Faster, Taller, Better: Transit Improvements and Land Use Policies*

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Abstract

We study the interaction between transit improvements and land use policies, an issue of growing policy importance. Bengaluru, one of the India's largest cities, inaugurated a metro system in 2011 but has extremely low building heights, even near metro stations. We build a rich dataset and a quantitative spatial model where heterogeneous workers choose among different commuting modes. We find that the metro increases citywide output and welfare, even net of costs. However, the net gains are several times larger when height limits are relaxed near stations (transit-oriented development). Moreover, transit-oriented development and construction of the metro are complementary policies.

Key Words: urban, transit, land use, building heights, transportation, transit-oriented development, spatial equilibrium, development, India

JEL Codes: O18, R31, R33, R41, R42, R52

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1 Introduction

In recent decades, rapid urbanization and accompanying congestion have increased the demand for more efficient mass transit in developing countries. The introduction of metro rail systems is often seen as a key part of the solution. In India, about 15 cities currently have active metro rail systems and many more are under construction or in planning. Given the high cost of metro systems, it is important to understand how effectively they improve within-city mobility and provide wider economic benefits.

At the same time, Indian cities impose strict controls on building heights through limits on floor-to-area ratios (FARs). A comparison of FARs in central business districts of major cities around the world shows that some of the lowest FARs are in India–between 1 and 1.5 for Chennai, Delhi and Mumbai compared to over 10 for cities such as Chicago, Los Angeles, New York, Tokyo, and Singapore (World Bank, 2013). Analysis of building heights around the world by Barr and Jedwab (2023) indicates that large Indian cities have very few tall buildings.

While the effects of transit improvements and land use policies have been studied extensively, little is known about their interaction. The goal of this paper is to examine how the benefits of transit depend on existing land use regulations, as well as how these regulations can be redesigned in order to maximize the benefits of transit.

In this paper, we study the interaction of transit improvements and land use policies in the context of Bengaluru, one of India's largest cities.[1] We build a quantitative spatial model, where low- and high-skilled workers commute between residence and workplace and choose between different modes of transportation. The Bengaluru metro was inaugurated in late 2011. It currently has 52 stations and is being expanded. We first calibrate the model to pre-metro Bengaluru at the ward level using a rich dataset we constructed. Our data includes unique building height estimates from multi-view remote-sensing images, land use information at parcel level from digitized land use maps for existing and future land use plans, commuting time data for multiple modes of transportation from Google Maps, and travel behavior data from a travel survey. We complement these data with ward-level data on employment, residents, and wages. We then simulate the model by examining the introduction of a metro network in Bengaluru and land use reforms that would allow for higher density in central areas of the city or near metro stations.

We find that the introduction of the metro increases welfare by about 1.3% and that these gains do not differ between low- and high-skilled workers. At the same time, our

[1]The city of Bengaluru is also known as Bangalore. The city's official name was changed from Bangalore to Bengaluru in 2006.

empirical findings suggest that both residential and commercial development is severely restricted in the central areas of the city: the height gradient decreases gradually as it moves away from the city center, with a sharp decline at the boundary of central wards. To understand how the welfare effects of the metro depend on these density constraints, we run counterfactual experiments in which the introduction of the metro is accompanied by a relaxation of FAR limits in wards with metro stations ("transit-oriented development" or TOD) or in central wards of the city ("central upzoning"). Even a modest relaxation of FAR limits on residential and commercial development boosts welfare gains from the metro to 3.4% in the case of TOD and to 3.2% in the case of central upzoning. We also evaluate the proposed 2031 Land Use Plan that called for restrictions on commercial development in the city center. We show that the lack of coordination between transportation improvements and land use changes can be detrimental to the city's economy.

Our back-of-the-envelope calculations suggest that, while the metro increases Bengaluru's output by 6% or $1.7 billion per year, these gains are mostly due to endogenous migration into the city. On a per-worker basis, the gains are almost entirely offset by the costs of building and maintaining the network. Only when metro construction is complemented by a relaxation of FAR limits, do the gains significantly exceed the costs.

What makes TOD materially different from central upzoning is that the former policy is complementary with the metro: their joint effect on incomes, prices, and welfare is larger than the combined effect of these two policies when implemented separately. This is because increases in productivity and floorspace supply are positively correlated with improvements in transport connectivity across wards. The complementarity between TOD and the metro unlocks additional gains equivalent to about $64 million or one-half of annual operating costs of the metro system.

Furthermore, we demonstrate that modeling FAR limits is quantitatively important. Our findings suggest that most previous work that evaluated the benefits of transit improvements may overstate their welfare gains by not taking into account density limits that are commonplace in many cities around the world. We also show that our results are robust to various modifications in parameters and model assumptions.

The results of this paper highlight the importance of jointly designing transportation and land use policies. The fact that important elements of India's urban planning norms can limit the economic gains from investments in transport infrastructure has not been lost on reform-oriented policymakers. Indeed, India's central government has taken several initiatives to induce state governments to improve urban planning and align it more closely with transport infrastructure investments. Among the most recent initiatives is a National Transit Oriented Development Policy, formulated in 2017, that provides states with guidelines and incentives to encourage densification along urban mass transit corridors. The extent to which India's cities will apply these recommendations remains to be seen, and in this context, research that evaluates alternative urban planning norms is highly relevant for policymakers.

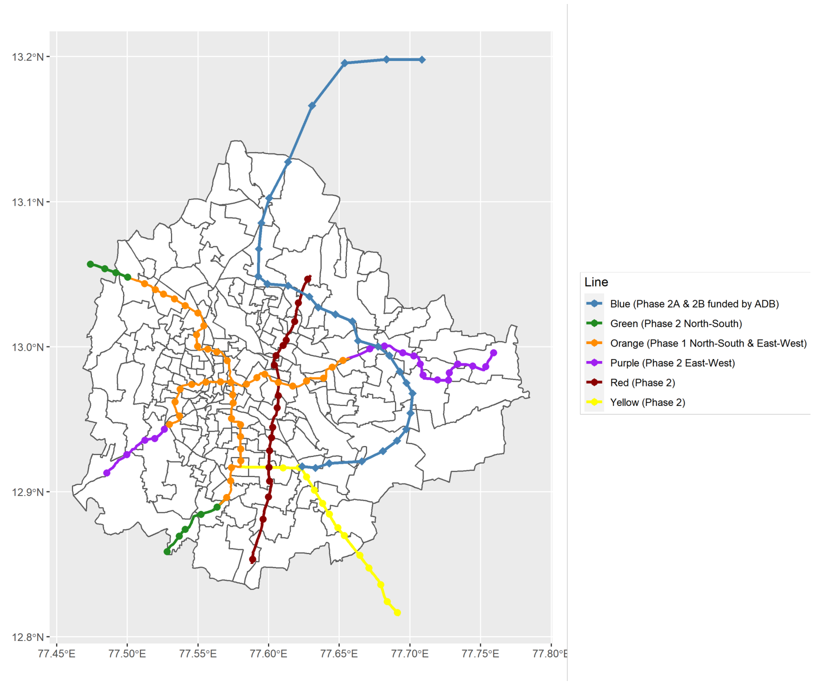
The main contribution of our paper is to bridge the gap between two distinct strands of literature. First, it relates to the literature that evaluates the welfare impact of transit infrastructure (Heblich, Redding, and Sturm, 2020; Balboni, Bryan, Morten, and Siddiqi, 2020; Severen, 2021; Warnes, 2021; Zárate, 2022; Tsivanidis, 2023; Velásquez, 2023; Conwell, 2023; Kreindler, Gaduh, Graff, Hanna, and Olken, 2023). Many of these papers focus on developing countries. For instance, Tsivanidis (2023) examines how the bus rapid transit (BRT) system in Bogotá affects welfare; Zárate (2022) looks at how a new subway line in Mexico City lowers barriers to accessing formal employment; while Balboni, Bryan, Morten, and Siddiqi (2020) study the differential effects of the BRT system in Dar es Salaam on low- and high-income residents. Our paper contributes to this literature by focusing on how the interplay of land use policies and metro investments can amplify or dampen the welfare benefits of new transit infrastructure.

Second, it relates to the literature that evaluates the costs of restrictive land use regulations (Allen, Arkolakis, and Li, 2016; Herkenhoff, Ohanian, and Prescott, 2018; Hsieh and Moretti, 2019; Anagol, Ferreira, and Rexer, 2021; Song, 2022; Acosta, 2022; Yu, 2022; Duranton and Puga, 2022; Parkhomenko, 2023). Most of this literature studies developed countries and does not explicitly take into account transportation networks. Moreover, it primarily focuses on the effects of land use restrictions on housing supply. Our paper adds to this literature by examining how land use regulations may not only constrain housing supply but also undermine the effectiveness of transportation improvements.

This paper also contributes to the literature on the effect of land use management on city form and labor market outcomes (Bertaud and Brueckner, 2005; Geshkov and DeSalvo, 2012; Brueckner and Sridhar, 2012). For example, Bertaud and Brueckner (2005) use a monocentric city model to show that height limits cause spatial expansion of cities, which in turn results in welfare losses due to higher commuting costs. Brueckner and Sridhar (2012) provide supporting empirical evidence by examining cities in India.

The remainder of the paper is organized as follows. Section 2 describes the city of Bengaluru and the data. Section 3 examines the key patterns in the building heights and land use use data, and how they conform with the relationships highlighted by the theory. Section 4 describes the theoretical framework. Section 5 describes the methodology used to quantify the model. Section 6 analyzes the effects of introducing the metro and changing land use policies. Section 7 concludes.

Figure 1: Bengaluru Metro Map (existing and planned lines)



Note: This figure shows the map of existing and planned metro lines and stations. *Source:* Bengaluru Metro Rail Corporation Limited.

2 Setting and Data

In this section, we describe the city of Bengaluru, its metro network, and FAR policies. We also discuss the data used to document various facts about building heights and land use, and to construct the quantitative model.

2.1 The City of Bengaluru

Bengaluru, the capital of the Indian state of Karnataka, has experienced decades of rapid economic growth as a leading center of information technology and high-tech industries. The city has expanded dramatically, growing from 160 square kilometers in 1991 to 741 square kilometers in 2011. Its population was 8.4 million in 2011, more than double the population twenty years earlier, and it is one of the densest cities in the world, with 11,876 people per square kilometer. Private vehicle ownership increased from 58 to 503 per 1,000 inhabitants between 1981 and 2013. However, public transportation has not kept up with the pace of urbanization, and restrictive zoning regulations have contributed to urban sprawl, making Bengaluru one of the most congested cities in the world (ADB, 2019; Akbar, Couture, Duranton, and Storeygard, 2023a,b).

Bengaluru Metro. The Bengaluru Metro is an important initiative to address increasing traffic congestion. It is being built and operated by Bangalore Metro Rail Corporation Limited (BMRCL), a joint venture between the Government of India and the Government of Karnataka. The Bengaluru Metro consists of three phases with a total length of 170.4 km and 125 stations. Figure 1 shows the map of the existing and planned lines of the metro. Phase 1 (43.3 km) was completed and fully operational in 2017. It comprises the East–West and the North–South lines. Phase 2 (74.1 km) extends the existing lines and adds two new lines, and is expected to be fully operational by 2024. Phases 2A and 2B (51.5 km) are planned and will add two more lines to the network. Construction costs for all phases are estimated at $7.2 billion in 2020 prices, with annual operating costs estimated at $0.7 million per km. Appendix Figure C.1 depicts the evolution of the metro network, and Appendix Table A.4 provides more detailed information on each phase.

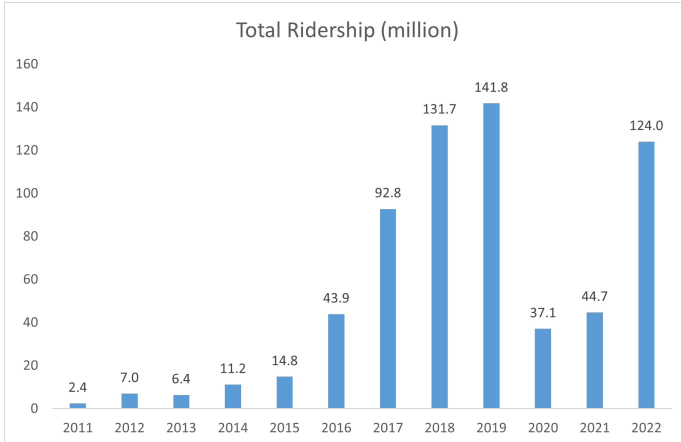
The metro is increasingly becoming a popular mode of transportation for commuters in Bengaluru. Figure 2 shows the evolution of ridership since the inauguration in 2011. Before the East-West and the North-South lines were integrated in 2016 and 2017, respectively (see Appendix Figure C.1), ridership was relatively low. Starting in 2016, ridership began to grow rapidly, with a brief pause caused by the COVID-19 pandemic.

FAR limits. Another feature of Bengaluru is that, like many other Indian cities, it has strict regulations on building heights imposed through FAR limits. The city's Revised Master Plan of 2015 provides the maximum FAR for various categories of land use (Bangalore Development Authority, 2007). These tend to also vary by plot size and the width of the road the plot faces. For example, the FAR limit is 1.75 for residential plots up to 360 square meters and associated with road width up to 12 meters. This increases to 3.75 for residential plot sizes between 4,000 and 20,000 square meters and road width above 30 meters. The limit for commercial land (including land used by information technology businesses) on plots up to 12,000 square meters and road width above 30 meters is 3.25. Even though amendments to the Revised Master Plan 2015 allow for a FAR of 4 within a 150 meter radius of metro stations, the allowance appears to be largely unused (Ramulu, Sankar, and Randhawa, 2021). Existing developments, which tend to feature large numbers of small plots with buildings of low height, and various conditionalities associated with the extra FAR appear to be the reason.[2]

The rationale offered by Indian urban planners for low FARs is that these limit population and job density and keep them in line with low "carrying capacity" of existing urban infrastructure (Bertaud and Brueckner, 2005). However, low FARs can dampen the

[2]Sood (2022) shows that land fragmentation is a key barrier to real estate development in India.

Figure 2: Metro Ridership



Note: This figure shows annual ridership for the Bengaluru metro. *Source:* Bengaluru Metro Rail Corporation Limited.

wider benefits of metro systems if they restrict residential and job densities (Roy and Shah, 2018) and lead to urban sprawl (Bertaud and Brueckner, 2005; Geshkov and DeSalvo, 2012; Lall, Lebrand, Park, Sturm, and Venables, 2021). The benefits of transportation improvements can also be constrained by zoning regulations. In the case of Bengaluru, the draft Master Plan 2031, prepared by the Bengaluru Development Authority (BDA) in 2017, called for restrictions on commercial development in the city center.

2.2 Data

To deploy a quantitative spatial model and study the effects of the metro on the economy of Bengaluru, we prepare data on labor markets, commuting, land use, and building heights for 198 Bengaluru wards around 2015, before the metro became a major mode of transportation in the city (see Figure 2). We briefly discuss the data sources and processing below. For more details and summary statistics, see Appendix Section A.

Geography of Bengaluru. We collect data on all 198 wards in Bengaluru.[3] A ward is the smallest administrative unit in Indian cities, and also the smallest geographic unit for which socioeconomic data is available. For the metro network, we collect alignment shapefiles and station locations, design speed, and opening date for each of the existing and planned corridors at the time of writing.

[3]Bengaluru is administered by a municipal corporation, the Bruhat Bengaluru Mahanagara Palike (BBMP), which translates as the Greater Bengaluru City Corporation. Like other large municipalities in India, the area covered by the BBMP has grown over time to include nearby towns and neighboring areas. This study covers all 198 wards of the municipality in 2015.

Another notable aspect of Bengaluru's geography is the Outer Ring Road (ORR). The ORR, constructed around 2000, is approximately 60 km long and envelops the core of Bengaluru (see Appendix Figure C.3). The areas within the ORR are generally considered the city center. They have the highest population density, and most government, business, commercial, and institutional establishments are located within or along the ORR.

Place of residence and place of work. The data source for place of residence is the Village and Town Primary Census Abstract (PCA) from the Bengaluru District Census Handbook, based on the 2011 Indian Population Census. It provides the number of workers residing in each ward.[4] As there is no information on ward-level employment, we estimate it by combining the place of residence from the PCA data and information on commuting origin-destination (OD) from the Bengaluru travel survey conducted by Rail India Technical and Economic Service (RITES) in 2015.[5] Since the travel survey records the residence and workplace location for each respondent, we use this information and calculate the ward-level residential-workplace commuting matrix for all employed individuals over the age of 14. From the commuting matrix, we calculate the probability of commuting from one ward to all wards, and combine the results with PCA employment in the residential ward to yield the estimates of employment in the workplace ward.[6]

We estimate the ward-level share of high-skilled workers using educational attainment data from the RITES travel survey for all employed individuals over age 14. We categorize individuals with a graduate degree and above as high-skilled and others as low-skilled.[7] In the absence of information on wages, we use the average monthly income data for the workplace ward and residential ward recorded in the survey.

[4]Workers in Census 2011 are defined as those "who participated in any economically productive activity for any length of time during the reference period." The reference period is 1 year preceding the date of enumeration. Individuals producing for own consumption are not included, except for agricultural production for own consumption (e.g., growing of crops, rearing of animals, and milk production).

[5]The RITES survey samples 38,122 individuals in 10,167 households across Bengaluru. The survey records a travel diary for respondents' trips taken in the past 24 hours, which includes travel information on origin ward, destination ward, travel time, duration, and mode. It also records respondents' demographic characteristics, such as age, employment status, etc.

[6]To validate the estimated employment at workplace ward, we cross-reference the results with reported employment at workplace wards from the RITES Bengaluru Metro Feasibility Report 2015. The two sets of employment estimates are highly correlated with the correlation coefficient of 0.94.

[7]Graduate degree is a tertiary degree. The overall high-skilled share is 44.4%. We cross reference the results with the Periodic Labor Force Survey (PFLS) 2018–2019 of Urban Karnataka in the National Sample Survey (NSS) Region 293 (Inland Southern Region). The estimated corresponding high-skilled share (graduate or above) is 34.8% in the PFLS, or 9.6 percentage points lower than the travel survey, which could be due to the fact that Bengaluru has the highest number of colleges and universities in India, while the PLFS NSS sampling region includes 8 other districts.

Travel times. We estimate ward-to-ward travel times for driving, bus transit, and metro by combining several data sources. First, we use Google Maps (GM) to collect driving and bus travel time data between ward-to-ward, ward-to-station, and station-to-ward origin-destination (OD) pairs during peak hours on normal working days in October 2021 and March 2022. The ward-to-ward driving and bus travel time is used as the commute time for driving and bus, respectively. We also estimate metro station-to-station travel time using published information on the metro design speed, the inter-station distance, and the estimated train stopping time and interchange time via walking. These estimates are combined with the GM ward-to-station and station-to-ward driving and bus travel time to determine ward-to-ward travel time by metro, with driving or bus as the last mile mode. Appendix Section A.1 details the process for estimating travel times.

Land use. We acquire land use planning maps for 2015 and 2031 from public resources.[8] The Government of Karnataka and the governing body of Bengaluru periodically publish and update the Master Plan Report as a vision document for the city's development path. The 2015 maps are a part of the Revised Bengaluru Master Plan of 2015, published in 2007, and the Draft 2031 Master Plan, released for public consultation in 2017.[9] Each map outlines land parcels with color-coded land use, such as residential, industrial, and commercial. We digitize the maps and spatially adjust them to the WGS84 coordinate system (see panel b in Appendix Figure A.2 for the 2015 map).

Because buildings located on industrial and commercial parcels represent places of employment, we combine the two types in our empirical analysis and quantitative model. In what follows, we label the combined land use as "commercial."

