Beyond the density dilemma: Do denser municipalities combine lower transport emissions with greater climate-related burdens? Evidence from South Kore

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Abstract

Compact development is widely promoted for low-carbon mobility, while flood and heat risks are often addressed separately. This separation leaves unresolved whether denser urban form lowers transport-sector emissions at the cost of greater climate-related burdens. Using a 2019–2023 panel of 229 South Korean municipalities, this study examines urban density in relation to per-capita VKT-based transport-sector greenhouse gas emissions, VKT, reported hydrometeorological damage, and heat illness. Staged panel models, municipality fixed effects, between-within decomposition, zero-outcome models, spatially robust inference, a 120-specification nonlinearity audit, and joint-outcome diagnosis assess identification and robustness.

Higher-density municipalities have lower per-capita transport-sector emissions and VKT, but these associations arise mainly from persistent differences between municipalities rather than observed densification within municipalities. Hydrometeorological damage and heat illness do not rise systematically with density, and no stable density threshold supports a common planning standard. The clearest result is a pronounced density gradient in joint outcomes. In the lowest-density quintile, 33 of 46 municipalities occupy the high-emission–high-burden configuration in both outcome spaces. In the highest quintile, 37 municipalities occupy the low-emission–low-hydrometeorological-burden configuration and 41 occupy the low-emission–low-heat-burden configuration; neither space contains a high-emission–high-burden municipality. Density-configuration associations are substantial (Cramér's V = 0.430 and 0.459) and remain strong across aggregation, cut-point, temporal, and alternative-density checks. The findings challenge the assumption that lower-density municipalities are comparatively protected from climate-related burdens and support place-specific integration of mobility, land use, infrastructure, health, and risk reduction rather than a uniform density prescription.

Keywords: urban density; compact urban development; transport-sector greenhouse gas emissions; hydrometeorological damage; heat illness; density dilemma; Korean municipalities

1. Introduction

Cities must reduce greenhouse gas emissions while limiting the losses and health burdens associated with a changing climate. These objectives are often assigned to different policy domains. Transport and land-use planning focus on travel demand, accessibility, and emissions, whereas flood management and heat-health planning focus on hazards, exposure, vulnerability, and response capacity. Yet the underlying urban system is shared. The spatial distribution of people, activities, infrastructure, and services shapes both everyday mobility and the consequences of climatic extremes (IPCC, 2023; Sharifi, 2020, 2021).

Compact urban development sits at the centre of this interdependence. Concentrating residents, destinations, and public transport can shorten travel distances, improve accessibility, reduce automobile dependence, and lower per-capita transport emissions. This logic has made density a longstanding component of low-carbon urban planning (Cervero & Kockelman, 1997; Ewing & Cervero, 2010; Gudipudi et al., 2016). The same concentration, however, may coincide with greater impervious cover, runoff pressure, heat storage, concentrated assets, and neighbourhoods in which failures of drainage or cooling affect many people at once. This possibility motivates what we call the urban density dilemma: the proposition that a spatial form favourable to transport mitigation may impose higher climate-related burdens.

The strong form of this dilemma should not be assumed. Dense municipalities may also concentrate hospitals, emergency services, drainage systems, cooling access, public facilities, and administrative capacity. These conditions can limit the translation of hazards into reported losses and illness. Lower-density municipalities may face a different combination of disadvantages. They can be highly automobile-dependent while also encompassing extensive riverine, coastal, or mountainous exposure, older populations, outdoor employment, dispersed settlements, and long distances to medical and emergency services. Urban density may therefore be associated with a transport advantage without producing a uniform flood or heat penalty.

Existing research offers important but incomplete evidence. The built-environment literature has established consistent associations between density, destination accessibility, street-network design, vehicle travel, and transport-related emissions (Cervero & Kockelman, 1997; Ewing & Cervero, 2010; Gately et al., 2015; Boeing et al., 2024). Flood and heat research points to a wider set of determinants. These include hazard intensity, topography, land cover, drainage, asset exposure, housing, health, occupation, and social vulnerability (Brody et al., 2013; Lee & Brody, 2018; Chang et al., 2021; Choi et al., 2022). These literatures are rarely integrated at the same municipal scale. As a result, it remains unclear whether compactness generates a general trade-off between transport mitigation and climate-related burdens or whether municipalities occupy more differentiated joint positions.

A second difficulty concerns interpretation. Denser municipalities are not simply less dense municipalities at a later date. Their transport systems, economic functions, infrastructure, institutions, and demographic profiles have co-evolved. Cross-municipality density-emission associations cannot therefore be interpreted automatically as effects of densifying a given municipality, especially in a short panel with limited within-municipality change.

A third difficulty concerns nonlinearity. Planning debates often seek a density level at which transport benefits flatten or climate burdens begin to rise. Such a benchmark is credible only if it remains stable across outcome transformations, density definitions, controls, resampling, and out-of-sample validation. Otherwise, the cut point is sample-dependent rather than structural.

This study addresses these problems using a 2019–2023 panel of all 229 Korean municipalities. Korea provides a demanding national setting for the density dilemma. Very high-density metropolitan districts coexist with rural, coastal, mountainous, industrial, and rapidly ageing municipalities under a common statistical and administrative system. The contrast allows us to examine whether lower density is associated with greater transport emissions but lower climate-related burdens, as the strong dilemma would imply, or whether the joint pattern is more heterogeneous.

The study asks three questions. First, is urban density associated with lower per-capita VKT-based transport-sector greenhouse gas emissions and VKT, and is it simultaneously associated with greater reported hydrometeorological damage or heat-illness burden? Second, are the observed relationships driven primarily by persistent differences between municipalities or by change within municipalities, and does any common density threshold remain stable across specifications and validation exercises? Third, how are low- and high-emission municipalities distributed across low- and high-burden configurations along the density gradient?

This study makes three linked contributions. First, it evaluates the transport-mitigation premise and two climate-related burdens within the same national municipal panel. Second, it makes the source of identification explicit by separating persistent cross-municipality differences from within-municipality change and by auditing whether nonlinear cut points survive resampling and validation. Third, it moves beyond separate mean associations to test whether joint emission-burden configurations follow a systematic density gradient, thereby revealing lower-density double burdens that sector-specific analyses can miss.

Section 2 develops the joint-outcome framework. Sections 3 and 4 describe the data and methods. Section 5 presents the results, Section 6 discusses their implications, and Section 7 concludes.

2. Literature and conceptual framework

2.1 Urban density and transport-sector greenhouse gas emissions

The transport case for compact urban form is one of the most established arguments in planning research. The classic 3Ds framework links density, land-use diversity, and design to trip generation, mode choice, and travel distance (Cervero & Kockelman, 1997). Subsequent synthesis shows that destination accessibility and proximity to public transport also influence vehicle travel and automobile dependence (Ewing & Cervero, 2010). Density is therefore not simply a demographic attribute. It changes the distances between origins and destinations, the viability of transit, and the relative cost of car use.

Observed emissions research supports this mechanism. Dense cities and urban regions often exhibit lower per-capita fuel use or greater carbon efficiency, especially where density is combined with accessible destinations and public transport (Newman & Kenworthy, 1989; Gudipudi et al., 2016). Road-based inventories further demonstrate that traffic-related emissions can be measured as an urban activity outcome rather than inferred only from planning theory (Gately et al., 2015). Scenario studies reach a similar conclusion: infill-oriented development can generate lower future passenger-vehicle greenhouse gas emissions than continued low-density expansion (Hankey & Marshall, 2010).

