Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Directional Disorder and Its Discontents: The Effect of Street Network Regularity on Life Satisfaction

Haosheng Yan
Central University of Finance and Economics
Zihua Yan
Harvard University
Guoqin Zhao
zhaogq@cufe.edu.cn
Central University of Finance and Economics
Yibing Zhao
Central University of Finance and Economics

Research Article

Keywords:

Posted Date: October 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11281774/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Directional Disorder and Its Discontents: The Effect of Street Network Regularity on Life Satisfaction

Abstract

Urban street networks shape how residents move through and experience cities, yet the causal effects of their spatial organization on well-being remain poorly understood. Combining a nationwide survey from China with street-network data, we use an instrumental variable approach to estimate the effect of street-network regularity on residents' well-being. We find that less regular street layouts significantly reduce residents' life satisfaction. A one-standard-deviation increase in orientation entropy lowers life satisfaction by 0.060 standard deviations, a magnitude comparable to the well-documented effect of an 18-minute increase in one-way commuting time. This effect arises because irregular networks lengthen commuting time and raise transportation costs. This negative effect is stronger for older and low-income residents. In addition, street-network disorder lowers self-rated health. Finally, technology adoption, including digital navigation tools and private-vehicle access, attenuates the welfare loss from irregular street layouts. Our research provides policy implications for effective street-network optimization and improved residents' subjective well-being.

Keywords: Street network, Life satisfaction, Orientation entropy, Technology adoption

JEL Codes: R41, R11, I31, O18

1 Introduction

The urban street network shapes spatial connectivity, determines traffic capacity, and influences congestion patterns, ultimately affecting how residents perceive everyday urban life (Möller & Zierer, 2018; Ossokina, Van Ommeren, & Van Mourik, 2023). In fact, traffic-related frustrations consistently rank among urban residents' top complaints. For instance, transportation-related concerns are a leading driver of the decline in the Los Angeles County quality-of-life index[1]. Similar concerns are also prominent in developing countries, with traffic issues long ranking among the top complaints on Beijing's citizen service hotline [2]. These patterns suggest that street networks matter not only for mobility, but also for residents' everyday well-being.

Despite their importance in everyday urban life, the role of street networks has received limited attention in the literature on the built environment and well-being. A large body of studies focus on the social impacts of green space (Ambrey & Fleming, 2014), facility density (Dong, Yun, Sun, & Wang, 2022), housing conditions (Fernández-Portero, Alarcón, & Padura, 2017), urban form and density (Dong et al., 2022; Mouratidis, 2019), and commuting experiences (Ingenfeld, Wolbring, & Bless, 2019; Stutzer & Frey, 2008). Among them, a small strand of literature examines how urban streets affect life satisfaction (C. Zhang et al., 2026). However, existing studies mainly focus on the quantitative properties of street networks. Much less is known about the spatial organization of streets. Although navigating irregular street layouts is a common source of frustration in urban life, whether such spatial irregularity has an independent causal effect on residents' well-being remains unclear.

Building on advances in characterizing urban street-network morphology(Boeing, 2020), we focus on the effect of the regularity of urban street network morphology on residents' life satisfaction. The regularity of urban street network morphology refers to the orderliness exhibited in the layout of urban streets. As illustrated in Fig. 1, a less regular street network is characterized by more disordered orientations, and therefore a higher orientation entropy (Boeing, 2019). Intuitively, highly ordered networks (grid-like structures) may enhance living experiences by improving spatial connectivity and mitigating navigation difficulties associated with complex layouts.

To empirically test this intuition, we use the orientation entropy indicator proposed by Boeing (2019) to quantify the spatial morphology of urban street networks. Combining it with nationwide survey data from China, we then investigate the impact of street spatial morphology on residents' life satisfaction. To address endogeneity concerns, we instrument street network orientation entropy with the orientation entropies of rivers and mountain ridgelines. Baseline estimation results reveal that more irregular street networks (higher orientation entropy) correspond to significantly lower residents' life satisfaction. A one-standard-deviation rise in street network irregularity reduces life satisfaction by 0.060 standard deviations, a magnitude of welfare loss comparable to that caused by an 18-minute increase in one-way commuting time (Stutzer & Frey, 2008). In addi-

[1]Lewis Center for Regional Policy Studies (2024), *Los Angeles Quality of Life Index*. Available at: https://www.lewis.ucla.edu/programs/data/qualityoflife/.

[2]Beijing Municipal Administration of Government Services and Data Management (2024), *2024 Annual Report of Beijing Citizen Service Hotline*. Available at: https://www.beijing.gov.cn/hudong/jpzt/2024ndsjbg/index.html.

tion, we find that irregular street networks significantly worsen residents' self-rated health. These findings suggest that irregular street networks generate substantial adverse effects on residents' well-being.

We extend the analysis in three directions. First, we examine the distributional effects of irregular street networks. We find that older and lower-income residents experience greater well-being losses. Second, we identify transportation costs as a key mechanism. Less regular networks make routes more circuitous and journeys more complex. Thus, they leads to longer commuting times and higher transportation expenditures. Finally, we explore potential strategies to mitigate these adverse effects. Given the high costs and geographic constraints associated with redesigning existing street networks, we examine whether technology adoption can alleviate their negative consequences. The results suggest that digital navigation and private vehicles substantially attenuate the negative effects of irregular street networks.

This paper contributes to the literature on the urban built environment and its effects on well-being by introducing street network regularity as a new dimension. Existing studies typically focus on road and population density (Brown, Oueslati, & Silva, 2016), land use mix (Krekel, Kolbe, & Wüstemann, 2016), urban green space (White, Alcock, Wheeler, & Depledge, 2013), public transit accessibility (Sun & Du, 2023), neighborhood quality (Huebner, Oreszczyn, Direk, & Hamilton, 2022), and residential environmental conditions (Kawakubo, Arata, & Kamata, 2026). To our knowledge, this paper is the first to identify the causal effect of street network morphology on residents' well-being. Moreover, it documents its effect on residents' health. It therefore provides a unique perspective to understand the relationship between urban built environment and residents' well-being.

Second, this paper contributes to research on how residential environments shape well-being inequalities across population groups. Previous studies document racial disparities in pollution exposure (Currie, Voorheis, & Walker, 2023), socioeconomic disparities in neighborhood-related mental well-being (Mitchell, Richardson, Shortt, & Pearce, 2015), and stronger cognitive effects of pollution among older adults (X. Zhang, Chen, & Zhang, 2018). We find that street network irregularity has a stronger negative effect on life satisfaction among older and low-income residents. These patterns suggest that irregular street networks may reinforce existing disadvantages, as these groups have less capacity to navigate complex street networks or adjust their travel modes. Accordingly, we also examine ways to mitigate these effects by adopting new technology, including digital navigation and private vehicles.

Finally, this paper contributes to the literature on the economic and social effects of urban infrastructure. Existing studies mainly examine the quantity of infrastructure, such as road construction and expansion (Gibbons, Lyytikäinen, Overman, & Sanchis-Guarner, 2019; Hoogendoorn, Van Gemeren, Verstraten, & Folmer, 2019; Möller & Zierer, 2018; Ossokina et al., 2023) and road network density (Duranton & Turner, 2012). A smaller strand studies specific road configurations, such as ring roads and radial highways (Baum-Snow, Brandt, Henderson, Turner, & Zhang, 2017; Garcia-López, 2012). This paper shows that the spatial regularity of urban infrastructure provides independent explanatory power for residents' well-being and further explores the underlying mechanisms. These findings suggest that the welfare consequences of urban in-

frastructure depend not only on how much is built, but also on how the network is spatially organized.

The remainder of this paper is organized as follows. Section 2 summarizes the related key literature and develops the research hypotheses. Section 3 presents data and stylized facts. Section 4 provides empirical strategy. Section 5 presents our empirical findings. Section 6 concludes the paper with a discussion of policy implications.

2 Theoretical Analysis

2.1 Street network regularity and residents' well-being

Transportation is a major determinant of residents' subjective well-being. Commuting is consistently rated among the least enjoyable activities of the day (Kahneman, Krueger, Schkade, Schwarz, & Stone, 2004), and longer commutes are associated with lower life satisfaction (Nie & Sousa-Poza, 2018). This effect persists even though the labor and housing markets could compensate commuters for the burden (Stutzer & Frey, 2008). The cost of daily travel depends on the street network. A large body of research shows that street connectivity and density shape how residents travel and therefore affect their life satisfaction (Mouratidis, 2021). Beyond connectivity and density, the regularity of street orientations may also affect travel. Urban areas with similar density and connectivity may still differ considerably in the ease of travel. A grid-like layout allows movement along a few consistent directions, whereas in a network with disordered orientations, the direction of a street provides little information about its destination.

Irregular street networks raise the cost of travel in two related ways. First, they make wayfinding more difficult. Navigation in a city depends on residents' ability to orient themselves in space. When street orientations are dispersed, residents must process more spatial information. This leads to more mistakes in finding ways, especially on unfamiliar trips (Fancello et al., 2025; Liloia & Filomena, 2025). Second, even on familiar routes, irregular layouts often lack direct connections between origins and destinations, which leads to more detours. Both frictions increase travel time and distance. Additional travel time crowds out time that could otherwise be spent on activities that support well-being (De Vos, Schwanen, Van Acker, & Witlox, 2013; Ettema, Gärling, Olsson, & Friman, 2010). Longer distances raise transportation expenditure and reduce the income available for other consumption (Fang & Wu, 2026).