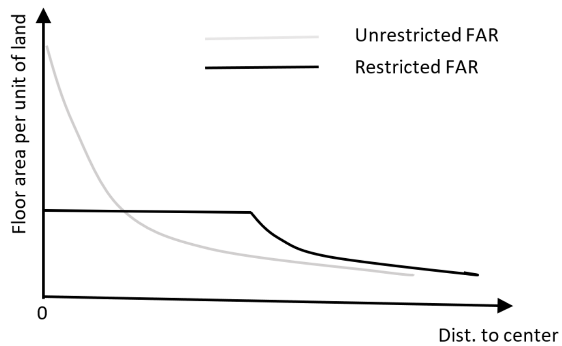
Building heights. To measure building heights, we use the machine learning trained ZiYuan-3 (ZY-3) satellite multi-view imagery building height data at a resolution of 2.5 meters (Liu, Huang, Wen, Chen, and Gong, 2017; Liu, Huang, Zhu, Chen, Tang, and Gong, 2019). The main advantage of using ZY-3 is that the data are based on simultaneous multi-view images, which, compared to existing methods that use single view images (Frantz, Schug, Okujeni, Navacchi, Wagner, van der Linden, and Hostert, 2021), provide a more accurate prediction of building heights (Amirkolaee and Arefi, 2019).[10] We overlay the building height data with digitized land use maps to obtain the maximum height (i.e., the height of the tallest pixel), minimum height (i.e., the height of the shortest pixel), and average height (averaged across pixels) for each land parcel. We

[8]Open City: https://opencity.in (accessed in June 2021)

[9]This version of the 2031 draft Master Plan has been withdrawn, possibly due to inadequate adherence to transit-oriented-development principles. See, for example, Bharadwaj (2020).

[10]Appendix Section A.2 details the methodology and advantages of the ZY-3 building height data.

Figure 3: Height Gradient with Unrestricted and Restricted FAR in a Monocentric City



Note: This figure adapts Figure 1 from Bertaud and Brueckner (2005).

then collapse the parcel-level data at the ward level to obtain the average building height (using the average parcel height, weighted by parcel area) and the area for commercial and residential land use in each ward. Appendix Section A.2 provides more details.

3 Building Heights and Land Use

In this section, we discuss empirical evidence on the building height gradient, transit-oriented development, and compare the 2015 and the 2031 land use plans.

3.1 Building Height Gradient

Bertaud and Brueckner (2005) built a monocentric city model in which the floor area per unit of land is subject to an upper limit. In equilibrium, the restriction is binding in the central part of the city and nonbinding elsewhere. Figure 3 illustrates the building height patterns of the model with unrestricted and restricted FAR, respectively. In the absence of FAR limits, building heights decline smoothly from the center to the edge of the city. In contrast, with FAR limits, building heights are not only considerably lower in the city center, but their height gradient is also relatively flat as one moves away from the center. The height starts to decline at a certain distance to the center.

We examine the actual building height patterns in Bengaluru in two ways, using the data at land parcel level. First, we run an OLS regression of the log of the parcel's mean and maximum heights on the parcel's distance to the city center, the squared distance, and the interactions of the two distance variables with an indicator of whether the parcel is outside the ORR, while controlling for land area. The results (Panel A in Table 1) show that for the different types of land use, both the parcel's mean and maximum heights increase with

Table 1: Regressions of Building Heights on Parcel Characteristics by Land Use

	Residential		Commercial	
	Mean log height	Max log height	Mean log height	Max log height
	(1)	(2)	(3)	(4)
Panel A: Parcel-level height on parcel area and location variables				
Area (log)	0.042***	0.121***	0.015***	0.143***
	(0.001)	(0.001)	(0.002)	(0.002)
Distance to city center	-0.012***	0.003	-0.002	-0.001
	(0.004)	(0.003)	(0.005)	(0.005)
Squared distance to city center	-0.002***	-0.002***	-0.001**	-0.001**
	(0.000)	(0.000)	(0.000)	(0.000)
Distance to center x Outside ORR	-0.039***	-0.040***	-0.021***	-0.024***
	(0.003)	(0.002)	(0.004)	(0.003)
Squared distance to center x Outside ORR	0.002***	0.002***	-0.000	0.001*
	(0.000)	(0.000)	(0.000)	(0.000)
Constant	0.876***	0.822***	0.928***	0.641***
	(0.009)	(0.008)	(0.018)	(0.015)
Observations	115,370	115,504	43,668	43,700
R-squared	0.114	0.195	0.093	0.191
Panel B: Parcel-level height on proximity to metro station				
Area (log)	0.044***	0.123***	0.016***	0.143***
	(0.001)	(0.001)	(0.002)	(0.002)
Distance to city center	-0.049***	-0.036***	-0.018***	-0.022***
	(0.002)	(0.002)	(0.003)	(0.002)
Squared distance to city center	-0.000***	-0.000***	-0.002***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Within 500 meters from metro	0.060***	0.052***	-0.029***	-0.003
	(0.005)	(0.005)	(0.008)	(0.006)
Constant	0.942***	0.894***	0.995***	0.712***
	(0.007)	(0.006)	(0.015)	(0.013)
Observations	115,370	115,504	43,668	43,700
R-squared	0.109	0.189	0.084	0.182

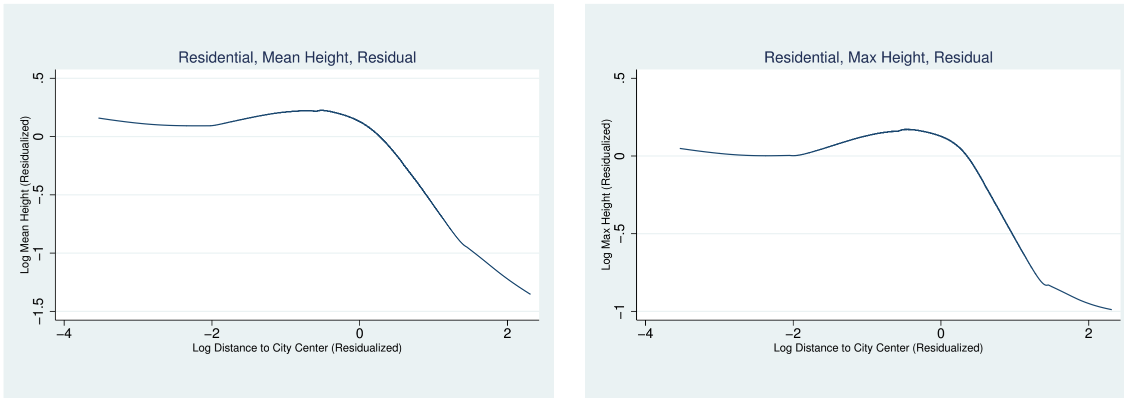
Note: Standard errors are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

parcel area, with the coefficients significantly higher for the maximum height. Conditional on land area, the mean and maximum heights decrease linearly for commercial land and in a convex way for residential land as the distance to the city center increases. Our results show that the commercial height gradient is lower than the residential gradient, which is consistent with the prediction of Ahlfeldt and Barr (2022).[11] Moreover, the coefficients of the interaction between distance to the center and outside-ORR indicator are negative and statistically significant. This indicates that mean and maximum heights decrease considerably faster outside the ORR than within the ORR.

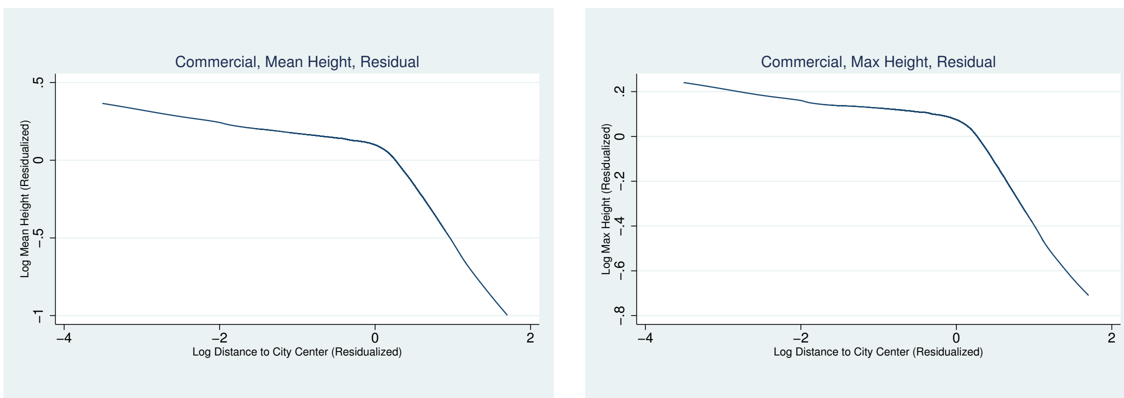
[11]Building a general equilibrium monocentric city model with endogenous land use, they show that in the absence of height limits commercial development has a steeper density gradient than residential development.

Figure 4: Height Gradients of Bengaluru (Residualized)

Panel (a): Residential



Panel (b): Commercial



Note: The figures show lowess regression results using residualized log of height on residualized log of distance to city center after their respective regressions on log area.

Second, we estimate a locally weighted regression of the log of the mean or maximum height of a parcel on its distance to the city center. To control for land parcel area, we first residualize the two variables by regressing them on the log of parcel area. The results are plotted in Figure 4. For residential and commercial land, the heights gradually decrease as one moves away from the city center, and then sharply after hitting a certain distance from the center. Simple calculations suggest that the turning points fall between 5 and 7 kilometers from the city center, which is in the vicinity of the ORR alignment. These findings are consistent with the theoretical predictions in Bertaud and Brueckner (2005). They imply that FAR restrictions exist, and are likely to be binding within the ORR and nonbinding outside.

3.2 Transit-Oriented Development

Our data could also be used to examine another land use policy, transit-oriented development (TOD). TOD has emerged as a paradigm for more sustainable, livable urban planning by integrating land use and public transport. The Government of India has advocated TOD in the National Urban Transport Policy (2014), the National TOD Policy (2017), and the Metro Policy (2017), and called for cities to raise maximum permitted FARs around transit stations. However, progress on TOD projects has been slow due to various constraints, such as legacy urban development issues, policy and regulation, involvement of multiple agencies in planning and development of urban infrastructure, land acquisition issues, and insufficient financing (Ramulu, Sankar, and Randhawa, 2021).

Among the indicators reflecting the application of the TOD principles, functional diversification and densification of areas surrounding the transport nodes are considered among the most important. Our data on land use and building heights allow us to undertake a quantitative assessment of the status quo of the two indicators in Bengaluru.

In panel A of Appendix Table A.6, we present the shares of land area for residential and commercial use for 70 wards with existing or planned metro station(s), and for areas within 500 meters around the 112 metro stations, respectively. Compared to citywide land use allocations, the wards with metro stations have a smaller land share devoted to residential purposes (47.2% vs. 53.4%) and slightly more for commercial purposes (19.3% vs. 18.5%). When we look at areas within 500 meters of the stations, the share of land devoted to commercial use increases to over 29%, while the share of residential land is only 41%. The higher relative concentration of commercial land use next to metro stations suggests that jobs are more likely to locate in places that are relatively easy to access by metro.

However, the number of jobs that locations next to metro stations can support depends not only on land use, but also on density. To check whether density of these locations differs from rest of the city, we estimate two sets of regressions. First, we regress the log mean or maximum height at the parcel level on whether the parcel is within 500 meters of a metro station, while controlling for the area, distance, and squared distance to the city center. As our general spatial equilibrium exercise takes the ward as the unit of analysis for policy simulations, we also examine how height varies between wards hosting metro stations and those that do not.

As shown in panel B of Table 1, residential buildings in the 500-meter neighborhood of metro stations are 6% taller than those outside, conditional on land area and location relative to the city center. However, commercial buildings near metro stations are 3% shorter. Moreover, the difference for residential buildings is economically small consider-

Table 2: Comparison of Land Use Allocations between the 2015 and the 2031 Master Plans

	(1) Number of wards	(2) Resid.	(3) Comm.	(4) Other	(5) Total
2015 allocation	198	18,530	6,649	18,731	43,910
2031 allocation	198	31,895	4,823	26,566	63,284
Change from 2015 to 2031					
All wards	198	13,365	-1,826	7,835	19,374
Inside ORR	132	1,177	-1,059	1,982	2,100
Outside ORR	66	12,188	-767	5,853	17,274
With metro station	70	7,070	-667	3,527	9,930
Without metro station	128	6,295	-1,159	4,308	9,444
Inside ORR, with station	40	373	-320	788	842
Inside ORR, without station	92	804	-740	1,194	1,259
Outside ORR, with station	30	6,697	-348	2,739	9,089
Outside ORR, without station	36	5,491	-419	3,114	8,185

Note: Land area is in hectares. "Other" land use type includes agriculture, defense, forest, open space, public utilities, public and semi-public, quarry, transport and communication, water bodies, and national green tribunal's buffer.

ing that the permissible FAR for TOD in Bengaluru is set at 4 (Jain and Singh, 2019), while the actual average FAR in residential parcels is 1.05. The results in Appendix Table C.1 suggest that our conclusions do not change if instead of using a 500-meter radius around stations, we simply use an indicator of whether the parcel is in a ward with at least one metro station.

Overall, we find no evidence of TOD in Bengaluru. This suggests that there is considerable room to increase density in areas near existing and planned metro stations. Using the counterfactual analysis in Section 6, we will quantitatively assess how relaxing FAR limits in parcels surrounding metro stations affects welfare.

3.3 Land Use Allocations across the 2015 and the 2031 Master Plans

In 2017, the Bengaluru Development Authority (BDA) prepared the draft 2031 Land Use Master Plan, which contained significant proposed changes to land use, particularly the addition of land for commercial and residential land use outside the center and the reduction of commercial use in the center. Although the plan has since been retracted, it offers a valuable opportunity to assess land use planning in Bengaluru.

Table 2 shows a comparison between the 2015 and 2031 land use allocations and reveals the following patterns. First, there is a significant increase in residential land use (13,655 hectares), but a decrease in commercial land use (1,826 hectares). As a result, the supply of residential land increases by 72%, while commercial land shrinks by 27%.[12] Appendix Figure C.6 shows the map of the changes in land use stipulated by the plan.

Second, the increase in residential land comes from different sources depending on whether the ward is inside or outside the ORR. For wards inside the ORR, the increase in residential land is mainly at the cost of land allocated to commercial use (i.e., rezoning). Outside the ORR, most of the increase in residential land is due to drawing down of land from the "unallocated" category.[13]

Third, we find no obvious consideration of TOD in the 2031 Land Use Plan. Whether or not a ward contains a metro station does not seem to matter for changes in land allocation patterns. With or without a metro station, wards tend to have more land for residential use and less for commercial use. In section 6.2, we will examine the welfare implications of the 2031 Land Use Plan if it were to be implemented.

4 Spatial Model of Bengaluru

Next, we build a quantitative spatial model of Bengaluru to assess the general equilibrium effects of the introduction of the metro in the context of land use restrictions. The model belongs to the class of quantitative spatial equilibrium models with commuting.[14]

Consider an urban area that consists of a finite set $\mathcal{I}$ of discrete locations (wards), each populated by workers, firms, and floorspace developers. *Workers* differ by skill: low and high. They supply their labor to firms and consume residential floor space and a numeraire consumption good. Workers suffer disutility from time spent commuting between home and work. They commute by either public or private transport, and the choice of transportation affects commute time. The choice of residence and employment locations depends on commute time, wages at the place of employment, housing costs and amenities at the place of residence, and idiosyncratic location and transport mode preferences. *Firms* use labor and commercial floorspace to produce the numeraire consumption good,

[12]Total land increases by 19,374 hectares or 44%. The additional land comes from the "unallocated" land category, which is land inside the study area but previously not identified for any land use.

[13]For example, see Appendix Figure C.2 for a ward, whose residential land area has increased from 381 hectares in 2015 to 1,019 hectares in 2031. Only a small amount of the increase is from rezoning commercial land, while most of the new residential land comes from the previously unallocated land.

[14]A canonical example of this model is Ahlfeldt, Redding, Sturm, and Wolf (2015). Sturm, Takeda, and Venables (2023) show how such a model can be built for a city in a developing country with minimal data requirements.

which is traded within the urban area at no cost. Firms' total factor productivity depends on agglomeration spillovers that are increasing in local density of employment. *Developers* use land and the numeraire to produce floorspace, which can be used for residential or commercial purposes. The supply of floorspace in each location is restricted by zoning regulations and FAR limits. Total employment in the city is endogenous and responds to changes in expected utility. More details of the model can be found below.

4.1 Workers

A worker has skill $s \in \{L, H\}$. The total number of workers with each skill is N_s. Workers make choices in the following sequence. First, they choose the location of residence $i \in \mathcal{I}$ and the location of work $j \in \mathcal{I}$. Second, they choose transportation mode $m \in \mathcal{M} \equiv \{T, P\}$ to go from i to j, where T stands for transit and P for private. Third, they choose the quantity of goods and housing to consume. Workers also experience two preference shocks: (1) shock for the residence-workplace pair, υ_{ij}, drawn from the Fréchet distribution with cdf $F(\upsilon) = \exp(-\upsilon^{-\epsilon})$; (2) shock for the transportation mode, $\tilde{\upsilon}_m$, drawn from the Fréchet distribution with cdf $\tilde{F}(\tilde{\upsilon}) = \exp(-\tilde{\upsilon}^{-\sigma})$.

Utility and demand. The utility function of individual n is given by

$$u^s_{mij}(n) = \upsilon_{ij}(n) X^s_i E^s_j (c^s_{G,ij})^{1-\gamma} (c^s_{S,ij})^{\gamma} \frac{\tilde{\upsilon}_m(n) B_m}{d_{mij}}, \tag{4.1}$$

where c_G and c_H denote the consumption of goods and housing (shelter), and d_{mij} is the utility cost of commuting from location i to location j using mode m. Parameters X^s_i, E^s_j, and B_m are amenity terms associated with residence location, workplace location, and transportation mode. In the baseline model, we assume that residential amenities X^s_i are exogenous. Later, in Section 6.6, we study how sensitive our results are to this assumption. The budget constraint is $w^s_j = c^s_{G,ij} + q_{Ri} c^s_{H,ij}$, where q_{Ri} is the cost of renting one unit of residential floorspace in location i.

The commuting cost d_{mij} is modeled as the "iceberg" cost:

$$d_{mij} = e^{\kappa t_{mij}}, \tag{4.2}$$

where t_{mij} is the time in minutes it takes to travel from i to j using mode m. Parameter κ measures the strength of the relationship between the cost of commuting and the commuting time.[15]

[15]The exponential functional form is standard in the literature. See Ahlfeldt, Redding, Sturm, and Wolf

The demand functions for housing and the consumption good are

$$c^s_{G,ij} = (1-\gamma)w^s_j \quad \text{and} \quad c^s_{H,ij} = \gamma \frac{w^s_j}{q_{Ri}}. \tag{4.3}$$

The indirect utility function, conditional on idiosyncratic shocks, is

$$v^s_{mij} = X^s_i E^s_j \frac{w^s_j}{q^{\gamma}_{Ri}} \frac{B_m}{d_{mij}}. \tag{4.4}$$

Choice probabilities. The probability that an s-skilled worker chooses location pair (i, j) is given by

$$\pi^s_{ij} = \frac{\left(v^s_{ij}\right)^{\epsilon}}{\sum_{i' \in \mathcal{I}} \sum_{j' \in \mathcal{I}} \left(v^s_{i'j'}\right)^{\epsilon}}, \tag{4.5}$$

where

$$v^s_{ij} \equiv \left[\sum_{m \in \mathcal{M}} \left(v^s_{mij}\right)^{\sigma}\right]^{\frac{1}{\sigma}} \tag{4.6}$$

is the expected value of choosing pair (i, j) before knowing the realization of the transportation mode shock. The probability that this worker chooses mode m, conditional on having chosen residence-workplace pair (i, j), is

$$\pi^s_{m|ij} = \frac{\left(v^s_{mij}\right)^{\sigma}}{\sum_{m' \in \mathcal{M}} \left(v^s_{m'ij}\right)^{\sigma}}. \tag{4.7}$$

Finally, the probability of choosing residence i, workplace j, and commuting mode m is

$$\pi^s_{mij} = \pi^s_{m|ij} \pi^s_{ij}. \tag{4.8}$$

Welfare. The expected utility of a worker with skill s (and our measure of worker's welfare) is

$$V^s = \Gamma\left(\frac{\sigma-1}{\sigma}\right)\Gamma\left(\frac{\epsilon-1}{\epsilon}\right)\left[\sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} \left[\sum_{m \in \mathcal{M}} \left(v^s_{mij}\right)^{\sigma}\right]^{\frac{\epsilon}{\sigma}}\right]^{\frac{1}{\epsilon}}, \tag{4.9}$$

where $\Gamma(\cdot)$ denotes the Gamma function.

(2015), Tsivanidis (2023), Zárate (2022), and many others.