The relationship is not uniform. Urban form is multidimensional, and density is only one component of compactness (Galster et al., 2001). Land-use mix, street connectivity, regional accessibility, network structure, and metropolitan scale can all alter travel and emissions outcomes (Mindali et al., 2004; Mohajeri et al., 2015; Boeing et al., 2024). Nonlinear studies also show that the marginal association between density and emissions can vary across the observed range and with the spatial unit of analysis (Hong, 2017; Ribeiro et al., 2019). Recent Korean evidence similarly indicates that the relationships among compactness, VKT, and carbon emissions differ by urban size (Mun & Jung, 2025a, 2025b).

These findings motivate two analytical choices. The first is to treat density as a transparent first-order axis rather than as a complete measure of urban form. The second is to test whether the negative transport association is robust across models and density groups without assuming that it represents a causal effect of densification. We therefore expect higher-density municipalities to exhibit lower per-capita transport-sector emissions and VKT, while recognising that much of this relationship may reflect persistent differences in urban structure.

2.2 Urban density and climate-related burdens

The relationship between density and climate-related burdens is more ambiguous. The physical pathways behind a high-density penalty are plausible. Concentrated development can increase imperviousness, accelerate runoff, reduce infiltration, store heat, and place more people and assets within a limited area. These mechanisms can increase flood exposure or heat stress under adverse conditions.

Flood losses, however, cannot be reduced to density alone. They emerge from the interaction of meteorological hazards, topography, riverine and coastal exposure, development patterns, drainage, asset values, and protective landscapes. Studies of the Gulf Coast and the United States more broadly show that development form and open-space protection condition flood losses (Brody et al., 2013; Brody & Highfield, 2013). Coastal wetlands can substantially reduce storm damage (Narayan et al., 2017), while low-impact development can moderate the runoff consequences of urbanisation (Pour et al., 2020). In Seoul, land-use composition and compact design are associated with flood losses in ways that do not support a simple density penalty (Lee & Brody, 2018). Social-ecological-technological assessments further show that exposure, sensitivity, and response capacity vary independently across urban systems (Chang et al., 2021). Recent evidence on high-density development and urban flooding similarly emphasises moderation rather than a uniform effect (Son et al., 2023).

Heat-related illness is also produced by multiple pathways. Urban form affects land cover, ventilation, heat storage, and the urban heat island. Yet illness depends on age, occupation, housing, cooling access, health-care accessibility, and social protection. Sprawling metropolitan form has been associated with the frequency of extreme heat events (Stone et al., 2010), while the effect of greenness on heat-related mortality varies across cities (Choi et al., 2022). Reviews of compactness and urban heat emphasise the role of design, climate, and comfort strategies (Giridharan & Emmanuel, 2018). Cross-city evidence from China likewise shows that macro-scale form–temperature relationships differ by climate zone, city size, and industrial structure (Su et al., 2021).

This literature has two implications. First, the strong density-dilemma hypothesis is empirically testable but not theoretically predetermined. Higher density may increase physical exposure in some settings while coinciding with stronger infrastructure and service capacity in others. Second, reported losses and illness should not be interpreted as direct measures of adaptation effectiveness. They are realised burdens generated by the joint influence of hazards, exposure, vulnerability, and response capacity. A municipality with low reported damage may be well protected, may have experienced less severe hazards, or may report losses differently.

The appropriate empirical question is therefore limited but important. Do higher-density municipalities systematically exhibit greater reported hydrometeorological damage or heat-illness burden? If not, the strong form of the density dilemma is not supported at the municipal scale. This conclusion would not establish that density is protective. It would show that density alone is insufficient to explain climate-related burdens.

2.3 From a universal trade-off to joint outcome configurations

Urban climate research increasingly recognises that mitigation and adaptation measures can generate synergies, conflicts, and co-benefits (Sharifi, 2020, 2021). Compact development is a prominent example because it reorganises transport, land use, infrastructure, and exposure simultaneously. Yet the empirical evaluation of these interactions is often reduced to separate average effects. Such an approach can miss how municipalities combine outcomes.

A joint-outcome perspective asks a different question. Instead of determining whether density is favourable or unfavourable in the abstract, it identifies how emissions and climate-related burdens coincide within municipalities. This logic is consistent with recent multi-outcome research on urban configuration, which evaluates urban form across emissions, heat, air pollution, traffic, and health rather than through a single sustainability indicator (Iungman et al., 2024).

We define four a priori diagnostic configurations. The first combines low transport emissions with low climate-related burden. The second combines low emissions with high burden. The third combines high emissions with low burden. The fourth combines high emissions with high burden and is described as a double burden. These categories are not latent classes and do not establish causal trade-offs. They are relative positions in the observed municipal distribution.

The empirical contribution lies in how these configurations are distributed across density quintiles. A universal density dilemma would predict that higher-density municipalities move systematically toward the low-emission–high-burden configuration. A uniformly favourable compact-city pattern would predict concentration in the low-emission–low-burden configuration. A more differentiated system would contain all four configurations, with their prevalence depending on municipal context.

This framework also has a practical advantage. Municipal governments rarely begin with enough evidence to estimate the causal effect of every land-use or infrastructure intervention. They still need to identify where transport reform, flood-risk reduction, heat-health protection, or integrated action warrants closer evaluation. Joint-outcome configurations provide a first-stage diagnostic rather than a final policy prescription.

2.4 Analytical expectations

The literature yields four expectations. Higher urban density should be associated with lower per-capita transport-sector greenhouse gas emissions and VKT. No unambiguous direction is expected for hydrometeorological damage or heat illness because opposing pathways operate. Persistent between-municipality differences should explain more of the association than short-term within-municipality change. If the strong density dilemma does not hold, joint outcomes should extend beyond a simple progression from low-density safety to high-density trade-off. Figure 1 summarises this framework.

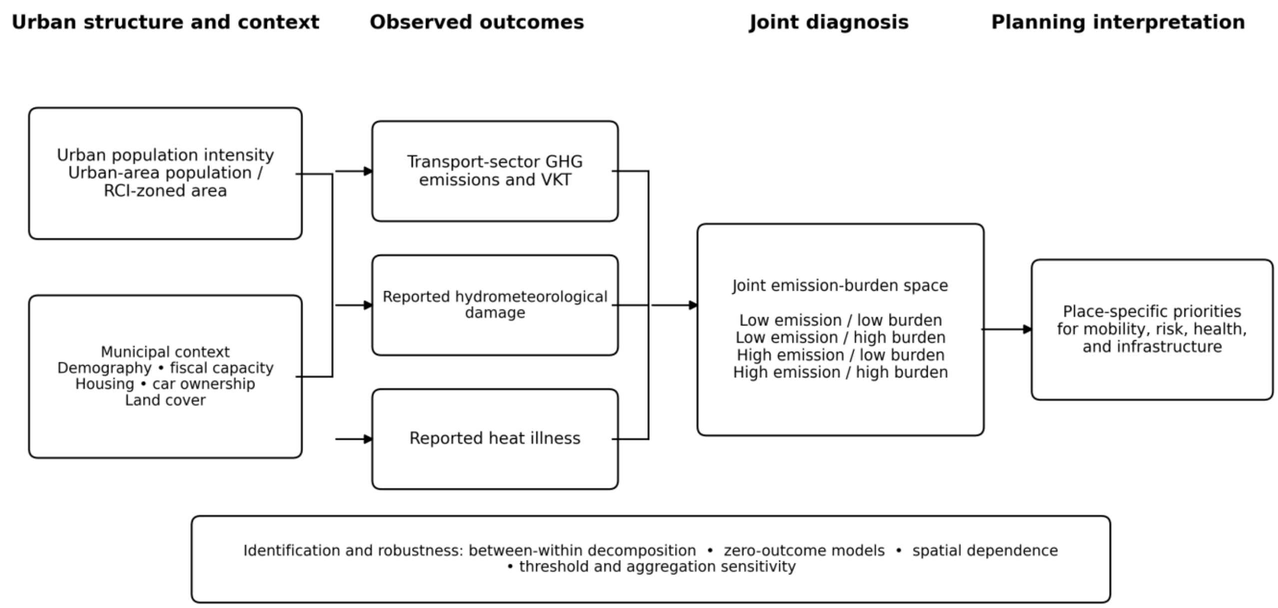

Figure 1. *Analytical framework. Urban density is used as a first-order planning axis. Transport-sector greenhouse gas emissions and two reported climate-related burdens are examined separately and jointly; robustness analyses address identification, zero-valued outcomes, spatial dependence, threshold instability, and aggregation sensitivity.*

3. Data and measurement

3.1 Municipal panel and fixed geography

The analysis uses an annual panel of 229 Korean municipalities from 2019 to 2023. The fixed geography includes autonomous districts, cities, counties, Sejong as a single municipality, and Jeju-si and Seogwipo-si as separate administrative cities. Administrative changes are harmonised to this common geography so that municipal units remain comparable over time.

