for managing transport-related emissions in high-density metropolitan areas and providing insights applicable to other rapidly urbanizing regions worldwide. Although numerous studies have examined TOD and transport-related carbon emissions, this study offers an incremental contribution by addressing several remaining conceptual and methodological gaps.

2. Literature Review

As early as 2008, Banister [8] criticized the premises of conventional transportation planning and proposed a sustainable mobility paradigm. He asserted that travel should be recognized not merely as derived demand but as a valuable activity, and that reasonable travel time and reliability are more important than time minimization. To this end, he proposed policy directions including alternatives for travel, mode shift, distance reduction, and technological innovation, as well as specific measures including information and communications technology (ICT) utilization, policy implementation prioritizing walking, cycling, and public transit, high-density and mixed-use development, and introduction of eco-friendly technologies. He further argued that long-term strategies involving stakeholder collaboration and citizen participation make such shifts possible. Building upon Banister's early conceptual framework, subsequent studies have examined the feasibility of implementing such sustainable mobility transitions across diverse European contexts.

Hickman et al. (2013) reviewed the potential for sustainable mobility transitions through integrated urban planning and transport investment in London and Oxfordshire, UK [9]. CO₂ reductions in the transport sector were modeled by setting four possible scenarios by the year 2030: current trends, low-carbon vehicles, enhanced local mobility, and sustainable mobility. The results indicated that intensive investment in public transit and urban regeneration policies was necessary in the high-density city of London, whereas different policies were required in Oxfordshire, with its low-density structure. Making reference to other case studies of European cities (Stockholm, Paris, and Freiburg), the authors emphasized the importance of polycentric urban structures and public transit connectivity. Although the contrast is relatively simple—high-density vs. low-density cities—the point was made that TOD policies should be adjusted based on urban characteristics and transportation systems.

In a 2017 analysis of Belgian transportation policy [10], the authors pointed out the paradox that the discourse of 'sustainable transport' can actually result in unsustainable outcomes. Seven cases of urban planning were reviewed from the perspectives of growth pressures and social justice. Examples of incomplete analysis or problematic situations included the use of statistics that did not include international aviation emissions, a case where improved airport rail access promoted air travel demand, and another case where redevelopment of station influence areas and free bus policies actually generated more traffic. The authors of the review indicated that these policies were distorted by misplaced goals and biased indicator selection, emphasizing that sustainable transport policies must be precisely designed in consideration of social justice.

A nationwide study of urban and transport policies in Spain carried out by Mozos-Blanco et al. (2018) included a comparative analysis of Sustainable Urban Mobility Plans (SUMP) in 38 cities [11]. The specificity and implementation level of the SUMP were evaluated based on 16 criteria, including transport mode, parking, walking/cycling, public transit, and environmental pollution reduction. The authors of the study found that although walking and cycling infrastructure, bus route restructuring, and parking management were relatively well-addressed, other important aspects, including logistics systems, public transit connectivity, public participation, and environmental sustainability, were insufficiently addressed. Furthermore, the long-term monitoring system and specific budget amounts and schedules were also less than satisfactory. The conclusion is that while a nationwide program such as SUMP lays the foundation for a paradigm shift in urban transportation, more public participation, strengthening of environmental considerations, improved spatial design, and the establishment of a long-term evaluation system are necessary to achieve tangible outcomes.

Similar issues were identified in a review of sustainable mobility policies in Norwegian cities. Bardal et al. (2020) analyzed the barriers and limiting factors found in the design and implementation of sustainable mobility policies in three cities: Bodø, Trondheim, and Bergen [12]. An assessment of interviews as well as a literature review revealed a number of obstacles: cultural, political, legal, organizational, knowledge-based, and financial. A vehicle-oriented planning culture, institutional rigidity, and lack of inter-agency cooperation were found to be key issues. Their analysis emphasized that it was possible to effectively design sustainable transportation policies through tailored approaches based on city size and urban context.

In terms of linking transportation policy with environmental sustainability, five studies in particular are worth noting: a 2011 global assessment by Schwanen et al. [13] and four more recent studies of TOD impacts, all in Asian cities [14–17]. Schwanen et al. (2011) [13] critically reviewed climate change mitigation research in the transport sector, categorizing it into five domains: technological innovation, pricing and taxation, infrastructure, behavioral change, and institutional governance. Most studies were found to rely on quantitative modeling, at the expense of social and cultural factors. The authors proposed that incorporation of social science perspectives, such as socio-technical transition theories and implementation doctrine, would enable an understanding of decarbonization in the transport sector in a multidimensional sense and promote substantial change.

Ashik et al. (2022) [14] examined the impact of TOD on transportation-related CO₂ emissions in Dhaka, Bangladesh. Based on the data on 31,101 residents, they estimated individual emissions for commuting, school travel, and other non-work travel, used the 5D indicators to determine the TOD status, and analyzed the data using a multilevel model. As a result, TOD residents were found to contribute significantly lower CO₂ emissions from commuting and school travel, but no difference was found in terms of non-work travel. Vehicle ownership and income level exerted a proportionally greater impact on emissions. This study demonstrated that TOD only partially contributes to environmental sustainability in urban areas of a developing country, highlighting the need for tailored approaches per travel purpose.

Yang et al. (2024) [15] examined the sustainability of TOD within the context of urban shrinkage in the Tokyo metropolitan area. While targeting the Denentoshi Line, they defined 27 station influence areas as three TOD circles (800, 1600, and 3200 m) and analyzed variations between 2011 and 2019 by incorporating a time dimension into the Node-Place-Ecology (NPE) model. The results indicated that sustainability was strengthened in the primary and secondary circles within the city center, whereas the tertiary circle, particularly in suburban areas, showed signs of decline. The study proposed the TOD circle concept and a dynamic NPE model, emphasizing the need for different policy approaches across different zones.

Subway stations were the focus of a 2025 TOD study of Shenzhen, China [16]. The spatial coupling relationship between subway station accessibility and employment and population density was examined, and an index of Accessibility of Metro Stations (AMS) was derived by applying social network analysis. The distribution of employment and population was mapped across 15,176 grid units based on the 2019 mobile phone signal data. Kernel density estimation and spatial autocorrelation analysis revealed moderate levels of correlations and significant positive spatial correlations between AMS and both employment and population densities. Although 41% of metro stations showed a coupling relationship with the resident population and 33% with the employed population, more than half exhibited weak correlations. This study demonstrated regional disparities in TOD outcomes and emphasized the need for appropriate policy responses.

Similarly, taking 122 urban rail transit stations in the Bangkok metropolitan area as the points of interest, Vichiensana et al. (2025) identified the correlation structure between factors by applying the 5D indicators (i.e., density, diversity, design, destination accessibility, and distance to transit) and performing a multiple correlation analysis (MCA) [17]. The analysis indicated that areas with a high density of employment and commercial uses were closely associated with land use diversity, whereas commercial districts were also connected to accessibility to large-scale business facilities. On the other hand, low-density residential areas were related to low diversity and limited public transit access. The authors of the study identified interactions among TOD indicators and proposed the need for type-specific policy approaches based on the categorization of station influence areas.