Labor supply. The choice probabilities specified above determine local residential population by skill,

$$N_{Ri}^{s} = \sum_{j\in\mathcal{I}} \sum_{m\in\mathcal{M}} \pi_{mij}^{s} N^{s}, \tag{4.10}$$

as well as local employment,

$$N_{Wj}^{s} = \sum_{i\in\mathcal{I}} \sum_{m\in\mathcal{M}} \pi_{mij}^{s} N^{s}. \tag{4.11}$$

In the previous two expressions, N^s is the total supply of s-skilled workers. It is determined endogenously by migration in or from the city, as described below. Thus, total residential population and total employment of a location are

$$N_{Ri} \equiv N_{Ri}^{L} + N_{Ri}^{H} \quad \text{and} \quad N_{Wj} \equiv N_{Wj}^{L} + N_{Wj}^{H}. \tag{4.12}$$

Migration. We allow for migration into and out of the city.[16] Let the indirect utility of living outside the city for an s-skilled worker be exogenous and given by V_o^s. Suppose that prior to deciding whether to live in the city or elsewhere, workers draw a location preference shock from the Fréchet distribution with shape parameter ζ. The total number of s-skilled workers who live outside the city is exogenous and given by N_o^s. Then, the number of workers who live in the city is

$$N^{s} = N_{o}^{s} \left(\frac{V^{s}}{V_{o}^{s}} \right)^{\zeta}. \tag{4.13}$$

Commuter market access. How attractive is a given residential location i to a given worker? Using equations (4.4) and (4.6), we can write the utility of choosing residence i before knowing the value of the workplace-mode shock as $v_i^s = X_i^s q_{Ri}^{-\gamma} \left(\mathcal{R}_{mi}^{s}\right)^{\frac{1}{\epsilon}}$, where

$$\mathcal{R}_{mi}^{s} \equiv \sum_{j\in\mathcal{I}} \left(\frac{E_j^s w_j^s}{\tilde{d}_{ij}} \right)^{\epsilon} \tag{4.14}$$

is the residential commuter market access (CMA), and $1/\tilde{d}_{ij} \equiv \left[\sum_{m\in\mathcal{M}} \left(B_m/d_{mij}\right)^{\sigma}\right]^{\frac{1}{\sigma}}$ is the expected commuting cost. The residential CMA measures how easily high-paying jobs with good job amenities are accessible for workers of skill s from a given residential location i. We can also characterize the attractiveness of workplace j in a similar way. Firm CMA measures how easily accessible are workers of skill s for workplace j and is given by

[16] In Section 6.6, we study the sensitivity of our results to the open city assumption.

$$\mathcal{F}^s_{mj} \equiv \sum_{i \in \mathcal{I}} \left(\frac{X^s_i q^{-\gamma}_{Ri}}{\tilde{d}_{ij}} \right)^{\epsilon}. \tag{4.15}$$

4.2 Production Firms

A large number of perfectly competitive firms produce a homogeneous consumption good with the production function

$$Y_j = A_j \tilde{N}_j^{\alpha} H_{Wj}^{1-\alpha}, \tag{4.16}$$

where A_j is the TFP in location j, $\tilde{N}_j$ is the labor input, and H_{Wj} is the commercial floorspace input. The labor input is a CES aggregate of high- and low-skilled labor,

$$\tilde{N}_j = \left[\omega^L_j \left(N^L_{Wj} \right)^{\frac{\xi-1}{\xi}} + \omega^H_j \left(N^H_{Wj} \right)^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}, \tag{4.17}$$

where ξ is the elasticity of substitution, and ω^s_j determines the relative productivity of each skill. The consumption good is traded across locations at no cost. Therefore, it has the same price and we use the good as the numeraire.

The problem of a firm is to choose labor and floorspace inputs so as to maximize the profit given by

$$Y_j - w^L_j N^L_{Wj} - w^H_j N^H_{Wj} - q_{Wj} H_{Wj}, \tag{4.18}$$

where w^s_j is the wage of s-skilled labor, and q_{Wj} is the per-unit cost of commercial floorspace. In equilibrium, the relationship between wages and employment is given by

$$\frac{w^H_j}{w^L_j} = \frac{\omega^H_j}{\omega^L_j} \left(\frac{N^L_{Wj}}{N^H_{Wj}} \right)^{\frac{1}{\xi}}. \tag{4.19}$$

In addition, profit maximization and zero profits imply the following equilibrium relationship between low-skilled wages, productivity, and floorspace prices,

$$w^L_j = \alpha (1-\alpha)^{\frac{1-\alpha}{\alpha}} A_j^{\frac{1}{\alpha}} \left(\omega^L_j \right)^{\frac{\xi}{\xi-1}} q_{Wj}^{-\frac{1-\alpha}{\alpha}} \left[1 + \left(\frac{\omega^H_j}{\omega^L_j} \right)^{\xi} \left(\frac{w^L_j}{w^H_j} \right)^{\xi-1} \right]^{\frac{1}{\xi-1}}. \tag{4.20}$$

The equilibrium demand for commercial floorspace is

$$H_{Wj} = \left(\frac{(1-\alpha) A_j}{q_{Wj}} \right)^{\frac{1}{\alpha}} \tilde{N}_j. \tag{4.21}$$

The total factor productivity of location j is determined by an exogenous component, a_j, and an endogenous component that is increasing in the density of employment in this location:

$$A_j = a_j \left(\frac{N_{Wj}}{\Lambda_j} \right)^{\lambda}. \tag{4.22}$$

Parameter $\lambda > 0$ measures the elasticity of productivity with respect to local employment density.[17] In Section 6.6, we examine how our results depend on the assumption of endogenous productivity.

4.3 Construction and Land Use Regulations

Each location is endowed with an amount Λ_i of land that is available for floorspace development. Land is owned by landowners who have no alternative use of the land but to sell it to developers. There are two types of floorspace: residential ($f = R$) and commercial ($f = W$). Floorspace is produced by perfectly competitive construction firms (developers). The production function is

$$H_{fi} = \phi_{fi} L_{fi}^{\eta} K_{fi}^{1-\eta}, \tag{4.23}$$

where ϕ_{fi} is the productivity of construction, L_{fi} is the land input, K_{fi} is the non-land input, and η is the land share in construction. The non-land input is converted one-to-one using the homogeneous consumption good and therefore has a price of 1 in all locations.

There are two types of regulatory restrictions on the construction of each type of floorspace.[18] First, *zoning* specifies how much land in each ward can be used for residential or commercial use. In particular, a fraction ν_{fi} of land can be used for development of type f, with $\nu_{Ri} + \nu_{Wi} = 1$. Thus, the developers' land input must satisfy:

$$L_{fi} \leq \nu_{fi} \Lambda_i. \tag{4.24}$$

Second, *FAR limit* specifies how much floorspace of a given type can be constructed on one unit of land. In particular, the supply of floorspace of type f per unit of land zoned for use f cannot exceed $\bar{h}_{fi}$:

$$h_{fi} \equiv \frac{H_{fi}}{L_{fi}} \leq \bar{h}_{fi}. \tag{4.25}$$

[17]We do not include spatial spillovers of productivity between locations. These spillovers are highly localized, as found in Ahlfeldt, Redding, Sturm, and Wolf (2015) and several other studies. Given that the size of locations in our quantitative model is relatively large, the effect of the spillovers may not be first-order.

[18]The specification of land use regulation in our model is similar to the one in Acosta (2022).

Thus, the vector $\Xi_i \equiv \{\nu_{Ri}, \nu_{Wi}, \bar{h}_{Ri}, \bar{h}_{Wi}\}$ fully describes land use regulations in location i.

Developers choose L_{fi} and K_{fi} to maximize their profit,

$$q_{fi}H_{fi} - l_{fi}L_{fi} - K_{fi}, \tag{4.26}$$

subject to constraints (4.24) and (4.25). Since there is no alternative use of land, all land will be developed, i.e., the optimal land input is $L_{fi} = \nu_{fi}\Lambda_i$. The equilibrium floorspace supply is

$$H_{fi} = \min\left\{ \bar{h}_{fi}\nu_{fi}\Lambda_i\,,\, \phi_{fi}(1-\eta)^{1-\eta}\left(D_{fi}\right)^{1-\eta}\left(\nu_{fi}\Lambda_i\right)^{\eta} \right\}. \tag{4.27}$$

In the previous expression, D_{fi} is the total expenditure demand on floorspace of type f in location i. Using equation (4.3), we can solve for total residential expenditure demand,

$$D_{Ri} = \gamma\left(w_i^H N_{Ri}^H + w_i^L N_{Ri}^L\right). \tag{4.28}$$

Using equation (4.21), we can solve for total expenditure demand for commercial floorspace,

$$D_{Wj} = (1-\alpha)^{\frac{1}{\alpha}} A_j^{\frac{1}{\alpha}} q_{Wj}^{-\frac{1-\alpha}{\alpha}} \tilde{N}_j. \tag{4.29}$$

The equilibrium price of type-f floorspace is

$$q_{fi} = \max\left\{ \frac{D_{fi}}{\bar{h}_{fi}\nu_{fi}\Lambda_i}\,,\, \frac{D_{fi}^{\eta}}{\phi_{fi}(1-\eta)^{1-\eta}\left(\nu_{fi}\Lambda_i\right)^{\eta}} \right\}. \tag{4.30}$$

Equations (4.27) and (4.30) illustrate the idea that when local demand for type-f floorspace is relatively high and land use regulations restrict the supply of type-f floorspace, either by zoning or imposing FAR ratios, then developers will undersupply floorspace of this type. As a result, the equilibrium price of floorspace will be higher than under free market.

4.4 Equilibrium

Given local fundamental productivity and residential amenities, a_i and X_i^s, employment amenities, E_i^s, transportation mode shifters, B_m, commuting times, t_{mij}, floorspace development productivity, ϕ_i, land area, Λ_i, land use regulation, Ξ_i, as well as economy-wide skill supply, N^s, and elasticities α, γ, ϵ, η, κ, λ, ξ, σ, and χ, an **equilibrium** consists of (1) allocations of workers of each skill level s to residences, workplaces, and transportation modes π_{mij}^s; (2) local productivities, A_j; (3) local skill-specific wages, w_m^s, and employment, N_{Wj}^s; (4) local price and supply of each type of floorspace, q_{fi} and H_{fi}; and (5) citywide employment of each skill, N_s; such that (a) π^s_{mij} is consistent with optimal choices of workers, as specified in equation (4.8); (b) A_j is determined according to equation (4.22); (c) w^s_{mj} clears the skill-specific local labor market, while N^s_{Wj} is consistent with profit-maximizing choices of firms, as described in equations (4.19) and (4.20); (d) q_{fi} clears the local floorspace market, while H_{fi} is consistent with profit-maximizing choices of floorspace developers, as described in equations (4.30) and (4.27); and (e) N_s satisfies equation (4.13). By the Walras' Law, the nationwide market for the tradable numeraire good will clear as long as all other markets clear.

5 Quantification of the Model

This section describes how the values of model parameters are determined and what data are used in the quantitative model.

5.1 Model Parameters

Economy-wide parameters. Table 3 summarizes the economy-wide parameters. We use the share of housing in consumption $\gamma = 0.215$, the estimated share of housing consumption for urban Karnataka from the NSS Consumer Expenditure Survey (CES) in 2011–2012. We set the share of land in production to $1 - \alpha = 0.18$, following the estimate of Valentinyi and Herrendorf (2008) for the United States. The elasticity of substitution between college and non-college labor is $\xi = 2$, the mid-range of 1.5–2.5 estimated by Card (2009), also for the U.S. The elasticity of productivity with respect to density is set to $\lambda = 0.086$, as estimated by Heblich, Redding, and Sturm (2020) for the city of London, UK.[19] To calibrate η, the share of land in construction, we use the elasticity of housing supply estimated by Saiz (2010) for the U.S. He estimates the elasticity of 1.75. Since in our model the elasticity is $(1 - \eta)/\eta$, we obtain $\eta = 0.3636$. The migration elasticity is set to $\zeta = 3$, following Bryan and Morten (2019) and Tsivanidis (2023). In Section 6.6, we evaluate the sensitivity of counterfactual results to the values of several of these parameters.

Commuting parameters. To estimate the Fréchet elasticity of the preference shock for residence-workplace pairs ϵ, we use the pseudo-Poisson maximum likelihood (PPML)

[19]Meta-analysis in Ahlfeldt and Pietrostefani (2019) finds an average productivity elasticity of 0.06 from 15 studies (category 2 from Table 3). Our slightly higher value is consistent with the evidence that this elasticity is higher in developing countries (Bryan, Glaeser, and Tsivanidis, 2020).

Table 3: Model Parameters

Parameter	Description	Value	Source
γ	consumption share of housing	0.215	NSS Consumer Expenditure Survey
α	labor share in production	0.82	Valentinyi and Herrendorf (2008)
ξ	elasticity of substitution between college and non-college labor	2	middle of the 1.5–2.5 range in Card (2009)
λ	elasticity of local productivity to employment density	0.086	Heblich, Redding, and Sturm (2020)
κ	elasticity of commuting cost to commuting time	0.013	Tsivanidis (2023)
η	land share in construction	0.3636	Saiz (2010)
ζ	migration elasticity	3	Bryan and Morten (2019) and Tsivanidis (2023)
B_P	preference for private transport	1.1928	calibrated
σ	Fréchet elasticity of the residence-workplace shock	6.9359	estimated
ϵ	Fréchet elasticity of the transportation mode shock	1.1878	calibrated

Note: The table lists economy-wide model parameters.

estimator and maximize the following log-likelihood function,

$$\ln \mathcal{L} \equiv \sum_{m\in\mathcal{M}} \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{I}} N_{mij} \ln\left(\varphi_{Mm}\varphi_{Ri}\varphi_{Wj}e^{-\kappa\epsilon t_{mij}}\right), \tag{5.1}$$

where N_{mij} is the number of commuters from i to j that use mode m; φ_{Mm}, φ_{Ri}, and φ_{Wj} are mode, origin, and destination fixed effects that subsume all relevant local variables that appear in the expressions for location choice probabilities; and t_{mij} is the commuting time from i to j with mode m. Appendix Table C.2 reports estimation results. Because we cannot separately identify the commute cost elasticity κ and the Fréchet elasticity ϵ, we first estimate the product $\kappa\epsilon$ and obtain 0.0902. Then, to recover ϵ we set $\kappa = 0.013$, as estimated by Tsivanidis (2023) for the city of Bogota, Colombia.[20] Thus, our estimate of ϵ is equal to $6.9359 = 0.0902/0.013$. In Section 6.6, we study how sensitive our results are to this value.

Transport mode choice. The parameter that reflects preferences for transport modes B_m is normalized to 1 for transit and calibrated for private vehicles during model inversion to match the fraction of commuters who use the private mode, as described in Appendix

[20]Other studies that estimate the commute cost elasticity arrive at similar estimates. For instance, Ahlfeldt, Redding, Sturm, and Wolf (2015) find a value of 0.011 and Zárate (2022) finds 0.009.

Section B.1. The calibrated value of B_P is 1.19, which reflects the relative preference for using a private vehicle.

We calibrate the Fréchet elasticity of the transportation mode preference shock σ as follows. The relative probability of choosing transit versus private mode on a given route is

$$\frac{\pi^s_{T|ij}}{\pi^s_{P|ij}} = \left(\frac{v^s_{Tij}}{v^s_{Pij}}\right)^{\sigma}. \tag{5.2}$$

The elasticity of this probability ratio with respect to commuting time is

$$\frac{\partial \ln\left(\pi^s_{T|ij}/\pi^s_{P|ij}\right)}{\partial \ln t_{Tij}} = -\sigma\kappa t_{Tij}. \tag{5.3}$$

Note that the left-hand side can be decomposed into the difference between the own-elasticity, $\partial \ln \pi^s_{T|ij}/\partial \ln t_{Tij}$, and the cross-elasticity, $\partial \ln \pi^s_{P|ij}/\partial \ln t_{Tij}$. We use available estimates of own- and cross-elasticities of transit ridership with respect to commuting times on transit and by car from Frank, Bradley, Kavage, Chapman, and Lawton (2008): -0.39 and 0.02. This implies that $-\sigma\kappa t_{Tij} = -0.41$. Finally, using the average commuting time by transit in Bengaluru, 26.55 minutes, and the calibrated value of κ, we obtain $\sigma = 1.1878$. In Section 6.6, we investigate how our results depend on this value.

Local parameters. Local parameters X^s_i, ω^s_j, ψ_j, ϕ_{fi}, a_j, and E^s_j are computed by inverting the model, i.e., finding parameters that are consistent with the data being an equilibrium of the model. A detailed description of the model inversion is contained in Appendix Section B.1. Appendix Figure C.5 shows the distribution of residential (X^s_i) and employment (E^s_j) amenities, as well as total factor productivity A_i, while panels (a)–(d) in Appendix Figure C.4 show skill-specific residential population and employment. Appendix Table C.4 summarizes ward-level population and job counts, population and job density, wages, floorspace prices, and other variables used in the quantitative model.

Land use parameters. The value of ν_{fi}, the share of land zoned for use f, is obtained from the data on the fraction of land zoned for commercial or residential use in each ward. Land area of a ward, Λ_i, is equal to the sum of land used for commercial and residential purposes.

As can be seen from equation (4.30), the expression for floorspace prices depends on whether the FAR limits are binding (i.e., the development has reached maximum height and no further development is possible) or not binding in a given ward. Moreover, the equation shows that we can only identify the FAR limit $\bar{h}_{fi}$ when the limit is binding and construction productivity ϕ_{fi} when the limit is not binding.

To obtain the values of $\bar{h}_{fi}$, we rely on the evidence for density gradients presented in Section 3.1 and assume that the wards inside the ORR have binding FAR limits. Thus, the calibrated FAR limits $\bar{h}_{fi}$ in wards within the ORR are equal to the observed FAR. For wards outside the ORR, we assume that their FAR limit is equal to either the average FAR limit of within-ORR wards or the observed FAR, whichever is greater. This implies that some wards outside the ORR where the density of development is higher than the average within the ORR are also assumed to have binding FAR limits.[21] In Section 6.5 below, we study how our results would change if the FAR limits were nonbinding everywhere.

To obtain the values of ϕ_{fi}, we proceed as follows. In wards where the FAR limit is nonbinding, ϕ_{fi} can be identified from equation (4.30) using observed heights and the predicted value of q_{fi} (see Appendix Section B.1 for details). In wards where the limit is binding, we assign the average value of ϕ_{fi} in nonbinding wards. In some wards, this means that the value of ϕ_{fi} is such that the equation (4.30) takes the value of the second argument of the max operator, which is a contradiction because the ward was assumed to have a binding FAR limit. For these wards, we increase ϕ_{fi} to the level that makes both arguments of the max operator equal to each other.

5.2 Model Validation

While we have the data on commuting flows, we do not feed them directly into the model.[22] Yet, the correlation between the flows in the model and in the data is high: 0.63 for transit flows and 0.48 for private vehicle flows.

Panels (e) and (f) of Appendix Figure C.4 show the model-predicted residential and commercial floorspace prices. Although we do not have the data to compare with our model-predicted prices, the prices tend to be higher in the central areas of the city, as is the case in most cities around the world.

We can also examine the model's prediction for the value of time (VOT). An increase in commute time by one hour implies that indirect utility falls to $e^{-60\kappa} \approx 46\%$ of the original level. Since indirect utility is linear in wages, it means that a worker is willing to give up 54% of wages to reduce commute by one hour. Assuming an eight-hour workday, this implies that the VOT is $54\% \times 8 = 432\%$ of hourly wage, which is remarkably close to Kreindler (2023)'s VOT estimate of 370% of hourly wage for the city of Bengaluru.

[21]Twelve out of 66 outside-ORR wards have binding residential FAR limits, and 7 out of 66 wards have binding commercial FAR limits.

[22]If we did, we would have to calibrate pair-specific shifters for each location pair, and given that many pairs have zero commuters, many shifters would have a value of zero. These pairs would inevitably have zero commuters in any counterfactual. See Dingel and Tintelnot (2021) for a discussion of this issue.

6 Effects of the Metro and Land Use Policies

In this section, we examine several counterfactual scenarios in which the metro is introduced and land use policies are changed.

6.1 Introduction of the Metro

In our first counterfactual, we introduce the metro without making any other changes. We compare an equilibrium without the metro (the "benchmark economy") with an equilibrium where the full metro network with 125 stations (see Figure 1) is constructed.