The panel combines official population, land-use zoning, transport emissions, vehicle travel, natural-disaster, heat-illness, fiscal, housing, vehicle-ownership, land-cover, and regional statistics. Transport-sector emissions, VKT, heat illness, and the main controls are available for 2019–2023. Hydrometeorological damage is available for 2020–2023; 2019 is retained as missing rather than coded as zero. The full panel contains 1,145 municipality-year observations. Density-based models include 228 municipalities because Ongjin-gun has both zero urban-area population and zero residential-commercial-industrial zoned area in the source statistics, making the density ratio undefined rather than zero.

3.2 Urban density

The conceptual term in this paper is urban density. The operational measure is urban-area population intensity over residential, commercial, and industrial zoned area. For municipality i in year t,

$$D_{it} = \frac{UrbanPopulation_{it}}{RCIZonedArea_{it}}.$$

The measure is expressed as persons per square kilometre and enters the regression models in natural logarithms. It captures the concentration of urban-area population relative to the land zoned for the main urban uses. It should not be interpreted as direct residential density within RCI polygons or as a complete compactness index. Land-use diversity, network connectivity, accessibility, and development intensity are not directly included.

The municipality-year mean is 10,944.9 persons per square kilometre, with a median of 7,848.4. Municipalities are also grouped into five balanced density quintiles using their 2019–2023 mean intensity. The groups contain 46, 46, 45, 46, and 45 municipalities from Q1 to Q5.

3.3 Outcomes

The principal transport outcome is per-capita VKT-based transport-sector greenhouse gas emissions, measured in tonnes of CO_2 equivalent per person. Per-capita annual vehicle kilometres travelled is used as an activity-consistent auxiliary outcome. Because the emissions inventory is partly constructed from transport activity, VKT is not treated as an independent validation measure; it indicates whether the emissions pattern is consistent with the underlying mobility activity.

Two climate-related burden indicators are examined. The first is reported monetary damage from heavy rain and typhoons, converted to real 2020 Korean won per resident. The outcome is available for 2020–2023 and includes verified zero-loss municipality-years. The second is reported heat-related illness, measured as cases per 100,000 residents for 2019–2023. Municipality-years with no reported cases are coded as zero.

These outcomes are not measures of adaptation policy or adaptive capacity. They are observed burdens. Hydrometeorological damage is influenced by hazard intensity, exposure, assets, topography, infrastructure, and reporting. Heat illness is influenced by temperature, age, occupation, housing, cooling, health services, and surveillance. The analysis therefore estimates associations with realised burdens rather than weather-normalised adaptation effects.

3.4 Controls and conditioning variables

The staged models use a parsimonious control set. Log resident population accounts for municipal scale. The elderly population ratio captures demographic vulnerability. Fiscal self-reliance represents local fiscal capacity. The old-housing ratio captures a dimension of building vulnerability. Car ownership per resident is introduced only in the final model because it is a plausible pathway linking urban form to transport outcomes.

Imperviousness and green/natural cover are examined in supplementary interaction models. Imperviousness is physically relevant to runoff and heat storage. Green/natural cover includes forests, grassland, wetlands, rivers, and other natural categories. It is therefore not equivalent to urban parks or designed green infrastructure. These variables are treated as broad municipal contexts rather than as isolated causal mechanisms.

Table 1 summarises the study design and data periods. Table 2 reports descriptive statistics on the original scales.

4. Empirical strategy

4.1 Staged panel models

We begin with descriptive density-response curves using municipality-year observations and locally weighted smoothing. These curves show the shape and support of the data but are not used for causal inference.

The main regressions estimate the association between log urban density and each outcome. For municipality i and year t,

$$Y_{it} = \alpha + \beta \ln(D_{it}) + \tau_t + \theta C_{it} + \varepsilon_{it},$$

where τ_t denotes year fixed effects and C_it denotes the staged control vector. Transport emissions and VKT enter in logarithms. Hydrometeorological damage and heat illness enter as ln(1+x) because they are non-negative, strongly right-skewed, and include zero observations.

Model 1 includes log density and year fixed effects. Model 2 adds log resident population, the elderly ratio, fiscal self-reliance, and the old-housing ratio. Model 3 adds car ownership. Model 2 is the preferred total-association specification. Model 3 is interpreted as a mechanism-adjusted sensitivity model because car ownership may mediate part of the urban-form relationship with transport outcomes.

All pooled models use municipality-clustered standard errors with finite-sample correction. Raw-scale models, quadratic terms, and density-quintile models are reported as functional-form checks.

4.2 Between–within identification and robustness

A central concern is whether the pooled association reflects persistent differences between municipalities or change within municipalities. We address this in two ways. First, municipality and year fixed-effects models use only within-municipality variation. Second, a between–within hybrid model decomposes each time-varying predictor into a municipality mean and a deviation from that mean. Let $d_{it} = \ln(D_{it})$. The specification is:

$$Y_{it} = \alpha + \beta_W(d_{it} - \bar{d}_i) + \beta_B \bar{d}_i + \theta_W(C_{it} - \bar{C}_i) + \theta_B \bar{C}_i + \tau_t + \varepsilon_{it}.$$

The within coefficient β_W represents the association with temporal change relative to a municipality's own mean. The between coefficient β_B represents persistent cross-municipality differences. Because the panel is short, the hybrid model is especially useful for making the empirical source of variation explicit.

The climate-burden outcomes require additional checks. We estimate an occurrence model for whether the outcome is positive, a positive-part log-linear model conditional on a positive observation, and a Poisson pseudo-maximum-likelihood model with population offset. PPML is used as a robust conditional-mean estimator for non-negative outcomes; it is not interpreted as a literal count process for monetary damage.

Spatial dependence is assessed using municipal boundaries and multiple spatial weights. Global Moran diagnostics are applied to residuals. Province fixed effects absorb broad regional differences, and spatial-HAC covariance estimates are evaluated with 50, 100, and 200 kilometre Bartlett kernels (Moran, 1950; Conley, 1999). Multiple spatial tests are adjusted using the Benjamini–Hochberg procedure (Benjamini & Hochberg, 1995).

Influence is examined by leaving out each municipality in turn. These checks assess whether the sign or magnitude of the pooled density coefficient depends on a single municipal case.

Supplementary Tables S1-S5 and Figures S2-S5 report the full functional-form, fixed-effects, zero-outcome, spatial, and influence diagnostics.

4.3 Nonlinearity and threshold stability

The presence of a universal density threshold is tested rather than assumed. We examine continuous-hinge and segmented jump-and-slope specifications over the interior of the density distribution. These models follow the logic of threshold analysis but are not presented as formal Hansen panel-threshold estimates (Hansen, 1999).

