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Journal

Transportation Research Part D: Transport and Environment, 127(103961)

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Publication Date

2024

DOI

10.1016/j.trd.2023.103961

Peer reviewed

Transportation Research Part D 127 (2024) 103961

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Urban street network design and transport-related greenhouse gas emissions around the world

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ARTICLE INFO

Keywords:
Street networks
Urban design
Urban form
Climate change
CO2 emissions
Urban planning

ABSTRACT

This study estimates the relationships between street network characteristics and transport-sector CO_2 emissions across every urban area in the world and investigates whether they are the same across development levels and urban design paradigms. The prior literature has estimated relationships between street network design and transport emissions – including greenhouse gases implicated in climate change – primarily through case studies focusing on certain world regions or relatively small samples of cities, complicating generalizability and applicability for evidence-informed practice. Our worldwide study finds that straighter, more-connected, and less-overbuilt street networks are associated with lower transport emissions, all else equal. Importantly, these relationships vary across development levels and design paradigms – yet most prior literature reports findings from urban areas that are outliers by global standards. Planners need a better empirical base for evidence-informed practice in under-studied regions, particularly the rapidly urbanizing Global South.

1. Introduction

Earth's climate is changing, characterized by rising temperatures and increasingly erratic weather events such as flooding, drought, landslides, and hurricanes (Grimm et al., 2008). The growing frequency and magnitude of these phenomena adversely affect human life (Alfieri et al., 2015; Myhre et al., 2019). Greenhouse gas (GHG) emissions constitute one of the principal drivers of climate change, and transport accounts for a substantial share of such emissions (Lashof and Ahuja, 1990). For example, roughly one-third of US GHG emissions arise from transport (US EPA, 2021), as does 29% of emissions in Europe (European Environment Agency, 2018). Around the world, rapid urbanization and ever-growing automobile dependence have led to massive growth in transport demand and distances traveled – and, in turn, transport-sector GHG emissions.

Sustainable urbanization requires planners to better understand the climate impacts of their plans. To this end, many recent studies have sought to measure the relationship between urban form – particularly street network design – and transport emissions. Variables such as street length, straightness, and intersection density appear in many such studies (Handy et al., 2002; Hankey and Marshall, 2010; Hong and Goodchild, 2014; Mohajeri et al., 2015; Reckien et al., 2007). However, most existing studies focus on individual countries or regions, particularly those with plentiful high-quality data, and usually collect relevant data from local or regional organizations (Boeing et al., 2022). A lack of consistent global data has stymied investigating relationships worldwide (Boeing, 2022). This poses problems for both scientific generalizability and evidence-informed practice (Giles-Corti et al.,

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https://doi.org/10.1016/j.trd.2023.103961
Received 23 July 2023; Received in revised form 21 October 2023; Accepted 25 October 2023

2022a). Better and more-comprehensive local estimates of the relationship between street network design and transport emissions would provide an important evidence base for planners to build more sustainable cities.

This study addresses this need and asks: what is the relationship between street network design and transport-sector CO_2 emissions across all of the world's urban areas – and to what extent is this relationship heterogeneous between different kinds of cities? Using street network characteristics and data on transport-sector emissions, we estimate relationships between street network design and corresponding urban area transport CO_2 emissions, including how these relationships vary across different development levels and urban design paradigms. Using a global ordinary least squares (OLS) regression model with a full set of controls, we find significant *ceteris paribus* associations between several street network design variables and transport-sector CO_2 emissions. Broadly consistent with the prior smaller-sample and regional literature (e.g., Boarnet and Crane, 2001; Boarnet, 2011; Crane, 2000; Ewing and Cervero, 2010; Hankey and Marshall, 2010), our worldwide results reveal that straighter, more-connected, and less-overbuilt street networks are associated with lower transport CO_2 emissions. However, important differences exist between different types of urban areas, which we unpack through spatial regimes models of UN development groups and design paradigms discovered through a cluster analysis.

This study is the first to comprehensively estimate the relationships between street network design and transport emissions across all of the world's urban areas. It offers practitioners both generalized estimates of these relationships for evidence-informed sustainability planning and paradigm-specific estimates for better local applicability. More specifically, it allows insights into how useful studies from other parts of the world may be to settings other than where they were conducted. In doing so, this study also offers researchers a new set of data and methods to conduct further case studies to identify localized relationships through a novel method of clustering cities based on street network attributes.

The rest of this article is organized as follows. First we briefly review the literature of street network design and transport emissions, highlighting its limitations. Next we describe our methods for measuring street network design, transport emissions, and their relationships worldwide, as well as how we cluster urban areas. Then we present our findings on these global and heterogeneous relationships. Finally we discuss their implications for both transport research and practice around the world before concluding.

2. Background

An extensive literature explores and tests how the built environment influences people's travel behavior, and with it, their emissions. Such studies have converged on a set of central factors – such as density, diversity, and design, the "three Ds" originally identified by Cervero and Kockelman (1997) – as dimensions of the built environment informing variable selection and model specification.