Preferences between private and public transportation are the same as before and are determined by the combination of B_T and σ. Now, however, workers can choose their preferred mode of transit: bus or metro. We assume that they always choose the faster option, i.e., $t_{Tij} = \min\left\{t_{\text{bus},ij}, t_{\text{metro},ij}\right\}$. In Section 6.6, we also consider a scenario in which workers have an explicit preference to ride the metro. In the data, the metro is a little faster on average: the weighted average one-way commute time (weighted by transit commuting flows) is 28.6 minutes by bus and 26.6 minutes by metro. As a result, commuters on routes well served by the metro prefer it to the bus.

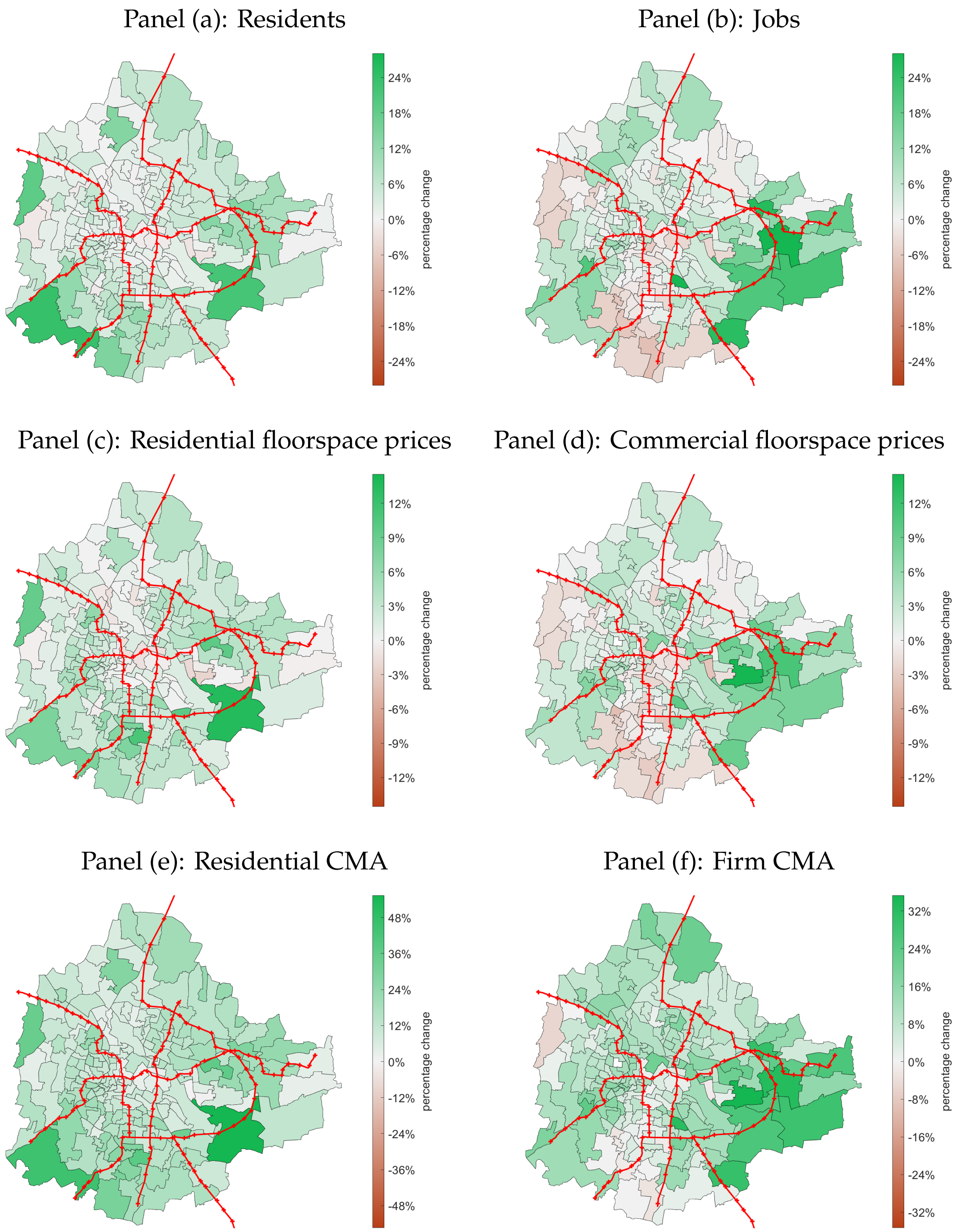
Panels (a) and (b) of Figure 5 show the counterfactual changes in residents and jobs. There is mild decentralization of both: as shown in column (1) of panel A in Table 4, the share of residents in central wards declines by 0.7 percentage points, while the share of jobs declines by 1 percentage point. There is particularly strong growth in residents in selected wards to the southeast and southwest of the city center, and strong job growth in the southeast. These places are seeing a large increase in their residential and firm CMA thanks to the construction of metro stations. Relocations of jobs and residents feed into floorspace prices: panels (c) and (d) show that changes in residential and commercial prices largely mimic the patterns in resident and job movement.

Column (1) of panel A in Table 4 summarizes the aggregate results of this counterfactual experiment. Wages barely change because the metro has a negligible effect on labor productivity. The population increases by 4%, causing an increase in residential floorspace prices of nearly 2% and commercial prices of nearly 3%.

Welfare gains are similar for high- and low-skilled workers, amounting to about 1.3% for an average resident. What drives these welfare gains? Note that wages do not change much and housing costs go up, which reduces utility from consumption for an average worker. The key source of welfare gains is the increase in the residents' CMA.[23] As panel

[23]CMA is a sufficient statistic for welfare gains, as shown in Tsivanidis (2023), and it also incorporates changes in wages and housing costs, as can be seen from equations (4.14) and (4.15).

Figure 5: Local Effects of Introducing the Metro



Note: The maps show results for the counterfactual where the metro is introduced. Panels (a) and (b) show changes in residents and jobs. Panels (c) and (d) show changes in residential and commercial floorspace prices. Panels (e) and (f) show changes in weighted-average (by skill and transport mode) residential and firm commuter market access. Red lines represent the metro network and red crosses are metro stations.

Table 4: Aggregate Effects of Metro and Land Use Policies

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		4.0	5.8	10.5	5.5	9.7	-18.5	-14.6
low-skilled		3.9	4.8	9.5	4.8	9.0	-18.3	-14.5
high-skilled		4.2	6.9	11.8	6.3	10.7	-18.7	-14.8
Shares, p.p. chg								
residents within ORR		-0.7	2.0	1.0	2.7	1.9	-4.5	-5.5
jobs within ORR		-1.0	4.0	2.4	4.7	3.7	-8.9	-10.4
residents next to stations		0.5	1.7	2.5	-0.5	0.0	0.4	0.9
jobs next to stations		0.4	3.7	4.6	-0.4	0.0	6.2	6.6
Wages, % chg		0.1	2.9	3.0	2.5	2.6	-7.7	-7.6
low-skilled		0.1	2.4	2.6	2.2	2.3	-7.9	-7.7
high-skilled		0.0	2.8	2.8	2.4	2.3	-7.4	-7.4
Residential floorspace prices, % chg		1.9	0.5	2.0	0.6	2.5	-12.5	-11.9
Commercial floorspace prices, % chg		2.8	-2.7	-1.4	-2.5	0.1	29.9	32.7
Land prices, % chg		4.1	8.8	13.8	8.1	12.5	7.9	13.2
Welfare, % chg		1.3	1.9	3.4	1.8	3.2	-6.6	-5.1
low-skilled		1.3	1.6	3.1	1.6	2.9	-6.5	-5.1
high-skilled		1.4	2.2	3.8	2.1	3.4	-6.7	-5.2
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.4	21.8	23.4	21.8	23.5	22.0	23.7
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.3	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.7	40.8
bus	39.6	25.0	39.7	24.7	39.6	25.0	39.7	24.7
metro	0.0	15.7	0.0	16.1	0.0	15.8	0.0	16.1
low-skilled	39.8	40.9	39.9	40.9	39.8	40.9	39.9	40.9
high-skilled	39.4	40.6	39.5	40.6	39.4	40.6	39.4	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

(e) of Figure 5 demonstrates, nearly all residents benefit from better connectivity and access to jobs brought by the metro. Similarly, as panel (f) shows, firms in most locations enjoy better access to workers.

Column (1) of panel B in Table 4 summarizes the counterfactual commuting patterns. The share of residents using transit increases by 1.1 percentage points, from 39.6% to 40.7%.

The majority of those who use transit still take the bus, but for 15.7% of Bengalureans, the metro becomes the primary mode of transportation to work.[24] The uptake does not differ much across skill groups.

Interestingly, despite the fact that metro makes commuting faster on many routes, workers' commutes are getting slightly longer: the average travel time to work increases from 22.7 to 23.4 minutes. There are two important reasons for this result. First, some workers are switching to transit thanks to the shorter travel times. However, transit is still slower than private vehicles and the commuting time of an average worker increases. Second, workers have idiosyncratic location preferences. A more efficient transportation network creates more options as workers are freer to choose their preferred locations and can take combinations of residences and jobs that are farther apart.

6.2 Land Use Policies

As we have seen, the metro brings nontrivial welfare gains. However, these gains may not reach their full potential because in many locations where the metro increases demand for housing or commercial real estate, supply is limited by the FAR restrictions. As Appendix Figure C.7 shows, in most wards where the FAR limits were binding in the benchmark economy, the limits remain binding in the counterfactual. In a few wards where real estate demand declined, the limits became non-binding; however, several wards that received stations and where the limits were not binding are now hitting their FAR limits.

In what follows, we study how changes in land use regulations interact with the introduction of the metro. First, we simulate a policy of TOD by increasing FAR limits near metro stations. Second, we increase FAR limits in all central wards. Finally, we change zoning as envisaged by the 2031 Land Use Plan.

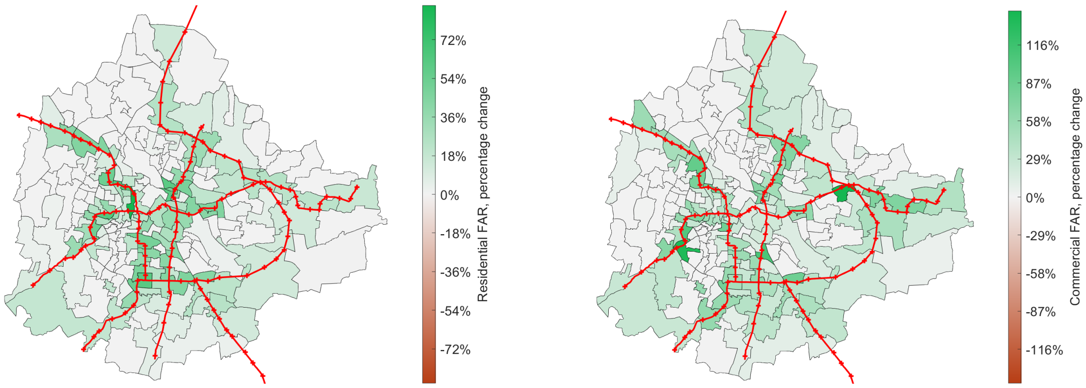
Transit-oriented development. We simulate what would happen to ward-level FAR if we implement TOD by raising the FAR of land parcels within 500 meters of metro stations from their current level to 2.[25] This results in varying increases in FARs at the ward level. The affected wards include those with metro stations (70 wards) and those with land parcels within 500 meters of a station. Figure 6 shows the percentage changes in FAR limits in each ward for both residential and commercial development. Within the ORR,

[24]The small increase in the transit share but large reallocation from the bus to the metro parallels Tsivanidis (2023)'s findings for the city of Bogotá. He finds that about fifteen years since the introduction of the bus rapid transit it accounted for 21% of commutes, while the share of conventional buses fell from 74% to 48%. However, the share of car commutes changed little, from 17% to 15%.

[25]The limit of 2 is below the current limit of 4 near metro stations. However, as discussed in Dhindaw, Kumaraswamy, Prakash, Chanchani, and Deb (2021), the FAR of 4 may not be achievable because most land parcels near stations are too small to accommodate tall buildings.

Figure 6: Transit-Oriented Development

Panel (a): Residential FAR Panel (b): Commercial FAR



Note: Panel (a) shows the percentage increase in the FAR limit for residential development in the counterfactual with transit-oriented development, while panel (b) reports the increase for commercial development.

where the FAR limits are binding, the average ward sees a 15% increase in residential FAR limits and a 27% increase in commercial FAR limits. Appendix Figure C.8 demonstrates that almost all wards where the FAR limit was binding expand their floorspace to the new limit, making FAR restrictions binding again.

We proceed in two steps. First, we increase the FAR limits without introducing the metro. Then, we also introduce the metro. This allows us to understand the effects of each policy individually and then to study the complementarity between the two types of policies.

Column (2) of panel A in Table 4 shows that less strict density limits lead to much lower growth in residential prices and a nearly 3% fall in commercial prices. These price changes are a combination of greater supply in response to less tight restrictions and greater demand from nearly 6% additional workers that move into the city. Small increases in housing prices allow workers to maintain their consumption levels, while lower prices of commercial real estate allow employers to raise wages. This policy results in a welfare gain of 1.9% for an average worker. It also leads to a large relocation of jobs and residents to central wards and wards with metro stations.

In column (3), we report the results of an experiment in which we introduce the metro in addition to increasing FAR limits. Population growth doubles from the previous experiment and, as a result, residential prices increase more, while the decline in commercial prices is much smaller. There is a greater movement of jobs and residents to locations with metro stations and there is greater wage growth. In addition, greater concentration near metro stations leads to a larger increase in metro use, as shown in column (3) of panel

B in Table 4.

Unlike the scenario with metro only, in which the welfare gains for high- and low-skilled workers were similar, the counterfactuals with TOD result in greater gains for the high-skilled and larger migration of high-skilled labor into Bengaluru. This occurs primarily because TOD leads to greater employment within the ORR, where wards have relatively high job amenities E_j^s for high-skilled workers.[26] Thus, by disproportionately treating central wards that specialize in high-skilled jobs, TOD and the metro yield larger benefits for high-skilled workers.

Central upzoning. Next, we increase the FAR limits in all locations within the ORR uniformly by the same total amount as in the previous experiment, i.e., by 15% for residential parcels and 27% for commercial parcels within the ORR. This counterfactual attempts to alleviate the problem of constrained development in the city center without explicitly targeting areas near metro stations. As before, we proceed step by step: first, we increase the FAR limits without introducing the metro, then we increase the FAR limits and introduce the metro.

Columns (4) and (5) of Table 4 summarize the results. Many of the outcomes are comparable to the counterfactuals with TOD. One difference is that in this scenario, there is much more concentration of jobs and residents in the city center, which is not surprising since the policy treats only central wards. At the same time, the share of residents and jobs near metro stations decreases in this experiment, since many stations are located outside of the center and are not treated by the policy. The welfare gains in this scenario are somewhat smaller than the gains from the TOD policy. As with TOD, high-skilled residents benefit more from upzoning central wards than their low-skilled counterparts because these wards specialize in high-skilled jobs.

2031 Land Use Plan. In the following counterfactual experiment, we examine how the introduction of the metro would affect the local economy if the urban development authority's proposed land use plan for 2031 were fully implemented. As discussed in detail in Section 3.3, the plan increases the total land available for development. However, while the amount of land available for residential development increases, the amount of land available for commercial development decreases. Moreover, land supply increases predominantly in the periphery of the city where few people live and which are far from most jobs (see Appendix Figure C.6). We first implement the 2031 plan without introducing the metro, and then implement the plan and introduce the metro.

Columns (6) and (7) of Table 4 show the results. The economy suffers huge welfare

[26]This reflects the abundance of high-skilled jobs in the city center in the data.

losses of 5.1%–6.6%. The main reason is the reduction of land that can be used for commercial development. The prices of commercial floorspace increase by 30%–33%, making it more difficult for employers to hire workers. As a result, wages fall by nearly 8% and city-wide employment declines by 15%–18%. This policy also significantly reduces the share of residents and jobs in the city center. At the same time, the share of jobs next to the metro stations increases by 6 percentage points, primarily because a number of wards in the southeast receive several metro stations and do not see large reductions in commercial land. In addition, as we show in Appendix Section D.1, the 2031 plan recommended greater *reductions* in commercial land in places that would contribute the most to city-wide welfare if commercial land were *increased*!

6.3 Cost-Benefit Analysis

The introduction of the metro increases workers' welfare and land values, but are these gains large enough to justify the construction of the metro? To answer this question, we perform a simple back-of-the-envelope calculation and compare the costs and the benefits of the metro network. The details are presented in Appendix Section D.2.

Table 5 shows the cost-benefit analysis for all counterfactuals where metro was introduced. Building metro results in a 6% increase in output. Given our estimates of the present value of construction and operation costs of about 1.7% of GDP, the net gain is 4.3% of GDP. Note, however, that most of the increase in GDP is due to the additional 4% of workers moving to Bengaluru from the rest of the country. As a result, the net benefit of the metro *per worker* basis is a mere 0.2% of GDP.

In scenarios with TOD and central upzoning, the net gains are much larger: 14.7% and 13.4% of GDP, respectively. These gains do not only reflect the increase in labor supply, but also higher labor productivity and greater housing consumption thanks to relaxed limits on real estate development. As a result, the gains per worker increase from nearly zero in the previous scenario to 3.6% and 3.2%, respectively. At the same time, the 2031 plan results in a large net loss from metro construction of nearly 18% of GDP. Even though land values increase by more than 13%, thus benefiting landowners, this is not sufficient to offset the massive drop in workers' income.

These results suggest that building the metro in Bengaluru brings sizable economic benefits and is also a good investment for the city, even if the net gains for an average worker are close to zero.[27] However, the construction of the metro could have much

[27] In practice, a nontrivial portion of the metro costs are not borne by the city. For phases 2, 2A, and 2B, the state and the central government will bear 30% and 20% of the project cost, respectively. The remaining will be obtained through loans.

Table 5: Cost-Benefit Analysis

Introduce metro:	✓	✓	✓	✓
Increase FAR next to stations:	–	✓	–	–
Increase FAR within the ORR:	–	–	✓	–
2031 land use plan:	–	–	–	✓
	(1)	(2)	(3)	(4)
GDP-equivalent gross benefit, $ million	1,712	4,707	4,326	-4,657
% of GDP	6.0	16.4	15.0	-16.2
Construction and maintenance, $ million	479	479	479	479
% of GDP	1.7	1.7	1.7	1.7
Net benefit, $ million	1,233	4,228	3,846	-5,136
% of GDP	4.3	14.7	13.4	-17.9
GDP-equivalent gross benefit per worker, %	1.8	5.3	4.9	-1.8
Net benefit per worker, %	0.2	3.6	3.2	-3.5

Note: The table shows the cost-benefit analysis of introducing the metro under different scenarios.

greater aggregate benefits and also positive net gains per worker if it is accompanied by a relaxation of constraints on floorspace development.

6.4 Complementarity between the Metro and Land Use Policies

The results in Sections 6.1 and 6.2 suggest that both transit improvements, such as the construction of the metro, and land use reforms, such as TOD or upzoning in central areas, can increase welfare and improve various outcomes. However, it is equally important to understand whether or not these policies complement each other. For example, if complementarity is strong, it would be advisable for policymakers to accompany transportation improvements with appropriate land use changes. Otherwise, both types of policies can be implemented independently without the need for coordination.