The stability audit spans five outcomes, transformed and raw outcome scales, the main and alternative density axes, three control specifications, and two nonlinear forms, producing 120 specifications. Candidate cut points are then evaluated using municipality bootstrap resampling, leave-one-municipality-out analysis, and municipality-grouped cross-validation. A threshold is considered substantively meaningful only if its location and slope pattern are stable across these checks.

4.4 Joint outcome diagnosis

The final analysis combines transport emissions with each climate-related burden at the municipality level. We calculate original-scale annual means for 2019–2023 transport emissions, 2020–2023 hydrometeorological damage, and 2019–2023 heat illness. Municipalities are then classified relative to the median of each outcome into four a priori configurations:

1. low emission–low burden;
2. low emission–high burden;
3. high emission–low burden; and
4. high emission–high burden.

The categories describe relative positions in the sample. They do not identify latent urban types, causal trade-offs, or normative optima.

We test the association between the four configurations and density quintiles using a 5×4 Pearson chi-square statistic, a 9,999-permutation p-value, and Cramér's V with municipality-bootstrap intervals. We also compare Q5 with Q1, evaluate ordered trends, and test sensitivity to alternative aggregation rules, cut points, time samples, and density measures. Strictly non-dominated observations are retained only as supplementary diagnostics because their membership is sensitive to aggregation.

5. Results

5.1 Urban density and transport-sector outcomes

The transport results provide the clearest support for the compact-city argument. The descriptive curves show a broad decline in both per-capita transport-sector greenhouse gas emissions and VKT as urban density increases. The pattern is strongest across the central range of the data and is not driven solely by the highest-density municipalities.

Table 3 reports the staged estimates, while Figure 2 shows the descriptive response curves. In Model 2, the elasticity of per-capita transport-sector emissions with respect to urban density is -0.237 (SE=0.038, $p<0.001$). A 10% difference in density is associated with approximately 2.4% lower per-capita emissions, conditional on the included controls. The corresponding VKT elasticity is -0.225 (SE=0.034, $p<0.001$). Both results use 1,140 municipality-year observations from 228 municipalities.

Adding car ownership reduces the absolute coefficients to -0.145 for emissions and -0.133 for VKT. The attenuation is consistent with car ownership forming part of the pathway between urban form and transport activity. It does not constitute a formal mediation estimate. The negative coefficients remain statistically distinguishable from zero in the log models.

Raw-scale estimates are less stable after car ownership is included, which reinforces the value of reporting functional-form sensitivity. Density-quintile models nevertheless show a clear ordering: the highest-density municipalities have markedly lower transport outcomes than the lowest-density municipalities. The central transport conclusion is therefore robust in direction but remains associational.

5.2 Climate-related burdens

The climate-burden results do not support a universal high-density penalty. In the pooled Model 2 specification, log density is negatively associated with ln(1+hydrometeorological damage), with a coefficient of -1.904 (SE=0.200, $p<0.001$). It is also negatively associated with ln(1+heat-illness burden), with a coefficient of -0.413 (SE=0.049, $p<0.001$). These coefficients should not be interpreted as simple elasticities because the outcomes use $\ln(1+x)$ transformations and contain many small or zero values.

Figure 3 decomposes the climate-burden estimates across occurrence, positive-part, and PPML models. For hydrometeorological damage, density is negatively associated with the probability of any reported damage, positive conditional magnitude, and the population-normalised PPML mean. The Model 2 coefficients are -1.742, -0.730, and -0.431, respectively. For heat illness, the corresponding coefficients are -0.912, -0.540, and -0.625. All are statistically significant at conventional levels.

These results do not mean that dense municipalities are inherently safer or better adapted. The outcomes combine hazard occurrence, exposure, vulnerability, infrastructure, and reporting. The negative associations show only that higher density is not accompanied by a systematic increase in reported municipal burdens. Rain-only damage is less robust than the broader hydrometeorological measure and is retained as an auxiliary result.

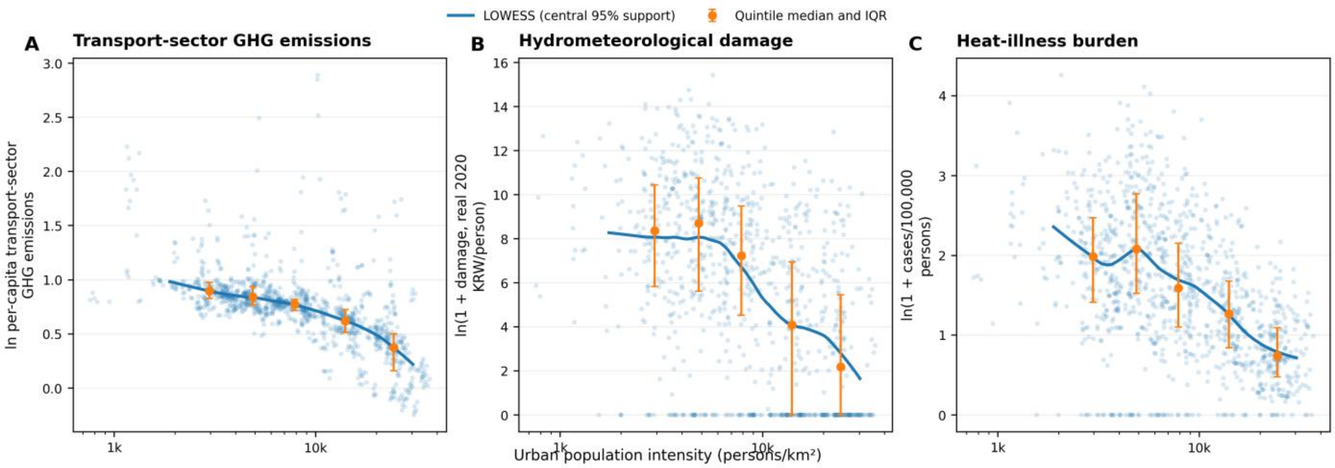

Figure 2. Descriptive density-response curves. Small points are municipality-year observations. LOWESS curves are restricted to the central 95% support of log density. Large points show urban-density-quintile medians and interquartile ranges.

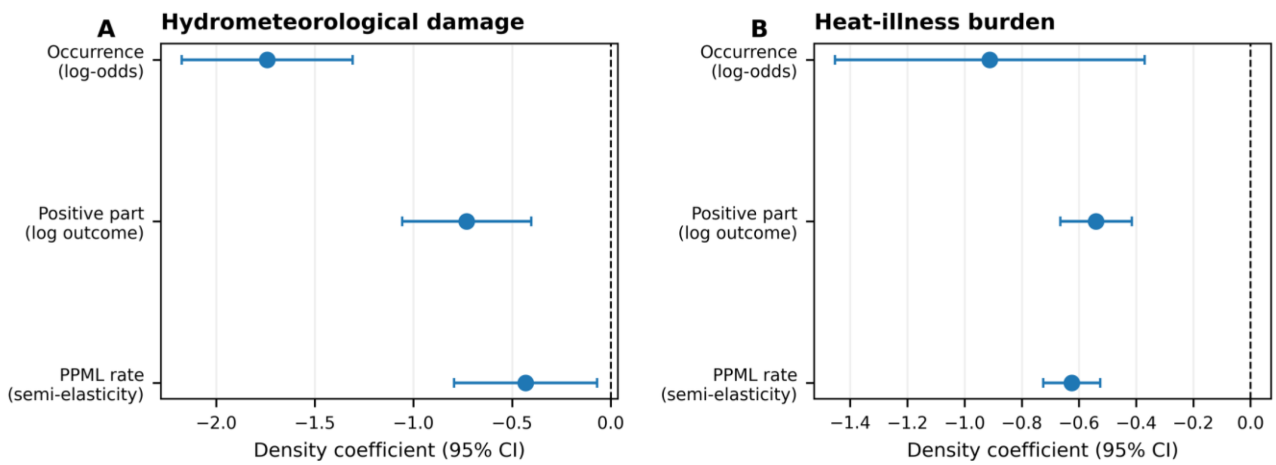

Figure 3. Alternative formulations of reported climate-related burdens. Points and bars show density coefficients and 95% confidence intervals from occurrence, positive-part, and population-offset PPML models. Coefficients are on different scales and should not be compared as common effect sizes.