The costs of irregular street networks are not limited to time and money. Difficulty in wayfinding also makes travel more uncertain and frustrating. Such psychological costs accumulate as trips become longer, and longer commutes have been shown to raise both perceived and physiological stress (Chatterjee et al., 2020; Evans & Wener, 2006). Sustained exposure to such stress may in turn impair health. Because these costs recur on most trips and persist even on familiar routes, residents are unlikely to adapt to them fully. This leads to our first two hypotheses:

H_1 Irregular urban street network morphology significantly reduces residents' life satisfaction.

H_2 Irregular urban street network morphology reduces residents' well-being by increasing transportation cost, including commuting time and transportation expenditure.

2.2 Distributional effects across residents

If irregular street networks lower life satisfaction by raising the cost of travel, the magnitude of the effect depends on the additional cost residents incur and their capacity to absorb it. Older residents are likely to have greater difficulty finding their way, as spatial navigation abilities tend to decline with age (Lester, Moffat, Wiener, Barnes, & Wolbers, 2017; Tansan, Nguyen, & Newcombe, 2022; van der Ham & Claessen, 2020). Therefore, they are more prone to getting lost in irregular street networks. Although many older residents no longer commute, their routine non-work trips also become more costly. They are also less able to bear the physical effort of additional walking and other travels.

Low-income residents have fewer ways to avoid these costs. They rely more on walking and fixed-route public transit. Therefore, low-income residents are more likely to experience transport disadvantage, whereas high-income residents have greater flexibility in route choice by taking private vehicles (Glaeser, Kahn, & Rappaport, 2008; Lucas, 2012; Mouratidis, 2025). Moreover, a given increase in transportation expenditure accounts for a larger share of a low-income household's budget. Therefore, low-income residents potentially experience a larger loss in well-being. Combined, we expect:

H_3 The negative effect of irregular urban street network morphology on well-being is stronger among older and lower-income residents.

2.3 Technological adoption as a mitigating channel

Established street networks are difficult to change, but residents can reduce costs by adopting new technology that improves access to information and transportation resources. For example, digital navigation tools directly address the difficulty of wayfinding by offloading part of the cognitive work of route planning to external systems (Miola, Muffato, Sella, Meneghetti, & Pazzaglia, 2024; Risko & Gilbert, 2016). Route recommendations and real-time traffic information help residents choose more efficient routes and reduce travel uncertainty. These functions are particularly valuable in irregular networks, where efficient routes are harder to identify without assistance.

Private vehicles provide another form of adoption by increasing flexibility in route choice and travel timing. Compared with walking or fixed-route public transit, driving allows residents to cover longer routes in less time and to adjust their routes more flexibly. Thus, it expands individuals' access to opportunities and activities (Lucas, 2012; Mouratidis, 2025), which directly affects residents' life satisfaction. This effect is more profound where the streets are more disordered and detours are more frequent. Accordingly, we propose the following hypothesis:

H_4 New technology adoption, such as digital navigation tools and private vehicles, mitigates the negative effect of irregular urban street network morphology on residents' life satisfaction.

3 Data and Stylized Facts

3.1 Explanatory variable: street network regularity

To explore the effect of urban street network morphology on residents' life satisfaction, we first quantify the regularity of urban street network. Data on urban street networks are obtained from OpenStreetMap (OSM), a global, open-source geospatial database that provides detailed information on road geometry and functional classification. For each county, we collect street network data from the OSM historical archive for 2014 and 2022. The extracted data include the full geometric representation of road segments, their lengths, bearings, and node structures, which together characterize the spatial and topological properties of urban street network.

Street network data are initially clipped using official administrative boundaries. However, administrative boundaries often encompass extensive rural or peripheral areas whose roads do not reflect urban morphology or residents' daily experience. In addition, irregular jurisdictional shapes may mechanically affect street orientations. To address these concerns, we use the 2010 Global Human Settlement Layer (GHSL) to identify each county's primary built-up area. [3] Using the 2010 GHSL snapshot helps avoid post-treatment bias and is appropriate given the relative stability of the structure of already-built street networks over time. We then identify the geometric centroid of built-up area and construct a circular buffer centered on it, with an area equal to that of the identified built-up area. The street network is subsequently clipped to this equal-area circle. This procedure reduces the influence of rural roads and irregular administrative boundaries while ensuring that street networks from different years are measured within a standardized spatial extent.

We measure street network regularity by the length-weighted orientation entropy proposed by Boeing (2019), which captures the dispersion of street orientations within a county. The index is defined as

$$H_{h,w} = -\sum_{i} P_i \ln P_i \tag{1}$$

where i indexes the directional bins into which the full 360° range of street orientations is divided, and P_i is the share of total street length whose orientation falls within bin i. By weighting directions by segment length, the index emphasizes the structural role of major roads and arterial corridors. A higher value indicates more dispersed, less regular orientations; a lower value indicates more ordered, grid-like layouts. Meanwhile, following Boeing (2019), we replace our explanatory variable with unweighted orientation entropy for robustness checks. This index assigns equal weight to every street segment without weighting by road length and better reflects the pure topological regularity of the network.

Using this measure, we document a pronounced north–south pattern in street network regularity across Chinese prefecture-level cities. As shown in Fig. 2A, northern cities display more regular, grid-like layouts with strong orderliness in orientation, whereas southern cities show more

[3] Built-up pixels are binarized using a threshold of built-up surface fraction $\geq 25\%$, after which noise removal, morphological opening and closing, and connected-component analysis are applied to retain the largest contiguous built-up component.

flexible and less regular layouts. The Getis–Ord Gi* analysis in Fig. 2B provides statistical support for this pattern, indicating that low-entropy clusters are mainly located in the north, whereas high-entropy (irregular) clusters occur in the south. This spatial differentiation is primarily determined by natural topography. The north-south dividing line is roughly consistent with the Qinling–Huaihe line, China's major geographical boundary (Ebenstein, Fan, Greenstone, He, & Zhou, 2017). North of this line the terrain is mostly plains, while the south is dominated by hills and dense river networks.

To provide empirical evidence on the relationship between terrain and street network morphology, we calculate the orientation entropy of river networks and ridgelines. [4] Fig. A1 presents the relationship between terrain orientation entropy and street network orientation entropy. The two measures are strongly positively correlated, with a partial correlation coefficient of 0.56 that is statistically significant. This result indicates that greater dispersion in terrain orientations is associated with higher street network orientation entropy and, consequently, lower street network regularity. This stylized fact suggests that topography is an important source of variation in street network regularity and motivates our identification strategy in Section 4.

3.2 Outcome variable: residents' life satisfaction

Residents' life satisfaction and other individual characteristics are drawn from the China Family Panel Studies (CFPS), a nationally representative longitudinal household survey conducted by Peking University's Institute of Social Science Survey. CFPS uses multistage probability sampling and tracks individuals, households, and communities over time, collecting information on demographics, economic status, social attitudes, and subjective evaluations (Hu, Zhai, & Yan, 2023). Our sample includes respondents with valid information on life satisfaction and county of residence, covering survey waves from 2010 to 2022. Individual records are matched to county-level spatial indicators using consistent geographic identifiers.

We use self-reported life satisfaction as the main outcome variable, and employ subjective happiness and household life satisfaction as alternative outcomes in the robustness analysis. We additionally use residents' self-rated health as an outcome to examine whether the consequences of street-network regularity extend beyond residents' life satisfaction. Fig. A2 presents the binscatter partial correlation plot between resident life satisfaction and street orientation entropy. The figure shows a negative relationship. This pattern indicates that lower orientation entropy, and thus more regular street networks, is associated with higher life satisfaction. To explore transportation costs as a potential mechanism linking street network regularity to life satisfaction, we further examine residents' one-way commuting time and monthly expenditure on local transportation.

[4] River network data are extracted from OSM waterway features, including rivers, streams, and major channels. Ridgeline features are extracted from an inverted digital elevation model (DEM) using a hydrology-based procedure that identifies dominant topographic divides. River networks and ridgelines are processed using the same clipping and buffering procedures as the street networks. Their orientation entropy, hereafter referred to collectively as terrain orientation entropy, is calculated using the same orientation-binning approach as for roads.

3.3 Control variables

Drawing on prior studies, we additionally incorporate a set of covariates that may be related to street network regularity and residents' well-being. These covariates consist of two groups. One is geographical and historical characteristics of a county. They include drainage density, slope and roughness of the land. The historical characteristics shape the long-term spatial form of urban street networks. They include two historical variables. The first, historical capital dummy, indicates whether the city served as a dynastic capital in Chinese history. The second, the wall dummy (Xue, Jin, Cheng, Yang, & Zhou, 2021), indicates whether the county contained a walled city. These variables also provide support for the validity of our identification strategy, as discussed in the Identification Assumptions section.

The other set of covariates are the individual and household level characteristics. The variables include age, gender, hukou status, education level, marital status, and net household income per capita in the last twelve months (log-transformed). All individual and household characteristics are drawn from the CFPS. Table 1 reports summary statistics for all variables used in the analysis.