We measure the complementarity between the metro and a change in land use policy for variable of interest Z as

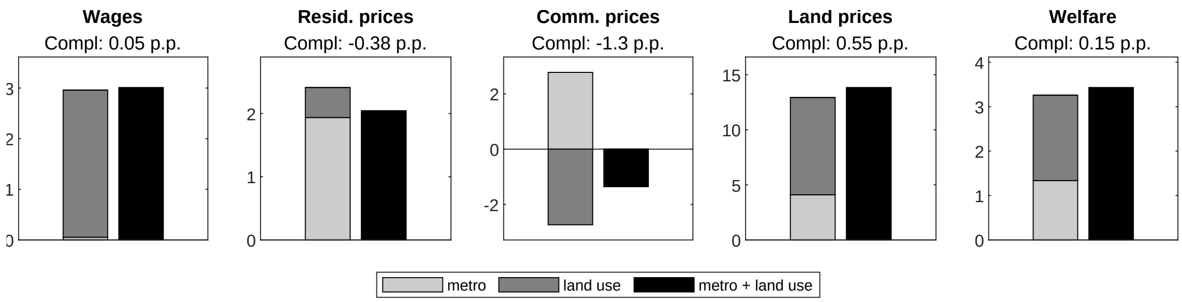
$$C(Z) = \left(\frac{Z_{\text{metro+land use}}}{Z_0} - 1\right) - \left(\frac{Z_{\text{metro}}}{Z_0} \times \frac{Z_{\text{land use}}}{Z_0} - 1\right), \tag{6.1}$$

where Z_0 is the value of the variable in the benchmark economy, $Z_{\text{metro+land use}}$ is the value when both the metro is introduced and a land use policy is implemented, whereas Z_{metro} and $Z_{\text{land use}}$ are the values when only the metro or only the land use policy is implemented.[28] "Land use" can represent any of the three land use policies studied

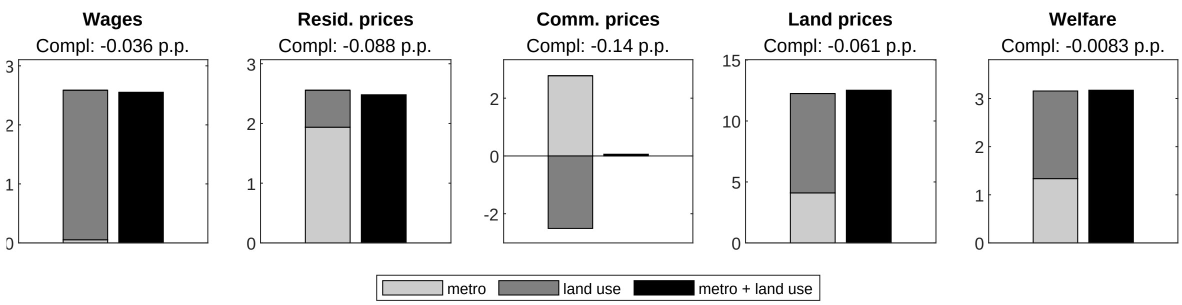
[28]For example, if Z increases by 3% in the counterfactual with both metro and a land use policy but only by 1% in counterfactuals where only the metro is introduced or only land use is changed, then

Figure 7: Complementarity of Transportation and Land Use Policies

Panel (a): TOD



Panel (b): Central upzoning



Note: The left bar of each chart shows separate effects of constructing the metro and changing land use. The right bar shows the joint effect of constructing the metro and changing land use. "Compl" reports the complementarity between the two policies in percentage points, calculated with formula (6.1). Panel (a) reports the effects on wages, residential prices, commercial prices, and welfare of transit-oriented increase in FAR. Panel (b) repeats the analysis for the policy that increases FAR in central wards.

above.

We study the complementarity between the metro on the one hand, and TOD and central upzoning on the other.[29] The results are reported in Figure 7. Panel (a) shows that in the case of TOD, the simultaneous application of both policies leads to a 0.05 percentage point higher increase in wages and a 0.15 percentage point higher welfare gain, compared to the combined effect of the two policies when implemented separately. When both policies are applied, residential prices increase by 0.38 percentage points less, commercial prices change by as much as 1.3 percentage points less, and land prices grow by an additional 0.55 percentage points. In other words, TOD and the metro are highly complementary and the simultaneous introduction of both leads to higher wage growth, greater reductions in floorspace costs, higher increases in land values, and larger welfare

$C(Z) = (1.03 - 1) - (1.01 \times 1.01 - 1) \approx 0.01$. That is, the complementarity between the two policies leads to a 1 percentage point larger effect on variable Z.

[29]Because the 2031 Land Use Plan results in large welfare losses, we do not study the complementarity between the metro and the 2031 plan.

gains.

The same calculation as in Section 6.3 implies that the additional welfare gain of 0.15 percentage points and land value growth of 0.55 percentage points are equivalent to an increase in output per worker of $0.82 \times 0.15 + 0.18 \times 0.55 = 0.22$ percentage points. In other words, by relaxing density limits in places that become more connected thanks to the metro, TOD unlocks additional gains equivalent to 0.22% of Bengaluru's GDP or about $64 million per year, which is about one-half of annual operating costs.

Panel (b) shows that increasing FAR limits in central areas and the introduction of the metro are not complementary. The changes in wages, land prices, and welfare are approximately equal when the two policies are implemented jointly and separately. The changes in residential and commercial floorspace prices exhibit some complementarity, but much less so than with TOD.

The main difference between increasing FAR limits near metro stations and increasing limits in central areas is that in the former case, the increase in density is targeted to areas that *become* more connected, i.e., experience an increase in the CMA. In the latter case, while central wards *are* more connected in the benchmark economy, many of them do not receive metro stations and their CMA does not change much. Increasing density in these locations at the expense of non-central wards that receive metro stations prevents some employers and workers from fully benefiting from a better transportation network.

6.5 Importance of Modeling FAR Limits

Most of the previous quantitative studies of transit improvements use models where floorspace supply responds to changes in demand with a certain elasticity. One of the distinctive features of our paper is that we introduce explicit density limits in the form of FARs. To evaluate the role of FAR limits in our results, we calibrate a model in which all locations have nonbinding FAR limits (i.e., $\bar{h}_{fi}$ is high enough that the density of development is always below it). Then we rerun the counterfactuals.[30]

The results can be found in Appendix Table C.5. When FAR limits are nonbinding, the construction of the metro results in a higher population growth (5.1%, compared to 4% in the main set of experiments) and smaller reduction in the share of jobs and residents within the ORR, where FAR limits are binding in our main model. This is because real estate developers have a greater ability to supply floorspace for the additional workers and jobs attracted to the city thanks to transit improvements. At the same time, increases in floorspace prices are lower and welfare gains are larger (1.7%, compared to 1.3% in the

[30]Counterfactuals with TOD and central upzoning would result in the same effects of the metro because limits that are adjusted in these counterfactuals were nonbinding in the first place.

main set of experiments). These findings suggest that, by not taking into account density limits, previous research that studied the effects of transit improvements may significantly overestimate their welfare gains.

6.6 Sensitivity Checks and Extensions

We also study how sensitive our results are to values of key parameters and to some assumptions we have made. First, we endogenize amenities. Second, we allow commuters to derive additional utility from riding the metro compared to the bus. Then, we prohibit migration in and out of the city. Next, we shut down local productivity externalities. After that, we lower skill substitution to think about formal and informal labor that may be less substitutable than high- and low-skilled workers. We also evaluate how robust our results are to different values of Fréchet elasticities, ϵ and σ. Finally, we lower the housing supply elasticity.

The results are discussed in detail in Appendix Section E. We find that endogenizing amenities and lowering the Fréchet elasticity of location choices would make our results quantitatively larger but qualitatively the same. If migration into Bengaluru were not allowed, then real estate demand would be lower and welfare gains would be significantly larger. In all other sensitivity checks, the results barely change. Most importantly, the complementarity between TOD and metro and the lack of complementarity between central upzoning and metro remain unchanged in all of the sensitivity checks.

Furthermore, in Appendix Section F, we discuss how our results may change if we also consider traffic congestion, environmental effects, dynamic effects, informal housing, and population growth.

7 Conclusions

In this paper, we studied the benefits of improving transportation infrastructure in the presence of land use restrictions. We conducted our study in the context of one of India's largest cities, Bengaluru, which is building a metro network but where development is severely constrained by zoning and FAR limits. Using detailed data on local labor markets, building heights, land use, and commuting patterns, we built a quantitative spatial equilibrium model of the city and then used it to evaluate the effects of building the metro and reforming land use policies. We found that the construction of the metro led to output and welfare gains, even net of costs. However, these gains could be much larger if the FAR limits were relaxed and more development was allowed in areas near the newly built metro stations or in central parts of the city. We also found that transit-oriented development is complementary to the metro network, which highlights the importance of coordinating land use policies with transportation improvements.

Finally, we would like to highlight the policy relevance of our findings. As mentioned earlier, India's restrictive urban planning norms have come under criticism from reform-oriented policymakers. Our results show how key elements of these norms, namely strict FAR limits and zoning regulations that restrict commercial and residential development, detract from the benefits of modern mass transit systems. Our results also underline the importance of recent efforts by the Indian government to provide incentives for state and city governments to reconsider building regulations and adopt TOD principles that emphasize the need to densify transport corridors. To be sure, implementation of TOD principles is not easy, especially in brownfield locations which are characterized by the presence of large numbers of small residential or commercial plots. Amalgamating these plots into larger land parcels and then availing of much higher FARs and the necessary supporting infrastructure is one way forward. Research examining the conditions under which land amalgamation can be facilitated would be particular useful. In the meantime, as India's urbanization gathers space, it is critical that TOD principles be adopted in locations where legacy issues are not as constraining.

Bibliography

Acosta, C. (2022): "The Incidence of Land Use Regulations," Working Paper.

ADB (2019): *Fostering Growth and Inclusion in Asia's Cities*. Asian Development Bank.

Ahlfeldt, G., and J. Barr (2022): "The Economics of Skyscrapers: A Synthesis," *Journal of Urban Economics*, 129(C), S0094119021001017.

Ahlfeldt, G. M., and E. Pietrostefani (2019): "The Economic Effects of Density: A Synthesis," *Journal of Urban Economics*, 111, 93–107.

Ahlfeldt, G. M., S. J. Redding, D. M. Sturm, and N. Wolf (2015): "The Economics of Density: Evidence From the Berlin Wall," *Econometrica*, 83(6), 2127–2189.

Akbar, P., V. Couture, G. Duranton, and A. Storeygard (2023a): "The Fast, the Slow, and the Congested: Urban Transportation in Rich and Poor Countries," Working Paper.

——— (2023b): "Mobility and Congestion in Urban India," *American Economic Review*, 113(4), 1083–1111.

Allen, T., and C. Arkolakis (2014): "Trade and the Topography of the Spatial Economy," *The Quarterly Journal of Economics*, 129(3), 1085–1140.

Allen, T., C. Arkolakis, and X. Li (2016): "Optimal City Structure," Working Paper.

AMIRKOLAEE, H. A., AND H. AREFI (2019): "Height Estimation from Single Aerial Images Using a Deep Convolutional Encoder-Decoder Network," *ISPRS journal of photogrammetry and remote sensing*, 149, 50–66.

ANAGOL, S., F. V. FERREIRA, AND J. M. REXER (2021): "Estimating the Economic Value of Zoning Reform," Working Paper 29440, National Bureau of Economic Research.

BALBONI, C., G. BRYAN, M. MORTEN, AND B. SIDDIQI (2020): "Transportation, Gentrification, and Urban Mobility: The Inequality Effects of Place-Based Policies," Working Paper.

BARR, J., AND R. JEDWAB (2023): "Exciting, boring, and nonexistent skylines: Vertical building gaps in global perspective," *Real Estate Economics*, n/a(n/a).

BERTAUD, A., AND J. K. BRUECKNER (2005): "Analyzing Building-Height Restrictions: Predicted Impacts and Welfare Costs," *Regional Science and Urban Economics*, 35(2), 109–125.

BHARADWAJ, K. V. A. (2020): "BDA Withdraws Draft Revised Master Plan - 2031, To Review and Rewrite," https://www.thehindu.com/news/cities/bangalore/bda-withdraws-draft-revised-master-plan-2031-to-review-and-rewrite/article31929610.ece.

BRUECKNER, J. K., AND K. S. SRIDHAR (2012): "Measuring Welfare Gains from Relaxation of Land-Use Restrictions: The Case of India's Building-Height Limits," *Regional Science and Urban Economics*, 42(6), 1061–1067.

BRYAN, G., E. GLAESER, AND N. TSIVANIDIS (2020): "Cities in the Developing World," *Annual Review of Economics*, 12(1), 273–297.

BRYAN, G., AND M. MORTEN (2019): "The Aggregate Productivity Effects of Internal Migration: Evidence from Indonesia," *Journal of Political Economy*, 127(5), 2229 – 2268.

CAO, Y., AND X. HUANG (2021): "A Deep Learning Method for Building Height Estimation Using High-Resolution Multi-View Imagery over Urban Areas: A Case Study of 42 Chinese Cities," *Remote Sensing of Environment*, 264, 112590.

CARD, D. (2009): "Immigration and Inequality," *American Economic Review*, 99(2), 1–21.

CONWELL, L. (2023): "Subways or Minibuses? Privatized Provision of Public Transit," Working Paper.

DHINDAW, J., S. K. KUMARASWAMY, V. S. PRAKASH, R. CHANCHANI, AND A. DEB (2021): "Synergizing Land Value Capture and Transit-Oriented Development: A Study of Bengaluru Metro," Practice Note. World Resources Institute India.

DINGEL, J. I., AND F. TINTELNOT (2021): "Spatial Economics for Granular Settings," Working Paper.

DURANTON, G., AND D. PUGA (2022): "Urban Growth and Its Aggregate Implications," Working Paper.

DURANTON, G., AND M. A. TURNER (2011): "The Fundamental Law of Road Congestion: Evidence from US Cities," *American Economic Review*, 101(6), 2616–52.

FRANK, L., M. BRADLEY, S. KAVAGE, J. CHAPMAN, AND T. LAWTON (2008): "Urban Form, Travel

Time, and Cost Relationships with Tour Complexity and Mode Choice," *Transportation*, 35(1), 37–54.

Frantz, D., F. Schug, A. Okujeni, C. Navacchi, W. Wagner, S. van der Linden, and P. Hostert (2021): "National-Scale Mapping of Building Height Using Sentinel-1 and Sentinel-2 Time Series," *Remote Sensing of Environment*, 252, 112128.

Gechter, M., and N. Tsivanidis (2023): "Spatial Spillovers from High-Rise Developments: Evidence from the Mumbai Mills," Working Paper.

Geshkov, M. V., and J. S. DeSalvo (2012): "The Effect of Land-Use Controls on the Spatial Size of US Urbanized Areas," *Journal of Regional Science*, 52(4), 648–675.

Heblich, S., S. J. Redding, and D. M. Sturm (2020): "The Making of the Modern Metropolis: Evidence from London," *Quarterly Journal of Economics*, 135(4), 2059–2133.

Henderson, J. V., T. Regan, and A. J. Venables (2020): "Building the City: From Slums to a Modern Metropolis," *The Review of Economic Studies*, 88(3), 1157–1192.

Herkenhoff, K. F., L. E. Ohanian, and E. C. Prescott (2018): "Tarnishing the golden and empire states: Land-use restrictions and the U.S. economic slowdown," *Journal of Monetary Economics*, 93, 89 – 109, Carnegie-Rochester-NYU Conference on Public Policy held at the Stern School of Business at New York University.

Hsieh, C.-T., and E. Moretti (2019): "Housing Constraints and Spatial Misallocation," *American Economic Journal: Macroeconomics*, 11(2), 1–39.

Jain, D., and E. Singh (2019): "Transit Oriented Development in India: A Critical Review of Policy Measures," *International Journal of Recent Technology and Engineering*, 7(6S2).

Kreindler, G. (2023): "Peak-Hour Road Congestion Pricing: Experimental Evidence and Equilibrium Implications," Working Paper 30903, National Bureau of Economic Research.

Kreindler, G., A. Gaduh, T. Graff, R. Hanna, and B. A. Olken (2023): "Optimal Public Transportation Networks: Evidence from the World's Largest Bus Rapid Transit System in Jakarta," Working Paper.

Lall, S., M. Lebrand, H. Park, D. Sturm, and A. Venables (2021): "Pancakes to Pyramids," World Bank Publications - Reports 35684, The World Bank Group.

Li, M., E. Koks, H. Taubenböck, and J. van Vliet (2020): "Continental-Scale Mapping and Analysis of 3D Building Structure," *Remote Sensing of Environment*, 245, 111859.

Li, X., Y. Zhou, P. Gong, K. C. Seto, and N. Clinton (2020): "Developing a Method to Estimate Building Height from Sentinel-1 Data," *Remote Sensing of Environment*, 240, 111705.

Liu, C., X. Huang, D. Wen, H. Chen, and J. Gong (2017): "Assessing the Quality of Building Height Extraction from ZiYuan-3 Multi-View Imagery," *Remote Sensing Letters*, 8(9), 907–916.

Liu, C., X. Huang, Z. Zhu, H. Chen, X. Tang, and J. Gong (2019): "Automatic Extraction of Built-Up Area from ZY3 Multi-View Satellite Imagery: Analysis of 45 Global Cities," *Remote Sensing of Environment*, 226, 51–73.

Parkhomenko, A. (2023): "Local Causes and Aggregate Implications of Land Use Regulation," Working Paper.

Ramulu, D., K. Sankar, and A. Randhawa (2021): "Challenges of Transit Oriented Development (TOD) in Indian Cities," *Institute of Town Planners, India Journal*, 18(2), 37–55.

Roy, S., and A. Shah (2018): "Concerns with Delhi Metro," blog.theleapjournal.org/2018/12/concerns-with-delhi-metro.html.

Saiz, A. (2010): "The Geographic Determinants of Housing Supply*," *The Quarterly Journal of Economics*, 125(3), 1253–1296.

Severen, C. (2021): "Commuting, Labor, and Housing Market Effects of Mass Transportation: Welfare and Identification," *The Review of Economics and Statistics*, pp. 1–99.

Song, J. (2022): "The Effects of Residential Zoning in U.S. Housing Markets," Working Paper.

Sood, A. (2022): "Land Market Frictions in Developing Countries: Evidence from Manufacturing Firms in India," Working Paper.

Sturm, D. M., K. Takeda, and A. J. Venables (2023): "How Useful are Quantitative Urban Models for Cities in Developing Countries? Evidence from Dhaka," Working Paper.

Tsivanidis, N. (2023): "The Aggregate and Distributional Effects of Urban Transit Infrastructure: Evidence from Bogotá's TransMilenio," Working Paper.

Valentinyi, A., and B. Herrendorf (2008): "Measuring Factor Income Shares at the Sectoral Level," *Review of Economic Dynamics*, 11(4), 820–835.

Velásquez, D. (2023): "Transit Infrastructure, Couples' Commuting Choices, and Gender Inequality," Working Paper.

Warnes, P. (2021): "Transport Infrastructure Improvements and Spatial Sorting: Evidence from Buenos Aires," Working Paper.

WorldBank (2013): *Urbanization beyond municipal boundaries: Nurturing metropolitan economies and connecting peri-urban areas in India*. The World Bank.

Yu, Y. (2022): "Land-Use Regulation and Economic Development: Evidence from the Farmland Red Line Policy in China," Working Paper.

Zárate, R. D. (2022): "Spatial Misallocation, Informality, and Transit Improvements," Working Paper.

Appendix A Data

A.1 Travel Time Estimates

In this section, we describe how we estimate travel times between wards for different modes of transportation. We first compute travel times by bus and driving, both between wards and between wards and metro stations. Then we compute the travel times by metro between each pair of stations. Finally, we combine the estimates for bus and driving ward-to-station with metro travel times to obtain the travel times by transit. Our procedure is described in detail below.

A.1.1 Data on Bus and Driving Travel Times

1. We collected Google Maps (GM) driving and bus travel time data for Bengaluru for ward-to-ward, ward-to-metro station, and metro station-to-ward origin-destination (OD) pairs for the morning and evening peak hours on a normal working day.[31]

2. The working day selected for the collection data are Wednesday, 27 October 2021 for driving trips and Wednesday, 2 March 2022 for bus trips. We identified 8:30–9:30 a.m. and 6–7 p.m as morning and evening peak hours, respectively. The peak hours are based on data from the 2015 Bengaluru Travel Survey. See Figure A.1.

3. To construct the OD pairs, we used the ward coordinates (based on 2015 NTL cells with the highest luminosity value) and the metro station coordinates. There are 198 wards and 125 metro stations in Bengaluru. From these, we created $198 \times 198 = 39,204$ ward-ward OD pairs and excluded the 198 self-links, leaving us with a total of 39,006 pairs. Also, there are $198 \times 125 = 24,750$ ward-to-metro station and $125 \times 198 = 24,750$ metro station-to-ward OD pairs.