Typically, studies of how urban form relates to emissions rely on case study research utilizing data from one site (e.g., Reckien et al., 2007; Hong and Goodchild, 2014; Cao and Yang, 2017; Xu et al., 2018) or from several cities within the same country (e.g., Mohajeri et al., 2015; Hankey and Marshall, 2010; Schweitzer and Zhou, 2010; Wang et al., 2017). Such studies have frequently investigated Europe (e.g., Mohajeri et al., 2015; Reckien et al., 2007), North America (e.g., Curtis et al., 1984; Hong and Goodchild, 2014; Hankey and Marshall, 2010; Schweitzer and Zhou, 2010), and China (e.g., Cao and Yang, 2017; Xu et al., 2018; Wang et al., 2017). However, other world regions – such as South and Southeast Asia, Latin America, and Africa – remain underrepresented. Research designs also vary widely, comprising both travel surveys – where each observation represents an individual's travel and associated emissions (Hong and Goodchild, 2014) – and aggregate-level simulations – where each observation represents an entire city, urban area, or other areal unit (Hankey and Marshall, 2010; Wang et al., 2017; Mohajeri et al., 2015).

While measuring density in some form and including it as an explanatory variable is common across almost all studies, operationalizations of density – and what other variables are included – vary dramatically. Emissions themselves can be measured as fuel consumption (Curtis et al., 1984; Siew Yin and Chin Siong, 2010), carbon emissions (Mohajeri et al., 2015; Cao and Yang, 2017), or as a variety of other pollutants of interest such as ozone (Schweitzer and Zhou, 2010) or particulate matter (Boeing et al., 2023). Population density – that is, the number of residents in an urban area divided by its area – is almost always included as a variable, but land use mix and other built environment dimensions like accessibility are less common, particularly when using aggregate units of observation (Ewing and Cervero, 2010; Hong and Goodchild, 2014). Measures of street network design also vary. Researchers define network density variously as intersection density (e.g., Hong and Goodchild, 2014), edge density (e.g., Wang et al., 2017), street length (Mohajeri et al., 2015), or the area occupied by street networks (Mohajeri et al., 2015). Similarly, control variables included in studies often reflect local data availability or unique sociodemographic variables relevant to the particular study area, including such things as industrial composition (Wang et al., 2017) or a person's migrant status (Hong and Goodchild, 2014) in Chinese studies, or income levels and vehicle ownership in Europe (Reckien et al., 2007).

In sum, the heterogeneity in research designs and model specifications makes it challenging to compare these studies directly, generalize universal theory from their diverse estimates, or apply their evidence in practice in different urban contexts. Nevertheless, these studies' findings converge on certain principles: greater intersection density, street connectedness, land-use diversity, and pedestrian-oriented design are associated with less automobile travel, in turn potentially leading to lower transport emissions (Boarnet and Crane, 2001; Boarnet, 2011; Crane, 2000; Ewing and Cervero, 2010; Hankey and Marshall, 2010). Regardless of how exactly these variables are defined, greater population densities and shorter streets are consistently associated with lower transport emissions (Mohajeri et al., 2015; Reckien et al., 2007; Hong and Goodchild, 2014; Xu et al., 2018; Wang et al., 2017) and lower neighborhood exposure to pollutants (Schweitzer and Zhou, 2010).

Planners and policymakers need to understand the interconnectedness of urban form and transport emissions on a global scale. This becomes particularly crucial for benchmarking and monitoring cities with comparable urban characteristics. While existing

Table 1
Urban area counts and population summary statistics, by world region.

	Count	Min Pop	Median Pop	Mean Pop	Max Pop
Africa	1,382	50,016	121,050	304,473	19,734,085
Asia	4,103	50,012	136,949	427,439	40,589,878
Europe	1,049	50,053	106,710	273,569	14,077,364
Latin America & Caribbean	1,006	50,179	106,072	343,191	19,559,564
Northern America	372	50,238	111,423	464,800	15,950,674
Oceania	41	51,492	104,070	376,981	3,745,334

research predominantly examines land use and built-up area to assess the physical structure of cities (Lemoine-Rodríguez et al., 2020; Uhl et al., 2021), some studies also incorporate socioeconomic factors like population size and density as indicators of urban form (Frenkel and Ashkenazi, 2008). Recent studies have also used morphological configurations of urban landscapes (Taubenböck et al., 2020) and polycentricity for city clustering (Jung et al., 2022).

However, urban research and practice are context-specific. While most of this literature focuses on the Global North and large cities – often due to data availability and researcher familiarity – many of the most pressing urban and environmental challenges exist in the Global South and in smaller cities (McPhearson et al., 2016). Different development trajectories, social contexts, and geographies mean that coefficient estimates and lessons learned in, for instance, the United States are not necessarily applicable to cities in less-developed countries. The literature's geographical contexts and heterogeneity in specifications pose challenges for generalizability and applying findings to places unlike those originally studied. To better serve practitioners, planning scholars must expand research in less-studied and rapidly changing urban contexts (Giles-Corti et al., 2022b).

3. Methods

This study takes up this challenge to estimate these relationships worldwide while also unpacking geographical heterogeneity. It estimates the *ceteris paribus* relationships between urban area street network design and transport emissions, then tests how these relationships differ between development contexts. Next, it uses a cluster analysis to discover street network design paradigms and then retest these relationships between design paradigms. Our data measure the same variables the same way for all the places we study.