4 Empirical strategy

4.1 Estimation framework

We begin with a baseline ordinary least squares (OLS) specification that links county-level street network regularity to residents' life satisfaction:

$$LS_{iht} = \alpha + \beta \cdot Regularity_h + X'_{iht}\gamma + W'_h\phi + \mu_t + \varepsilon_{iht} \tag{2}$$

where LS_{iht} denotes the life satisfaction of individual i in county h, $Regularity_h$ measures the directional regularity of the county's street network (its orientation entropy, defined in Section 3.1), X_{iht} is a vector of individual- and household-level controls, W'_h captures county-level controls, μ_t is time fixed effects, and ε_{iht} is the error term. The coefficient β reflects the partial correlation between urban spatial order and life satisfaction, conditional on observed covariates. However, counties with different road structures may systematically differ along unobserved dimensions that also shape residents' life satisfaction, so $Regularity_h$ is likely endogenous and this conditional correlation cannot be interpreted causally.

To address this concern, we implement an instrumental-variable (IV) strategy. The instrument exploits cross-county variation in the directional structure of natural terrain, specifically the orientation dispersion of river systems and mountain ridgelines (the terrain orientation entropy defined in Section 3.1). The key idea is that terrain direction constrains feasible road alignments through engineering costs and long-run path dependence, generating plausibly exogenous variation in the regularity of urban street networks. This logic is consistent with research showing that spatial networks are strongly shaped by geographic constraints and historical development processes (Barthélemy, 2011; Bogart, 2007; Marshall, 2004), and that transport infrastructure leaves persistent imprints on urban spatial structure (Baum-Snow et al., 2017).

We estimate the causal effect using two-stage least squares (2SLS). The first-stage relationship is

$$Regularity_h = \pi_0 + \pi_1 \cdot RHEntropy_h + W_h'\phi + u_{ih} \tag{3}$$

where $RHEntropy_h$ is terrain orientation entropy in county h, W_h' captures observable county characteristics, and μ_{ih} are time fixed effects. The second-stage equation is

$$LS_{iht} = \alpha + \beta \cdot \widehat{Regularity}_h + X_{iht}'\gamma + W_h'\phi + \mu_t + \varepsilon_{iht} \tag{4}$$

where $\widehat{Regularity}_h$ is the predicted regularity from the first stage. The parameter of interest, β, captures the causal effect of street network regularity on individual life satisfaction, conditional on observed controls and fixed effects.

The baseline uses a cross-sectional measure of street network regularity for 2022. The reasons are twofold. First, it is consistent with the IV design, which exploits cross-county variation in urban form induced by natural-landscape constraints. Second, we use the 2022 OSM data because more recent OSM data provide more complete road network coverage. Moreover, 2022 is the most recent wave in our CFPS survey data. As a robustness check, we also use a panel dataset with time-varying street network regularity. This allows us to better capture the effect of contemporaneous street network regularity on residents' life satisfaction in the same year. As shown by the robustness checks, the results remain consistent.

4.2 Identification assumptions

The validity of the IV strategy rests on two assumptions: relevance and the exclusion restriction. Relevance requires that terrain orientation predicts urban street network regularity. River systems and hill ridgelines impose directional constraints on infrastructure placement. When natural features spread out in many different directions, road building has to adapt to these varied orientations, resulting in more irregular networks. We also empirically test the relevance. The partial correlation between terrain orientation entropy and street network orientation entropy is 0.56 and highly significant, and the first-stage F-statistic on the excluded instrument far exceeds the conventional threshold of 10, indicating strong relevance (Fig. A1).

The exclusion restriction requires that the orientation of terrain affects residents' life satisfaction only through its influence on street network regularity. This assumption is supported by the fact that terrain orientations are shaped by long-run geological processes and are therefore predetermined to modern urban planning. In addition, our instruments capture the directional dispersion rather than the presence or overall intensity of rivers and ridgelines. They are therefore conceptually distinct from terrain density, elevation, slope, and other physical attributes that may directly affect local living conditions.

A potential concern is that terrain orientation may be correlated with other factors that independently affect residents' well-being. This directly threatens the exclusion restriction. We address this concern in two ways. First, we directly control for the major confounding factors. Terrain orientation may be correlated with other geographic characteristics. We therefore control

for drainage density, land slope and roughness that directly affect residents' daily travel within a city and are thus particularly likely to influence their life satisfaction. Besides, Chinese cities differ in their historical origins. Such differences affect contemporary urban development and residents' well-being through channels including economic development and urban infrastructure construction. Therefore, we directly control for the most plausible historical confounding channels. We include a county-level wall dummy and a historical capital dummy (Section 3.3). These controls help isolate directional variation from other factors that independently affect residents' well-being.

Second, although these controls account for the most plausible channels, they cannot rule out all possible violations of the exclusion restriction. We therefore further assess the sensitivity of our IV estimates using the plausibly exogenous approach proposed by Conley, Hansen, and Rossi (2012). This approach relaxes the strict exclusion restriction by allowing terrain orientation to have a nonzero direct effect on life satisfaction. We then examine how large this direct effect would have to be before the estimated effect of street network regularity becomes statistically insignificant. This exercise allows us to assess whether our conclusions remain robust to moderate violations of the exclusion restriction. The results are reported in Robustness Checks Section (Section 5.6).

5 Results

5.1 Impact of street network regularity on residents' well-being

We first investigate the effect of street network regularity on residents' life satisfaction. The results are reported in Table 2. Columns (1) and (2) report the correlation between street network regularity and residents' life satisfaction. The coefficients of orientation entropy are significantly negative, suggesting that a more disordered street network is associated with lower life satisfaction. Columns (3) and (4) report the IV-2SLS results. Column (3) only control for individual and household characteristics and year fixed effects, whereas Column (4) further add geographical characteristics as controls. The IV estimates are consistent with the OLS findings. As shown in Column (4), the coefficient of orientation entropy on life satisfaction is -0.163, significant at the 1% level. This result suggests that lower street network regularity reduces residents' life satisfaction.

The magnitude is economically meaningful. The IV estimate implies that a one-standard-deviation increase in orientation entropy lowers life satisfaction by about 0.060 standard deviations. To compare this effect with the literature, note that Stutzer and Frey (2008) find that a standard deviation increase in commuting time (18 minutes one way) reduces life satisfaction by 0.086 points on a scale of 0-10, equivalent to approximately 0.052 standard deviations. Our estimate is almost identical in magnitude. Our findings demonstrate that the orientation structure of street layouts carries independent explanatory power. This is consistent with the arguments that urban geometry has measurable consequences for urban outcomes (Ewing & Cervero, 2010; Harari, 2020) and that urban compactness significantly affects residents' well-being (Mouratidis,

2019).

5.2 Heterogeneous effects across socioeconomic groups

The baseline results document the overall effect of irregular street networks on residents' life satisfaction. However, its distributional implications may also matter. This effect may differ across population groups. Older residents may find complex street layouts more difficult to navigate, while lower-income households may have fewer resources to adapt. Such differences may widen existing inequalities in well-being. We therefore examine heterogeneity by age and household income.

First, to examine heterogeneity by age, we split the sample into four age groups (18–29, 30–44, 45–59, and 60+) and re-estimate the baseline specification within each subsample. Panel A of Table 3 reports the results. The effect of orientation entropy on life satisfaction increases monotonically with age. Among respondents aged 18–29, the coefficient is the smallest. It almost doubles for those aged 30–44 and grows further for the 45–59 group. By far the largest effect emerges among those aged 60 and above, more than six times the estimate for the youngest group. This gradient is consistent with the view that older residents, whose adaptive capacity is more limited, incur greater well-being losses stemming from irregular street networks.

Second, to examine heterogeneity by income, we partition the sample into three income terciles and re-estimate the baseline specification. As shown in Panel B of Table 3, low-income households experience the strongest effect. The coefficient of low-income households is more than double the estimate for high-income households. Middle-income respondents fall in between. This pattern therefore widens existing gaps in life satisfaction across income groups. Taken together, the negative effect of irregular street network on life satisfaction is stronger among residents with fewer resources to avoid or mitigate it. These heterogeneous effects suggest that irregular street networks may reinforce existing inequalities in subjective well-being.

5.3 Transportation costs as a mechanism

A key mechanism through which irregular street networks reduce residents' life satisfaction is higher transportation costs. First, dispersed street orientations force residents onto more circuitous routes with extra turns, thereby increasing travel distance and commuting time. Second, less regular road layouts may increase navigation difficulty, leading to detours and longer travel times. To test this channel, we replace the dependent variable with residents' commuting time and transportation expenditure.

As shown in Table 4, Column (4) adopts terrain orientation entropy as the instrumental variable for urban street network regularity, while controlling for individual and household characteristics, geographical characteristics and year fixed effects. For commuting time, Column (4) of Panel A shows that the coefficient of orientation entropy is 2.662 and statistically significant at the 1% level. This finding implies that a higher orientation entropy value corresponds to more scattered street orientations and significantly longer one-way commuting time for residents. As for transportation expenditure, Column (4) of Panel B shows that the coefficient on orientation

entropy equals 126.042 and is statistically significant at the 1% level, which indicates that lower street network regularity leads to a marked rise in residents' monthly transportation spending. Both estimates are statistically significant at the 1% level. These results indicate that less regular street networks lengthen commuting time and raise transportation expenditure, providing evidence consistent with transportation costs as a mechanism linking street network regularity to life satisfaction.

5.4 Impact of street network regularity on residents' self-rated health

Beyond residents' life satisfaction, we investigate whether irregular street networks have broader well-being implications by examining their effects on residents' self-rated health. Chronic psychological stress caused by irregular street networks can also worsen residents' self-rated health. To test this intuition, we replace the dependent variable with residents' self-rated health. The results are reported in Table 5. Columns (1) and (2) report the correlation between street network regularity and residents' self-rated health. The results suggest that a more disordered street network is associated with lower self-rated health. Columns (3) and (4) report the IV-2SLS results. The IV estimates are consistent with the OLS findings. As shown in Column (4), the coefficient of orientation entropy on self-rated health is -0.098, significant at the 1% level. These findings suggest that irregular street networks not only reduce residents' life satisfaction but also generate broader health consequences.