A number of studies have advanced the methodology of TOD-based planning to reduce CO₂ emissions; among them are a 2018 study by Okraszewska et al. [18] and a 2025 study by Mangu et al. [19]. In assessing the practical usefulness of SUMP, Okraszewska et al. (2018) [18] proposed including Multilevel Model of Transport Systems (MST) models that support scenario evaluation, goal setting, and measure validation at the strategic, tactical, and operational stages through the linkage of macro-, meso-, and micro-level models. In Gdynia, Poland, MST was found to improve policy acceptability in the processes of analyzing bus lane effectiveness, visualizing traffic, and facilitating public participation, while enabling the implementation of a SMART indicator-based monitoring system. In general, MST strengthened decision-making by providing data transparency and quantitative evidence.

Mangu et al. (2025) [19] evaluated TOD in the context of developing countries by targeting the influence areas of 10 subway stations in Hyderabad, India. This study utilized 9D criteria, including density, diversity, design, distance to transit, destination accessibility, demand management, public transit preference, mismatch, and environmental respect. Twenty-seven indicators identified by the Delphi technique were applied to the Best-Worst Method and K-means cluster analysis to estimate a TOD index. As a result, the maturity level and deficiency factors for each station influence area were identified, and based on them, policy improvement directions were suggested.

In recent years, Transit-Oriented Development (TOD) research has evolved beyond the classical 3D and 5D frameworks toward a more holistic and multi-dimensional understanding that incorporates behavioral, environmental, and institutional perspectives. Zhang (2025) [20] proposed a “Next-Gen TOD” framework that shifts the analytical focus from node-based projects to corridor and network-level systems, balancing outcomes of efficiency, equity, and eco-adaptivity instead of merely prescribing physical design attributes. His work emphasizes that sustainable TOD implementation must address social justice and environmental resilience alongside mobility efficiency.

Extending this conceptual shift, Xia et al. (2024) [21] performed a meta-analysis of 146 empirical studies from 2000 to 2023, identifying 59 built-environment variables that influence TOD performance across transport, economic, social, and environmental dimensions. Their social-network and cluster analyses confirmed that TOD outcomes are determined by synergistic interactions among density, diversity, accessibility, and active-mobility factors rather than by any single indicator, supporting the extension of the 5D model into a 7D framework.

Methodologically, Robillard et al. (2025) [22] advanced a transferable five-step framework for generating TOD typologies adaptable across contexts, demonstrating through case studies in Montreal and Rotterdam that while density and accessibility metrics are universally applicable, contextual attributes such as cycling infrastructure and socio-demographic composition require regional calibration. Their findings emphasize that robust TOD classi-

fication must combine standardized indicators with context-sensitive adaptation, thereby operationalizing multidimensional models such as the 7D framework.

Zhang et al. (2025) [23] expanded the scope of TOD evaluation by incorporating life-cycle assessment (LCA) methods to account for the complete carbon footprint of TOD projects in Xi'an, China. Their results showed that while construction phases produce significant embodied emissions, modal-shift effects during operation yield notable carbon reductions (approximately 6.8% in their case study). This life-cycle perspective offers a scientific basis for integrating energy and transport policies into low-carbon TOD planning.

At the urban-form scale, Tiwari et al. (2023) [24] compared two districts in Naples, Italy, and found that variations in density, functional mix, and parking supply strongly affect modal choice and travel behavior. Their study suggested that similar levels of density can produce contrasting mobility outcomes depending on design and social diversity.

Furthermore, several recent studies consistently demonstrate that the effects of Transit-Oriented Development (TOD) are not simple linear responses to single indicators, but rather nonlinear processes accompanied by threshold effects, variable interactions, and spatial heterogeneity.

Pan and Huang (2024) [25] applied an interpretable machine learning (Interpretable ML) framework to analyze station-area vibrancy and reported that even identical TOD indicators exert nonlinear and context-dependent influences, with both the magnitude and direction of effects varying according to station typology and locational hierarchy. This finding highlights the limitations of treating all station areas as a homogeneous group in linear comparisons and underscores the need for typology-specific and context-sensitive design strategies.

Yang et al. (2024) [26] employed Multiscale Geographically Weighted Regression (MGWR) to examine the spatially non-stationary effects of TOD on housing rents, used as a proxy for urban vibrancy and economic performance. Their analysis revealed strong nonlinear and location-specific effects of walkability and land-use entropy, suggesting that TOD performance is far from uniform across metropolitan space and instead depends on local accessibility networks, land-use diversity, and pedestrian infrastructure.

Guo et al. (2023) [27] utilized micro-level commuting data to quantify the nonlinear, interactive, and spatially heterogeneous effects of built-environment variables on commuting-related carbon emissions. The study identified significant synergistic and suppressing interactions among urban density, land-use mix, and transit accessibility, with distinct threshold differences between urban cores and peripheral areas. These results highlight the necessity of explicitly modeling multidimensional interactions and region-specific parameters in analyses of the TOD-carbon relationship.

Taken together, these empirical findings confirm that TOD outcomes are governed by nonlinear interaction mechanisms and spatial non-stationarity. Consequently, the 7D analytical framework adopted in this study—combining cluster analysis with hierarchical regression—is well suited to capture both type-specific heterogeneity and inter-variable synergies inherent in urban development and transport-emission dynamics.

A review of the aforementioned previous studies suggests several implications. As emphasized by Banister [8] and Schwanen et al. [13], the paradigm of transportation planning must go beyond a mere focus on reducing travel time and vehicle-oriented planning toward city and regional plans that encompass sustainability and social value. As revealed in a number of the studies discussed above [10–12], given that transportation policies often exhibit a gap between discourse and actual outcomes, it is necessary to adopt approaches tailored to local contexts and consider social equity. As demonstrated in a number of studies from different regions [9,14–17], there is a direct association of TOD, urban density, and land-use structure with CO₂ emission reductions, but the effects may vary depending

on contextual factors such as urban density levels, spatial location, and travel purpose. As confirmed by Okraszewska et al. [18] and Mangu et al. [19], the advancement of quantitative and econometric methodologies and multilevel modeling has become a crucial foundation for practical transportation policy design. At the same time, growing empirical evidence indicates that the effects of these factors on transport performance [20,21] and carbon emissions [23] are nonlinear and spatially heterogeneous [25–27]. This evolving body of research suggests that TOD outcomes should not be interpreted as a mere byproduct of high-density development but rather as the result of interactive processes among urban form, transport systems, and human behavior. However, few studies have quantitatively examined these multidimensional and spatially heterogeneous interactions within high-density Asian metropolitan contexts.

Accordingly, this study reflects these international discussions and empirical advancements by applying the TOD 7D framework to the Seoul Metropolitan Area to quantitatively assess the relationship between urban development and transport-related CO₂ emissions. Furthermore, by identifying and verifying city-type-specific decoupling mechanisms, this study aims to contribute both theoretical insights and policy implications for sustainable urban transition strategies.

3. Methodology and Data

We analyzed the impact of the Transit-Oriented Development (TOD) 7D factors on CO₂ emissions from the road sector across 66 local administrative areas (cities, counties, and districts) in the Seoul metropolitan area. The study protocol consisted of four stages: (1) data collection and variable setting, (2) exploratory analysis, (3) verification of the main hypothesis, and (4) identification of policy and planning implications (see Figure 1).