3.1. Data

We use the European Union's Global Human Settlement Layer's Urban Centres Database (UCD), which reports data on every urban area around the world (Florczyk et al., 2019). These urban areas are defined, per the United Nations Statistical Commission's methodology, by having a population of at least 50,000 across contiguous 1×1 kilometer grid cells with a density of at least 1500 inhabitants per square kilometer based on satellite data, censuses, and other inputs (Dijkstra et al., 2020). Table 1 lists our urban area counts by world region, as well as population summary statistics, after excluding urban areas missing emissions data or with fewer than 100 street network nodes.

Table 2 lists the variables used in this study alongside their summary descriptions, units, and sources. To measure street network design, we use the OSMnx package to model street network characteristics from OpenStreetMap (Boeing, 2017). These include the average node degree (the number of streets connected to each intersection), the average straightness of streets, the median street grade, the length of streets per capita, and the intersection density within the built-up area, for each urban area in the UCD (Boeing, 2022). Many researchers have validated OpenStreetMap's completeness and accuracy over the years (Barron et al., 2014; Basiri et al., 2016; Corcoran et al., 2013; Haklay, 2010; Zielstra et al., 2013). Barrington-Leigh and Millard-Ball (2017) caveat that Chinese OpenStreetMap data was relatively incomplete as of 2016 due to national restrictions on geospatial data. OpenStreetMap data are imperfect, but they represent the state-of-the-art today and the best available worldwide data.

The GHSL UCD reports estimated tonnes of CO_2 emissions produced in 2015 by the transport-sector from non-short cycle organic fuels – more commonly referred to as "fossil fuels" – in each of the world's urban areas (Florczyk et al., 2019, pp. 36–38). It also reports estimated tonnes of CO_2 emissions produced in 2015 from short-cycle organic fuels – that is, biofuels – for those same urban areas. Its definition of "transport-sector" encompasses all sectors coded "1A3" by the IPCC – including road, aviation, rail, shipping, and pipeline transport (Krey et al., 2014, p. 1303). While there are no data specifically reporting on-road transport CO_2 emissions at this granular a scale for all urban areas on the planet, on-road transport CO_2 emissions account for approximately 72% of all transport-sector emissions (Sims et al., 2014, p. 606). However, this figure can vary between different urban areas, so we include controls discussed below. The reported emissions are totals: to create our dependent variable of per-capita transport-sector CO_2 emissions, we divide total transport-sector CO_2 emissions from both fossil and short-cycle organic fuels for each urban area by that urban area's population (also from the UCD). Theoretically, vehicle ownership rates are a key predictor of emissions, but no consistent data exist worldwide, so we use GDP per capita and nighttime light emission as proxies capturing dimensions of development and wealth.

Table 2
Variables' descriptions, units, and sources.

Variable	Description and units	Source
CO_2 Emissions	The emissions of transport-related CO_2 per capita in 2015 (tonnes/person)	GHSL UCD
k average	Average node degree (network edges [i.e., streets] per node [i.e., intersection or dead-end])	OpenStreetMap
Straightness	Ratio of straightline distances between nodes to network distances between nodes	OpenStreetMap
Intersection Density	Density in units of 10,000 intersections per square kilometer	OpenStreetMap
Length	Mean street segment length (meters)	OpenStreetMap
Built up area	Built-up surface area in 2015 (km^2)	GHSL UCD
Open space	Percentage of open space in 2015	GHSL UCD
Population density	Residential population per built up area in 2015 (persons/km^2)	GHSL UCD
GDP per capita	Gross domestic product per person in 2015 (USD)	GHSL UCD
Night light	Urban night light emission (nano-watt per steradian per square centimeter)	GHSL UCD
Grade median	Median absolute street grade (rise over run)	OpenStreetMap
Airport	Dummy variable: 1 = has at least one airport, 0 = otherwise	OurAirports
Waterport	Dummy variable: 1 = has at least one waterport, 0 = otherwise	NaturalEarth
World region	Major geographical region (e.g., Asia, Europe, etc.)	GHSL UCD
UN development group indicator	LDCL = less developed countries, LDC = least developed countries, MDR = most developed countries	United Nations

3.2. Model specification

We model the urban areas' per capita transport emissions as a function of their street network characteristics, built-up area, population density, open space, and economic controls in Model I with the form:

$$\log y = \beta_0 + \beta_1 X + \epsilon \tag{1}$$

where β_1 represents the association between each predictor in the design matrix, X, and the response, y (per capita transport sector CO_2 emissions).

For a better linear fit, we take the natural logarithm of the response and several predictors. This also allows us to interpret the coefficients of logged predictors – i.e., street length per capita, built-up area size, population density, GDP per capita (adjusted for purchasing power parity), and night light emission – as percent changes in emissions associated with percent changes in each respective predictor. Coefficients for the other predictors – i.e., average node degree (k average), straightness, intersection density, percent open space, and median street grade – can be interpreted as percent changes in emissions associated with a unit change in each respective predictor.