5.5 Technological adoption as a mitigating channel

Given the adverse effects of irregular street networks, an important policy question is how to mitigate them. Directly reshaping existing street networks is often costly, particularly in established cities where urban layouts are constrained by natural features. Technologies provide alternative means of helping residents adapt to irregular street layouts. To examine this possibility, we conduct heterogeneity analyses based on mobile-internet usage and private-car ownership.

First, digital tools such as navigation software may ease wayfinding difficulties in complex street layouts and thereby mitigate the adverse effects of irregular street networks. Because direct information on navigation-tool use is unavailable, we use mobile internet usage as a proxy for residents' access to such digital tools. As displayed in Columns (1) and (2) of Table 6, the coefficient of street network orientation entropy on life satisfaction is -0.247 for residents without mobile internet access, while the corresponding coefficient for internet users is only -0.070. This indicates that the popularity of mobile internet and navigation applications can effectively weaken the adverse effect of irregular street networks on residents' life satisfaction. Second, private-car ownership similarly increases residents' flexibility in travel timing and route choice. As shown in Columns (3) and (4), the negative impact of disordered networks is stronger for non-car owners than for car owners.

Taken together, both digital tools and private-vehicle access serve as buffers against the welfare costs of irregular street networks. Digital technologies can offset deficiencies in physical urban infrastructure, while private cars expand route flexibility and travel autonomy (Ellaway,

Macintyre, Hiscock, & Kearns, 2003; Steg, 2005). These findings are consistent with the broader insight that individual mobility resources can compensate for deficiencies in the built environment (Lucas, 2012).

5.6 Robustness

Alternative subjective happiness outcome. To address the concern that our baseline findings are sensitive to the choice of the life satisfaction measure, we replace the dependent variable with two commonly used indicators, namely, residents' subjective happiness and household life satisfaction. As shown in Panels A and B of Table 7, the estimated coefficients are highly consistent with the baseline results. Less regular street networks significantly reduce residents' subjective happiness and household life satisfaction, and this negative effect remains statistically stable across different model specifications. These results indicate that our main findings are robust to the use of an alternative measure of subjective well-being.

Unweighted orientation entropy. To verify that our conclusions are not sensitive to the measurement approach of street network disorder, we replace the core explanatory variable with unweighted orientation entropy of street networks. As shown in Panel C of Table 7, the estimated effects align closely with the baseline results. Unweighted orientation entropy still exerts a significant impact on residents' life satisfaction, with identical coefficient signs and statistical significance as observed in baseline results. These outcomes confirm that our main conclusions remain substantively unchanged when adopting an alternative indicator of street network disorder.

Time-varying orientation entropy. To align the baseline specification with instrumental variable variation, we adopt cross-sectional street orientation entropy in the baseline analysis. To examine whether the main findings are specific to that year or driven by the use of a static measure of street morphology, we re-estimate the model using time-varying measures of orientation entropy. Panel D of Table 7 shows that the result is materially unchanged, indicating that our main findings are robust to temporal variation of street network morphology.

Urban-only sample. Because our street network measure is constructed for urban areas, we restrict the sample to urban households to ensure consistency between the measured street network and the population under study. As shown in Panel E of Table 7, the coefficient equals -0.172 for the urban-only sample and is statistically significant at the 1% level, which is larger in magnitude than the full-sample estimate of -0.163. This finding implies that irregular street networks exert a stronger negative impact on urban residents.

Plausible exogeneity test. To further assess the sensitivity of the IV estimates, we follow Conley et al. (2012) and relax the strict exclusion restriction. We allow terrain orientation to have a direct effect on life satisfaction and then re-estimate the IV coefficient. Specifically, we allow the direct effect to take any value from zero up to a specified percentage of the reduced-form

effect. For each admissible range of direct effects, we calculate the union of the corresponding 95% confidence intervals of the IV coefficient. Figure A3 plots the bounds of these union confidence intervals (y-axis) against the maximum admissible direct effect (x-axis), expressed as a percentage of the reduced-form effect. We find that the union of the 95% confidence intervals first includes zero when the direct effect of terrain orientation reaches approximately 73% of the overall reduced-form effect. This threshold is similar to the 74%–78% range reported in Caprettini and Voth (2020). Given that our baseline specification already controls for drainage density, slope, land roughness, historical capital status, and wall history, such a large residual direct effect is unlikely to exist. Therefore, this plausible exogeneity test lends support to the validity of our IV design.

Spatially correlated inference. Finally, both the treatment and the instrument vary at the county level and exhibit pronounced spatial clustering across China (Fig. 2). We therefore complement cluster-robust inference with the spatial HAC standard errors proposed by Conley (1999). This approach allows errors to be correlated across geographically proximate counties without relying on administrative boundaries. We keep the estimation sample unchanged and residualize the dependent and endogenous variables with respect to all controls. We then aggregate the data to the county level using observation-count weights and estimate the IV specification with a Bartlett kernel based on great-circle distances between county centroids. The bandwidths are 50, 100, 200, and 500 km. As shown in Table 8, the corresponding standard errors are 0.060, 0.062, 0.067, and 0.063, and the estimate remains statistically significant at the 1% level even with a 500 km bandwidth. This bandwidth spans major regional terrain belts in China and covers 15% of all county pairs in the sample. Thus, our main finding remains robust after allowing for spatial correlation over a substantially broader geographic scale.

6 Discussion and Conclusion

Using nationwide survey data from China, this paper provides, to our knowledge, the first causal evidence on how the regularity of urban street networks shapes residents' life satisfaction. The results suggest that less regular street layouts significantly reduce life satisfaction and lower self-rated health. The welfare loss induced by a one-standard-deviation rise in orientation entropy is roughly equivalent to the subjective-well-being penalty from an 18-minute increase in one-way commuting time. This effect arises because irregular networks lengthen commuting time and raise transportation costs. This negative effect is stronger for the elderly and low-income residents. Finally, digital navigation tools and private-vehicle access mitigate the welfare loss from irregular street layouts.

These findings suggest that the spatial regularity of street networks also matters for residents' well-being. Therefore, they complement existing evidence that urban form, commuting conditions, and neighborhood environments shape residents' well-being (Mitchell et al., 2015; Mouratidis, 2019; Ossokina et al., 2023). They also echo broader research showing that urban geometry can have measurable consequences for urban outcomes (Ewing & Cervero, 2010; Harari, 2020). Moreover, the stronger effects among older and low-income residents highlight the unequal well-

being consequences of the built environment. Finally, the mitigating roles of technology adoption directly speak to the growing literature on the effect of technology adoption on people's well-being (Castellacci & Tveito, 2018; Liu, Chen, Yu, & Wang, 2024).

These findings have three policy implications. First, street-network orientation should receive greater attention in the planning of newly developed urban areas. More regular layouts and greater directional consistency of major roads can reduce navigation frictions and improve residents' life satisfaction. Second, in existing built-up areas where street morphology is difficult to reshape, technological adoption offers a more practical response. Digital navigation tools and targeted mobility support can help residents cope with complex street layouts. Third, policy design should account for the unequal effects of street-network disorder across population groups. Because older and lower-income residents experience larger losses in life satisfaction, policies should give greater attention to these groups. This distributional pattern suggests that street-network design is not only an efficiency issue, but may also have implications for inequality in subjective well-being.

This paper has several limitations. First, orientation entropy captures only one dimension of street-network morphology. Other features such as block size and intersection density are still unrecognized. Second, due to data limitations, our mechanism analysis focuses on travel costs. It does not directly examine psychological channels such as disorientation and stress. Future research could explore these dimensions with richer spatial and survey data.

References

Ambrey, C., & Fleming, C. (2014). Public greenspace and life satisfaction in urban australia. *Urban Studies*, *51*(6), 1290–1321, doi: https://doi.org/10.1177/0042098013494417

Barthélemy, M. (2011). Spatial networks. *Physics Reports*, *499*(1–3), 1–101, doi: https://doi.org/10.1016/j.physrep.2010.11.002

Baum-Snow, N., Brandt, L., Henderson, J.V., Turner, M.A., Zhang, Q. (2017). Roads, railroads, and decentralization of Chinese cities. *Review of Economics and Statistics*, *99*(3), 435–448, doi: https://doi.org/10.1162/rest_a_00660

Boeing, G. (2019). Urban spatial order: Street network orientation, configuration, and entropy. *Applied Network Science*, *4*, 67, doi: https://doi.org/10.1007/s41109-019-0189-1

Boeing, G. (2020). A multi-scale analysis of 27,000 urban street networks: Every US city, town, urbanized area, and Zillow neighborhood. *Environment and Planning B: Urban Analytics and City Science*, *47*(4), 590–608, doi: https://doi.org/10.1177/2399808318784595

Bogart, D. (2007). Neighbors, networks, and the development of transport systems: Explaining the diffusion of turnpike trusts in eighteenth-century England. *Journal of Urban Economics*, *61*(2), 238–262, doi: https://doi.org/10.1016/j.jue.2006.11.002

Brown, Z.S., Oueslati, W., Silva, J. (2016). Links between urban structure and life satisfaction in a cross-section of oecd metro areas. *Ecological economics*, *129*, 112–121, doi: https://doi.org/10.1016/j.ecolecon.2016.05.004