5.3 What the panel identifies: between-municipality structure, spatial dependence, and threshold instability

Table 4 and Figure 4 show that the pooled transport association is driven primarily by differences between municipalities. The within-municipality standard deviation of log density is only about 5.0–5.7% of the between-municipality standard deviation. Municipality fixed-effects estimates for transport emissions and VKT are not statistically distinguishable from zero: the Model 2 within coefficients are 0.186 and 0.059. The between coefficients are -0.239 and -0.226, both with $p<0.001$.

The same pattern appears for heat illness. The within coefficient is imprecise, whereas the between coefficient is -0.413 and highly significant. Hydrometeorological damage has a negative within coefficient that is borderline at the 5% level and a strongly negative between coefficient. These results show that the main evidence concerns persistent municipal structures rather than observed densification over five years.

Spatial analysis changes the precision of the climate-burden estimates but not the main interpretation. Residual hydrometeorological and rain-only burdens remain strongly clustered across neighbouring municipalities after province and year fixed effects. Heat-illness residuals show weaker but detectable clustering. At a 100-kilometre spatial-HAC bandwidth, the province-fixed-effect coefficients remain negative for all four main outcomes. They are -0.117 for transport emissions (p=0.019), -0.104 for VKT (p=0.024), -0.749 for hydrometeorological damage (p=0.008), and -0.281 for heat illness (p=0.001). The rain-only result is bandwidth-sensitive and is not treated as a main finding.

Leave-one-municipality-out estimates preserve the sign of every main pooled coefficient. Shinan-gun affects the magnitude of the transport coefficients, especially after car ownership is included, but its exclusion does not reverse the result.

The threshold audit rejects a common planning cut-off. Candidate values vary widely across outcome scales, density definitions, controls, and nonlinear forms. Bootstrap intervals are broad for the transport outcomes, leave-one-municipality-out shifts are substantial, and grouped cross-validation yields only small improvements over linear models. None of the audited candidates meets the pre-specified stability criteria. The evidence therefore supports a continuous cross-municipality gradient rather than a single structural threshold.

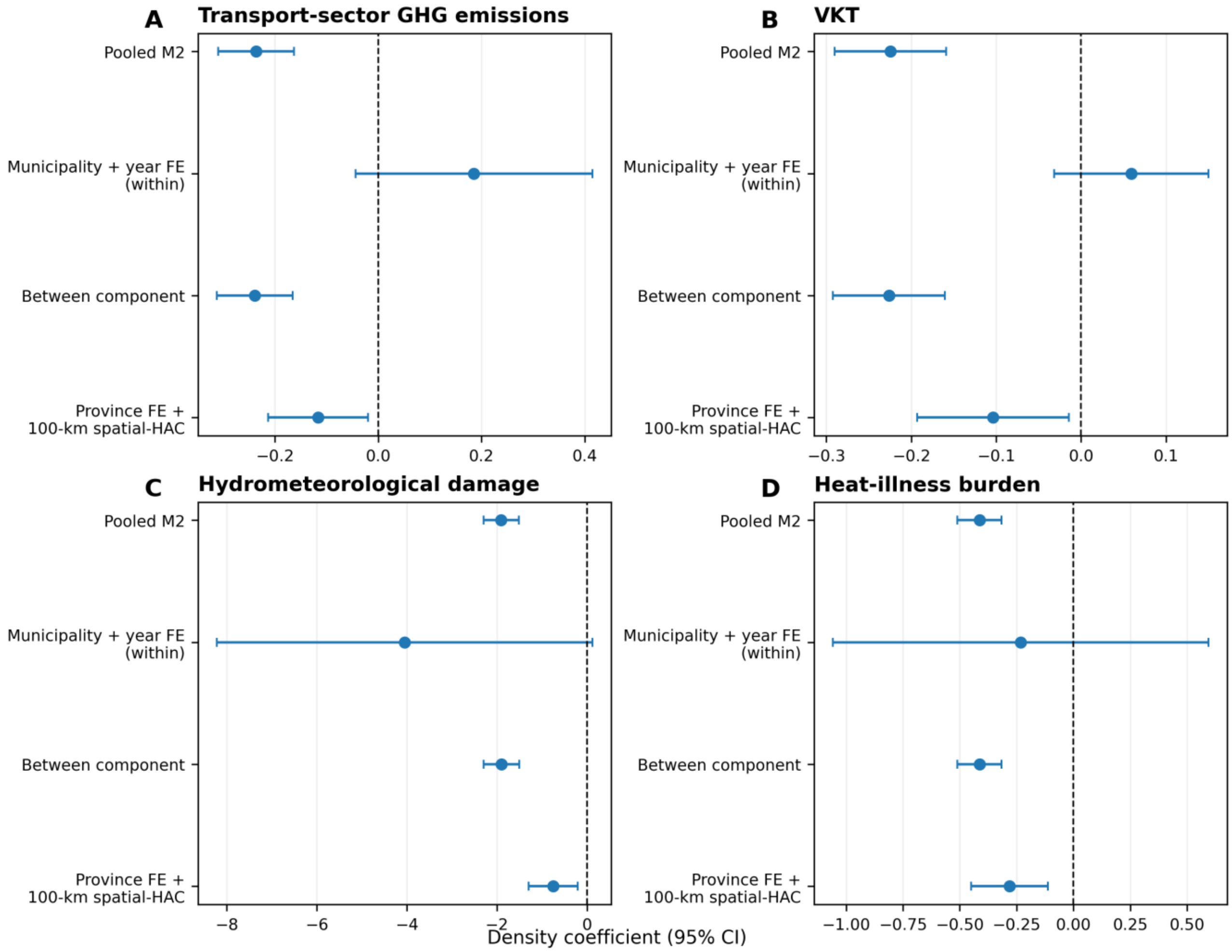

Figure 4. Identification and spatial robustness. Points and bars show density coefficients and 95% confidence intervals. The between component captures persistent cross-municipality differences; the municipality fixed-effects estimate uses only within-municipality change. Municipality fixed-effects and hybrid within estimates coincide numerically, so only the fixed-effects estimate is shown. The spatial model includes province and year fixed effects with a 100-km same-year spatial-HAC covariance.

5.4 Joint outcome configurations across density quintiles

Table 5 provides the clearest numerical synthesis. Figure 5 maps the joint outcome spaces, and Figure 6 shows their distribution across density quintiles. In the transport-emissions–hydrometeorological-damage space, 86 municipalities occupy the low-emission–low-burden configuration, 28 the low-emission–high-burden configuration, 28 the high-emission–low-burden configuration, and 86 the high-emission–high-burden configuration. These totals are distributed very unevenly across density quintiles.

In Q1, only three municipalities occupy the low-emission–low-burden configuration, while 33 occupy the high-emission–high-burden configuration. The corresponding counts in Q5 are 37 and zero. The middle quintiles show a gradual transition rather than an abrupt break. The association between density quintile and configuration is strong: $\chi^2(12)=126.29$, permutation p=0.0001, and Cramér's V=0.430, with a municipality-bootstrap 95% range of 0.394–0.494.

