Identifying Optimal City Size by Considering Inverse U-Shaped Relationship Between Population and GDP

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Abstract:
Identifying the optimal population size at which cities maximize economic benefits while minimizing congestion and pollution is a challenge. This research explores the optimal city size by examining the relationship between population and economic performance, measured by city GDP. Using data from OECD regions for about 562 cities, the analysis employs a quadratic regression model to test an inverse U-shaped relationship between city population and GDP in 2020. The empirical results show that cities initially experience economic growth as populations increase, but after a certain point (8.85 million), the benefits diminish due to congestion and pollution. The study concludes that an optimal city size exists, balancing the advantages of agglomeration with the costs of urban expansion. Additionally, population density, territorial fragmentation, working-age population, and built-up area positively affect city GDP, whereas air pollution negatively impacts it. Finally, several policies are recommended for sustainable urban development and efficient resource allocation.

Keywords: Urban growth, optimal city size, population size, economic measurement, OECD cities.

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1. Introduction

Identifying the population size at which a city maximizes the benefits of urban living while minimizing associated costs is a key challenge in urban economics. Identifying this optimal city size is vital for sustainable urban development and economic growth. An optimal city size is rooted in the idea that a city reaches its most efficient population level when the costs and benefits of urban living are balanced. Alonso (1971) and Richardson (1978) tried to define optimal city size based on cost-benefit analysis, but empirical evidence remains inconclusive.

The concept of optimal city size has been explored through various models and theories. Traditionally, optimal city size is measured by total population. The Alonso-Richardson model suggests that as a city grows, it benefits from agglomeration economies, such as lower transportation costs and better knowledge sharing. However, it also faces disadvantages like increased traffic and pollution. The optimal city size is where these opposing forces balance out, maximizing the city's contribution to national income.

Three primary approaches to defining optimal city size have emerged: minimum average cost, maximum net benefit, and long-run maximum profit. The minimum average cost approach identifies the city size where the average cost of providing services is minimized. The maximum net benefit approach seeks to maximize the difference between agglomeration benefits and the costs associated with a larger population. The long-run maximum profit approach identifies the city size where economic profit is zero, suggesting that cities can benefit from economies of scale even after reaching the net benefit peak (Brueckner, 1987; Henderson, 1974). Each method offers a unique perspective on balancing urban growth with economic efficiency.

Empirical studies have attempted to pinpoint this optimal size, with varying conclusions depending on the methodologies and datasets used. The Henry George Theorem (HGT) provides additional insight. It suggests that optimal city size is achieved when land rents cover the costs of public goods, balancing the benefits of agglomeration with the costs of congestion. Similarly, studies have highlighted how cities can experience significant economic gains from high population density due to improved efficiency and innovation. However, these benefits are countered by pollution and territorial fragmentation challenges, which can undermine overall economic performance.

The debate over optimal city size has gained renewed interest due to modern urban challenges. This research aims to contribute to the ongoing discussion on optimal city size by examining the relationship between city population and economic performance using data from OECD regions and cities. The study employs a quadratic model to explore whether the relationship between population size and GDP exhibits an inverse U-shape, where initial increases in population drive economic growth, but further increases lead to diminishing returns. By analyzing various economic and demographic factors, this research provides valuable insights for urban planners and policymakers better to balance city size with economic and social benefits.

The structure of the paper is as follows. The second section presents a review of the literature and research hypothesis. Data and methodology are presented in section 3. Section 4 presents the empirical results. Finally, the conclusion and discussions are made in section 5.

2. Review of literature and research hypothesis

2.1 Review of literature

Henderson (1974) and Fisch (1977) discussed the equilibrium city size that balanced welfare and quality of life. They found a positive relationship between population size and urban benefits, supporting the idea that larger populations often lead to increased economic opportunities and services. Glaeser et al. (1992) found that increased population density in urban areas leads to higher economic output due to the concentration of resources and talents. These studies suggest that as cities grow, they can harness economies of scale, leading to increased GDP. More recently, Bloom and Canning (2008) emphasized the role of urbanization in economic development, noting that urban areas typically exhibit higher productivity levels, contributing to national economic growth. According to Henderson (1974), cities that attract more residents often experience a boost in economic activities due to a larger labor force and consumer base. Additionally, studies by Sun et al. (2018) and Wu et al. (2017) on Chinese cities found that an optimal population size could balance economic performance and quality of life, suggesting a population size of around 4.2 million is ideal for maintaining economic and social benefits.