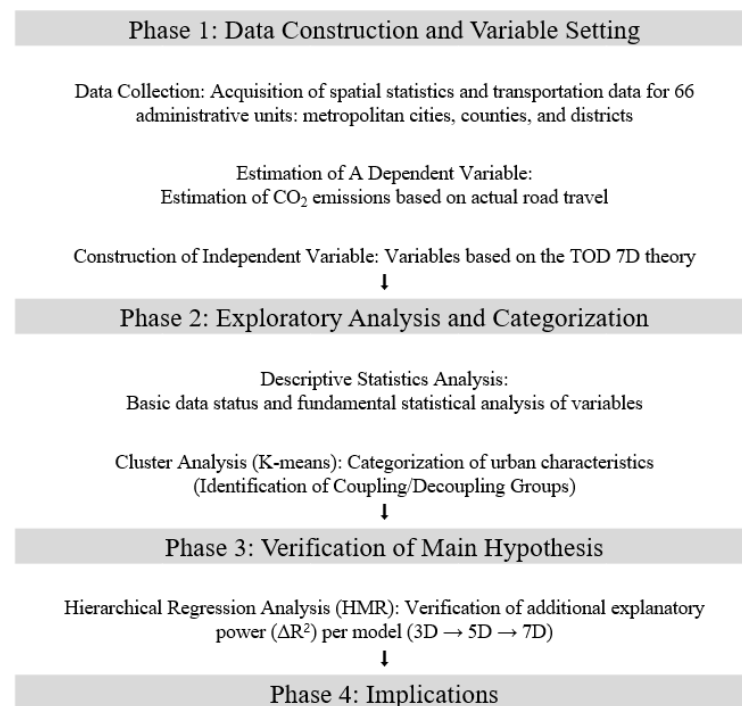


Figure 1. Research Work Flow.

First, we constructed the dependent variable (i.e., regional CO₂ emissions) and the independent variable (i.e., the variable group based on TOD 7D) by integrating various statistical and transportation data (Phase 1). Next, we categorized urban characteristics and emission levels through descriptive statistics and cluster analysis (K-means) (Phase

2). We then tested the research hypothesis by applying a hierarchical multiple regression model, which sequentially incorporates variables in the order of 3D→5D→7D3D→5D→7D (Phase 3). Lastly, based on the model results, we evaluated the hierarchical explanatory power of TOD factors and derived policy implications (Phase 4).

3.1. Data Collection and Variable Setting

By setting the spatial scope defined by an administrative unit, it was possible to capture urban structure and policy variables at the levels of station influence areas and neighborhoods. Such an approach ensures high consistency with statistics and transportation data based on administrative boundaries, facilitating data integration and comparability.

The dependent variable is CO₂ emissions from roads. The calculation was carried out based on the link-level estimation system of Ajou University's Urban Transportation Emission Assessment System (UTEAS). Specifically, on the basis of the results of the traffic demand model in the metropolitan area, we constructed activity data (e.g., traffic volume and speed per road type), which was combined with emission factors per vehicle type and speed, as provided by the National Institute of Environmental Research, in order to estimate CO₂ emissions per link. The results were calibrated by actual TMS traffic values to enhance their reality and aggregated at the city/county/district level through GIS overlay analysis. This approach is a bottom-up (Tier 3) approach rather than a top-down approach to the allocation of the total values, which has the advantage of more accurately reflecting spatial heterogeneity and traffic characteristics.

The explanatory variables were structured according to the TOD 7D framework. The 3D refers to Density, Diversity, and Design, including the density of population and employees in the area, mixed land use levels, and pedestrian/bicycle connectivity and street network characteristics. The 5D reflects transit stop/station accessibility, bus service levels, and commute time by adding destination accessibility and distance to transit. The 7D encompasses demand management and demographics, utilizing such variables as independence in financing, efficiency of transit operation, and scale of transportation-disadvantaged populations. The definitions and data sources for each variable are presented in Table 1.

Table 1. Analysis variable in TOD: 3D, 5D, and 7D.

Category		Variables	Source
Dependent	3D	Density Population density, employee density, and the density of population and employees in the area	Korea Statistical Yearbook
		Diversity Diversity in land use types, and diversity in land use	Korea Statistical Yearbook
		Design Urban block structure, pedestrian and bicycle accessibility, bicycle lane connectivity, etc.	Korea Transport DB, Local Government Statistics
	5D	Destination Self-sufficient urbanization, proportion of internal traffic volume, commuting travel time, etc.	Korea Statistical Yearbook, Korea Transport DB
		Distance to Transit Number of urban rail transit stations, number of bus stops, bus route extensions, etc.	Korea Transport DB, Public Transport DB, Local Government Statistics
	7D	Demand Management Parking facility level, and efficiency of transit operation	Korea Statistical Yearbook, Korea Transport Information DB
		Demographics Scale of transportation-disadvantaged populations, independence in financing, and income level	Population and housing census, local financial statistics, and real estate sales price statistics
Independent	Road carbon emissions	Carbon emissions from road transport in areas in operation	UTEAS model of Ajou University

According to the technical statistics results (Table 2), the dependent variable, road transport CO₂ emissions (V40), showed an annual average of 473,000 tons with a standard deviation of 258,000 tons. In terms of area standardization, the coefficient of variation (CV) between areas was approximately 0.55, with significant variation. Among 3D indicators, the average values for population density (D3_V1) and employee density (D3_V2) were 35,521 and 14,094 persons/km², respectively. In the 5D indicators, the average commuting time

(D5_V14) was 38.6 min, and among the 7D indicators, the average value of independence in financing (D7_V27) was 41.86% with a standard deviation of 9.43%. These basic statistics provide crucial foundational information for confirming distribution characteristics among variables and regional heterogeneity.

Table 2. Definitions and descriptive statistics of study variables. Number of administrative units (N) is 66.

Category	Variable		Description	Unit	Mean	SD
3D	Density					
	Population density	D3_V1	Population/land area	Persons/km ²	35,521	17,836
	Employee density	D3_V2	Number of employees/land area	Persons/km ²	14,094	11,404
	Density of population and employees in the area	D3_V3	(Population + Number of employees)/land area	Persons/km ²	49,615	24,524
	Diversity					
	Diversity in land use types	D3_V4	ln(1/Dispersion of standardized residential land and commercial land)	-	6.40	2.54
	Diversity in land use	D3_V5	ln(1/Dispersion of standardized housing units, number of distributors, and number of businesses)	-	5.78	2.11
	Urban Design					
	Urban block structure	D3_V6	Number of road intersections/land area	Number/km ²	479	366
	Pedestrian-friendly	D3_V7	Pedestrian traffic/land area	Traffic/km ²	20,339	12,441
5D	Bicycle-friendly	D3_V8	Bicycle traffic/land area	km/km ²	1692	1512
	Bicycle lane connectivity	D3_V9	Number of bicycle lane routes/land area	Number/km ²	0.49	0.69
	Bicycle lane infrastructure level	D3_V10	Extension of bicycle lanes/land area	km/km ²	6.11	5.48
	Accessibility to the destination					
	Self-sufficient urbanization	D5_V11	Number of employees/Number of employed persons	%	92.14	85.17
	Percentage of internal traffic from home to work	D5_V12	Internal traffic volume/Commuter traffic volume	%	41.68	18.02
	Number of businesses	D5_V13	Number of businesses	Number	27,376	16,765
	Average travel time for commuting from home to work	D5_V14	Average travel time for commuters from home to work	Minutes	38.56	6.17
	Average travel time for passenger cars	D5_V15	Average travel time for passenger vehicle users	Minutes	36.57	4.43
	Average bus travel time	D5_V16	Average travel time for bus users	Minutes	40.86	4.59
	Average travel time via urban rail transit	D5_V17	Average travel time for rail users	Minutes	53.07	20.44
	Ease of shopping	D5_V18	Number of distributors (e.g., markets)/land area	Number/km ²	1.48	1.40
	Public transit accessibility					
	Number of urban rail transit stations/	D5_V19	Number of urban rail transit stations/land area	Number/km ²	1.08	0.89
	Number of bus stops	D5_V20	Number of bus stops/land area	Number/km ²	1.59	0.45
	Number of bus routes	D5_V21	Number of bus routes/land area	Number/km ²	0.11	0.09
	Bus route extensions	D5_V22	Extension of bus routes/land area	Number/km ²	1.88	2.37
	Average scheduled speed of buses	D5_V23	Average scheduled speed per route	km/h	28.53	6.52