The heat-illness space shows an even sharper gradient. In Q1, one municipality is low emission–low burden and 33 are high emission–high burden. In Q5, 41 municipalities are low emission–low burden, none are low emission–high burden, and none are high emission–high burden. The density–configuration association is $\chi^2(12)=143.89$, permutation p=0.0001, and Cramér's V=0.459, with a bootstrap range of 0.426–0.518.

The distribution is not confined to Seoul. Most low-emission–low-burden municipalities lie outside the capital. Of the 86 municipalities in this configuration in the hydrometeorological space, 65 are outside Seoul. In the heat space, 58 of 82 are outside Seoul. The broader pattern therefore concerns the national urban system rather than a small group of metropolitan outliers.

Sensitivity tests support the configuration gradient more strongly than the exact classification of individual municipalities. Agreement with the main classification remains at least 84% across alternative aggregation rules and at least 85% when individual calendar years are omitted. Cramér's V remains in a moderate-to-strong range. The absence of any Q5 high-emission–high-burden municipality is fully stable in the heat space and highly, but not completely, stable in the hydrometeorological space. Municipalities near the median boundaries can change categories, so the configurations should be used as a screening device rather than a fixed typology.

The alternative density measures preserve the general gradient but weaken its separation. This result confirms that the empirical geography of the density dilemma depends partly on how urban concentration is represented. The main conclusion, however, remains: low-emission–low-burden configurations are concentrated at higher density, while high-emission–high-burden configurations are concentrated at lower density.

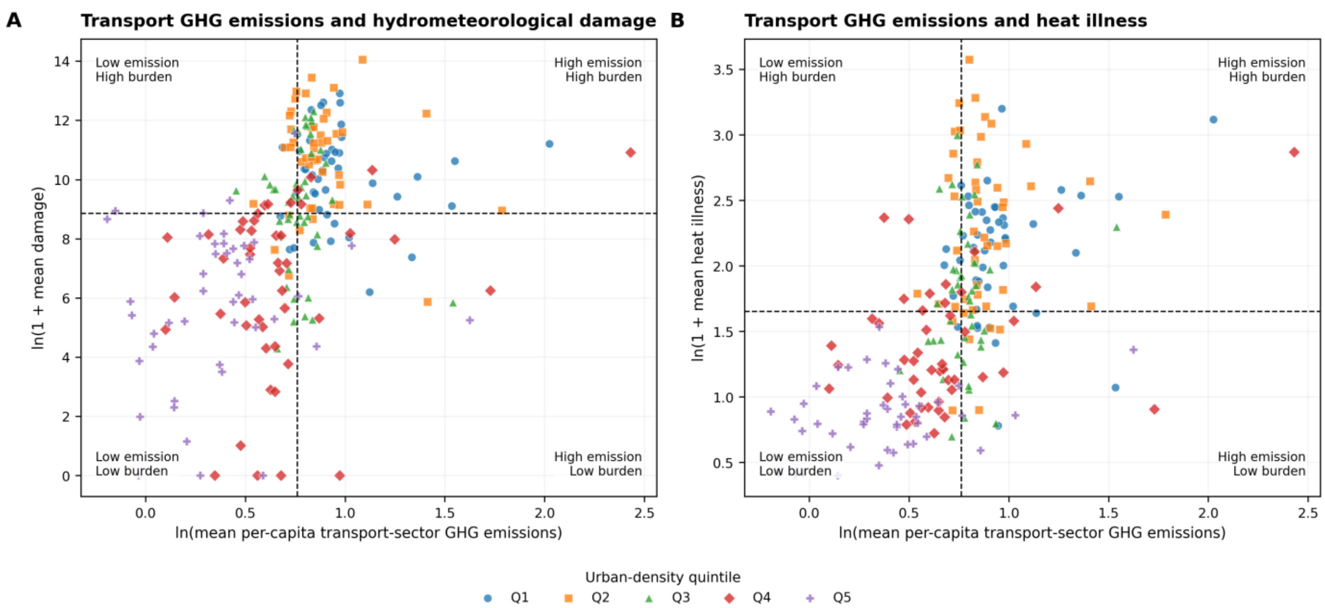

Figure 5. *Joint emission-burden spaces based on original-scale municipality arithmetic means. Dashed lines are sample medians, and points are grouped by urban-density quintile. The four quadrants are descriptive joint positions, not latent classes or causal trade-offs.*

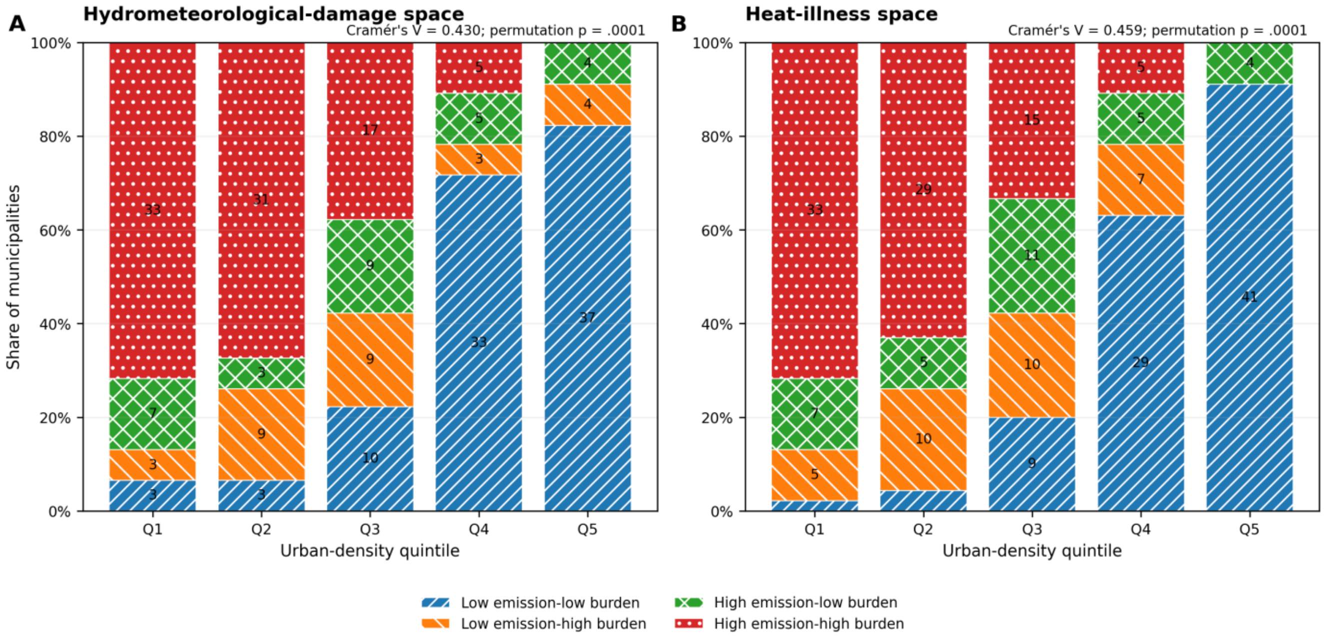

Figure 6. *Distribution of four a priori emission-burden configurations across urban-density quintiles. Hydrometeorological damage: $\chi^2(12)=126.29$, permutation p=.0001, Cramér's V=.430. Heat illness: $\chi^2(12)=143.89$, permutation p=.0001, Cramér's V=.459.*

6. Discussion

6.1 Reassessing the strong density dilemma

The study began with a plausible proposition: compact urban form may lower transport emissions at the cost of greater flood- and heat-related burdens. The Korean evidence supports the first part of this proposition but not the second as a general municipal pattern. Higher density is associated with lower per-capita transport-sector emissions and VKT. It is not systematically associated with higher hydrometeorological damage or heat-illness burden.