Caprettini, B., & Voth, H.-J. (2020). Rage against the machines: Labor-saving technology and unrest in industrializing england. *American Economic Review: Insights*, *2*(3), 305–320, doi: https://doi.org/10.1257/aeri.20190385

Castellacci, F., & Tveito, V. (2018). Internet use and well-being: A survey and a theoretical framework. *Research Policy*, *47*(1), 308–325, doi: https://doi.org/10.1016/j.respol.2017.11.007

Chatterjee, K., Chng, S., Clark, B., Davis, A., De Vos, J., Ettema, D., ... Reardon, L. (2020). Commuting and wellbeing: a critical overview of the literature with implications for policy and future research. *Transport reviews*, *40*(1), 5–34, doi: https://doi.org/10.1080/01441647.2019.1649317

Conley, T.G. (1999). Gmm estimation with cross sectional dependence. *Journal of econometrics*, *92*(1), 1–45, doi: https://doi.org/10.1016/s0304-4076(98)00084-0

Conley, T.G., Hansen, C.B., Rossi, P.E. (2012). Plausibly exogenous. *Review of Economics and Statistics*, *94*(1), 260–272, doi: https://doi.org/10.1162/rest_a_00139

Currie, J., Voorheis, J., Walker, R. (2023). What caused racial disparities in particulate exposure to fall? new evidence from the clean air act and satellite-based measures of air quality. *American Economic Review*, *113*(1), 71–97, doi: https://doi.org/10.1257/aer.20191957

De Vos, J., Schwanen, T., Van Acker, V., Witlox, F. (2013). Travel and subjective well-being: A focus on findings, methods and future research needs. *Transport Reviews*, *33*(4), 421–442, doi: https://doi.org/10.1080/01441647.2013.815665

Dong, Z., Yun, Y., Sun, Y., Wang, F. (2022). Building use-wellbeing associations: A spatial perspective. *Cities*, *121*, 103493, doi: https://doi.org/10.1016/j.cities.2021.103493

Duranton, G., & Turner, M.A. (2012). Urban growth and transportation. *Review of Economic Studies*, *79*(4), 1407–1440, doi: https://doi.org/10.1093/restud/rds010

Ebenstein, A., Fan, M., Greenstone, M., He, G., Zhou, M. (2017). New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. *Proceedings of the National Academy of Sciences*, *114*(39), 10384–10389, doi: https://doi.org/10.1073/pnas.1616784114

Ellaway, A., Macintyre, S., Hiscock, R., Kearns, A. (2003). In the driving seat: Psychosocial benefits from private motor vehicle transport compared to public transport. *Transportation Research Part F: Traffic Psychology and Behaviour*, *6*(3), 217–231, doi: https://doi.org/10.1016/s1369-8478(03)00027-5

Ettema, D., Gärling, T., Olsson, L.E., Friman, M. (2010). Out-of-home activities, daily travel, and subjective well-being. *Transportation Research Part A: Policy and Practice*, *44*(9), 723–732, doi: https://doi.org/10.1016/j.tra.2010.07.005

Evans, G.W., & Wener, R.E. (2006). Rail commuting duration and passenger stress. *Health psychology*, *25*(3), 408, doi: https://doi.org/10.1037/0278-6133.25.3.408

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association*, *76*(3), 265–294, doi: https://doi.org/10.1080/01944361003766766

Fancello, G., Chaix, B., Molina, M.A., Stickland, N., Barnett, A., Lautenschlager, N.T., ... Cerin, E. (2025). Urban environment and complexity of walking routes in mid-aged and older adults: the moderating effects of cognitive abilities. *Journal of Environmental Psychology*, *105*, 102660, doi: https://doi.org/10.1016/j.jenvp.2025.102660

Fang, Y., & Wu, J. (2026). How does transport poverty affect subjective well-being in china: Mechanisms analysis, and urban-rural disparity. *Cities*, *178*, 107301, doi: https://doi.org/10.1016/j.cities.2026.107301

Fernández-Portero, C., Alarcón, D., Padura, Á.B. (2017). Dwelling conditions and life satisfaction of older people through residential satisfaction. *Journal of environmental psychology*, *49*, 1–7, doi: https://doi.org/10.1016/j.jenvp.2016.11.003

Garcia-López, M.-À. (2012). Urban spatial structure, suburbanization and transportation in

barcelona. *Journal of Urban Economics*, *72*(2-3), 176–190, doi: https://doi.org/10.1016/j.jue.2012.05.003

Gibbons, S., Lyytikäinen, T., Overman, H.G., Sanchis-Guarner, R. (2019). New road infrastructure: The effects on firms. *Journal of Urban Economics*, *110*, 35–50, doi: https://doi.org/10.1016/j.jue.2019.01.002

Glaeser, E.L., Kahn, M.E., Rappaport, J. (2008). Why do the poor live in cities? the role of public transportation. *Journal of Urban Economics*, *63*(1), 1–24, doi: https://doi.org/10.1016/j.jue.2006.12.004

Harari, M. (2020). Cities in bad shape: Urban geometry in India. *American Economic Review*, *110*(8), 2377–2421, doi: https://doi.org/10.1257/aer.20171673

Hoogendoorn, S., Van Gemeren, J., Verstraten, P., Folmer, K. (2019). House prices and accessibility: Evidence from a quasi-experiment in transport infrastructure. *Journal of Economic Geography*, *19*(1), 57–87, doi: https://doi.org/10.1093/jeg/lbx027

Hu, D., Zhai, C., Yan, Z. (2023). Do social interactions foster household entrepreneurship? evidence from online and offline data from China Family Panel Studies. *China Economic Review*, *79*, 101965, doi: https://doi.org/10.1016/j.chieco.2023.101965

Huebner, G.M., Oreszczyn, T., Direk, K., Hamilton, I. (2022). The relationship between the built environment and subjective wellbeing–analysis of cross-sectional data from the english housing survey. *Journal of environmental psychology*, *80*, 101763, doi: https://doi.org/10.1016/j.jenvp.2022.101763

Ingenfeld, J., Wolbring, T., Bless, H. (2019). Commuting and life satisfaction revisited: Evidence on a non-linear relationship: J. ingenfeld et al. *Journal of Happiness Studies*, *20*(8), 2677–2709, doi: https://doi.org/10.1007/s10902-018-0064-2

Kahneman, D., Krueger, A.B., Schkade, D.A., Schwarz, N., Stone, A.A. (2004). A survey method for characterizing daily life experience: The day reconstruction method. *Science*, *306*(5702), 1776–1780, doi: https://doi.org/10.1126/science.1103572

Kawakubo, S., Arata, S., Kamata, T. (2026). Role of the residential environment in shaping subjective well-being. *Journal of Happiness Studies*, *27*(5), 59, doi: https://doi.org/10.1007/s10902-026-01043-1

Krekel, C., Kolbe, J., Wüstemann, H. (2016). The greener, the happier? the effect of urban land use on residential well-being. *Ecological economics*, *121*, 117–127, doi: https://doi.org/10.1016/j.ecolecon.2015.11.005

Lester, A.W., Moffat, S.D., Wiener, J.M., Barnes, C.A., Wolbers, T. (2017). The aging navigational system. *Neuron*, *95*(5), 1019–1035, doi: https://doi.org/10.1016/j.neuron.2017.06.037

Liloia, D., & Filomena, G. (2025). The neuropsychological correlates of urban navigation: A meta-analysis of 27 years of functional neuroimaging studies. *Journal of Environmental Psychology*, 102857, doi: https://doi.org/10.1016/j.jenvp.2025.102857

Liu, Y., Chen, M., Yu, J., Wang, X. (2024). Being a happy farmer: Technology adoption and subjective well-being. *Journal of Economic Behavior & Organization*, *221*, 385–405, doi: https://doi.org/10.1016/j.jebo.2024.03.028

Lucas, K. (2012). Transport and social exclusion: Where are we now? *Transport Policy*, *20*, 105–113, doi: https://doi.org/10.1016/j.tranpol.2012.01.013

Marshall, S. (2004). *Streets and patterns*. London: Routledge.

Miola, L., Muffato, V., Sella, E., Meneghetti, C., Pazzaglia, F. (2024). Gps use and navigation ability: A systematic review and meta-analysis. *Journal of Environmental Psychology*, *99*, 102417, doi: https://doi.org/10.1016/j.jenvp.2024.102417

Mitchell, R.J., Richardson, E.A., Shortt, N.K., Pearce, J.R. (2015). Neighborhood environments and socioeconomic inequalities in mental well-being. *American journal of preventive medicine*, *49*(1), 80–84, doi: https://doi.org/10.1016/j.amepre.2015.01.017

Möller, J., & Zierer, M. (2018). Autobahns and jobs: A regional study using historical instrumental variables. *Journal of Urban Economics*, *103*, 18–33, doi: https://doi.org/10.1016/j.jue.2017.10.002

Mouratidis, K. (2019). Compact city, urban sprawl, and subjective well-being. *Cities*, *92*, 261–272, doi: https://doi.org/10.1016/j.cities.2019.04.013

Mouratidis, K. (2021). Urban planning and quality of life: A review of pathways linking the built environment to subjective well-being. *Cities*, *115*, 103229, doi: https://doi.org/10.1016/j.cities.2021.103229

Mouratidis, K. (2025). Transport and quality of life: The car and its link to subjective well-being, health, and life domains. *Transport Policy*, *168*, 101–111, doi: https://doi.org/10.1016/j.tranpol.2025.04.014

National Geospatial Information Public Service Platform (2025). *Administrative division data of China.* https://cloudcenter.tianditu.gov.cn/administrativeDivision/.