Table 2. Cont.

Category	Variable		Description	Unit	Mean	SD
7D	Transport demand management					
	Parking facility level	D7_V24	Number of parking lots/number of registered passenger vehicles	Number/Number	1.31	0.54
	Efficiency of transit operation	D7_V25	Average driving speed	km/h	33	10
	Population and financial characteristics					
	Scale of transportation-disadvantaged populations	D7_V26	Number of children and elderly residents	-	93,054	59,059
	Independence in financing	D7_V27	(Local taxes + non-tax revenue)/Total budget of general account $\times 100$	%	41.86	14.27
	Independence in financing	D7_V28	(Own Revenue + Local Government Finance)/Total budget of general account $\times 100$	%	64.84	9.43
Sub-indicators	Income level	D7_V29	Average housing transaction prices	KRW 1000	322,389	178,570
	Modal share rate					
	Share rate of passenger vehicles	V30	Number of passenger vehicles generated/Total generation $\times 100$	%	38.31	14.17
Independent	Share rate of public transit	V31	Number of buses and urban rail transit generated/Total generation $\times 100$	%	18.72	6.31
	Emissions					
	CO ₂	V40	Road transport CO ₂ emissions	10,000 tons/yr	47.264	25.761

Shown in Figures 2 and 3 are the maps created from the results of road transport CO₂ emissions across 66 administrative units in the Seoul metropolitan area. As can be seen in Figure 2, showing total emissions per administrative unit, those cities, counties or districts that have combined large-scale development with industrial and logistics activities showed the highest emissions (e.g., Gangnam in Seoul, Namdong in Incheon, and Hwaseong in Gyeonggi Province). This indicates that absolute emissions are particularly pronounced along the metropolitan periphery–industrial axis, where wide-area transport demand and logistics activities are concentrated. We present in Figure 3 the emissions per unit area, with relatively high values evident in high-density residential and commercial districts such as central Seoul (including Jongno), the Gangnam area, Gwacheon, and Seongnam-bundang. As a result of the concentration of population and activities in a relatively small space, the emission intensity greatly increased, confirming that urban/high-density axes and peripheral/industrial axes show different patterns of emission concentration.

3.2. Cluster Analysis

We performed cluster analysis to categorize the heterogeneous characteristics of 66 administrative units (cities, counties, and districts) in the metropolitan area. The key variables in the analysis were CO₂ emissions from the transportation sector, population density, and the density of population and employees in the area, and the number of urban rail transit stations, as key variables. All variables were subject to Z-score standardization to eliminate unit differences. We also utilized the K-means method as the clustering algorithm due to its suitability for a large number of samples and intuitive result interpretation. The optimal number of clusters was set to $k = 4$, after considering statistical indicators and interpretability. This enabled the identification of interactions between urban development

characteristics and emission levels per type, laying the foundation for comparing urban transportation structures per cluster.

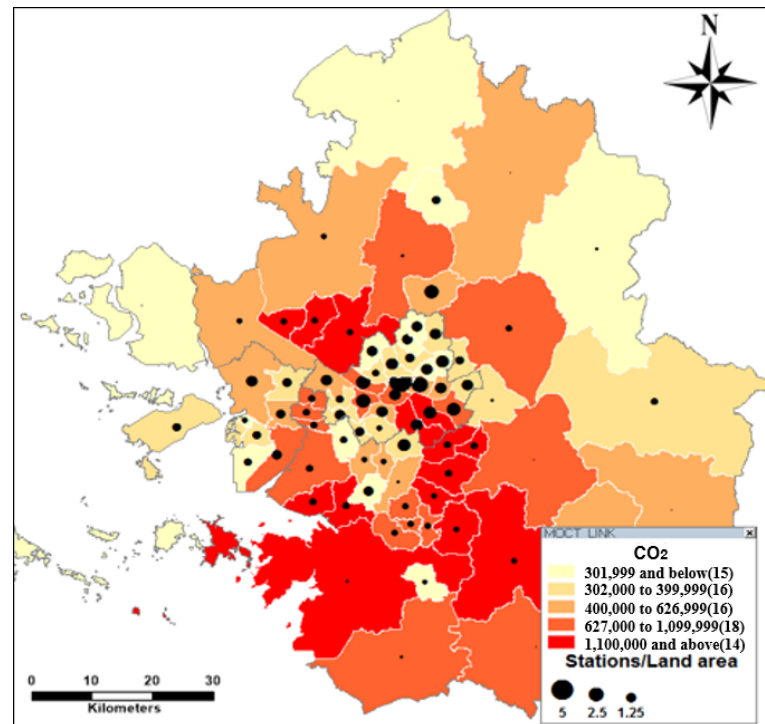


Figure 2. District-level road-transport CO₂ emissions in the Seoul metropolitan area.

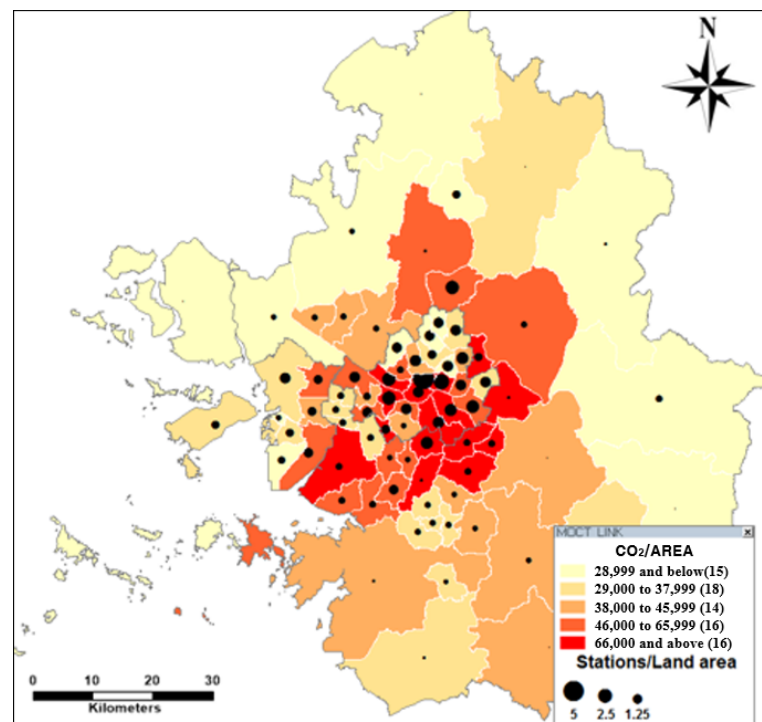


Figure 3. Road-transport CO₂ emissions per land area.