This result should not be simplified into a claim that density is universally beneficial. Dense neighbourhoods can face severe local flooding, heat exposure, infrastructure stress, and unequal vulnerability. The municipal evidence instead establishes an empirical boundary condition. Density alone does not generate a uniform climate-burden penalty. The realised burden depends on the hazards municipalities experience and on how exposure, vulnerability, infrastructure, services, and institutions mediate those hazards.

The absence of a stable density threshold reinforces this interpretation. The data do not support a single point at which transport benefits end or climate-related burdens begin. Urban form operates through a bundle of mobility, infrastructure, demographic, and spatial conditions. A universal density prescription would therefore compress heterogeneous systems into a number that the evidence cannot sustain.

6.2 Why identification matters for compact-city claims

The distinction between high-density places and densification is substantive, not semantic. The cross-municipality transport gradient is strong, but within-municipality density change is limited and imprecisely related to transport outcomes. Higher-density municipalities differ from lower-density municipalities in public transport, accessibility, economic function, street networks, service provision, and historical development. Density is embedded in this wider urban structure.

The results therefore support a comparative claim: municipalities with higher urban population intensity tend to have lower transport emissions and VKT. They do not establish that increasing density within a specific municipality will reproduce the same effect. Policy evaluation requires designs that observe meaningful changes in built form, transport supply, and development over longer periods or exploit plausibly exogenous interventions.

This identification result also changes how climate-related burdens should be read. The negative between-municipality associations may reflect service access, infrastructure, occupational composition, asset reporting, or regional hazard regimes. They are evidence against a universal high-density penalty, not evidence that density causes protection.

6.3 Low-density double burdens and territorial equity

The most policy-relevant finding is the concentration of high-emission–high-burden configurations in the lower density quintiles. Low density is often framed as a transport problem but an environmental refuge. The Korean municipal pattern challenges that assumption. Many lower-density municipalities combine automobile dependence with substantial hydrometeorological or heat-related burdens.

Several mechanisms may contribute. Dispersed settlement raises travel distances and limits the efficiency of public transport. Rural, coastal, riverine, and mountainous territories can encompass broad hazard exposure. Ageing populations and outdoor employment increase sensitivity to heat and disruptions. Lower service density can lengthen access to health care, emergency response, and cooling. These mechanisms are not individually identified here, but their plausible combination explains why low density is not necessarily climate-safe.

This pattern has an important territorial-equity implication. Climate policy that focuses only on metropolitan decarbonisation can overlook municipalities where carbon inefficiency and climate vulnerability are jointly concentrated. These places may have fewer fiscal and institutional resources to address either problem. The relevant policy challenge is not to reproduce metropolitan density, but to reduce mobility dependence and climate-related burdens in ways suited to dispersed and ageing settlements.

6.4 Planning implications by joint outcome configuration

Table 6 translates the four configurations into differentiated planning priorities. They are not fixed urban types or automatic policy assignments; they identify where more detailed diagnosis is warranted.

Low-emission–low-burden municipalities should preserve the accessibility and mobility conditions associated with lower transport emissions while monitoring local flood, heat, and infrastructure risks. Their relative position does not imply that all neighbourhoods are safe or that further action is unnecessary.

Low-emission–high-burden municipalities face a different problem. Their transport outcome is comparatively favourable, but reported climate-related burdens remain high. Planning should protect the mobility advantage while prioritising drainage, cooling, emergency access, health protection, and site-specific risk reduction.

High-emission–low-burden municipalities require stronger transport decarbonisation. Public transport, demand management, active travel, destination accessibility, and reductions in automobile dependence are central. Existing conditions associated with lower reported burdens should be protected rather than traded away.

High-emission–high-burden municipalities require the most integrated response. Mobility reform alone will not address damage and illness, while risk reduction alone will leave transport emissions unchanged. These municipalities need coordinated packages that combine accessible services, transport alternatives, settlement management, hazard mitigation, ageing and outdoor-work protection, and emergency infrastructure.

The framework is most useful as a first-stage screen. It can help national and regional agencies identify where detailed hazard modelling, infrastructure audits, community engagement, and programme evaluation should be prioritised. It cannot substitute for those processes.

6.5 Relevance to climate-neutral urban transitions

This study does not assess municipal climate neutrality. It examines the transport sector and two climate-related burden indicators, not complete greenhouse gas inventories, removals, governance, finance, or implementation. Its specific relevance lies in the urban-form and mobility assessment layer of climate-neutral transitions.

Current transition initiatives emphasise integrated action across mobility, built form, infrastructure, urban nature, governance, and investment (Shabb & McCormick, 2023; Istrate et al., 2025; Huovila & Hukkalainen, 2025; Ulpiani et al., 2025). A city cannot design such action coherently if transport mitigation and climate-risk burdens are diagnosed in isolation. The present framework contributes to the assessment layer of that process. It shows whether a commonly invoked urban-form strategy is associated with a general trade-off and identifies municipalities where mobility and risk require joint investigation.

The results also caution against transferring metropolitan compact-city prescriptions to every territory. Higher-density municipalities often occupy favourable joint positions, but the evidence is cross-sectional and context-dependent. Lower-density municipalities may require different combinations of transit, service accessibility, settlement adaptation, and hazard reduction. Climate-neutral transition planning should therefore be place-specific even when national targets are uniform.

6.6 Limitations and research agenda

The study has several limitations. First, the urban-density measure is a single-dimensional indicator. It represents urban-area population relative to RCI-zoned area but does not directly measure residential density inside those zones. It also omits land-use mix, network connectivity, accessibility, and built intensity. Future research should develop a multidimensional compactness measure while retaining transparent component-level interpretation.

Second, the panel covers five years, and within-municipality variation in density is limited. The analysis is therefore better suited to comparative diagnosis than to causal evaluation of densification. Longer panels and quasi-experimental designs are needed to assess how outcomes change when urban form, transit, or development policy changes.

Third, the climate-related outcomes are not fully normalised for hazard exposure. Daily rainfall, typhoon intensity, heatwave days, elevation, low-lying land, drainage, and detailed housing conditions are not integrated in the main models. The burden indicators therefore combine hazard, exposure, vulnerability, capacity, and reporting. Future work should spatially assign daily weather and infrastructure data and examine whether the same joint configurations persist after hazard adjustment.

Fourth, municipality-level averages mask within-city inequality. Flood-prone basements, low-lying districts, heat-vulnerable neighbourhoods, and local service deficits can coexist with favourable municipal averages. Neighbourhood-scale analysis is required before site-specific planning decisions are made.

Fifth, the four joint configurations are defined relative to sample medians. They are useful for comparison but are not natural classes, and some municipalities near the cut points change classification under alternative samples. Future studies could complement this screen with continuous multi-objective measures, latent profiles, or policy-relevant absolute thresholds where defensible.

Sixth, the VKT-based transport emissions measure does not represent whole-city greenhouse gas emissions. Buildings, industry, waste, electricity, and consumption-based emissions remain outside the scope. The results should therefore be interpreted as evidence about the transport and urban-form dimension of climate action.

Finally, reporting practices may vary across municipalities. Differences in damage assessment, health surveillance, and administrative capacity can affect observed outcomes. This issue is partly addressed through fixed effects, regional controls, spatial diagnostics, and sensitivity analysis, but it cannot be eliminated with the current data.