High population density is associated with numerous economic benefits, including increased efficiency in providing public services and enhanced innovation due to proximity and interaction among residents. Glaeser et al. (1992) argued that denser cities foster better information exchange and collaboration, leading to higher productivity and economic growth. This view is supported by Henderson et al. (2006), who used computable general equilibrium (CGE) models to demonstrate that densely populated cities can achieve significant economic gains. However, they also noted that migration restrictions have led to undersized cities in some developing countries, such as China, preventing them from fully realizing these benefits. These models also revealed that Chinese cities often remained undersized due to migration restrictions, causing economic inefficiencies.

Territorial fragmentation, characterized by a division of urban areas into smaller, disjointed jurisdictions, is generally seen as detrimental to economic growth. Alesina and Spolaore (2005) found a negative correlation between territorial fragmentation and economic growth, arguing that fragmentation leads to political instability and inefficient resource allocation. In their analysis of various cities, they observed that fragmented urban areas often suffer from duplicated services and higher administrative costs, which can hinder economic development. Similarly, Capello and Camagni (2000) suggested that less fragmented urban regions tend to be more efficient and competitive, fostering better economic performance.

A higher proportion of the working-age population is a significant driver of economic growth in cities. Bloom and Canning (2000) highlighted the positive relationship between the size of the working-age population and economic growth, emphasizing the role of demographic dividends in enhancing productivity. Cities with a large working-age population can benefit from a significant labour force supporting industrial and service sector growth. This demographic advantage is crucial in urban areas, where diverse job opportunities attract young and skilled workers, further stimulating economic activities.

Henderson (1974) examined the gap between market-determined and optimal city sizes, showing how unpriced externalities like pollution led to oversized cities. He argued that optimal pollution taxation could realign priorities, increase welfare, and potentially attract more people, thus raising city size. The neoclassical approach, examined by Hoch (1977), emphasized externalities such as pollution and congestion, advocating optimal city size distribution. This perspective aligned with the negative impact of air pollution on urban life, suggesting that higher pollution levels detract from the benefits of larger cities. Greenstone and Hanna (2004) found that high levels of air pollution significantly reduce agricultural productivity and overall economic output in urban areas. The adverse health effects of air pollution also lead to increased healthcare costs and reduced labour productivity.

Expanding the built-up area within cities is generally associated with positive economic outcomes. Built-up areas, including residential, commercial, and industrial spaces, support urban growth and development. Studies by Henderson (1974) and Camagni (2002) emphasized that well-planned built-up areas can enhance the economic functionality of cities by providing necessary infrastructure and facilities. A study by Arnott (2004) on the Henry George Theorem (HGT) suggested that the optimal allocation of built-up areas could maximize land rents and support sustainable urban development. Similarly, Yang (2020) developed a theoretical model analyzing the trade-off between congestion costs and agglomeration benefits, concluding that optimal city size occurs where the marginal costs of congestion offset the marginal benefits of agglomeration. Camagni (2002) incorporated spatial dimensions, suggesting that cities could specialize in different industries and roles, thereby optimizing their built-up areas positively. The supply-oriented dynamic model (SOUDY) provided a realistic framework by integrating spatial contexts and relaxing constraints between city levels and sizes. This model emphasized the negative impact of territorial fragmentation, where fragmented urban areas experience reduced economic efficiency and higher costs.

Petrikovičová et al. (2022) investigated whether city size affected the quality of urban life (QoUL) in Nitra, I Slovakia, and Moscow, Russia, revealing that smaller cities like Nitra scored higher in QOUL indices despite lower population sizes. This finding supports the notion that while larger populations and higher densities generally have positive effects, other factors like air pollution and territorial fragmentation can significantly detract from urban living quality. These contemporary models emphasized sustainable development, balancing economic, social, and environmental dimensions. Wau (2016) studied the economic measurement of optimal city size in seven cities in West Sumatra, Indonesia. and found that the optimal size varied according to the economic approach used. The maximum profit approach suggested a larger optimal size compared to the minimum cost and maximum net benefit approaches. This study measured optimal city size regarding population density, providing a relative index for comparison with other regions. Agglomeration economies significantly benefit cities by reducing transportation costs, sharing infrastructure, and enhancing knowledge spillovers (Rosenthal and Strange, 2004). However, as cities grow, they may encounter diseconomies of scale such as congestion, pollution, and higher living costs, which can offset these benefits (Duranton and Puga, 2004). The balance between these opposing forces determines the optimal city size.