3.3. Hierarchical Multiple Regression Model

Based on the urban types identified from the cluster analysis, we performed a hierarchical multiple regression analysis to quantitatively determine the impact of TOD factors on CO₂ emissions in the transportation sector. This method allows for the stepwise

introduction of variable groups (blocks) according to theoretical evidence, enabling verification of the increment in explanatory power (ΔR^2) of additional variable groups while controlling for the effects of preceding variables. This approach is appropriate for verifying the hypothesis that “explanatory power will expand in the order of 3D $\rightarrow$ 5D $\rightarrow$ 7D”. The model design is as follows.

Model 1 (3D): Urban physical structure variables such as population density, employee density, mixed land-use, and street network characteristics.

Model 2 (5D): Addition of destination accessibility and public transit accessibility to Model 1.

Model 3 (7D): Addition of socioeconomic variables, such as independence in financing and efficiency of transit operation, to Model 2.

All independent variables were standardized using Z-scores during the analysis. Multicollinearity was confirmed by applying the variance inflation factor (VIF), with all values within the threshold (≤ 10). Autocorrelation of residuals was also verified through the Durbin–Watson test. The increase in explanatory power at each stage was evaluated by ΔR^2 and F-change significance, while the effect of individual variables was interpreted based on standardized regression coefficients (β).

4. Results

4.1. Cluster Analysis Results

As a result of the K-means cluster analysis, in which the relationship between urban development characteristics and CO₂ emissions from the road transport sector was categorized across the 66 administrative units, we identified four heterogeneous clusters (Table 3). Each cluster showed distinct differences in emission levels in line with various combinations of development density, transportation infrastructure, and socioeconomic conditions. The four categorized land unit types are as follows (values of the different variables are reported as averages of all the units in the unit type category).

Table 3. Cluster analysis results and comparison of urban traffic system characteristics per type. Values shown are the average of all administrative units in the same Type category.

			Type 1 Sprawling Cities, (n = 11)		Type 2 Emerging Cities, (n = 22)		Type 3 Sustainable Cities, (n = 26)		Type 4 Conventional Cities, (n = 7)	
			Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Cluster Analysis Criteria	CO ₂ emissions (10,000 tons/yr)	V40	77.649	20.305	28.462	12.637	39.321	11.538	88.109	13.427
	Population density (persons/km ²)	D3_V1	39,110	9651	14,728	8359	50,108	9807	41,052	8904
	Density of population and employees in the area (persons/km ²)	D3_V3	52,960	11,325	19,885	10,509	65,198	9725	79,918	11,668
	Number of urban rail transit stations (Number/km ²)	D5_V19	1.16	0.67	0.38	0.44	1.23	0.50	2.56	1.32
Characteristics of Urban Traffic System	Pedestrian-friendly (Traffic/km ²)	D3_V7	23,293	11,006	5840	4282	29,611	6664	26,823	4166
	Ease of shopping (Number/km ²)	D5_V18	1.18	0.54	0.44	0.34	1.97	0.82	3.41	2.86
	Scale of transportation-disadvantaged populations (persons)	D7_V26	89,911	61,625	74,919	64,075	113,288	55,524	79,827	32,245
	Income level (KRW 1000)	D7_V29	370,952	185,816	191,282	55,581	343,667	131,758	579,098	241,990
	Share rate of public transit (%)	V31	18.73	5.28	17.47	3.79	19.73	4.54	18.90	15.43

Type 1: Low-Development/Inefficient Cities (Sprawling Cities, $n = 11$).

Average CO₂ emissions are 777,000 tons, the second highest among the four groups. However, population density (39,110 persons/km²) and density of population and employees in the area (52,960 persons/km²) are relatively low, with a low share rate of public transit (18.7%), confirming an inefficient structure with high emission patterns despite low development levels.

Type 2: Low-Density/Potential Cities (Emerging Cities, $n = 22$).

This type exhibits low CO₂ emissions (285,000 tons) and low population density (14,728 persons/km²), as well as a relatively low value of population and employees in the area (19,885 persons/km²). This type also has the lowest share rate of public transit (17.5%) in the greater metropolitan area. Although this type of land unit is maintaining a low-density, low-emission state, measures may be needed to aid a transition to a sustainable path during future growth.

Type 3: High-Efficiency/Mature Cities (Sustainable Cities, $n = 26$).

This urban type shows relatively high population density (50,108 persons/km²) and density of population and employees in the area (65,198 persons/km²), with a curbed level of emissions (393,000 tons/year). In particular, as its share rate of public transit accounts for 19.7% of the total, which is the highest among these four types of land units, it is categorized as a decoupling type that can curb emissions in a high-density and high-activity structure.

Type 4: Highly Developed/Carbon-Dependent Cities (Conventional Cities, $n = 7$).

This type demonstrates the highest density of population and employees in the area (79,918 persons/km²) as well as the highest income levels and highest level of CO₂ emissions, at 881,000 tons/year. The average population density is 41,052 persons/km², which is lower than that of Type 3, but the absolute emission rate is the highest due to the large total volume of travel activity. Thus, this type of urban land unit can be interpreted as a coupling type where high development and high activity directly lead to more emissions.

The spatial distribution of these clusters is presented in Figure 4. Type 3 urban units are concentrated in Seoul downtown areas (Jongno and Jung-gu), and parts of mature new towns such as Bundang, which is regarded as a decoupling case where public transit infrastructure and accessibility within the living areas are combined. Type 4 is found in high-density, high-income business districts such as Gangnam, Seocho, Songpa, and Yeouido. Type 1 urban units are mainly distributed in a new-growth area on the outskirts of Seoul (e.g., Gimpo, Hwaseong, Namyangju, and Yongin), and Type 2 is found in low-density areas like Yangpyeong, Yeoncheon, and Gapyeong.

The location of each cluster on a coordinate plane of urban development intensity (Y-axis) and CO₂ emissions (X-axis) is shown in Figure 5. Even within the same high-density structure, Type 3 shows emission reduction (decoupling), whereas Type 4 presents increased emissions (coupling). Furthermore, within the low-density structure, Type 2 is associated with low emissions and Type 1 with high emissions, confirming that TOD factors and transport efficiency are decisive factors in emission pathways.

As described in the Methods section, administrative units (cities, towns, counties) in the Seoul metropolitan area were categorized through cluster analysis into four types. Our analysis confirmed that high-density structures can lead to either emission reduction (decoupling) or emission increase (coupling). We conducted hierarchical regression analysis in the following section by sequentially incorporating the TOD 3D, 5D, and 7D variable groups to identify the factors explaining these heterogeneous results.