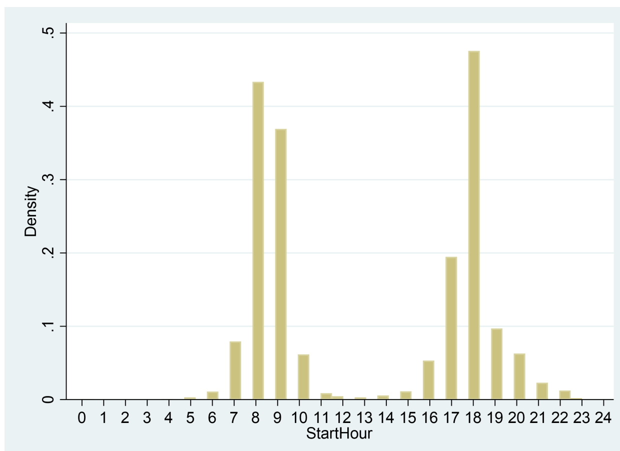
4. We prepared input files for collection, which included unique ID, the query time, the OD pair coordinates, and the day of collection. Then, for driving, we used the input files to run the query to GM using Amazon Web Services (AWS); for the bus, we initiated the query using GM's Distance Matrix API.

5. In Table A.1, we describe the data collected. GM did not return travel time information for a small number of AM and PM driving and bus trips, as described in Table A.2. We impute the missing OD data as follows. For driving, we conducted a simple imputation by regressing the log of time on the quadratic log of distance for the AM and PM ward-ward, as well as the AM and PM ward-station samples. Then, these coefficient estimates and the distance between missing ODs were used to predict the speed. Table A.3 shows the regression results. Meanwhile, for bus trips, we identified the OD pairs with missing travel information and also conducted a simple imputation. The following procedures are applied in imputing missing travel time by bus:

[31] Transit mode with bus preference was selected in the GM API query.

(a) Ward-ward: for ward #150, time of ward #150 to ward #86 + time from ward #86 to the missing wards + 10 minutes waiting time.
(b) Ward-station: for ward #150, time of ward #150 to ward #86 + time from ward #86 to missing stations + 10 minutes waiting time.
(c) Ward-station: for station #53, time of a nearby ward #190 to station #53 + time from all the missing wards to the nearby ward + 10 minutes waiting time.
(d) Ward-station: for station #102, similar to the above, the nearby ward is #86.
(e) Station to ward: for station #53, time of station #53 to ward #190 + time from ward #190 to ward #191 + 10 minutes waiting time.
(f) Station to ward: for station #102, similar to above, the nearby ward is #86.
(g) Station to ward: for station #118, similar to above, the nearby ward is #9.

Figure A.1: Distribution of Starting Hour of All Commuting Trips



Note: Calculated from the 2015 Bengaluru Travel Survey.

A.1.2 Data on Metro Travel Times

1. First we generated metro station-to-station travel times for all metro lines (existing, under construction, and proposed). We used the published average speed of metro trains (34 kilometers per hour) and inter-station distance. The inter-station distance was spatially calculated from the digitized metro line shapefiles. Table A.4 lists the details of metro alignment and stations.

2. Based on public information, a train stop time of 40 seconds for interchange stations and 30 seconds for other stations were applied to the computed inter-station travel time. Train stop time is defined as the time it takes for a train to stop on a certain station for alighting passengers to disembark.

3. For routes that involved a change of metro line, a 5-minute transfer time was added to travel time. Transfer time was defined as the time it takes to transfer from one

Table A.1: Distribution of Collected Data

	With Travel Data	Without Travel Data	Total
Driving			
Ward to Ward*			
AM	38,992	14	39,006
PM	38,870	136	39,006
Ward to Metro Station			
AM	24,746	4	24,750
PM	24,682	68	24,750
Bus			
Ward to Ward*			
AM	38,811	195	39,006
PM	38,811	195	39,006
Ward to Metro Station			
AM	24,534	216	24,750
PM	24,455	295	24,750
Metro Station to Ward			
AM	24,731	19	24,750
PM	24,681	69	24,750

Note: The table describes routes with and without data from Google Maps.

Table A.2: Ward and Stations with Missing Travel Information

	With Missing Data AM	PM	Remarks
Ward-Ward OD			
Ward #150 to	195 wards	195 wards	with data to #s 86 and 149
Ward-Metro Station OD			
Ward #150 to	120 stations	120 stations	
to Station #53	95 wards	172 wards	
to Station #102	2 wards	4 wards	AM: #s 6 and 16; PM: #s 3, 54, 83, and 84
Metro Station-Ward OD			
Station #53 to	1 ward	1 ward	#191 both for AM and PM
Station #102 to	12 wards	5 wards	
Station #118 to	6 wards	63 wards	

Note: The table describes routes with missing data from Google Maps.

metro line to another, including getting off a train, walking to another station, and waiting for another train.

4. The computed inter-station travel times were then used as the basis for creating the Bengaluru metro travel time matrix. Using the Bengaluru metro line and metro station shapefiles as a guide, the routes, especially those across different lines, were visually checked.

Table A.3: Regression Results for Imputation

	(1)	(2)	(3)	(4)
	Ward-ward		Ward-station	
Dep. variable	Log time AM	Log time PM	Log time AM	Log time PM
Log distance	0.902***	1.041***	1.106***	1.193***
	(0.00495)	(0.00508)	(0.00844)	(0.00864)
Log distance squared	-0.0254***	-0.0605***	-0.0771***	-0.101***
	(0.00114)	(0.00116)	(0.00173)	(0.00177)
Constant	1.457***	1.542***	1.219***	1.355***
	(0.00540)	(0.00558)	(0.0102)	(0.0105)
Observations	38,992	38,870	24,746	24,682
R-squared	0.920	0.914	0.873	0.860

Note: The table describes regression results that are used to impute commute time for routes with missing information in Google Maps.

Table A.4: Bengaluru Metro Station Alignment Information

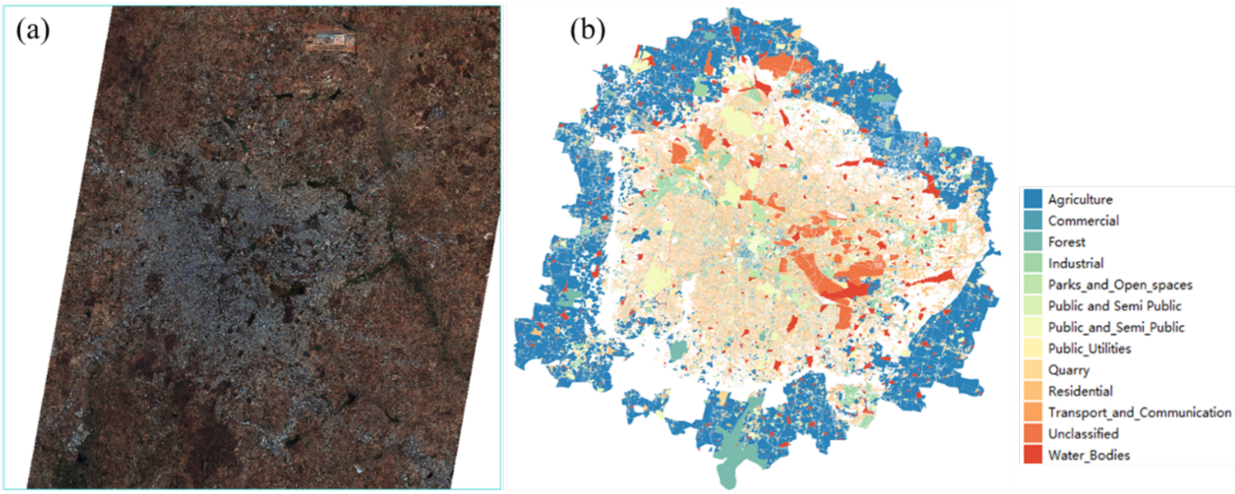
Line	Phase	No. of stations	Terminal Stations	
East-West Line/ Purple Line	Phase 1	6	Baiyappanahalli	Mahatma Gandhi Road
		6	Magadi Road	Mysore Road
		5	Mahatma Gandhi Road	City Railway
	Phase 2	13	Baiyyappanahalli	Sitharama Palya
			Kundalahalli	Whitefield
		6	Mysore Road	Pattanagere
			Mysore Road	Challaghatta
North-South Line/ Green Line	Phase 1	7	Yeshwanthpura	Sampige Road
		3	Peenya Industry	Yeshwanthpura
		3	Nagasandra	Peenya Industry
		5	National College	Rashtreeya Vidyalaya Road
		3	Rashtreeya Vidyalaya Road	Yelachenahalli
		3	Sampige Road	National College
	Phase 2	5	Yelachenahalli	Silk Institute
		3	Nagasandra	Madavara
Pink Line	Phase 2	16	Dairy Circle	Nagawara
Yellow line	Phase 2	18	Bommasandra	HSR Layout
			HSR Layout	RV Road
Blue line	Phase 2A	13	Central Silk Board	KR Puram
	Phase 2B	17	KR Puram	Kempegowda International Airport

Source: Bengaluru Metro Rail Corporation Limited.

A.1.3 Combined Transit Travel Times

Transit trips that include metro involve getting to metro station first, then taking metro, and then traveling from the metro station to a final destination. To obtain combined transit travel times, we followed the following steps.

Figure A.2: ZY-3 Multi-Spectral Images and Land Use Map of Bengaluru



Note: Panel (a) shows the ZY-3 multi-spectral images of Bengaluru. Panel (b) shows the land use map.

1. First, we found the nearest (in terms of travel time) station for each ward and each travel time (AM and PM). Then, we merged the ward origin-station file with the origin ward origin ID and the ward destination-station file with the destination ward ID. This step adds four variables in the ward-ward data: ward-station travel time, station-ward travel time, departure station ID, and arrival station ID.

2. Then, the dataset was merged with the transit timetable with the departure station ID and arrival station ID. This adds station-station travel time to the data.

3. Finally, the total transit time between wards is generated for AM and PM, respectively, by adding (a) origin ward-station travel time, (b) station-to-station travel time, (c) station-destination ward travel time, and (d) an assumed 7 minutes at the terminals (5 minutes for departure station and 2 minutes for arrival station).

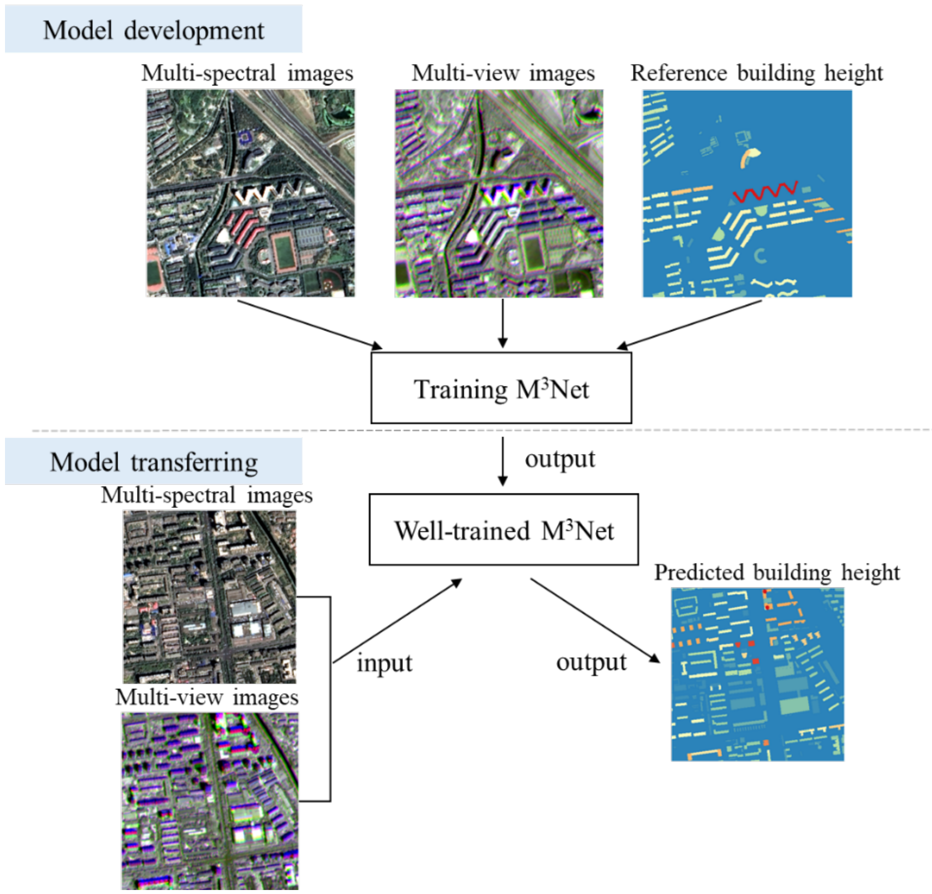
A.2 Building Heights Data

A.2.1 Methodology

We collected ZY-3 multi-view satellite images in Bengaluru, and carried out data preprocessing using methodology developed in (Liu, Huang, Zhu, Chen, Tang, and Gong, 2019). The ZY-3 stereo satellite constellation is composed of three satellites, i.e., ZY-3 01, 02, and 03, launched in 2012, 2016, and 2020, respectively. Each satellite can simultaneously acquire multi-spectral images (with a spatial resolution of 5.8 m) and multi-view images with nadir (2.1 m), +22° forward (2.5-3.5 m), and -22° backward (2.5-3.5 m) viewing angles. All the ZY-3 images were resampled to the spatial resolution of 2.5 m (Figure A.2).

Our method consists of two steps: (1) model development, and (2) model transferring. First, we trained a multi-spectral, multi-view, and multi-task deep network, also known as M3Net (Cao and Huang, 2021), with ZY-3 multi-view images to estimate building

Figure A.3: The Workflow of the Building Height Prediction



Note: The figure describes the building height prediction algorithm.

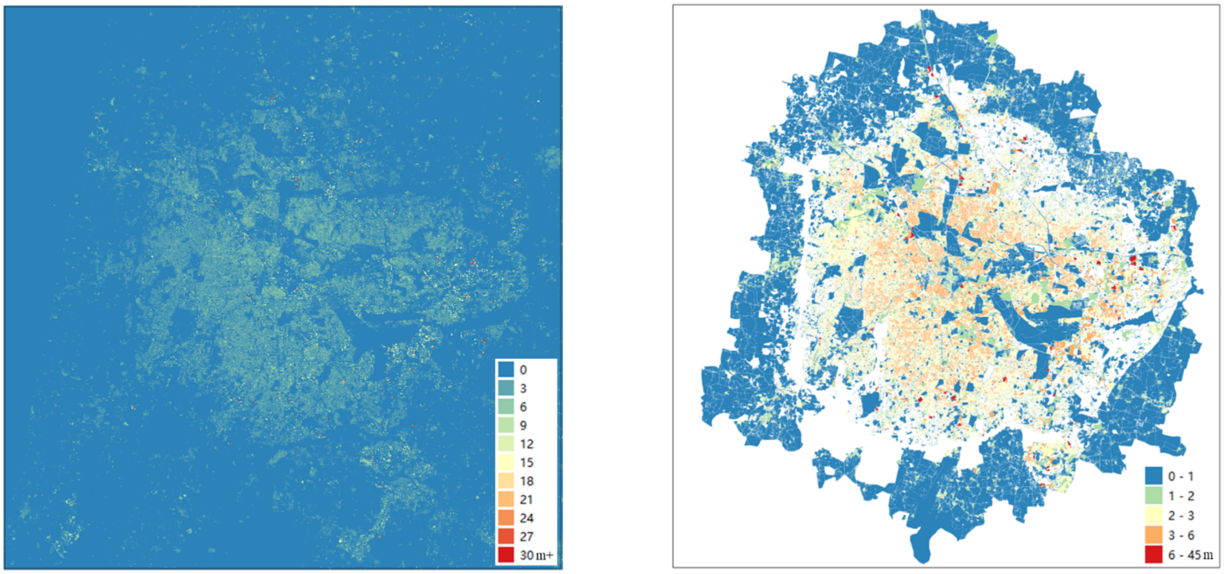
heights at the spatial resolution of 2.5 m. To optimize the network, we collected a total of 4,723 reference building height samples that are randomly distributed in 42 Chinese cities, where each sample has a size of 400 × 400 pixels. Then, the trained model was transferred to the ZY-3 images over Bengaluru.[32] Our method can be summarized in Figure A.3.

The main advantage of ZY-3 satellites over single view images in predicting building height is that ZY-3 satellites can simultaneously acquire high-resolution multi-spectral (5.8 m) and multi-view images with nadir (2.1 m), +22° forward (2.5-3.5 m), and -22° backward (2.5-3.5 m) viewing angles over the same area. Predicting building height from single view images is an ill-posed and challenging problem (Amirkolaee and Arefi, 2019). By contrast, multi-view images can lower the uncertainty of height estimation, and describe the vertical attribute of ground objects. Compared to existing methods using 10-m Sentinel-1 images (Frantz, Schug, Okujeni, Navacchi, Wagner, van der Linden, and Hostert, 2021; Li, Koks, Taubenböck, and van Vliet, 2020; Li, Zhou, Gong, Seto, and Clinton, 2020), our method

[32]The transferability of M3Net predictions has been tested to be robust. In the transferability experiment (Cao and Huang, 2021), it can be observed that even when the PRC model was directly applied to the three U.S. cities (without any sample from the US), the accuracies, i.e., RMSE values, for all the cities are satisfactory (3.3 m on average), indicating the robustness of the model in the case of spatial transferability.

Figure A.4: Predicted building heights

Panel (a): M3Net prediction Panel (b): Mean building heights



Note: The figure shows predicted building heights by the M3Net (panel a) and the map of building heights in Bengaluru obtained by combining the M3Net results with the land use map (panel b).

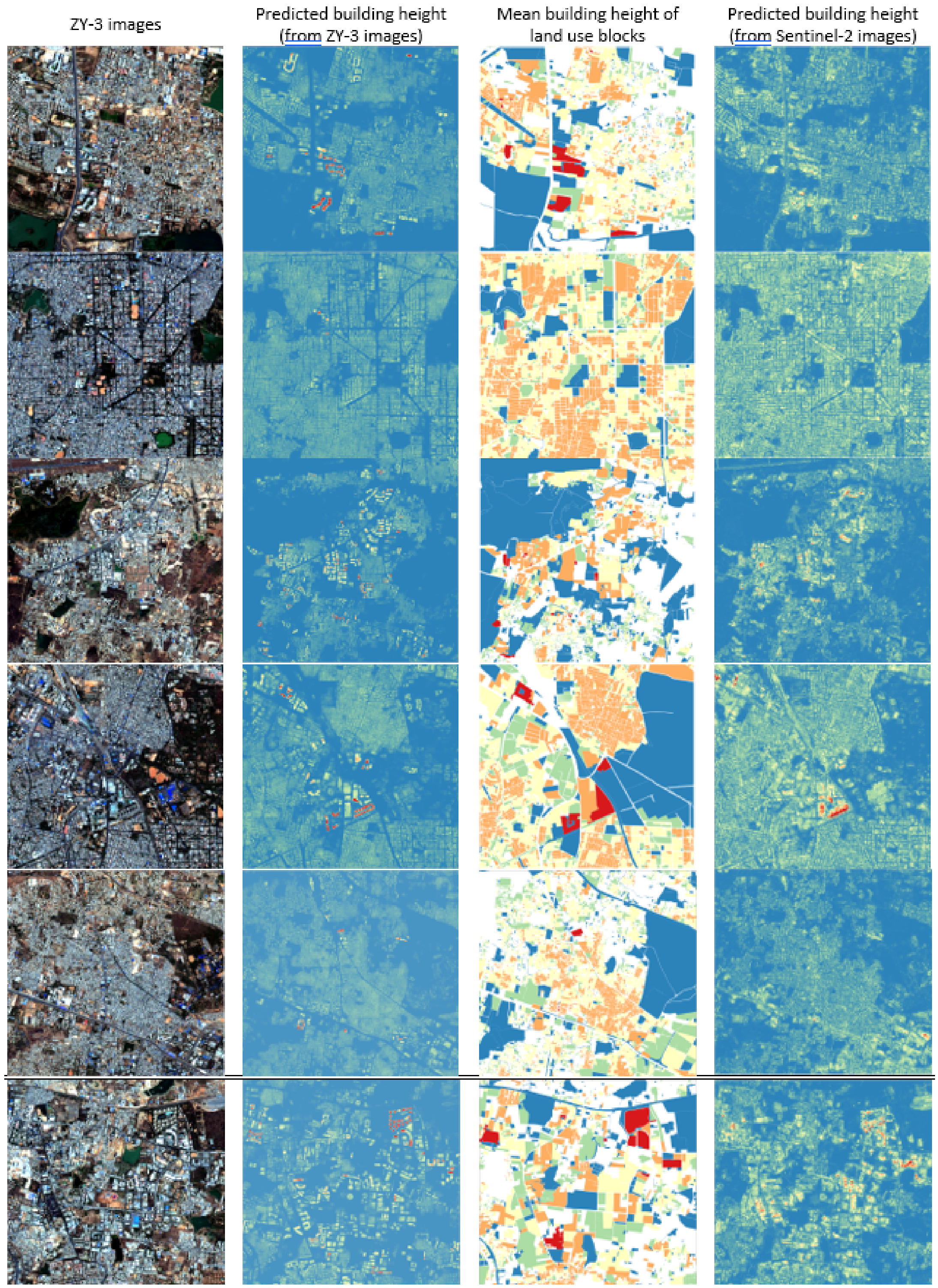
utilizes the ZY-3 multi-view observation mode, and can obtain a building height map with a spatial resolution of 2.5 m. In addition, the adopted end-to-end network can directly estimate the building height from images, which can alleviate the error accumulation of the traditional multi-step estimation strategy, e.g., DSM-to-nDSM (Liu, Huang, Wen, Chen, and Gong, 2017). The predicted building height corresponds to the normalized DSM (nDSM), i.e., the height of buildings relative to the ground.