These predictors reflect both policy decisions and local geography. For example, hilly cities' street networks often must curve with the landscape to maintain a feasible grade. Yet in cities like San Francisco, planners imposed a grid over hilly terrain, and many North American suburbs consist of curving culs-de-sac despite being built on level ground. Such urban design choices often reflect tastes of particular places and eras (Boeing, 2021). Accordingly, we control for terrain with the street grade variable to remove that effect from the coefficient on straightness. Thus, in our model, straightness represents a policy variable because we look at it while holding "hilliness" constant.

Our response variable represents emissions across the transport sector, so we include dummy variables to control for other important such emission sources – namely aviation and shipping – by identifying whether the urban area has an airport and/or water port, to limit their confounding effects. Such dummy variables are imperfect controls but the best available for isolating the relationships of interest. We also include country-level dummy variables to control for national policy differences. All regression parameter estimations are performed using OLS, weighting observations by the urban area population to not overweight small villages at the expense of large metropolises.

In a second specification (Model II), we test whether the relationships between street network design and transport-sector emissions are the same in both developed and less-developed countries. We do this through a spatial regimes model across UN development groups plus country dummy variables. Spatial regimes essentially runs separate regressions for each group. This allows the parameter estimates to vary between least developed countries (LDC) – e.g., Bangladesh, the Democratic Republic of the Congo, Liberia, and Nepal – less developed countries excluding least (LDCL) – e.g., China, India, Iran, Nigeria, and Turkey – and most developed regions (MDR) – e.g., the United States, Japan, Russia, and the European Union's members.

3.3. Cluster analysis of urban design paradigms

Although UN Development Groups capture rough groupings of development level, they ignore the heterogeneity of urbanization patterns, but the relationships between urban form and emissions could vary between latent urban design paradigms. In a third regression specification (Model III), we extend our analysis by testing whether there are differences in the relationships between urban form and transport-sector emissions across such paradigms, with cities clustered by their urban form.

To do so, we conduct a hierarchical cluster analysis using the first three principal components of six urban form variables: k average, straightness, intersection density, street length per capita, percent open space, and population density. Based on the cluster analysis dendrogram, we cut its tree at six clusters to obtain well-defined groups that also conform to theory. Similar to Model II, we estimate a spatial regimes model across design paradigm clusters and control for country dummy variables.

4. Results

4.1. Design paradigm clusters

Our cluster analysis reveals six clusters of urban areas that exhibit internally similar design optimizing within-group similarity and between-group dissimilarity. Fig. 1 illustrates these clusters, which comprise: (1) modernist superblocks, most prevalent in China and post-Soviet countries, (2) low-density deformed grids, most prevalent in modern Western cities, (3) high-density networks dominated by dead-ends, most prevalent in India and other less-developed countries, (4) medium-density deformed grids, most prevalent in the Mediterranean and Latin America, (5) circuitous networks dominated by T-intersections, most prevalent in older cities in Western Europe and its former colonies, and (6) high-density grids, most prominent in less-developed countries.

Importantly, not all urban areas in a given region (or even country) belong to the design paradigm cluster most closely associated with that region, due to within-region historical divergences and design heterogeneity. Fig. 2 maps the world's urban areas by cluster and visualizes each cluster's statistical distributions across ten variables.