2.2 Research hypothesis

This study aims to contribute to this body of literature by exploring the optimal city size through a comprehensive analysis of cities worldwide. Utilizing a dataset from the OECD Regions and Cities Atlas, this research examines the impact of various economic and demographic factors on GDP, a proxy for the benefits of urban living. The analysis employs a quadratic model to capture the potential non-linear relationship between city population and GDP, following the hypothesis that this relationship may exhibit an inverse U-shape. This hypothesis aligns with the notion that while initial increases in population can drive economic growth through agglomeration economies and increased productivity (Rosenthal and Strange, 2004), further increases may lead to diminishing returns due to congestion and pollution (Duranton and Puga, 2004).

The study analyzes several key variables to test this hypothesis, as outlined in Table 1. A larger population is expected to positively influence economic growth by expanding the labour force, market size, and consumption. Higher population density is anticipated to increase economic efficiency through agglomeration economies. Greater territorial fragmentation is predicted to impact economic growth negatively due to inefficiencies and administrative complexities. An increased working-age population is expected to support economic growth by providing a productive labour force. Higher air pollution levels are anticipated to reduce economic benefits by affecting health and productivity. Expanding built-up areas will likely positively impact economic growth by improving infrastructure and supporting development.

Table 1: Expected effects of variables on optimal city size

Variables	**Expected sign**
Population	Positive
Population density	Positive
Territorial Fragmentation	Negative
Working-Age Population	Positive

Air Pollution	Negative
Built-Up Area	Positive

Source: Authors' compilation

The above table outlines these expected relationships, providing a framework for analyzing how these factors interact to determine the optimal city size. The findings from this study aim to offer valuable insights for emphasizing the need to balance city size to optimize economic benefits while addressing potential challenges.

2. Methodology and Data

This study utilizes data from the OECD Regions and Cities Atlas for 2020 to explore the optimal city size and its effects on economic benefits. The analysis focuses on city Gross Domestic Product (GDP) as the dependent variable, which serves as a proxy for the benefits of urban living and reflects overall economic activity within cities. Independent variables include population, population density, territorial fragmentation, working-age population, air pollution, and built-up area, each selected for its theoretical impact on economic growth and urban development.

The primary goal is to identify the optimal city size, defined as the population level that maximizes the benefits of urban living, represented by GDP. To achieve this, ordinary least squares (OLS) regression analysis is employed. This method examines how different urban factors affect GDP and determines if there is a specific city size that optimizes economic benefits. Both linear regression models and a U-test are used in the analysis. The U-test helps assess whether the relationship between city size and GDP follows an inverse U- shape, suggesting that while initial increases in population enhance economic growth through economies of scale, further increases may lead to diminishing returns due to congestion and pollution. The dataset comprises between 358 and 363 observations, depending on the specific model used. A quadratic model is applied to capture the potential non-linear relationship between population and GDP, as follows:

$$GDP = \beta_0 + \beta_1\, population + \beta_2\, population^2 + \beta_3\, population\ density + \beta_4\, territorial\ fragmentation + \beta_5\, working\ age\ population + \beta_6\, air\ pollution + \beta_7\, built\ up\ area + \epsilon \quad \text{------------ (1)}$$

In this model, GDP represents Gross Domestic Product, while population indicates the total number of residents in the city. Population^2 captures potential non-linear effects of population on GDP. Population density refers to the number of people per unit area within the city, and territorial fragmentation measures the extent of administrative and political fragmentation within the urban area. Working age population denotes the proportion of the population that is of working age, air pollution encompasses the levels of pollutants in the city's atmosphere, and built up area represents the extent of developed land within the city. The error term, denoted by ϵ, accounts for any unexplained variability in GDP. Including quadratic terms for population allows for testing an inverse U-shaped relationship, where economic benefits are maximized at a certain city size before diminishing returns set in.

3. Empirical results

Table 2 presents the summary statistics for the variables used in this analysis. The correlation matrix indicates several important relationships among key variables (Table 3). GDP shows a strong positive correlation with both population (0.946) and the working-age population (0.908), suggesting that cities with larger and more productive labor forces tend to exhibit higher economic output (Glaeser et al., 1992). Additionally, GDP is positively correlated with built-up area (0.709), reflecting the role of infrastructure in supporting economic growth (Duranton & Turner, 2012). In contrast, territorial fragmentation has a weak negative correlation with GDP (-0.049), implying that the division of urban areas minimally impacts economic performance. Population density also positively correlates with GDP (0.358) and population (0.438), suggesting that higher density can contribute to economic activity. However, the effect is less pronounced than the overall population size (Glaeser, 2008). On the other hand, air pollution has a minimal positive correlation with GDP (0.010), indicating that its direct impact on economic output is negligible (Greenstone and Gallagher, 2008).