A.2.2 Results

By using the method described above, we obtained the building height map with 2.5-m resolution (panel a of Figure A.4). The unit of height is meters. Based on the provided land use map (panel b of Figure A.2), we calculated the mean, medium, maximum, and minimum height values for each land use block. The mean building height for each land use block is shown in panel b of Figure A.4.

Figure A.5 shows several examples. For comparison, we also show the predicted building height using Sentinel-2 images (with a spatial resolution of 10 meters). It can be observed that the building heights predicted by ZY-3 images contain much more spatial detail than those predicted by Sentinel-2 images. In particular, the predicted height data from the two methods show that the former is more capable of detecting high buildings.

Figure A.5: A Set of Predicted Building Height Results



Note: The figure shows several examples of ZY-3 images, predicted heights, mean heights obtained by combining the M3Net results with the land use map, and Sentinel-2 predictions.

A.3 Summary Statistics

In this section we provide summary statistics for the distribution of population and employment across wards, commuting times, land use, building heights, and FARs.

Employment and Commuting. As shown in Table A.5, the concentration of workers is higher at the workplace level than residential concentration, as the coefficient of variation of workplace employment is three times that of residence employment. Second, the employment concentration is mainly driven by high-skilled workers, presumably due to the clustering of the IT sector. Conversely, low-skilled employment does not have the same degree of workplace concentration. This may be partly because low-skilled workers tend to commute shorter distances, possibly, due to time or budget constraints. The household travel survey shows that an average commuter in Bengaluru spends a significant portion of their monthly income (about 10%) on transportation.

Not surprisingly, driving is the fastest mode of commuting. On average, the commute time for all ward pairs is about two-thirds that of bus or metro plus car. The metro with the bus as the connecting mode is significantly slower than the other three options. On average, it takes more than twice as much time compared to driving and one-third more time than commuting by bus alone or by metro plus driving. The metro with driving seems to be only slightly faster than commuting by bus only as far as average time is concerned, and the two have similar variation. This is partly because metro network coverage is limited: 70 of 198 wards will have metro stations, even after the full network with 125 is built. Comparing the two modes of transportation, there are 23,818 or 61.1% of ward pairs where traveling by metro and driving is faster than traveling by bus only. Moreover, traveling by metro and bus is faster than traveling by bus only for 7,696 or 19.7% of pairs of wards despite the higher mean time for the former. Thus, the metro is faster than bus within its catchment area.

Land Use, Building Heights, and FARs. As shown in panel A of Table A.6, 53.4% of the land was allocated for residential use and 18.5% for commercial use in 2015. Panel B shows statistics for parcel sizes, building heights, and distance from the center. The statistics are similar for residential and commercial parcels, and highlight the low average building heights. The average building height for residential parcels is 2.6 meters. If half of the parcel is covered by a building and the other half is land, the building is only 5.2 meter high, which is equivalent to a two-story house.

We aggregate the parcel-level heights into ward-level heights. Then, to obtain the ward-level floor-area-ratio (FAR), we divide the ward-level height by 2.75 meters, the minimum height required by the Indian National Building Code (2005). Panel C shows that the ward-level FAR ranges from 0.52 to 1.54 for residential land and from 0.22 to 1.86 for commercial land, lower than the FAR limits in the 2015 plan. This indicates that although the city is one of the densest in the world, it is dominated by low-rise development. In the counterfactual exercises in Section 6, we consider the implications of increasing ward-level FAR in the vicinity of the metro network or in the city center.

Table A.5: Summary Statistics for Residence, Workplace, and Commuting

Variable	(1) N	(2) Mean	(3) S.D.	(4) C.V.	(5) Min	(6) Median	(7) Max
Statistics by residence ward							
Population	198	42,645	12,471	0.29	21,171	39,551	95,368
Employment	198	18,648	6,631	0.36	8,297	16,842	42,330
High-skilled	198	8,348	3,773	0.45	2,325	7,292	22,545
Low-skilled	198	10,300	4,666	0.45	3,896	9,644	27,457
Share of high-skilled	198	0.45	0.13	0.28	0.16	0.45	0.74
Monthly income	198	23,267	9,011	0.39	9,534	22,049	56,944
Monthly transport expenditure	198	2,483	880	0.35	936	2,332	5,294
Statistics by workplace ward							
Employment	198	18,110	18,442	1.02	0	12,296	92,241
High-skilled	197	8,909	12,274	1.38	112	4,135	65,455
Low-skilled	197	9,293	6,968	0.75	543	7,772	35,067
Share of high-skilled	197	0.40	0.16	0.41	0.06	0.38	0.87
Monthly income	197	20,894	5,374	0.26	8,941	20,833	37,250
Commute time (minutes)							
Driving only	39,006	41.1	17.4	0.42	2.2	40.6	99.3
Bus only	39,006	65.3	24.7	0.38	3.0	64.0	180.9
Metro + driving	39,006	63.9	25.3	0.40	11.0	61.2	170.0
Metro + bus	39,006	86.2	32.9	0.38	14.2	81.5	257.6

Note: This table presents summary statistics for variables that describe residence, workplace, and commuting. N refers to the number of observations, S.D. stands for standard deviation, and C.V. for the coefficient of variation.

Table A.6: Statistics for Land Use, Building Heights, and FARs

Variable	(1) N	(2) Mean	(3) S.D.	(4) Min	(5) Median	(6) Max
Panel A: Land use						
Total ward area (hectares)	198	359	486	32	167	2,926
2015 land use						
Total land use area (hectares)	198	222	252	27	127	1,851
Share by land use type						
Residential	198	0.53	0.19	0.05	0.56	0.86
Commercial	198	0.19	0.14	0.01	0.14	0.78
Share by land use type for wards with metro station(s)						
Residential	70	0.47	0.18	0.11	0.47	0.83
Commercial	70	0.19	0.14	0.02	0.15	0.64
Share by land use type among parcels within 500 meters of the metro station						
Residential	112	0.41	0.22	0.00	0.42	0.79
Commercial	112	0.29	0.20	0.00	0.22	0.87
2031 plan						
Total land use area (hectares)	198	320	429	33	145	2,627
Share by land use type						
Residential	198	0.55	0.19	0.00	0.59	0.93
Commercial	198	0.10	0.14	0.00	0.04	0.94
Panel B: Area, height, and distance to city center of parcel						
Residential						
Area (square meters)	115,650	1,602	5,075	0	377	429,423
Mean building height (meters)	115,650	2.6	1.3	0.0	2.6	43.6
Max building height (meters)	115,650	4.3	2.6	0.0	4.1	82.2
Distance to city center (meters)	115,650	7,576	4,454	226	7,281	21,929
Commercial						
Area (square meters)	43,720	1,521	9,531	0	399	1,083,295
Mean building height (meters)	43,720	2.6	1.1	0.0	2.6	11.7
Max building height (meters)	43,720	4.4	2.3	0.0	4.2	69.1
Distance to city center (meters)	43,720	7,589	3,875	203	7,221	21,858
Panel C: Ward-level FAR						
Residential	198	1.05	0.16	0.52	1.04	1.54
Commercial	198	0.94	0.23	0.22	0.97	1.86

Note: This table presents summary statistics for variables that describe land use, building heights, and FARs. N refers to the number of observations and S.D. stands for standard deviation.

Appendix B Quantification

B.1 Model Inversion

We invert the model to obtain the values of X_i^s, ω_j^s, ψ_j, ϕ_{fi}, a_j, and E_j^s using the following sequence of steps.

1. First, we solve for $\tilde{X}_i^s \equiv X_i^s q_i^{-\gamma}$, the residential shifter; $\tilde{E}_j^s = E_j^s w_j^s$, the employment shifter; and B_m, the transportation mode shifter. These three sets of parameters are solved numerically using the following three sets of moments.

   First, the observed employment by residence and skill in the data, $N_{Ri,\text{data}}^s$, must be equal its counterpart in the model:

$$N_{Ri,\text{data}}^s = \sum_{j \in \mathcal{I}} \sum_{m \in \mathcal{M}} \pi_{mij}^s N^s. \tag{B.1}$$

   That is, we use equation (4.10) and set $\tilde{X}_i^s$ (which determines π_{mij}^s via equations (4.4)–(4.8)) at the level so that the right-hand side of (4.10) equals observed employment in the data.

   Second, the observed employment by residence and skill in the data, $N_{Wj,\text{data}}^s$, must also be equal its counterpart in the model:

$$N_{Wj,\text{data}}^s = \sum_{i \in \mathcal{I}} \sum_{m \in \mathcal{M}} \pi_{mij}^s N^s. \tag{B.2}$$

   That is, we use equation (4.11) and set $\tilde{E}_j^s$ (which determines π_{mij}^s via equations (4.4)–(4.8)) at the level so that the right-hand side of (4.11) equals observed employment in the data.

   Finally, we set B_m so that the observed fraction of workers who choose private vehicles, as opposed to public transportation, equals this fraction in the model:

$$\sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{I}} \sum_{s \in \{L,H\}} \pi_{mij}^s N^s. \tag{B.3}$$

2. ω_j^s: skill-specific productivity. We can rearrange equation (4.19) as

$$\frac{\omega_j^H}{\omega_j^L} = \frac{w_j^H}{w_j^L} \left(\frac{N_{Wj}^H}{N_{Wj}^L} \right)^{\frac{1}{\xi}}. \tag{B.4}$$

   Since we observe local wages and local employment by skill, we can solve for the ratio ω_j^H / ω_j^L.[33] Note that, without loss of generality, we can normalize ω_j^L and ω_j^H so

[33] We only observe average local wages by workplace. To obtain wages by skill, we assume that the skill premium is 1.727, the average skill premium in large Indian cities.

that $\omega_j^L + \omega_j^H = 1$ in all locations. Thus, finding the ratio ω_j^H/ω_j^L is sufficient.

3. Next, we construct the variable $\psi_j \equiv A_j^{\frac{1}{\alpha}} q_{Wj}^{-\frac{1-\alpha}{\alpha}}$ by rearranging equation (4.20) as follows

$$\psi_j = \frac{w_j^L}{\alpha(1-\alpha)^{\frac{1-\alpha}{\alpha}} \left(\omega_j^L\right)^{\frac{\xi}{\xi-1}}} \left[1 + \left(\frac{\omega_j^H}{\omega_j^L}\right)^{\xi} \left(\frac{w_j^L}{w_j^H}\right)^{\xi-1}\right]^{-\frac{1}{\xi-1}}. \tag{B.5}$$

4. Recall that floorspace prices, q_{Ri} and q_{Wj}, are unobserved. However, we can identify them using known parameters and data by first finding demand (equations 4.28 and 4.29) and then solving for prices (equation 4.30). Note that the variable ψ_j that we found in the previous step is necessary to identify commercial floorspace demand. We identify prices under two cases: binding FAR and nonbinding FAR.

5. ϕ_{fi}: construction productivity. We can recover construction productivity of residential developers in wards where the FAR limits are not binding by using the data on observed heights. The relationship between heights, floorspace supply, and land area is: $h_{fi} = H_{fi}/(\nu_{fi}\Lambda_i)$. Then ϕ_{fi} can be recovered using equation (4.27) and model-predicted floorspace demand. For wards where FAR limits are binding, we assign the average value of ϕ_{fi} in nonbinding wards. In some wards, this means that the value of ϕ_{fi} is such that the equation (4.30) takes the value of the second argument of the max operator, a contradiction because the ward is assumed to have a binding FAR limit. There are 13 wards that have this issue with residential prices and 33 with commercial prices. For these wards, we increase ϕ_{fi} to the level that makes both arguments of the max operator equal to each other.

6. Next, we can identify TFP, A_j by using the definition of ψ_j and known floorspace prices: $A_j = \psi_j^{\alpha} q_{Wj}^{1-\alpha}$.

7. Then, we recover local amenities using known wages and floorspace prices: $E_j^s = \tilde{E}_j^s / w_j^s$ and $X_i^s = \tilde{X}_i^s q_{Ri}^{\gamma}$.

8. Finally, we can find the exogenous component of productivity by using equation (4.22):

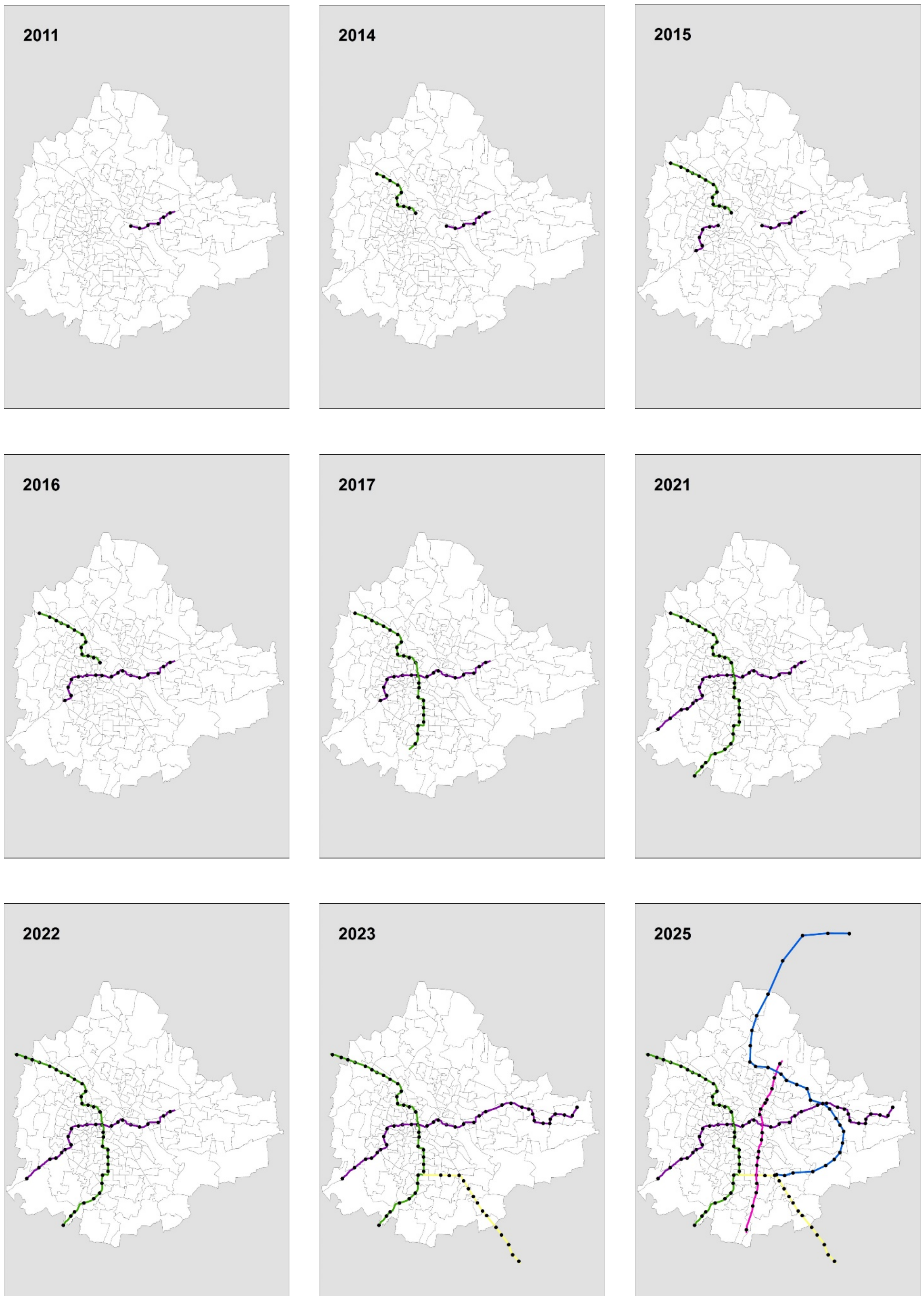
$$a_j = A_j \left(\frac{N_{Wj}}{\Lambda_j}\right)^{-\lambda}. \tag{B.6}$$

9. In a version of the model with endogenous residential amenities (see Section 6.6), we can find the exogenous component of amenities by using equation (E.1):

$$x_j = X_j \left(\frac{N_{Ri}}{\Lambda_j}\right)^{-\chi}. \tag{B.7}$$

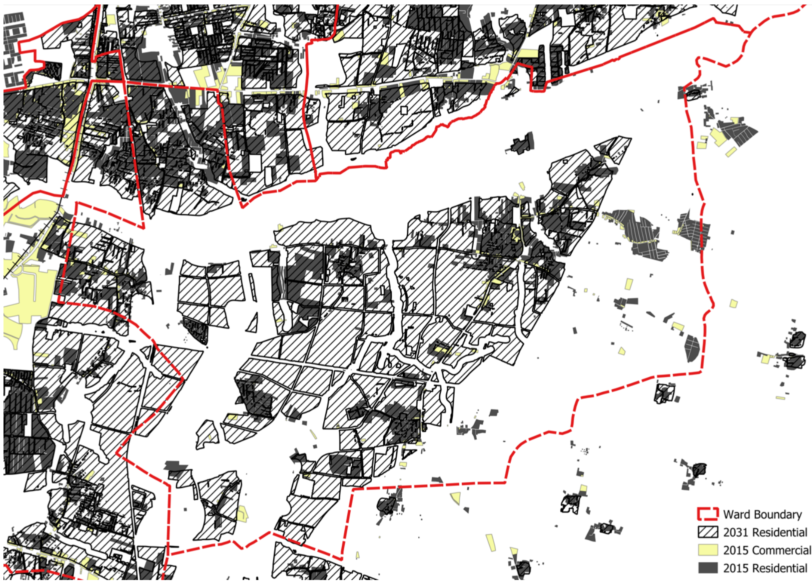
Appendix C Additional Figures and Tables

Figure C.1: Evolution of Bengaluru metro



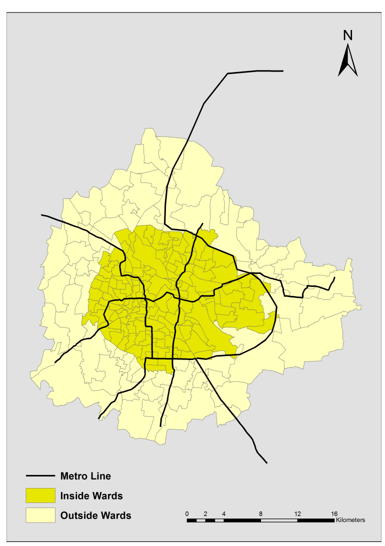
Note: The maps show the evolution of the constructed metro network. *Source:* Bangalore Metro Rail Corporation Limited.

Figure C.2: Land Use Map of the Southeasternmost Ward (#149 Varthuru)



Note: The map compares land use between the 2015 and the 2031 plans for Varthuru, one of the most southeast wards in Bengaluru. Its residential land increases from 381 hectares in 2015 to 1,019 hectares in 2031. Only a small amount of the increase is from rezoning commercial land, while the majority comes from the previously unallocated land.

Figure C.3: The Outer Ring Road



Note: The map shows the wards inside the Outer Ring Road in dark yellow and outside the road in light yellow.