4.2. Regression analysis

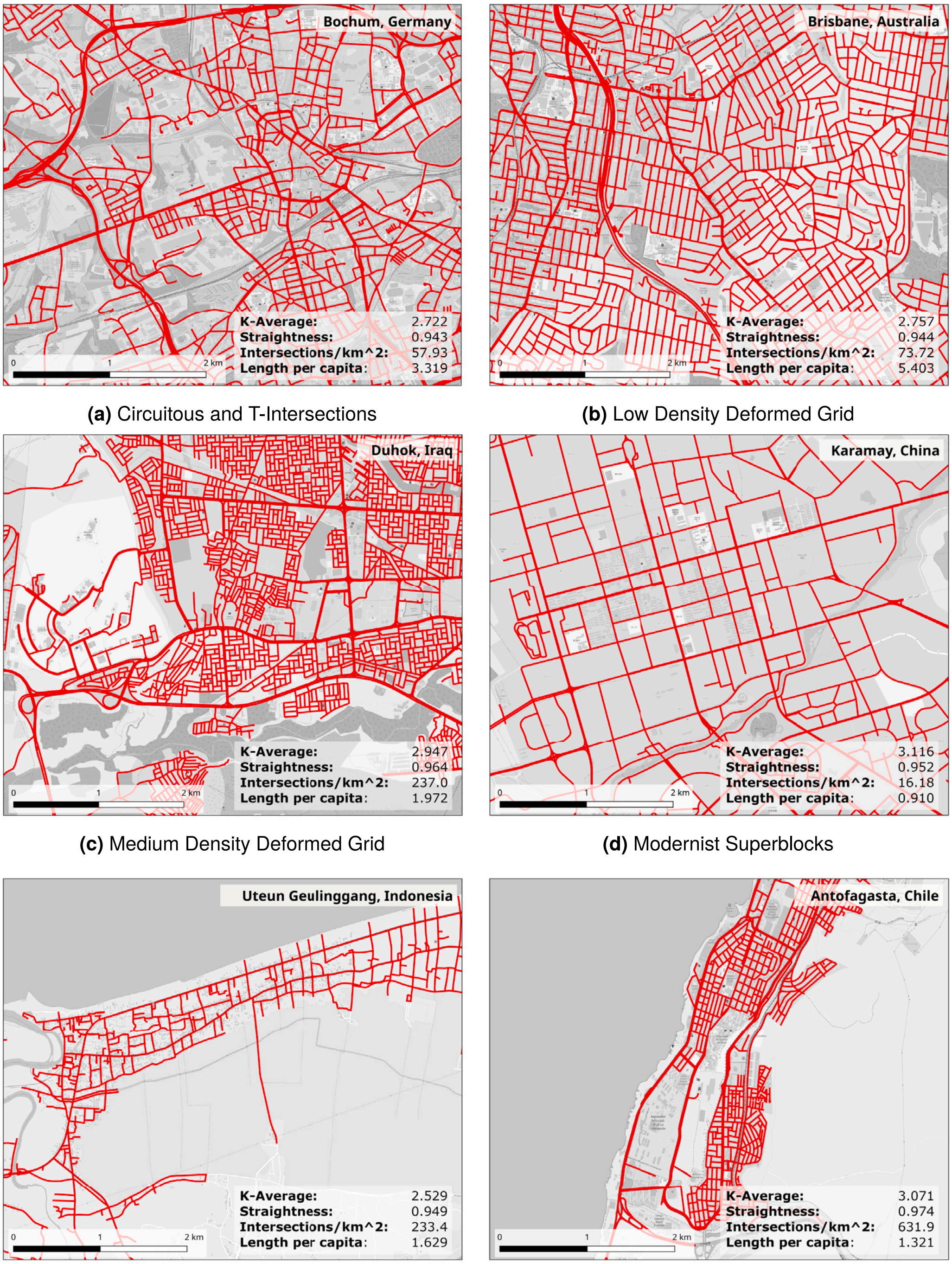
Worldwide, in Model I (Table 3), we observe negative associations between street network connectedness and transport-sector CO_2 emissions per capita, and between straighter streets and emissions. For example, a 1% increase in connectedness (i.e., k average) is associated with a 2.4% decrease in emissions. Furthermore, worldwide, we find positive relationships between per capita street length and emissions, but no significant relationship between intersection density and emissions. Even when controlling for population density, 1% more street length per capita is associated with a 0.8% increase in emissions. Both measures of economic development in our model – night lights and GDP per capita – are associated with greater emissions.

However, these estimates represent average relationships aggregated across a wide range of cities differing substantially in urban form. Testing whether these relationships are the same in sign and similar in magnitude everywhere, our spatial regimes models estimate separate coefficients for each variable for each UN development group in Model II, and for each design paradigm cluster in Model III.

In Model II (Table 4), we observe heterogeneity in magnitude and statistical significance. While both connectedness and straightness are negatively associated with emissions everywhere, these relationships are only significant in LDCL urban areas – perhaps due to the larger sample size. The relationship between per capita street length and emissions is significant and positive across all three development groups, but is the largest in LDC urban areas, suggesting that the association between road (over) building and emissions declines with rising development levels. However, these development levels themselves contain substantial within-group urban form heterogeneity.

Model III (Table 5) tests whether these relationships vary across design paradigms. Connectedness is consistently associated with lower emissions across all clusters, though the magnitude of this relationship is approximately three times as large in high density grid and modernist superblock urban areas than in the others. The relationship between straightness and emissions – while not as consistent as connectedness – is also negative, save for in the low density grid and dead ends clusters. Greater street lengths per capita on the other hand are associated with higher emissions in all clusters save for the high density grid cluster – that is, the urban areas that already have the shortest road lengths per capita. Finally, the relationship between intersection density and transport emissions is only statistically significant in the low density deformed grid cluster and in the modernist superblocks cluster – that is, the urban areas with the lowest intersection densities.

Tables 3, 4, and 5 also present standardized beta regression coefficients that estimate how many standard deviations of change in the response are associated with a one standard deviation change in a predictor. Table 5 shows that even when the relationships between predictors and transport-sector emissions possess the same sign, standardized magnitudes can vary dramatically between clusters. Increases in connectedness are associated with nearly twice as large a reduction in emissions in modernist superblock urban areas (which are common in China) than in low density deformed grid urban areas (which are common in North America). Table 6 summarizes the signs and significance of coefficient estimates across Models II and III.



(a) Circuitous and T-Intersections **(b)** Low Density Deformed Grid

(c) Medium Density Deformed Grid **(d)** Modernist Superblocks

(e) Dead Ends **(f)** High Density Grid

Fig. 1. Street networks exemplifying each of the six design paradigm clusters alongside four indicator values for that specific urban area.