Table 2. Summary statistics

	N	Mean	SD	CV	Min	Max
GDP	363	4.255e+10	8.618e+10	2.026	1.425e+09	9.322e+11
Population	562	1119604.7	2551168.243	2.279	200455	34589501
Population density	562	1432.367	2029.761	1.417	10.532	24401.441
Territorial fragmentation	539	2.479	5.499	2.218	0	43.1
Working age population	556	731976.6	1696391.288	2.318	119886	21956397
Air pollution	562	12.164	5.469	0.45	4.2	36.5
Built up area	562	247.811	532.406	2.148	1	6249

Source: Authors' calculation

Table 3. Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) GDP	1.000						
(2) Population	0.946	1.000					
(3) Population density	0.358	0.438	1.000				
(4) Territorial fragmentation	-0.049	-0.080	0.135	1.000			
(5) Working age population	0.908	0.958	0.264	-0.076	1.000		
(6) Air pollution	0.010	0.118	0.106	-0.089	0.145	1.000	
(7) Built up area	0.709	0.562	-0.051	-0.104	0.559	-0.214	1.000

Source: Authors' calculation

Table 4 presents the regression results with the log of GDP as the dependent variable across three models, using robust standard errors to address heteroskedasticity. Population shows a positive and statistically significant impact on GDP in Models 2 and 3, with coefficients of 0.0591 and 0.0719, indicating that larger populations boost economic output due to a larger labor force and increased economic activity (Glaeser et al., 1992). However, the negative and significant coefficients for population squared in both models (-3.34e-09 and -3.71e-09) reveal diminishing returns, suggesting the positive effect of population on GDP weakens at higher population levels. Territorial fragmentation has a positive and significant effect in Models 1 and 3, indicating that some fragmentation might enhance economic performance, possibly by fostering competition and specialization (Duranton and Puga, 2004). The working-age population has a consistent, positive impact across all models, supporting the idea that a larger working-age demographic drives economic output (Glaeser et al., 1992). In contrast, air pollution has a significant negative effect on GDP in all models, coefficients ranging from-0.0181 to -0.0318, reflecting the detrimental impact of pollution on productivity. Population density and built-up area show small but significant positive effects in Model 3, suggesting that urbanization and population concentration can contribute to economic growth, though their impact is less pronounced. The R-squared values range from 0.593 to 0.701, indicating that the models explain between 59.3% and 70.1% of the variation in GDP, with additional variables improving the models' explanatory power.

Table 4: Regression output: Relationship between GDP and Population

VARIABLES	Dependent variable		
	Log of city GDP		
	Model 1	Model 2	Model 3
City population size	0.0591***		0.0719***
	(0.00886)		(0.00456)
Squared of city population size	-3.34e-09***		-3.71e-09***
	(4.73e-10)		(4.30e-10)
Population density	3.61e-05	0.000133***	
	(2.76e-05)	(1.88e-05)	
Territorial fragmentation	0.00825*		0.00877**
	(0.00430)		(0.00406)
Working age population	3.39e-07***	3.36e-07***	3.08e-07***
	(8.62e-08)	(1.10e-07)	(4.82e-08)
Air pollution	-0.0272***	-0.0181**	-0.0318***
	(0.00612)	(0.00746)	(0.00522)
Built up area	0.000315	0.00112***	
	(0.000261)	(0.000331)	
Constant	23.28***	23.34***	23.36***
	(0.0975)	(0.121)	(0.0771)
Observations	358	358	358
R-squared	0.701	0.593	0.696

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

To ensure the robustness of our findings, we conducted a series of statistical tests and diagnostics. Initially, a heterogeneity test with robust standard errors was performed to address potential heteroskedasticity in the data, ensuring that coefficient estimates remain reliable despite variations in error variance. The Variance Inflation Factor (VIF) was computed for all variables to assess multicollinearity. Although the VIF for population was within acceptable limits, the VIF for population squared was notably high, indicating potential multicollinearity issues and necessitating cautious interpretation of the results for population squared.

We verified the expected signs of the coefficients and included control variables significant at the 1% level to enhance the model's explanatory power. This approach helps mitigate omitted variable bias and model misspecification, ensuring the robustness of our results.

To test the hypothesis of an inverse U-shaped relationship between population size and GDP, we employed a U-test. The hypothesis framework was: H1 posits an inverse U-shaped relationship, while HO suggests a monotonic or U-shaped relationship. The U-test, using the specification $f(x) = x^2$, revealed an extreme point at a population level of 8,854,469. The p-value for the test was below 0.05, leading to the rejection of the null hypothesis in favor of the alternative, confirming that the relationship between population and GDP is indeed inverse U-shaped.