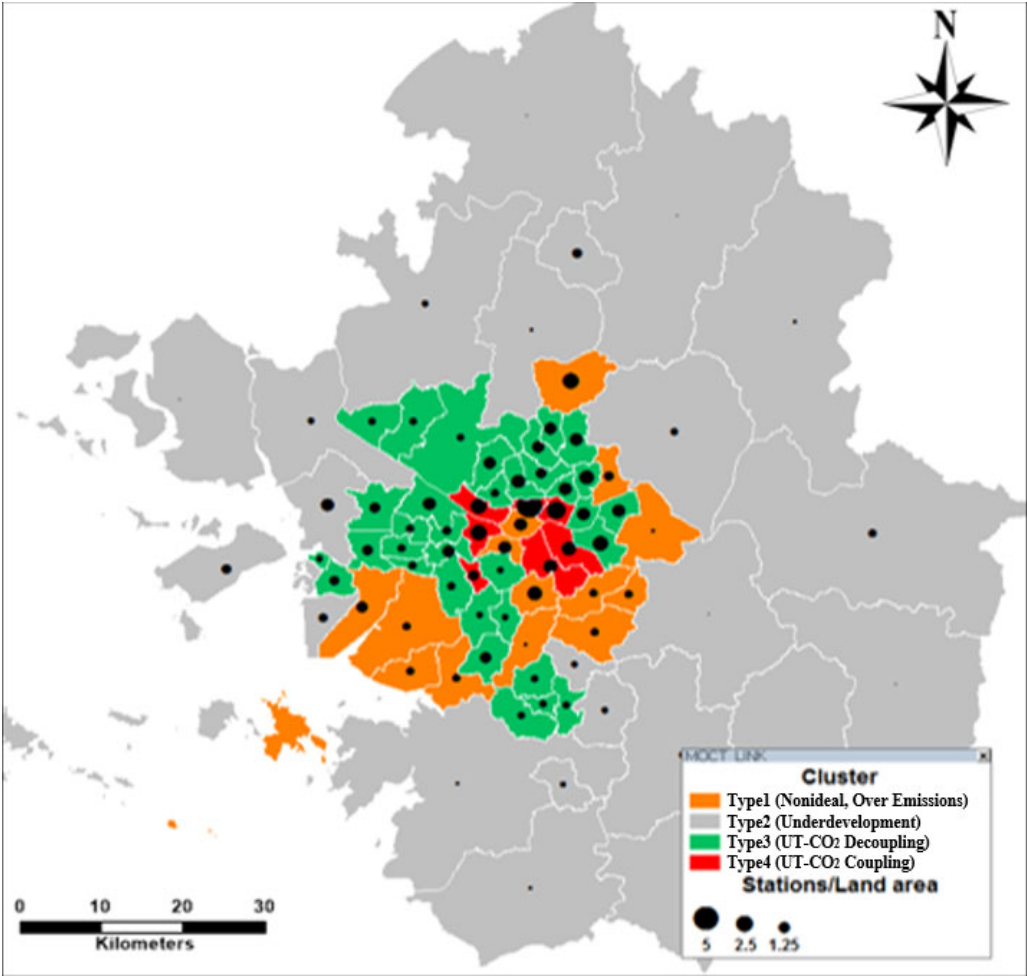


Figure 4. Spatial distribution of cluster types.

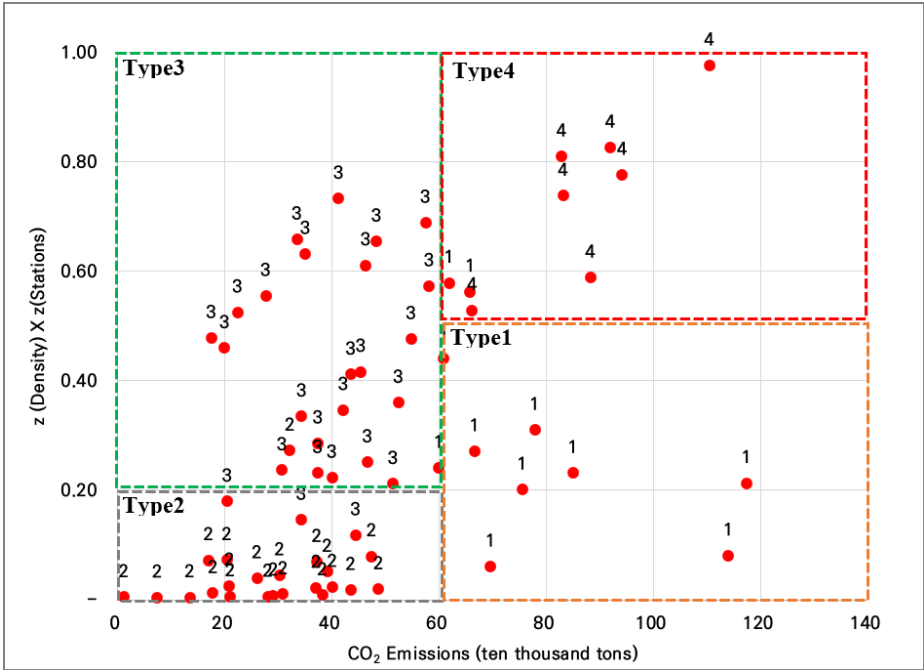


Figure 5. Relationship between urban development level and CO₂ emissions per cluster.

4.2. Hierarchical Regression Analysis Results

4.2.1. Validity of the Comprehensive TOD Model: Verification of Extension from 3D to 7D

We aimed to verify the effectiveness of a comprehensive TOD strategy that encompasses not only traditional urban form factors (3D) but also public transit accessibility (5D) and socioeconomic context (7D), to address carbon emissions issues in the transportation sector (Tables 4 and 5). As shown in Table 6, the explanatory power of the model (Adjusted R^2) improved significantly in phases from Model 1 (3D, $R^2 = 0.52$) to Model 2 (5D, $R^2 = 0.64$) and Model 3 (7D, $R^2 = 0.74$). A comprehensive comparison is presented in Table 7.

Table 4. Variable selection results for Model 1 (TOD 3D).

Variable	Correlation		Stepwise Regression						
	p(sig.)	Ent. or Exc.	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.	Durbin-Watson	R^2
			B	SE					
D3_V1	0.265(0.03) *	Exclude							
D3_V2	0.615(0.00) **	Enter	1	0	0.64	7.31	0.00		
D3_V3	0.479(0.00) **	Exclude							
D3_V4	−0.0(0.81)	Exclude							
D3_V5	−0.2(0.08)	Exclude							
D3_V6	0.04(0.73)	Exclude						1.781	0.517
D3_V7	0.347(0.00) **	Exclude							
D3_V8	0.267(0.03) *	Exclude							
D3_V9	0.327(0.01) **	Enter	14,018	3297	0.37	4.25	0.00		
D3_V10	0.15(0.21)	Exclude							

* = $p < 0.05$, ** = $p < 0.01$.

Table 5. Variable selection results for Model 2 (TOD 5D).