5. Discussion

In recent years, a large body of literature has explored the relationships between street network design and transport emissions. Its goal – often complementing research on novel transport technologies or alternative fuels – is to inform planners and policymakers how urban form and street network design interventions could reduce GHG emissions and in turn mitigate global climate change. However, this literature's real world impact has been circumscribed by its regional or small sample research designs that have

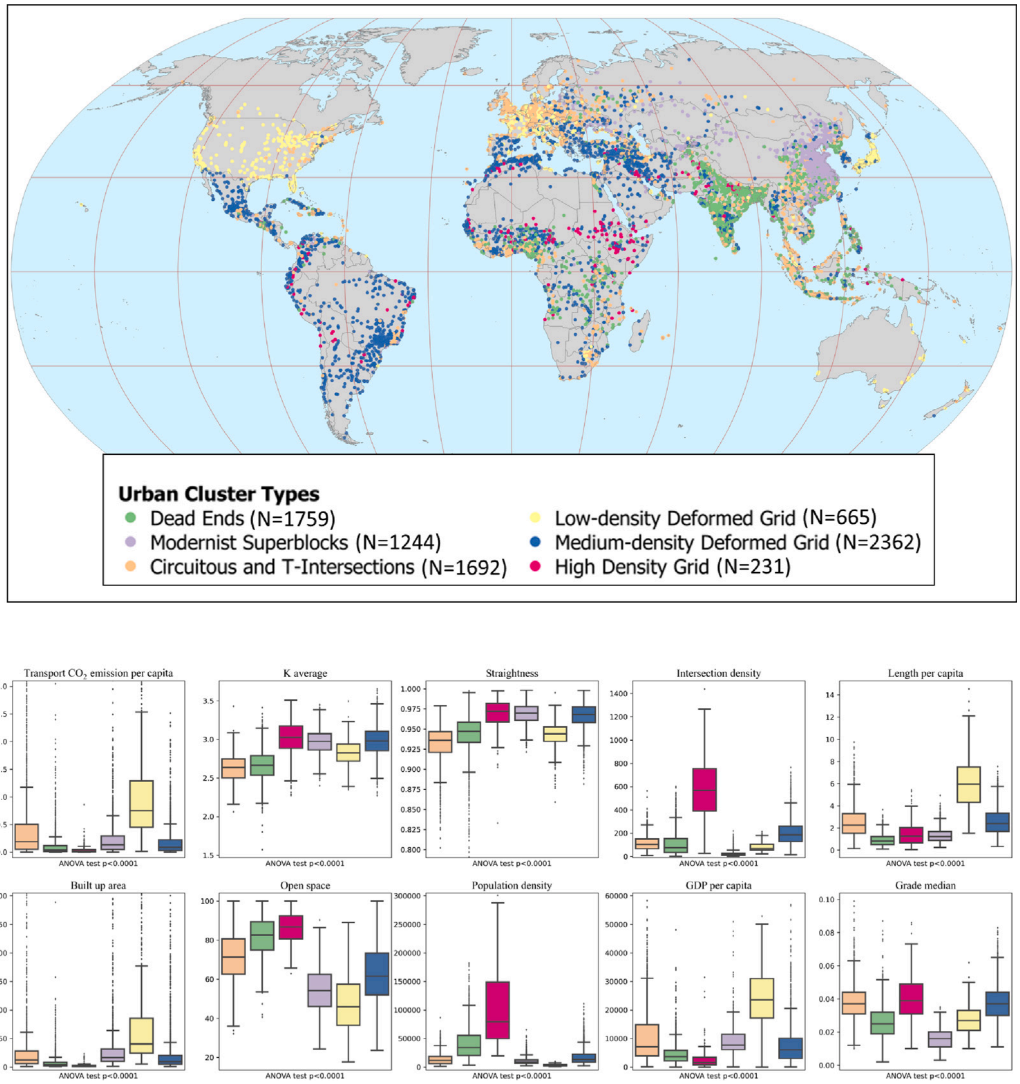


Fig. 2. The spatial (above) and statistical (below) distributions of our six design paradigm clusters. See Table 2 for variable descriptions.

limited its applicability to other geographical contexts. This in turn has curtailed our knowledge of global relationships between transport planning and emissions. Yet climate change is a global phenomenon with global causes and global consequences. Planners around the world need a context-sensitive evidence base for their interventions into this crisis, and transport offers a key leverage point.

In this study we estimated these global relationships. Then, to unmask geographical heterogeneity, we re-estimated these relationships across development groups and design paradigm clusters. Our findings provide new universal estimates of the relationships between street network design and transport emissions while also providing insights into their heterogeneity. Worldwide, all else held equal, we find that more-connected and straighter streets are associated with lower emissions, while greater street lengths per capita are associated with more emissions. This finding – that variables operationalizing denser urban form tend to be associated with lower transport-sector GHG emissions – is broadly consistent with current theory, but provides the first comprehensive global evidence of such in the literature.

At the same time, our models reveal important heterogeneity in these associations. Certain variables' relationships with transport emissions vary dramatically between different development levels or design paradigms. For instance, the association between greater intersection density and lower transport-sector CO_2 emissions – present in our global model – appears to be limited to the least intersection-dense types of urban form, the low density deformed grid (that is, most cities in North America or Australia) and the modernist superblocks (that is, most cities in China and post-Soviet states). Similarly, longer road lengths per capita have a larger association with transport emissions in those same clusters, and no statistical relationship with emissions at all in the high density grid cluster.

Table 3
Model I's parameter estimates, standard errors (in parentheses), and standardized beta coefficients. Dummies not shown.