Nie, P., & Sousa-Poza, A. (2018). Commute time and subjective well-being in urban china. *China Economic Review*, *48*, 188–204, doi: https://doi.org/10.1016/j.chieco.2016.03.002

Ossokina, I.V., Van Ommeren, J., Van Mourik, H. (2023). Do highway widenings reduce congestion? *Journal of Economic Geography*, *23*(4), 871–900, doi: https://doi.org/10.1093/jeg/lbac034

Risko, E.F., & Gilbert, S.J. (2016). Cognitive offloading. *Trends in cognitive sciences*, *20*(9), 676–688, doi: https://doi.org/10.1016/j.tics.2016.07.002

Steg, L. (2005). Car use: Lust and must. instrumental, symbolic and affective motives for car use. *Transportation Research Part A: Policy and Practice*, *39*(2–3), 147–162, doi: https://doi.org/10.1016/j.tra.2004.07.001

Stutzer, A., & Frey, B.S. (2008). Stress that doesn't pay: The commuting paradox. *Scandinavian Journal of Economics*, *110*(2), 339–366, doi: https://doi.org/10.1111/j.1467-9442.2008.00542.x

Sun, G., & Du, Y. (2023). New metro and subjective wellbeing among older people: A natural experiment in hong kong. *Transportation research part A: policy and practice*, *169*, 103592, doi: https://doi.org/10.1016/j.tra.2023.103592

Tansan, M., Nguyen, K.V., Newcombe, N.S. (2022). Spatial navigation in childhood and aging. *Annual Review of Developmental Psychology*, *4*, 253–272, doi: https://doi.org/10.1146/annurev-devpsych-121020-031846

van der Ham, I.J., & Claessen, M.H. (2020). How age relates to spatial navigation performance: Functional and methodological considerations. *Ageing research reviews*, *58*, 101020, doi: https://doi.org/10.1016/j.arr.2020.101020

White, M.P., Alcock, I., Wheeler, B.W., Depledge, M.H. (2013). Would you be happier living in a greener urban area? a fixed-effects analysis of panel data. *Psychological science*, *24*(6), 920–928, doi: https://doi.org/10.1177/0956797612464659

Xue, Q., Jin, X., Cheng, Y., Yang, X., Zhou, Y. (2021). The dataset of walled cities and urban extent in late imperial china in the 15th–19th centuries. *Earth System Science Data*, *13*(11), 5071–5085, doi: https://doi.org/10.5194/essd-13-5071-2021

Zhang, C., Elie, T.K., Li, W., Zheng, L., Li, J., Yao, D., ... Yao, W. (2026). The causal effect of network structures on subjective well-being among older adults. *Transportation Research Part D: Transport and Environment*, *155*, 105339, doi: https://doi.org/10.1016/j.trd.2026.105339

Zhang, X., Chen, X., Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. *Proceedings of the National Academy of Sciences*, *115*(37), 9193–9197, doi: https://doi.org/10.1073/pnas.1809474115

Figures

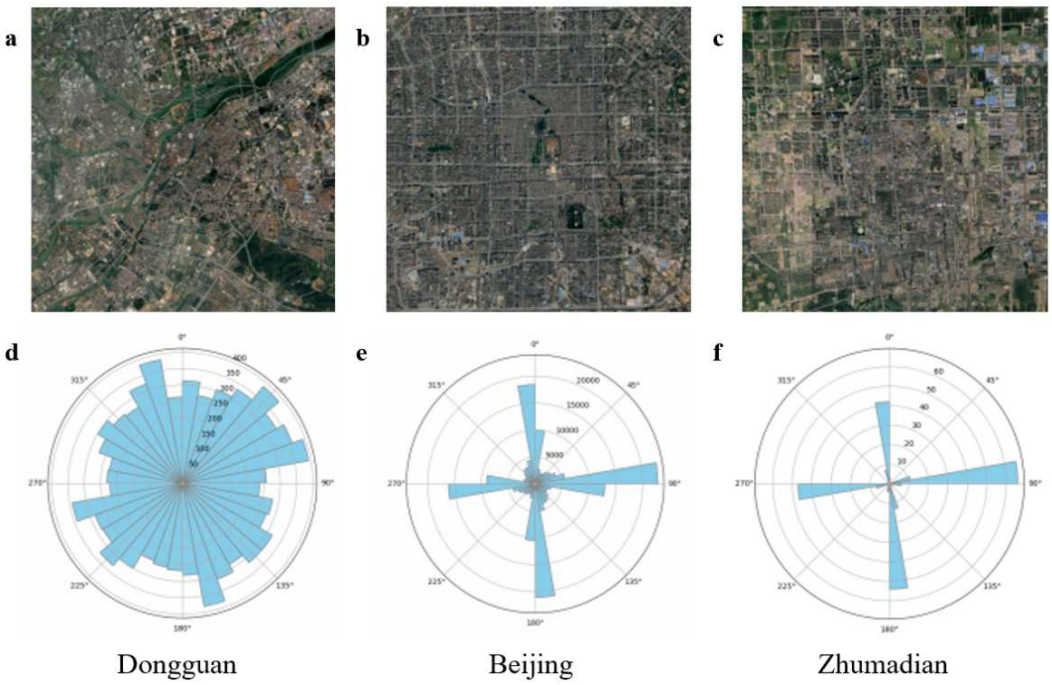


Figure 1: Urban street network morphology and orientation distributions in Dongguan, Beijing, and Zhumadian. (A–C) Satellite-based visualizations of urban road-network structures in Dongguan (A), Beijing (B), and Zhumadian (C). Dongguan exhibits a radial and irregular pattern shaped by rivers and terrain; Beijing displays a typical grid-like structure with directions concentrated along orthogonal axes; Zhumadian shows a sparser directional distribution clustered around a few specific orientations. (D–F) Corresponding polar histograms of street-segment orientations; each bar represents the proportion of road segments within a given angular bin. Orientation entropy values are 3.58 (Dongguan), 3.33 (Beijing), and 2.69 (Zhumadian), with higher values indicating more dispersed and less regular layouts. Base-map data are from the National Geospatial Information Public Service Platform (2025).

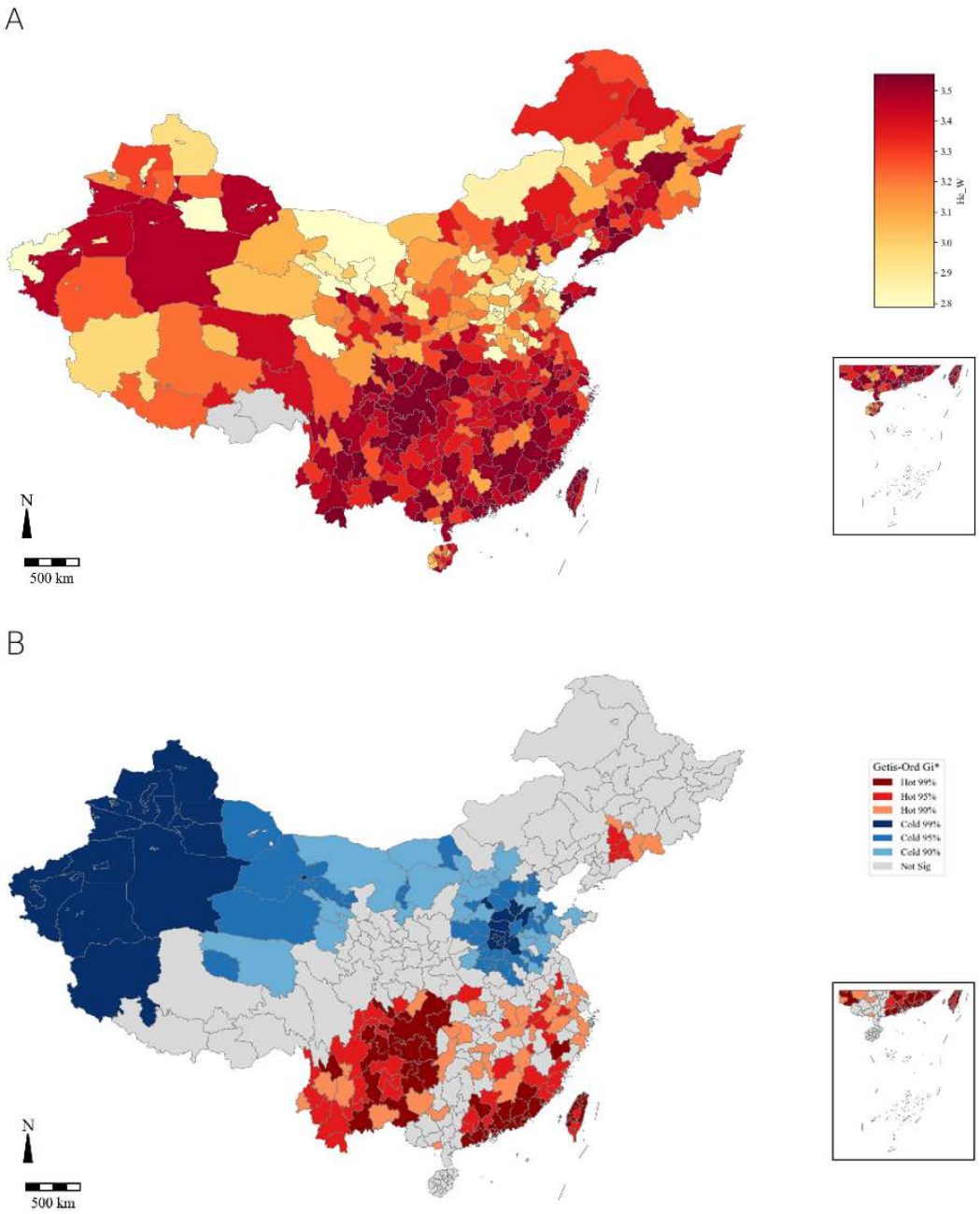


Figure 2: Spatial distribution and clustering of street network regularity across Chinese cities. (A) Orientation entropy of urban street networks at the prefecture-city level; warmer colors indicate higher entropy (more dispersed, less regular networks) and lighter colors indicate lower entropy (more ordered, grid-like layouts). (B) Local spatial autocorrelation (Getis–Ord Gi*) of orientation entropy; red areas denote statistically significant hotspots (clusters of high entropy) concentrated in southern mountainous and hilly regions, blue areas denote coldspots (clusters of low entropy) concentrated in northern China, and gray areas are not statistically significant. Base-map and urban-boundary data are from the National Geospatial Information Public Service Platform (2025).