Variable	Correlation		Stepwise Regression						
	p(sig.)	Ent. or Exc.	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.	Durbin-Watson	R^2
			B	SE					
D3_V2	0.615(0.00) **	Enter	1	0	0.64	7.31	0.00		
D3_V9	0.327(0.01) **	Enter	14,018	3297	0.37	4.25	0.00		
D5_V11	0.438(0.00) **	Exclude							
D5_V12	−0.40(0.00) **	Exclude							
D5_V13	0.326(0.01) *	Exclude							
D5_V14	0.22(0.07)	Exclude							
D5_V15	0.260(0.04)	Exclude						1.623	0.642
D5_V16	−0.0(0.95)	Exclude							
D5_V17	0.17(0.17)	Exclude							
D5_V18	0.350(0.00) **	Enter	−11,009	2539	−0.60	−4.34	0.00		
D5_V19	0.540(0.00) **	Enter	9310	3596	0.32	2.59	0.01		
D5_V20	0.22(0.07)	Exclude							
D5_V21	0.16(0.17)	Exclude							
D5_V22	0.272(0.03)	Exclude							
D5_V23	−0.33(0.01) *	Exclude							

* = $p < 0.05$, ** = $p < 0.01$.

Table 6. Variable selection results for Model 3 (TOD 7D).

Variable	Correlation		Stepwise Regression						
	p(sig.)	Ent. or Exc.	Unstandardized Coefficients		Standardized Coefficients (Beta)	t	Sig.	Durbin-Watson	R ²
			B	SE					
D3_V2	0.615(0.00) **	Enter	1	0	0.64	7.31	0.00	1.796	0.736
D3_V9	0.327(0.01) **	Enter	14,018	3297	0.37	4.25	0.00		
D5_V18	0.350(0.00) **	Enter	−11,009	2539	−0.60	−4.34	0.00		
D5_V19	0.540(0.00) **	Enter	9310	3596	0.32	2.59	0.01		
D7_V24	0.299(0.01) *	Exclude							
D7_V25	−0.1(0.2)	Exclude							
D7_V26	0.00(0.97)	Exclude							
D7_V27	0.568(0.00) **	Exclude							
D7_V28	0.478(0.00) **	Enter	633	213	0.23	2.97	0.00		
D7_V29	0.602(0.00) **	Enter	0.029	0.015	0.20	2.11	0.04		

* = $p < 0.05$, ** = $p < 0.01$.**Table 7.** Multiple linear regression analysis results.

Variable	Model 1 (3D)			Model 2 (5D)			Model 3 (7D)		
	Beta	Sig.	VIF	Beta	Sig.	VIF	Beta	Sig.	VIF
Employee density(D3_V2)	0.64	0.00	1.01	0.89	0.00	3.92	0.59	0.00	4.86
Bicycle lane connectivity (D3_V9)	0.37	0.00	1.01	0.41	0.00	1.01	0.39	0.00	1.04
Ease of shopping(D5_V18)				−0.60	0.00	3.27	−0.41	0.00	3.74
Number of urban rail transit stations (D5_V19)				0.32	0.01	2.65	0.28	0.02	3.27
Independence in financial resource use (D7_V28)							0.23	0.00	1.36
Income level (D7_V29)							0.20	0.04	2.07
R ²		0.52			0.64			0.74	
R ² change		0.52			0.13			0.09	
F		33.68			10.71			10.43	
Sig. F Change		0.00			0.00			0.00	

Model 1 achieved a certain level of explanatory power through physical density alone, but it had limitations in fully explaining the TOD effect. In particular, as a result of adding the 5D variable group to Model 1, explanatory power increased by 13%p ($\Delta R^2 = 0.13$, $p < 0.001$), which indicates that high-density and mixed-use development alone is insufficient and that public transit infrastructure supply is essential. Furthermore, as a result of adding the 7D variable group to Model 2, the explanatory power increased again by 9%p ($\Delta R^2 = 0.09$, $p < 0.001$). This outcome indicates that even in areas with a well-developed built environment and transportation infrastructure, the financial conditions and socioeconomic characteristics of the area exert an independent influence on the level of emissions.

In summary, the findings of this analysis confirm that urban policies for carbon reduction can achieve substantial effects through a comprehensive 7D-based approach that simultaneously considers transportation infrastructure and socioeconomic contexts, rather than relying on only physical density adjustment.

4.2.2. Complexity of Emission Increase Factors: The Paradox of Concentration and the Two-Faced Nature of Infrastructure

As a result of the analysis, some indicators generally viewed as beneficial in TOD policies nevertheless exhibited a positive (+) relationship with increased CO₂ emissions. This is interpreted as a result of the complex interaction of transportation and economic structures in the metropolitan area.

First, employee density was found to be the strongest positive (+) influence on CO₂ emissions in all models ($\beta = 0.59\sim 0.89$). This result illustrates the “Paradox of Concentration”, where high-density employment hubs become core sources of traffic induction and inflow, increasing overall traffic volume in the metropolitan area.

Second, the number of urban rail transit stations and bicycle lane connectivity also consistently exhibited a positive (+) influence on emissions. This outcome demonstrates that public transit and eco-friendly transportation infrastructure reduce vehicle usage and simultaneously improve overall urban accessibility, resulting in increased total travel distance. Particularly in metropolitan areas, the concentration of station influence areas leads to the higher concentration of commercial and service industries, increasing logistics demand (in South Korea, diesel freight truck traffic remains high due to delayed transition to zero-emission vehicles); more bicycle lanes can contribute to more emissions when combined with increased activities within living areas. This exhibits the “two-faced nature of infrastructure,” where expansion of transport infrastructure simultaneously generates opposing effects: emission increase as well as reduction.

Third, independence in financing and income levels (proxy housing transaction prices) also exhibited a positive (+) relationship with the level of emissions. This result demonstrates how higher housing prices tend to have a higher concentration of relatively high-income residents with higher vehicle ownership rates and more vehicle usage, resulting in an upward tendency for both transport demand and emissions. Therefore, emissions reductions are not achieved merely by increased housing prices or improved local economic conditions. Rather, it is necessary to link housing policies that enable various income groups to reside together (e.g., rental housing in the city center) with the facilitated public transit.

In summary, the contributors to emission increase in the metropolitan area are not merely from development density or transport infrastructure, but rather from a complex interplay between concentrated employment and commercial functions, freight logistics structures, and socioeconomic conditions. This implies that low-carbon urban transition strategies must extend beyond transport mode policies, while requiring multi-level policy interventions, including the supply of zero-emission vehicles, the spatial dispersion of commercial functions, and transportation demand management.

Conversely, several indicators exhibited neutral or negative (–) associations with CO₂ emissions. In particular, destination accessibility (ease of shopping) and mixed land use were found to reduce emission intensity by promoting localized travel behavior and shorter trip distances. Additionally, the demographic variable representing the share of the elderly population showed a neutral effect, implying limited behavioral elasticity in transport emissions.

4.2.3. Emission Reduction Factors: Local Self-Containment

Conversely, ease of shopping (V18) exerted a significant negative impact on CO₂ emissions ($\beta = -0.60\sim -0.41$). This indicates that areas with higher destination accessibility enable residents to resolve travel needs locally via walking or cycling, proving that ensured local self-containment is effective for emission reduction. Therefore, carbon emissions from the transportation sector in the metropolitan area cannot be explained simply by high density. Rather, it was confirmed that excessive concentration of employment hubs increased emissions; in contrast, dispersion of residential functions and encouragement of short-distance travel would appear to curb emissions. This result underpins the finding from the previous cluster analysis that the ‘decoupling’ city type can effectively achieve local self-containment.