Variable	Parameter	Beta
Intercept	1.025	
	(1.593)	
k average (log)	−2.351***	−0.088
	(0.269)	
Straightness	−5.245***	−0.057
	(0.811)	
Intersection density	1.735	0.011
	(1.772)	
Length per capita (log)	0.762***	0.258
	(0.059)	
Built up area (log)	1.426***	0.794
	(0.035)	
Open space (log)	0.418***	0.050
	(0.084)	
Population density (log)	0.945***	0.389
	(0.062)	
GDP per capita (log)	0.068**	0.045
	(0.026)	
Night light per capita (log)	0.123***	0.069
	(0.021)	
Grade median	−13.258***	−0.074
	(1.537)	
n	7953	
R^2	0.728	

Significance denoted as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 4
Model II's parameter estimates, standard errors (in parentheses), and standardized beta coefficients, across UN development groups. Dummies not shown.

	LDC		LDCL		MDR	
	Parameter	Beta	Parameter	Beta	Parameter	Beta
k average (log)	−1.296	−0.057	−2.685***	−0.108	−0.624	−0.030
	(0.965)		(0.334)		(0.369)	
Straightness	−5.758	−0.066	−5.591***	−0.066	−1.881	−0.024
	(3.282)		(1.008)		(1.033)	
Intersection density	−0.254	−0.003	1.207	0.008	−16.556	−0.048
	(4.730)		(2.177)		(8.491)	
Length per capita (log)	1.102***	0.281	0.785***	0.260	0.313*	0.107
	(0.198)		(0.072)		(0.123)	
Built up area (log)	1.573***	0.828	1.503***	0.811	1.039***	0.706
	(0.119)		(0.045)		(0.047)	
Open space (log)	1.099**	0.096	0.391**	0.045	0.393***	0.078
	(0.424)		(0.136)		(0.058)	
Population density (log)	1.167***	0.372	1.034***	0.370	0.504***	0.169
	(0.207)		(0.079)		(0.127)	
GDP per capita (log)	−0.052	−0.034	0.056	0.035	0.188***	0.156
	(0.083)		(0.033)		(0.040)	
Night light per capita (log)	0.162***	0.099	0.090***	0.051	0.098**	0.043
	(0.047)		(0.028)		(0.038)	
Grade median	−6.683	−0.037	−15.291***	−0.095	−2.786	−0.018
	(5.562)		(1.937)		(2.010)	
n	735		5708		1565	
R^2	0.711		0.629		0.868	

Significance denoted as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

One possible explanation for this pattern could be that the underlying relationships exhibit nonlinearity with diminishing returns at the margins. That is, at very low intersection densities, increasing intersection density and decreasing per capita road lengths may be associated with lower emissions, while this is not the case in places that already have high intersection densities (cf. Cerin et al., 2022). This nonlinearity may result from different types of cities – both in terms of income level and of network design – using transportation technologies differently, thus creating different relationships. For instance, gridded street networks with low intersection densities make automobile trips easier by design. They may also require greater detours for any given trip, compared to higher density grids.

Table 5
Model III's parameter estimates, standard errors (in parentheses), and standardized beta coefficients, across design paradigm clusters. Dummies not shown.

	Circuitous and T-intersections		Low density deformed grid		Medium density deformed grid		Modernist superblocks		Dead ends		High density grid	
	Parameter	Beta	Parameter	Beta	Parameter	Beta	Parameter	Beta	Parameter	Beta	Parameter	Beta
k average (log)	−1.824**	−0.054	−1.500**	−0.061	−1.596**	−0.047	−4.663***	−0.115	−1.761**	−0.056	−5.187*	−0.219
	(0.660)		(0.570)		(0.541)		(0.965)		(0.620)		(2.085)	
Straightness	−4.258*	−0.043	−2.682	−0.029	−13.963***	−0.097	−18.004***	−0.105	−0.377	−0.005	−16.598*	−0.165
	(1.720)		(1.795)		(2.228)		(4.073)		(1.545)		(7.607)	
Intersection density	−8.676	−0.025	−102.619***	−0.270	−2.331	−0.012	−133.809**	−0.173	−1.507	−0.006	3.898	0.088
	(12.616)		(20.849)		(5.650)		(48.483)		(8.397)		(4.535)	
Length per capita (log)	0.789***	0.203	1.204***	0.328	0.986***	0.224	1.445***	0.316	0.811***	0.222	0.519	0.231
	(0.224)		(0.292)		(0.174)		(0.228)		(0.148)		(0.405)	
Built up area (log)	1.259***	0.654	0.945***	0.702	1.426***	0.769	1.487***	0.675	1.562***	0.700	1.755***	0.564
	(0.077)		(0.115)		(0.051)		(0.133)		(0.086)		(0.252)	
Open space (log)	0.739**	0.063	0.279***	0.061	0.416**	0.046	0.202	0.021	1.718***	0.097	1.498	0.067
	(0.236)		(0.077)		(0.150)		(0.311)		(0.416)	(1.941)		
Population density (log)	0.844***	0.271	1.226***	0.393	1.134***	0.344	1.340***	0.321	1.078***	0.325	0.524	0.191
	(0.225)		(0.301)		(0.176)		(0.262)		(0.155)		(0.512)	
GDP per capita (log)	0.130*	0.086	0.254*	0.218	0.100**	0.071	0.116	0.066	−0.071	−0.040	−0.006	−0.004
	(0.059)		(0.104)		(0.036)		(0.103)		(0.063)		(0.132)	
Night light per capita (log)	0.204***	0.113	0.074	0.032	0.062	0.035	0.491***	0.202	0.014	0.008	0.064	0.052
	(0.052)		(0.070)		(0.036)		(0.076)		(0.045)		(0.094)	
Grade median	−4.154	−0.021	4.095	0.022	−7.716**	−0.039	−47.966***	−0.141	−17.644***	−0.079	−7.742	−0.056
	(3.354)		(3.430)		(2.437)		(8.473)		(4.507)		(8.745)	
n	1692		665		2362		1244		1759		231	
R^2	0.741		0.870		0.786		0.534		0.598		0.666	