Tables

Table 1: Summary Statistics

	Observations	Mean	Std. dev.	Min	Max
Dependent Variables.					
life satisfaction	156508	3.71	1.05	1	5
self-rated health	161042	2.63	1.26	1	5
subjective happiness	108694	7.45	2.25	0	10
household life satisfaction	51791	3.68	1.04	1	5
Explanatory Variables					
Orientation entropy	173465	3.05	0.38	1.65	3.55
Unweighted orientation entropy	173465	3.09	0.37	1.68	3.55
Instrumental Variables					
Terrain orientation_entropy	173465	2.43	0.67	0	3.34
Mechanism Variables					
Transportation expenditure	142998	229.41	428.25	0	10000
Commuting time	44061	19.97	22.12	0	540
Heterogeneous Grouping Variables					
Internet Users	133745	0.42	0.49	0	1
Private-Vehicle owners	146971	0.24	0.43	0	1
Individual and Household Control Variables					
Age	173453	46.34	18.07	9	110
Gender	173459	0.49	0.50	0	1
Hukou status	161317	1.59	0.92	1	5
Educational attainment	144355	2.67	1.36	1	8
Log of per capita net household income	167359	9.28	1.16	-1.10	15.75
Marital status	162800	2.08	0.86	1	5
Geographic Control Variables					
Drainage density	173465	1.33	0.37	0.33	2.16
Mean slope	173465	4.01	2.91	0.13	16.34
Roughness of the land	173465	16.98	16.99	1.09	96.03
Historical capital	173465	0.35	0.48	0	1
Wall status	173465	0.65	0.48	0	1

Notes: Gender, internet users, private vehicle ownership, historical capital and wall status are binary dummy variables. Gender equals 1 for male respondents and 0 for female respondents. Hukou status takes 1 for agricultural household registration, 3 for non-agricultural household registration, and 5 for individuals without formal household registration. Marital status equals 1 for unmarried respondents, 2 for respondents with a spouse, 3 for cohabiting respondents, 4 for divorced respondents, and 5 for widowed respondents. Internet usage is coded 1 if the respondent has mobile internet access and 0 otherwise. Private vehicle ownership equals 1 if the respondent owns a private car and 0 otherwise. Subjective happiness was recorded using both a 1–5 scale and a 0–10 scale. Under the equal-spacing assumption, we rescale responses from the earlier waves to the 0–10 scale adopted in subsequent survey rounds. Per capita net household income is log-transformed in subsequent regression analyses. Observations denote the number of valid non-missing samples for each variable. Values of Mean, Std. dev., Min and Max are rounded to two decimal places.

Table 2: Impact of street regularity on residents' life satisfaction.

	OLS		2SLS	
	(1)	(2)	(3)	(4)
Residents' life satisfaction				
Orientation Entropy	-0.124***	-0.124***	-0.147***	-0.163***
	(-10.43)	(-9.35)	(-6.91)	(-7.07)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	123882	123882	123882	123882
R^2	0.066	0.067	0.066	0.067
Year FEs	Yes	Yes	Yes	Yes

Notes: All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, and marital status; Columns (2) and (4) additionally control for geographical factors, including drainage density, mean slope, roughness of the land, and historical factors, including,wall status and year fixed effects. The t-statistics are reported in parentheses. Standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 3: Heterogeneity in the impact of street morphology on residents' life satisfaction.

	(1)	(2)	(3)	(4)
A. Age	18-29	30-44	45-59	60+
Orientation Entropy	-0.053	-0.103**	-0.180***	-0.333***
	(-1.55)	(-2.72)	(-4.40)	(-8.21)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	Yes	Yes	Yes	Yes
Historical factors	Yes	Yes	Yes	Yes
Observations	23125	31216	38752	30789
R^2	0.054	0.065	0.069	0.071
Year FEs	Yes	Yes	Yes	Yes
B. Income	Low-income	Middle-income	High-income	\
Orientation Entropy	-0.240***	-0.153**	-0.115***	\
	(-6.63)	(-4.34)	(-3.39)	
Individual and household characteristics	Yes	Yes	Yes	\
Geographical factors	Yes	Yes	Yes	\
Historical factors	Yes	Yes	Yes	\
Observations	47549	35073	38467	\
R^2	0.069	0.058	0.045	\
Year FEs	Yes	Yes	Yes	\

Notes: All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, marital status, drainage density, mean slope, roughness of the land,and historical factors, including wall status and year fixed effects. The t-statistics are reported in parentheses. Standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 4: Transportation costs as the mechanism linking street network regularity to life satisfaction.

	OLS		2SLS	
	(1)	(2)	(3)	(4)
A. Commuting Time				
Orientation Entropy	2.115***	1.746***	3.993***	2.662***
	(5.35)	(4.13)	(5.55)	(3.70)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	42562	42562	42562	42562
R^2	0.024	0.030	0.023	0.030
Year FEs	Yes	Yes	Yes	Yes
B. Transportation Expenditure				
Orientation Entropy	45.379***	39.190***	95.816***	126.042***
	(6.22)	(4.68)	(7.28)	(8.68)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	99863	99863	99863	99863
R^2	0.096	0.100	0.094	0.095
Year FEs	Yes	Yes	Yes	Yes

Notes: In panel A, the dependent variable is residents' commuting time. In panel B, the dependent variable is their transportation expenditure. All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, and marital status; Columns (2) and (4) additionally control for geographical factors, including drainage density, mean slope, roughness of the land, and historical factors, including wall status and year fixed effects. The t-statistics are reported in parentheses. Standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 5: Impact of street morphology on residents' self-rated health.

	OLS		2SLS	
	(1)	(2)	(3)	(4)
Residents' self-rated health				
Orientation Entropy	-0.106***	-0.080***	-0.128***	-0.098***
	(-8.43)	(-5.77)	(-5.50)	(-3.92)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	124312	124312	124312	124312
R^2	0.068	0.069	0.068	0.069
Year FEs	Yes	Yes	Yes	Yes

Notes: All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, and marital status; Columns (2) and (4) additionally control for geographical factors, including drainage density, mean slope, roughness of the land, and historical factors, including wall status and year fixed effects. The t-statistics are reported in parentheses. Standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 6: Mitigating channel: technological adoption.

	(1)	(2)	(3)	(4)
	Internet Users	Non-internet Users	Private-vehicle Owners	Non-Private-Vehicle Owners
Orientation Entropy	-0.070**	-0.247***	-0.034	-0.222***
	(-2.47)	(-8.20)	(-0.98)	(-7.69)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	Yes	Yes	Yes	Yes
Historical factors	Yes	Yes	Yes	Yes
Observations	51575	71732	27712	73366
R^2	0.044	0.081	0.038	0.078
Year FEs	Yes	Yes	Yes	Yes

Notes: The dependent variable is residents' life satisfaction. Columns (1) and (2) divide the sample by internet usage; Columns (3) and (4) divide the sample by private-vehicle ownership. All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, marital status, drainage density, mean slope, roughness of the land, and historical factors, including wall status and year fixed effects. The t-statistics are reported in parentheses. The standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 7: Robustness checks.

	OLS		2SLS	
	(1)	(2)	(3)	(4)
A. Residents' subjective happiness				
Orientation Entropy	-0.255***	-0.203***	-0.153***	-0.243***
	(-8.77)	(-6.34)	(-2.83)	(-4.23)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	99701	99701	99701	99701
R^2	0.024	0.026	0.024	0.026
Year FEs	Yes	Yes	Yes	Yes
B. Household life satisfaction				
Orientation Entropy	-0.128***	-0.131***	-0.146***	-0.175***
	(-6.61)	(-6.00)	(-4.16)	(-4.64)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	23490	23490	23490	23490
R^2	0.023	0.024	0.023	0.024
Year FEs	Yes	Yes	Yes	Yes
C. Unweighted orientation entropy				
Orientation Entropy	-0.120***	-0.119***	-0.153***	-0.171***
	(-9.87)	(-8.72)	(-6.91)	(-7.06)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	123882	123882	123882	123882
R^2	0.066	0.067	0.066	0.067
Year FEs	Yes	Yes	Yes	Yes
D. Time-varying indicators				
Orientation Entropy	-0.053***	-0.049***	-0.104***	-0.123***
	(-6.88)	(-6.16)	(-5.79)	(-6.13)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	95068	95068	95068	95068
R^2	0.044	0.045	0.043	0.043
Year FEs	Yes	Yes	Yes	Yes
E. Urban observations				
Orientation Entropy	-0.121***	-0.116***	-0.198***	-0.172***
	(-5.12)	(-4.53)	(-3.12)	(-2.87)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	No	Yes	No	Yes
Historical factors	No	Yes	No	Yes
Observations	36893	36893	36893	36893
R^2	0.079	0.081	0.079	0.081
Year FEs	Yes	Yes	Yes	Yes

Notes: All Columns control for individual and household characteristics, including age, gender, hukou status, educational attainment, per capita net household income, and marital status; Columns (2) and (4) additionally control for geographical factors, including drainage density, mean slope, roughness of the land, and historical factors, including wall status and year fixed effects. The t-statistics are reported in parentheses. Standard errors are clustered at the household level. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8: Spatially correlated inference.