5. Discussion and Conclusions

In this study we verified the impact of the TOD 7D factors on road transport CO₂ emissions across 66 administrative units (cities, counties, and districts) in the Seoul metropolitan areas, through cluster analysis and hierarchical regression analysis.

The results of the cluster analysis were found to be consistent with those of the hierarchical multiple regression model, thereby validating the robustness of the regression findings. In particular, both analyses consistently revealed the coexistence of “decoupling” and “coupling” city types, indicating that TOD factors can either mitigate or exacerbate emissions depending on the urban context.

First, cluster analysis confirmed that even within the same high-density development structure, there may be various emission pathways. Some urban units with high-density and high-activity structures achieved emission reduction by combining public transit networks with neighborhood-based travel. But other cities saw more emissions from higher total traffic activity due to concentrated employment and commercial functions. These outcomes present that the simplistic proposition “high density = low carbon” cannot apply to the Seoul metropolitan area case. Instead, the qualitative characteristics of urban structure and policy intervention status are key determinants of emission pathways.

Second, hierarchical regression analysis clearly demonstrated the scalability of the TOD 7D framework. Physical density (3D) alone is insufficient to fully explain differences in the level of emissions among urban units; however, explanatory power significantly improved when public transit accessibility (5D) and socioeconomic factors (7D) were incorporated in phases. Furthermore, employee density, railway stations, and bicycle lane infrastructure are typical contributors to higher transportation efficiency; however, in the metropolitan area, these elements were found to be associated with more emissions through more frequent travel across wide areas, and more commercial and logistics activities. This empirically demonstrates that TOD factors can function both to curb and increase emissions depending on the context. On the other hand, in areas with high Destination Accessibility within a region, improved short-distance travel curbed emissions, confirming that local self-containment is a core factor in emission reduction.

The contributions of this study to the relevant fields of research (in particular, urban planning, transportation, and carbon emissions management) are as follows:

(1) The hierarchy of explanatory power, from basic TOD to TOD 7, is confirmed; the built environment, transportation infrastructure, and socioeconomic factors are important factors that determine the level of emissions.

(2) Our analysis demonstrated that TOD factors can have opposing effects—curbing or increasing emissions—depending on context; the concepts of the ‘Paradox of Concentration’ and ‘Two-faced Infrastructure’ are discussed with particular reference to the Seoul metropolitan area. These findings provide a theoretical grounding for the two interrelated phenomena observed in this study—the Paradox of Concentration and the Two-faced Nature of Infrastructure. The Paradox of Concentration explains how compact, high-density urban forms, while designed to reduce travel distances, can paradoxically increase transport-related CO₂ emissions through intensified economic clustering, higher trip frequency, and logistic flows within limited urban space. This pattern, evident in the emission-increase clusters identified in Seoul’s core districts, demonstrates that agglomeration economies coexist with rising mobility demand, producing nonlinear effects between density and emissions.

Conversely, the Two-faced Nature of Infrastructure highlights the dual mechanism of transport investment, which enhances accessibility and public transit use but simultaneously induces rebound effects by stimulating additional travel demand. The empirical results confirm this duality—areas with extensive rail networks and high fiscal capacity

showed both reduced emission intensity per trip and increased total emissions at the metropolitan scale. Thus, these mechanisms jointly underscore that TOD effectiveness depends on the balance between accessibility improvement and demand management within dense metropolitan systems.

(3) Inter-city heterogeneity was clearly demonstrated; accordingly, we identified differentiated policy implications per type through a combination of cluster analysis and regression analysis. Our findings also suggest that, in terms of policy, simple compact development strategies alone are insufficient for achieving sustainable emission reduction. Rather, the reduction is possible only when accompanied by public transit infrastructure supply, demand management, local self-containment, and transition to zero-emission logistics systems. In addition, the “Demand Management” and “Demographics” dimensions of the 7D framework warrant deeper theoretical and empirical investigation. Although only briefly discussed in this study, these dimensions are essential for understanding the behavioral and social mechanisms that shape transport-related CO₂ emissions. Strengthening these two dimensions would substantially enhance both the comprehensiveness and the policy relevance of the 7D framework, allowing for a more nuanced interpretation of how physical, behavioral, and social factors interact to determine urban transport emissions. Building on these findings, more differentiated and actionable policy recommendations can be developed for each city type identified through cluster analysis. For high-density core cities, where emissions are primarily driven by congestion and concentrated logistics, integrated strategies combining demand management, congestion pricing, and zero-emission freight systems would be most effective. In contrast, low-density peripheral cities should prioritize improving public transit connectivity, encouraging mixed-use development, and enhancing last-mile accessibility. Medium-density transitional areas may require hybrid approaches that balance improved public transit service levels with car-dependence management. These type-specific policy combinations can strengthen the practical applicability of TOD-based carbon-reduction strategies across metropolitan regions.

In addition, future research should also consider the policy transferability and scalability of TOD-based carbon-reduction strategies. Comparative analyses across different institutional systems and governance structures would help determine how the 7D-framework findings can be adapted to cities with varying levels of infrastructure maturity, economic capacity, and cultural conditions.

Despite the extensive body of research on TOD and transport-related carbon emissions, several conceptual and methodological gaps remain. This study provides an incremental contribution rather than a wholly novel approach, addressing three specific aspects. First, it operationalizes a multi-dimensional TOD framework that systematically integrates the 3D, 5D, and 7D factors within a single analytical structure, allowing for empirical comparison across dimensions. Second, it estimates transport-related CO₂ emissions at the urban-administrative level (cities, counties, and districts) in the Seoul Metropolitan Area, thereby linking regional-scale emission patterns with localized TOD characteristics. Third, it offers an interpretation of positive correlations between certain TOD indicators (e.g., employment density, rail accessibility) and emission levels, explaining them through the “Paradox of Concentration” and “Two-faced Infrastructure” phenomena.

It should be noted that, like most cross-sectional studies on TOD and transport-related outcomes, this research is subject to limitations in identifying causal relationships due to potential simultaneity and spatial sorting effects. Although the analysis reveals statistically significant associations between TOD factors and CO₂ emissions, these findings should be interpreted as correlational rather than strictly causal. Future studies could enhance causal inference by applying instrumental variable approaches (e.g., historical rail alignment, topographic slope, or geological characteristics), natural experiments, or panel-based

Difference-in-Differences (DID) methods to better isolate the temporal and structural effects of TOD. Notwithstanding the value of these results, there are a number of limitations that should be pointed out; the study was based on cross-sectional data and linear regression models, which do not sufficiently reflect temporal changes or spatial interactions.

Future research should address these limitations through long-term trend analysis using panel data, spatial econometrics, and the application of nonlinear models. Furthermore, since this study focused exclusively on the Seoul Metropolitan Area, future research should evaluate the generalizability and cross-regional applicability of TOD effects through comparative analyses involving different urban structures, development stages, and cultural contexts.

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