Significance denoted as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6
Summary of coefficients' signs and significance across regimes in Models II and III. Dummies not shown. Zeros indicate statistical insignificance at a 95% confidence level.

	LDCL	LDC	MDR	Circuitous and T-intersections	Low density deformed grid	Medium density deformed grid	Modernist superblocks	Dead ends	High density grid
k average (log)	0	−	0	−	−	−	−	−	−
Straightness	0	−	0	0	0	−	−	0	−
Intersection density	0	0	0	0	−	0	−	0	0
Length per capita (log)	+	+	+	+	+	+	+	+	0
Built up area (log)	+	+	+	+	+	+	+	+	+
Open space (log)	+	+	+	+	+	+	0	+	0
Population density (log)	+	+	+	+	+	+	+	+	0
GDP per capita (log)	0	0	+	+	+	+	0	0	0
Night light per capita (log)	+	+	+	+	0	0	+	0	0
Grade median	0	−	0	0	0	−	−	−	0

Much of this literature's prior case study research was conducted in either the Global North or in China, both of which are outliers in terms of their relatively low intersection densities, as well as often exhibiting larger associations between street network characteristics and emissions. This calls into question how generalizable their findings are, and to what extent policy recommendations can be transferred to the rest of world. Our finding of different relationships between clusters underscores how the literature's estimated relationships are inherently specific to their individual contexts. Although we find that the directions of the relationships are overall consistent with existing theory, our study raises implications for how practitioners should interpret the literature for evidence-informed planning. Since the relationships between urban form and transport emissions are heterogeneous and context-specific, applying a body of evidence from one well-studied region to a different less-studied region will often be inappropriate.

For example, if an urban planner in the Middle East – an under-studied geographical region in which most cities fall into the "medium density deformed grid" cluster – followed the global literature, they would overestimate the local relationship between greater intersection density and transport-sector CO_2 emissions. Our study provides this hypothetical planner a different – and more locally-calibrated – evidence base for their planning interventions to achieve local goals. Accordingly, practitioners and researchers must carefully consider whether their local context is sufficiently similar to any given study's context for the relationships to hold. Given the prevalence of such studies from the Global North, our findings illustrate the importance of developing a stronger empirical base for planning rapidly developing cities in the Global South.

This study also offers several opportunities for further research. First, our research design is cross-sectional and does not attempt to identify causal relationships. Identifying such causal relationships is an important next step for both scientific theorizing and policymaking. Further, the literature has yet to converge on an authoritative set of urban variables to include in model specifications explaining variations in transport emissions, or on an authoritative way to cluster urban areas into internally similar groups. This study – like any other – is unable to resolve this conundrum on its own. However, it taps into recent advances in the open science, open data, and open source movements to propose a set of variables that can be freely and consistently obtained for all urban areas worldwide in a uniform, well-documented manner. Refining these statistical controls is an important next step, as our variables and model specifications are neither perfect nor authoritative. More data gathering and local research – especially in under-studied regions – are essential to understand what variables should be included. In particular, equivalent data on land use entropy remains an important gap for such worldwide analyses and represents an important next step for research.

6. Conclusion

Climate change presents an urgent challenge to all planners. In particular, transport plays a critical role as it represents a significant source of GHG emissions. Sustainable urban planning requires more careful attention to designing and building transport infrastructure that reduces emissions and offers individuals a variety of mode choices beyond automobile dependence. However, planners need a clearer body of knowledge about what that infrastructure should look like. While the relationships between street network design and transport emissions are fairly well-studied in some regions, including the US, Europe, and China, they are under-studied in many of the most rapidly developing parts of the world. Practitioners often lack a strong evidence base for evidence-informed planning.

This study estimated relationships between street network design and per capita transport-sector CO_2 emissions across every urban area on the planet. We then tested whether these relationships vary between different levels of development or between different design paradigms to unpack global heterogeneity. We find that, all else equal, more-connected and straighter streets are associated with lower emissions, while greater street lengths per capita are associated with more emissions. However, our models reveal substantial heterogeneity in these relationships. We argue that evidence-informed practice derived from global models or dissimilar world regions could yield conclusions inapplicable to local planning contexts.

This paper unlocks future research in estimating these relationships worldwide and, in particular, at more local scales and in less-developed regions. As these important relationships vary between different kinds of urban areas, more evidence is needed for local planners to both set and meet climate and sustainability goals. Taking advantage of these kinds of data and models can build up that evidence base for a more sustainable transport future.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgments

This work was funded in part by a grant from the Pacific Southwest Region University Transportation Center and the U.S. Department of Transportation.

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