Table 5: U-test

	Lower Bound	Upper Bound
Interval	200455	3.46e+07
Slope	0.000	-0.000
t-value	6.617	-6.276
P>t	0.000	0.000

Source: Authors' calculation

Table 5 presents the U-test results, with the extreme point identified at 8,854,469, and bounds ranging from 200,455 to 34,600,000. The slope at these bounds was approximately 0.000 for the lower bound and -0.000 for the upper bound, with t-values of 6.617 and -6.276, respectively. The overall t-value for the test was 6.28, and the p-value was 5.14e-10, supporting the presence of an inverse U-shaped relationship. The combination of robust regression analysis and U-test results highlights an optimal population size for maximizing GDP. Overall test of presence of an inverse U shape: t-value = 6.28, P>t = 5.14e-10.

4. Policy Recommendations

The findings of this study underscore the need for targeted policy interventions to balance the economic benefits of urban population growth with the adverse effects of over-expansion, congestion, and pollution. First, strategic urban planning should focus on accommodating population growth by investing in infrastructure, housing, and public services that enhance productivity without overstressing urban systems. These efforts can help cities reap the benefits of agglomeration economies while ensuring sustainable growth (Ahrend et al., 2017).

Second, recognizing the diminishing returns from population beyond the optimal size (8.85 million in this study), policymakers should implement measures to manage urban sprawl and control congestion and pollution. This can be achieved by promoting satellite cities, expanding public transportation networks, and implementing congestion pricing, as recommended by Duranton and Puga (2020). Furthermore, high-density, compact urban designs should be prioritized to maximize land use efficiency and reduce urban sprawl.

Additionally, addressing territorial fragmentation requires fostering regional cooperation and integration among neighboring municipalities to streamline governance and enhance resource sharing. Promoting inter-municipal collaboration can mitigate the negative effects of fragmented urban regions and improve overall economic performance (OECD, 2019). Moreover, investments in the working-age population through education, skills development, and labor market policies are critical to sustaining economic growth. Enhancing the human capital of the workforce is essential for maintaining competitiveness in an increasingly knowledge-based economy (Moretti, 2012). Finally, stringent environmental regulations and the promotion of green technologies are necessary to combat the negative impact of air pollution associated with large urban populations. The adoption of clean energy technologies and emission control measures will not only improve air quality but also contribute to long-term economic sustainability (Chen & Wang, 2018). By adopting these integrated strategies, cities can optimize their population size and economic outcomes while ensuring a sustainable urban future.

5. Conclusion and Discussion

This study provides critical insights into the intricate relationship between city size and economic performance, contributing valuable knowledge for urban planning and policy- making. Our findings confirm that larger cities generally enhance economic output; however, they also identify an optimal city size of approximately 8.85 million people. Beyond this size, the economic benefits of further expansion tend to decline due to negative factors such as congestion and pollution. This supports the hypothesis of an inverse U-shaped relationship between population size and GDP. Initially, increases in population are beneficial for economic growth, but further expansion may lead to diminishing returns, reflecting an optimal balance between the benefits of agglomeration and the drawbacks of excessive urban size.

These results are consistent with the broader literature on urban economics. The findings are notably aligned with Brülhart et al. (2009), who argue that while agglomeration benefits are significant at lower levels of economic development, they diminish as the economy grows beyond a certain threshold. This mirrors our observation that the economic advantages of city growth wane once the population surpasses the optimal size. Our study also aligns with the broader economic concept that spatial concentration and urban expansion yield diminishing returns after reaching a critical level of development.

Additionally, our research highlights several gaps in the existing body of knowledge. Many previous studies focus on specific regions or countries and often employ static models that do not account for rapid changes in urban conditions, technological advancements, or evolving infrastructure. There is a clear need for more dynamic and region-specific models that integrate a broader range of variables, including technological innovations, social equity, and infrastructure development. By addressing these gaps, future research can offer a more comprehensive understanding of the interplay between city size, economic performance, and quality of life.

Furthermore, future studies should explore the effects of emerging trends and technologies on urban dynamics. Comparative analyses across different global contexts could provide insights into how varying socio-economic conditions and policy environments influence the optimal city size and its impact on economic performance. Developing more sophisticated models that consider the interactions between economic, social, and environmental factors will be crucial for understanding how cities can grow sustainably while maximizing economic and social benefits.

In summary, our findings underscore the importance of identifying and maintaining an optimal city size to maximize economic benefits while mitigating the adverse effects associated with excessively large urban populations. By addressing the identified research gaps and exploring new dimensions of urban dynamics, future studies can contribute to more effective urban planning and policy development, fostering balanced and sustainable urban growth.

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