	(1)	(2)	(3)	(4)
	50km	100km	200km	500km
Orientation Entropy	-0.163***	-0.163***	-0.163**	-0.163***
	(-2.69)	(-2.61)	(-2.43)	(-2.59)
Individual and household characteristics	Yes	Yes	Yes	Yes
Geographical factors	Yes	Yes	Yes	Yes
Historical factors	Yes	Yes	Yes	Yes
Observations	123882	123882	123882	123882
R^2	0.063	0.063	0.063	0.063
Year FEs	Yes	Yes	Yes	Yes

Notes: The dependent variable is residents' life satisfaction. The endogenous variable is street orientation entropy, instrumented by terrain orientation entropy. All columns control for age, gender, hukou status, educational attainment, per capita net household income, marital status, drainage density, mean slope, roughness of the land, and historical factors, including wall status and year fixed effects. The estimation sample (N = 123882) is held fixed across columns. Estimates are obtained by residualizing the dependent and endogenous variables against all controls (FWL), aggregating to the county level with weights equal to the number of individual observations, and estimating the IV-2SLS regression at the county level. Standard errors are Conley (1999) spatial HAC computed with a Bartlett kernel over pairwise great-circle distances between county centroids, for bandwidths of 50, 100, 200, and 500 km; the time-series correction is disabled. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Appendixes

Additional Results

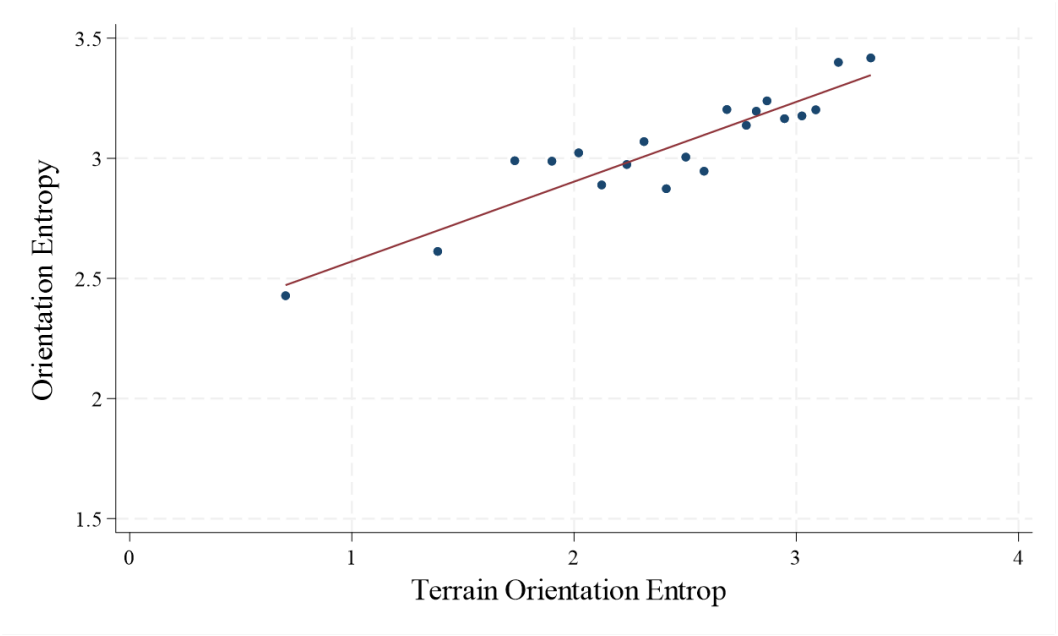


Figure A1: Relationship between terrain orientation entropy and street network orientation entropy. Scatter plot showing the association between terrain orientation entropy (x-axis) and street network orientation entropy (y-axis) at the county level. Each dot shows the average of the relevant street orientation entropy for a given range of values of the terrain orientation entropy. The fitted regression line indicates a strong positive relationship.

Additional Results

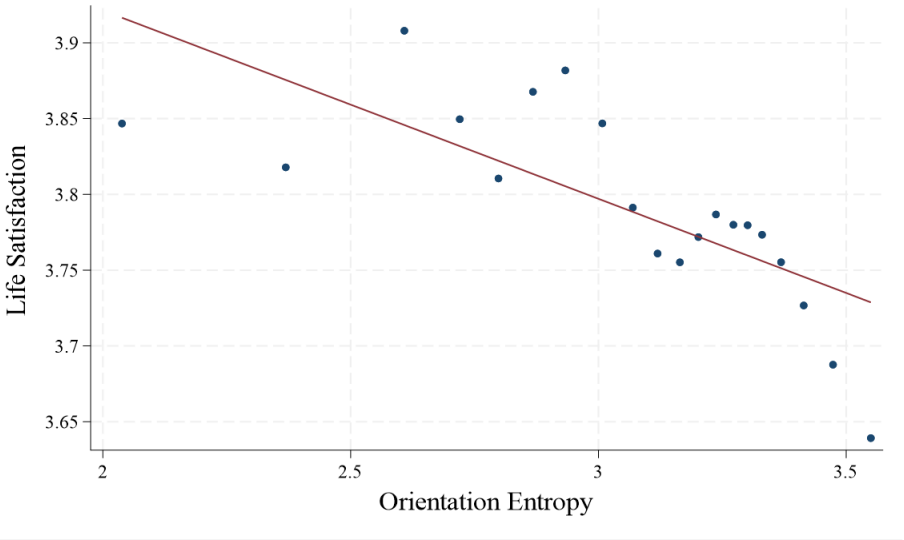


Figure A2: Binscatter partial correlation plot for the relationship between orientation entropy and residents' life satisfaction. The dependent variable is residents' life satisfaction. Each dot shows the average of the dependent variable for a given range of orientation entropy values. The sample size is 123882. The binscatter is constructed by controlling for individual and household characteristics, including age, gender, hukou status, educational attainment, marital status, per capita net household income, and year fixed effects. Results from regressing the response variables on the orientation entropy after partialling out control variables are presented as fitted line. The partial correlation coefficient $\rho = -0.048$, with $P < 0.001$.

Additional Results

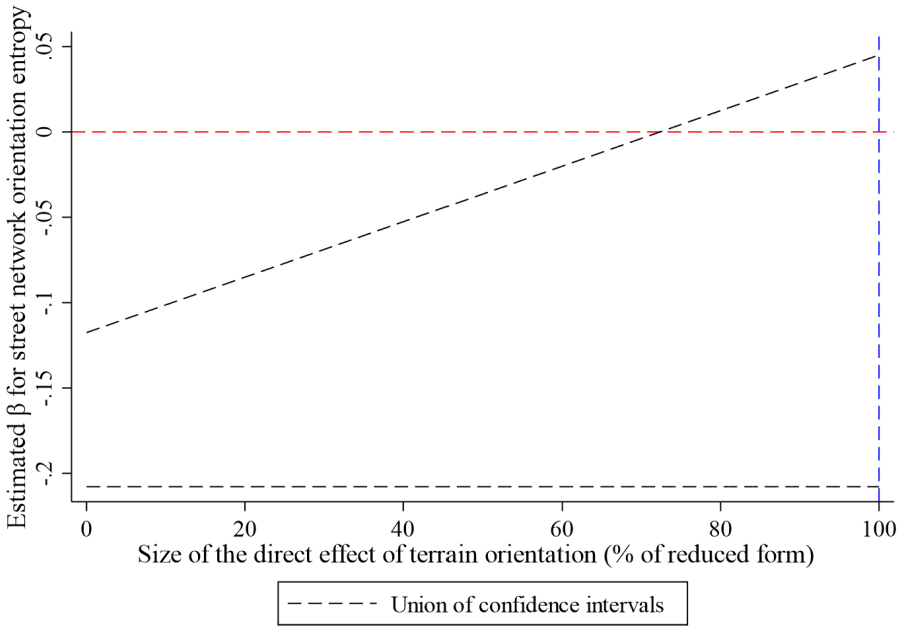


Figure A3: Plausible exogeneity test. Robustness test examining violations of the exclusion restriction (Conley et al., 2012). The figure plots the union of confidence intervals of the IV estimates (y-axis) against the assumed direct effect of terrain orientation, expressed as a percentage of the reduced-form effect (x-axis). The dashed black lines denote the bounds of these intervals for the estimated effect of street network orientation entropy under alternative assumptions. The horizontal red line denotes zero. The vertical blue line denotes a direct effect equal to 100% of the reduced-form effect.