These limitations define the next research steps without invalidating the central comparative result. The strong density dilemma is too simple for the Korean municipal system, and lower-density municipalities warrant greater attention as sites of joint transport and climate burden.

7. Conclusion

This study reassessed whether higher urban density lowers transport-sector greenhouse gas emissions at the cost of greater climate-related burdens. Across Korean municipalities, higher density is consistently associated with lower per-capita transport emissions and VKT. The association is driven mainly by persistent differences between municipalities rather than by observed densification within municipalities.

The evidence does not show a universal high-density penalty in reported hydrometeorological damage or heat illness, and it does not support a stable common density threshold. The most robust finding is a joint-outcome gradient: low-emission–low-burden configurations concentrate in the upper density quintiles, whereas high-emission–high-burden configurations concentrate in the lower quintiles.

The planning implication is not to prescribe density as a universal target. It is to diagnose how mobility, hazard exposure, vulnerability, infrastructure, and service access combine in each municipality. Higher-density municipalities may need to preserve transport efficiency while managing localised risk. Lower-density municipalities with double burdens require integrated strategies that reduce automobile dependence and climate-related vulnerability together. The density dilemma is therefore better understood as a place-dependent planning problem than as a universal trade-off.

Data and code availability

The harmonised municipal panel, variable dictionary, model outputs, spatial weights, and reproduction scripts will be deposited in a public research repository upon acceptance. The repository package will identify the original public data sources, document all transformations, and reproduce the reported tables and figures from the locked analytical specification.

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Tables

Table 1. Study variables, periods, and interpretation

Role	Measure	Period	Main interpretation
Urban density	Urban-area population per km² of residential, commercial, and industrial zoned area	2019–2023	First-order measure of urban population intensity; not a complete compactness index
Transport outcome	Per-capita VKT-based transport-sector GHG emissions	2019–2023	Transport-sector outcome, not whole-city emissions
Mobility outcome	Annual vehicle kilometres travelled per capita	2019–2023	Activity-consistent auxiliary outcome
Climate-related burden	Reported real per-capita monetary damage from heavy rain and typhoons	2020–2023	Realised burden; not weather-normalised adaptation effectiveness
Climate-related burden	Reported heat-related illness per 100,000 residents	2019–2023	Realised health burden; not a complete heat-health outcome
Controls	Resident population, elderly ratio, fiscal self-reliance, old housing, car ownership	2019–2023	Municipal scale, vulnerability, capacity, housing, and mobility context
Supplementary context	Imperviousness and green/natural cover	2019–2023	Broad land-cover context; not isolated causal mechanisms

Table 2. Descriptive statistics of the main analytical variables

Variable	N	Mean	SD	Median	Minimum	Maximum
Urban population intensity (persons/km²)	1,140	10,944.88	8,360.19	7,848.37	758.25	36,697.25
Per-capita transport-sector GHG emissions (tCO_2e/person)	1,145	2.23	1.14	2.14	0.78	17.99
Per-capita VKT (km/person)	1,145	7,527.95	3,932.00	7,200.02	2,858.32	61,288.50
Hydrometeorological damage (real 2020 KRW/person)	916	50,047.27	242,607.25	653.42	0.00	5,044,806.98
Heat illness (cases/100,000 residents)	1,145	5.93	7.41	3.40	0.00	69.80
Imperviousness (%)	1,145	21.68	21.65	11.02	1.21	91.29
Green/natural cover (%)	1,145	61.07	19.11	63.70	8.62	96.08
Elderly population ratio (%)	1,145	23.07	8.76	20.90	7.60	45.40
Fiscal self-reliance (%)	1,145	19.97	12.00	16.92	4.02	68.86
Old-housing ratio (%)	1,145	28.95	13.88	28.60	1.40	69.60
Car ownership (vehicles/person)	1,145	0.54	0.21	0.50	0.20	3.30

Note: Hydrometeorological damage is available for 2020–2023. The 2019 observations are missing by source design and are not coded as zero.

Table 3. Staged associations between urban density and the main outcomes

Outcome	Model 1	Model 2	Model 3	N
ln per-capita transport-sector GHG emissions	-0.262*** (0.025)	-0.237*** (0.038)	-0.145*** (0.031)	1,140
ln per-capita VKT	-0.251*** (0.023)	-0.225*** (0.034)	-0.133*** (0.029)	1,140
ln(1+hydrometeorological damage)	-2.361*** (0.142)	-1.904*** (0.200)	-1.779*** (0.197)	912
ln(1+heat-illness burden)	-0.541*** (0.035)	-0.413*** (0.049)	-0.383*** (0.049)	1,140

*Notes: Municipality-clustered standard errors are in parentheses. Model 1 includes year fixed effects. Model 2 adds log resident population, elderly ratio, fiscal self-reliance, and old-housing ratio. Model 3 adds car ownership and is interpreted as a mechanism-adjusted sensitivity model. *** p<0.001.*

Table 4. Identification and spatial-robustness results for Model 2

Outcome	Pooled M2	Municipality FE / within	Between component	Province FE + spatial HAC (100 km)
ln per-capita transport-sector GHG emissions	-0.237*** (0.038)	0.186 (0.117)	-0.239*** (0.038)	-0.117* (0.049)
ln per-capita VKT	-0.225*** (0.034)	0.059 (0.047)	-0.226*** (0.034)	-0.104* (0.045)
ln(1+hydrometeorological damage)	-1.904*** (0.200)	-4.051† (2.138)	-1.896*** (0.202)	-0.749** (0.280)
ln(1+heat-illness burden)	-0.413*** (0.049)	-0.232 (0.423)	-0.413*** (0.050)	-0.281** (0.086)

*Notes: Standard errors are in parentheses. The fixed-effects and within coefficients use only temporal variation within municipalities. The between coefficient captures persistent cross-municipality differences. The spatial model includes province and year fixed effects with a 100-km same-year spatial-HAC covariance. † p<0.10; * p<0.05; ** p<0.01; *** p<0.001.*

Table 5. Joint emission–burden configurations by urban-density quintile

Panel A. Transport emissions and hydrometeorological damage

Density quintile	Low emission–low burden	Low emission–high burden	High emission–low burden	High emission–high burden
Q1	3	3	7	33
Q2	3	9	3	31
Q3	10	9	9	17
Q4	33	3	5	5
Q5	37	4	4	0

Panel B. Transport emissions and heat illness

Density quintile	Low emission–low burden	Low emission–high burden	High emission–low burden	High emission–high burden
Q1	1	5	7	33
Q2	2	10	5	29
Q3	9	10	11	15
Q4	29	7	5	5
Q5	41	0	4	0

Notes: Panel A: $\chi^2(12)=126.29$, permutation p=0.0001, Cramér's V=0.430. Panel B: $\chi^2(12)=143.89$, permutation p=0.0001, Cramér's V=0.459. Categories are defined by sample medians and are descriptive joint positions, not latent classes.

Table 6. Planning priorities suggested by the joint outcome configurations

Configuration	Diagnostic reading	Planning priority
Low emission–low burden	Both observed outcomes are relatively favourable	Preserve accessibility and transport efficiency while monitoring localised flood, heat, and infrastructure risks
Low emission–high burden	Transport outcome is favourable, but reported climate-related burden is high	Retain mobility advantages while prioritising drainage, cooling, emergency access, and health protection
High emission–low burden	Reported burden is relatively low, but transport emissions remain high	Prioritise public transport, active travel, destination accessibility, and reduced automobile dependence
High emission–high burden	Transport emissions and reported burden are both high	Combine mobility reform with hazard reduction, ageing and outdoor-work protection, service access, and emergency infrastructure

Note: The table is a first-stage screening framework. It does not assign causal mechanisms or substitute for local risk assessment and programme evaluation.