Table C.1: Regressions of Building Heights on Parcel Characteristics by Land Use

	Residential		Commercial	
	Mean log height	Max log height	Mean log height	Max log height
	(1)	(2)	(3)	(4)
Area (log)	0.044***	0.123***	0.016***	0.143***
	(0.001)	(0.001)	(0.002)	(0.002)
Distance to city center	-0.052***	-0.040***	-0.015***	-0.021***
	(0.002)	(0.002)	(0.003)	(0.002)
Squared distance to city center	-0.000***	-0.000**	-0.002***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
In a ward with a metro station	0.003	0.039***	-0.060***	-0.001
	(0.004)	(0.004)	(0.006)	(0.005)
Constant	0.970***	0.901***	0.994***	0.711***
	(0.006)	(0.006)	(0.015)	(0.013)
Observations	115,370	115,504	43,668	43,700
R-squared	0.107	0.189	0.086	0.182

Note: Standard errors are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table C.2: Estimation of ϵ

t_{mij}	–0.0902
	(0.0020)
Residence f.e.	yes
Workplace f.e.	yes
Observations	78,012
Pseudo R^2	0.2101

Note: This table reports estimated values of $-\kappa\epsilon$ from equation (5.1). Standard errors are in parentheses.

Table C.3: Data Sources for Model Variables and Parameters

Model Variables/parameter	**Data Source**
Employment at residential ward	Primary Census Abstract (PCA) 2011
Employment at workplace ward	PCA 2011 and Origin-destination from Travel Survey 2015
Skill shares at workplace and residential ward	Travel survey. Corroborated with PFLS 2018-19
Wage at residential or workplace ward	Monthly income data from Travel Survey 2015
Travel time (driving, ward-to-ward)	Google Maps API and nighttime lights data
Travel time (transit, ward-to-station-to-station-to-ward)	Google Maps API, nighttime lights, and estimated metro network timetable
Land use area by ward	Digitized land use planning maps from Master Plan 2015 and 2031
Building height by ward and land use	ZY-3 satellite remote sensing data 2020
Share of housing consumption	Estimates from NSS Consumer Expenditure Survey (CES) 2011-12

Note: This table reports data sources used to build model variables and parameters.

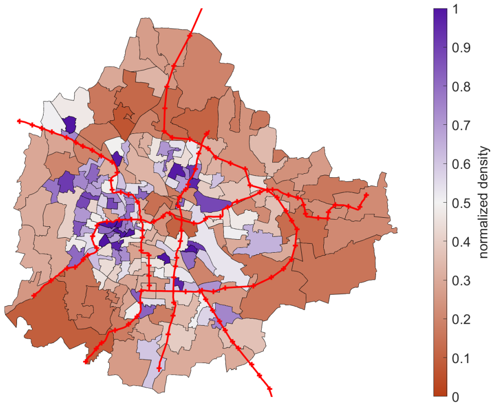
Table C.4: Summary Statistics of Data Inputs for Modeling

	(1) N	(2) mean	(3) s.d.	(4) min	(5) p1	(6) p10	(7) p25	(8) p50	(9) p75	(10) p90	(11) p99	(12) max
Labor												
Employment by res. ward	198	18,648	6,631	8,297	9,230	12,259	14,153	16,842	21,182	28,278	41,385	42,330
Employment by work. ward	198	18,110	18,442	0	1,139	3,434	6,828	12,296	20,204	45,193	90,653	92,241
Monthly income by res. ward (rupees)	198	23,267	9,011	9,534	10,472	12,464	16,327	22,049	30,063	35,111	50,795	56,944
Monthly income by work. ward (rupees)	197	20,894	5,374	8,941	10,939	14,026	16,717	20,833	24,859	27,889	34,600	37,250
Monthly transport expenditure (rupees)	198	2,483	879.7	935.8	1,043	1,475	1,767	2,332	3,143	3,813	4,978	5,294
Share of high-skilled by res. ward	198	0.45	0.13	0.16	0.17	0.28	0.37	0.45	0.54	0.62	0.74	0.74
Share of high-skilled by work. ward	197	0.40	0.16	0.06	0.07	0.19	0.29	0.38	0.52	0.63	0.74	0.87
High-skilled emp't by work. ward	197	8,909	12,274	111.8	119.9	778.6	2,149	4,135	8,652	24,050	60,196	65,455
Low-skilled emp't by work. ward	197	9,293	6,968	542.7	714.8	2,146	4,288	7,772	12,440	19,809	34,799	35,067
High-skilled emp't by res. ward	198	8,348	3,773	2,325	2,520	4,488	5,863	7,292	9,894	13,989	21,028	22,545
Low-skilled emp't by res. ward	198	10,300	4,666	3,896	3,967	5,317	6,727	9,644	12,142	16,312	27,218	27,457
Commute time												
Drive time by ward pair (min)	39,006	41.1	17.4	2.4	7.1	18.2	28.1	40.6	53.3	64.7	80.6	97.4
Drive + metro time by ward pair (min)	39,006	63.9	25.3	11.0	19.9	33.7	46.4	61.2	77.4	96.0	142.6	170.0
Land Use												
Building height, commercial land use (m)	198	2.59	0.63	0.62	0.86	1.81	2.18	2.67	2.99	3.27	4.20	5.12
Building height, residential land use (m)	198	2.88	0.43	1.43	2.02	2.34	2.62	2.88	3.09	3.40	4.14	4.24
FAR value commercial land use	198	0.94	0.23	0.22	0.31	0.65	0.80	0.97	1.09	1.19	1.53	1.86
FAR value residential land use	198	1.05	0.16	0.52	0.74	0.85	0.95	1.05	1.12	1.24	1.51	1.54
Area of commercial land use (1000s sqm)	198	336	419	38	40	77	111	199	398	705	2,556	2,930
Area of residential land use (1000s sqm)	198	936	776	119	133	320	454	702	1,066	2,019	4,148	5,266

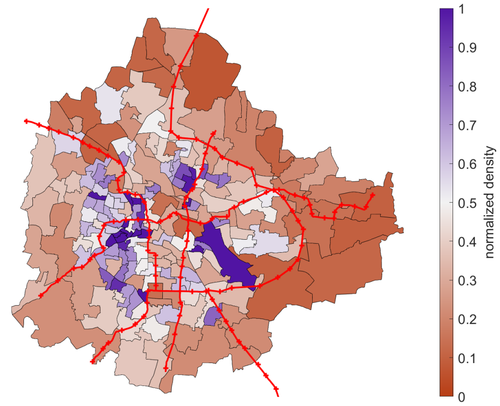
Notes: (i) There is no individual reporting ward #107 (Shivanagara) as their workplace, resulting in zero employment by workplace and unavailable monthly income data in this ward. It is the also the only ward with high-skilled share not defined. (ii) The drive/transit time by ward pair is the average time of mirrored pairs of corresponding travel mode. For example, if the GM driving time is x minutes in the AM peak hour from ward A to B and y minutes in the PM peak hour from ward B to A, we use $(x + y)/2$ as the driving commute time for A-B origin destination pair. (iii) We compute FAR value of by dividing remote sensing building height by 2.75 m, the regulatory average height of habitable rooms according to National Building Code of India 2016. N refers to the number of observations, s.d. is standard deviation, and px refers to the x-th percentile.

Figure C.4: Residents, Jobs, and Floorspace Prices in the Benchmark Economy

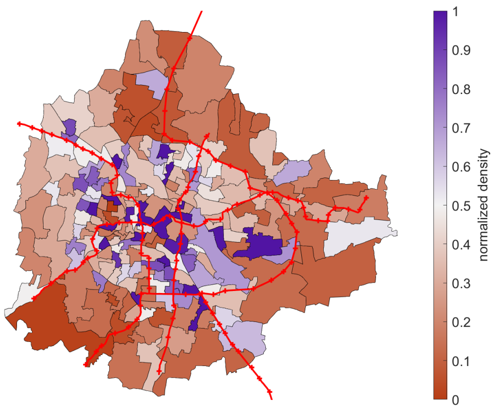
Panel (a): Residents, low-skilled



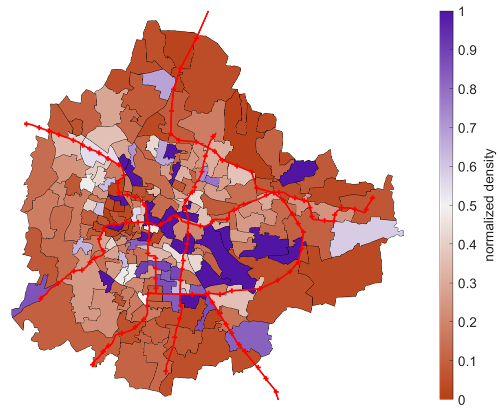
Panel (b): Residents, high-skilled



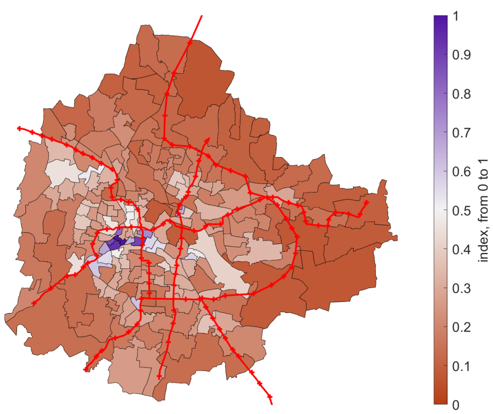
Panel (c): Jobs, low-skilled



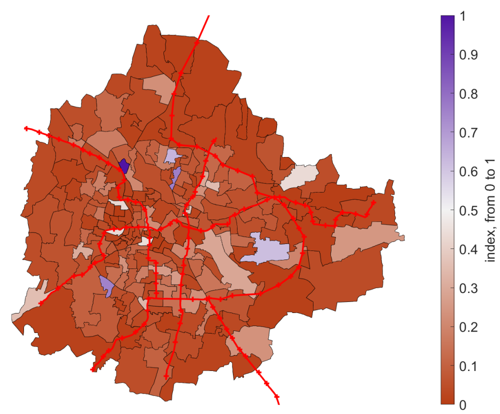
Panel (d): Jobs, high-skilled



Panel (e): Residential floorspace prices



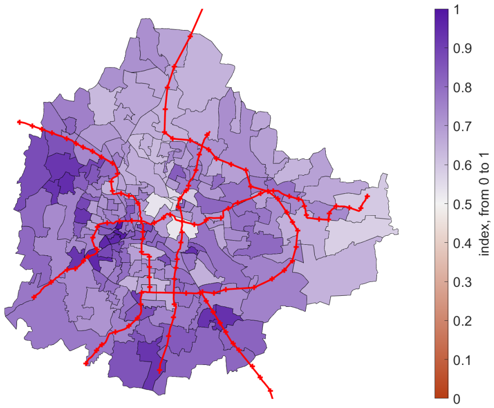
Panel (f): Commercial floorspace prices



Note: The maps show the distribution of residents, jobs, and floorspace prices. Panels (a) and (b) show the density of low- and high-skilled residents. Panels (c) and (d) show the density of low- and high-skilled jobs. Panels (e) and (f) show residential and commercial floorspace prices. Red lines represent the metro network and red crosses are metro stations.

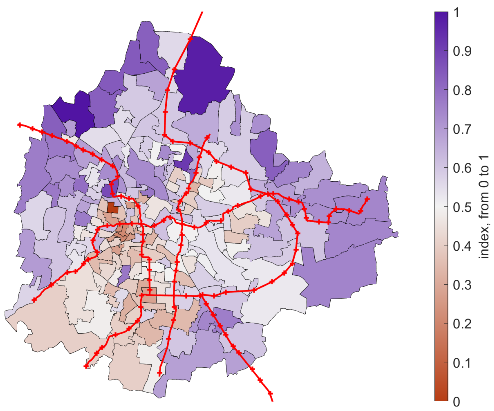
Figure C.5: Amenities and Productivity in the Benchmark Economy

Panel (a): Residential amenities, low-skilled

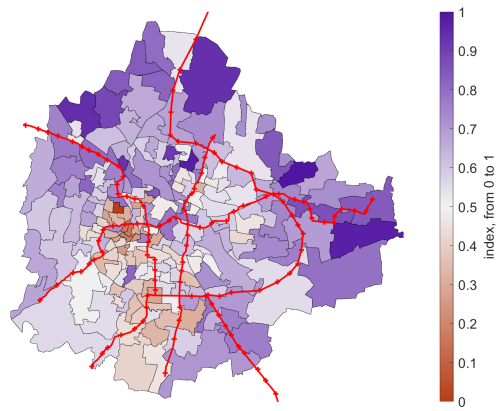


Panel (b): Residential amenities, high-skilled

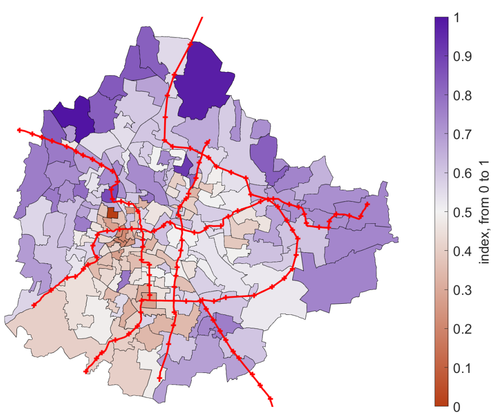
Panel (c): Employment amenities, low-skilled



Panel (d): Employment amenities, high-skilled



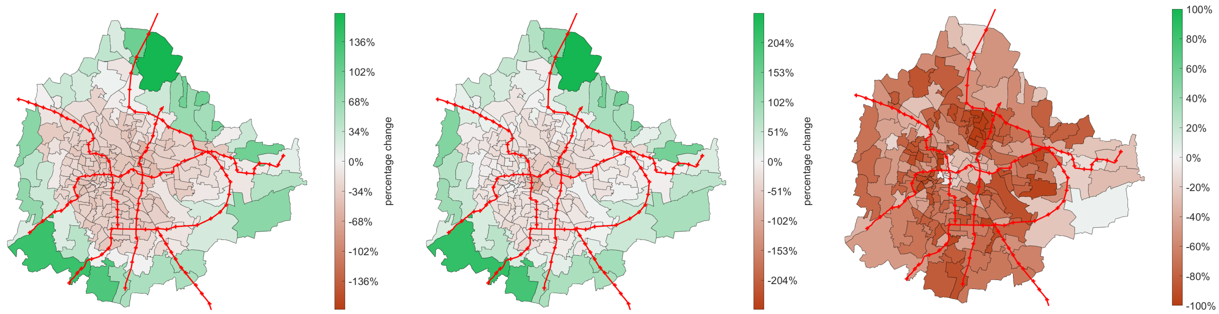
Panel (e): Total factor productivity



Note: The maps show the values of residential amenities X_i^s, employment amenities E_i^s, and productivity A_i in the benchmark model. Panels (a) and (b) show residential amenities for low- and high-skilled workers. Panels (c) and (d) show employment amenities for low- and high-skilled workers. Panel (e) shows total factor productivity. Red lines represent the metro network and red crosses are metro stations.

Figure C.6: Changes in Land Use: 2031 Plan

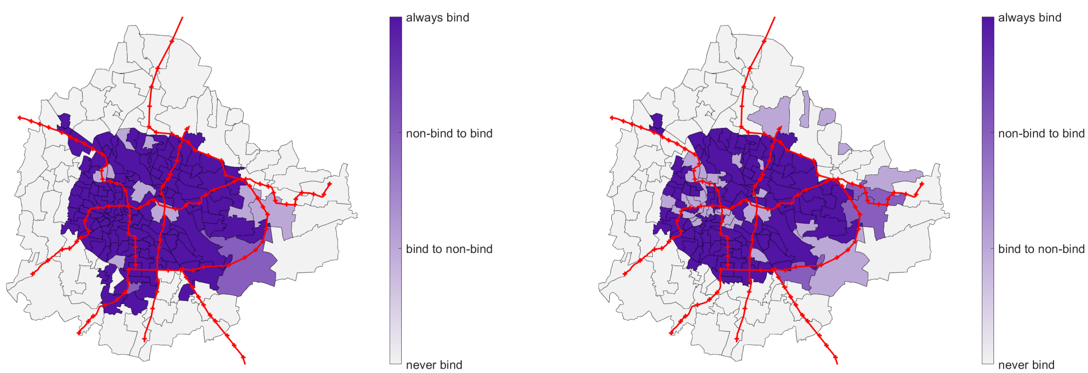
Panel (a): Total land Panel (b): Residential land Panel (c): Commercial land



Note: The maps show percentage changes in total land (panel a), residential land (panel b), and commercial/industrial land (panel c) in a counterfactual where the 2031 Land Use Plan was implemented compared to the benchmark economy.

Figure C.7: Binding and Nonbinding FAR Limits (Introduction of the Metro)

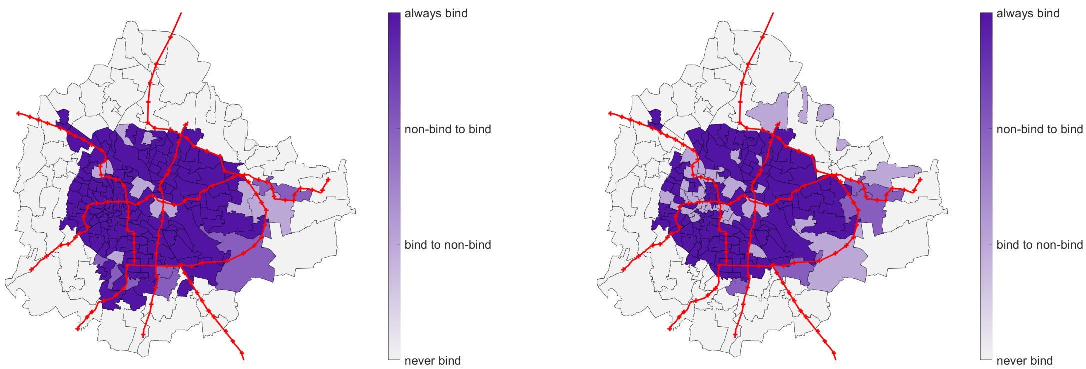
Panel (a): Residential FAR Panel (b): Commercial FAR



Note: The figure shows the wards where FAR limits are not binding in the benchmark (BM) and counterfactual (CF) economies ("never bind"), wards where FAR limits bind in BM but do not bind in CF ("bind to non-bind"), wards where FAR limits do not bind in BM but bind in CF ("non-bind to bind"), and wards where FAR limits bind in both BM and CF ("always bind").

Figure C.8: Binding and Nonbinding FAR Limits (Introduction of the Metro and TOD)

Panel (a): Residential FAR   Panel (b): Commercial FAR



Note: The figure shows wards where FAR limits are not binding in the BM and CF economies (“never bind”), wards where FAR limits bind in BM but do not bind in CF (“bind to non-bind”), wards where FAR limits do not bind in BM but bind in CF (“non-bind to bind”), and wards where FAR limits bind in both BM and CF (“always bind”).

Table C.5: Aggregate Effects of the Metro and Land Use Policies (No FAR Limits)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓

Panel A: Employment, wages, prices, and welfare

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg	5.1	–	–	–	–	-13.9	-9.5
low-skilled	5.0	–	–	–	–	-15.2	-10.9
high-skilled	5.3	–	–	–	–	-12.4	-7.8
Shares, p.p. chg							
residents within ORR	-0.5	–	–	–	–	-3.3	-3.9
jobs within ORR	-0.6	–	–	–	–	-1.5	-2.1
residents next to stations	0.6	–	–	–	–	0.8	1.3
jobs next to stations	0.3	–	–	–	–	6.5	6.9
Wages, % chg	0.3	–	–	–	–	-2.9	-2.6
low-skilled	0.4	–	–	–	–	-4.0	-3.6
high-skilled	0.2	–	–	–	–	-2.9	-2.8
Residential floorspace prices, % chg	1.3	–	–	–	–	-3.6	-2.8
Commercial floorspace prices, % chg	2.7	–	–	–	–	24.2	26.4
Land prices, % chg	5.4	–	–	–	–	19.8	26.4
Welfare, % chg	1.7	–	–	–	–	-4.8	-3.2
low-skilled	1.6	–	–	–	–	-5.4	-3.8
high-skilled	1.7	–	–	–	–	-4.3	-2.7

Panel B: Commuting patterns

	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	21.6	23.4	–	–	–	–	22.3	24.0
Private mode use, %	60.4	59.3	–	–	–	–	60.3	59.2
Transit use, %	39.6	40.7	–	–	–	–	39.7	40.8
bus	39.6	24.9	–	–	–	–	39.7	24.4
metro	0.0	15.9	–	–	–	–	0.0	16.3
low-skilled	39.8	40.9	–	–	–	–	39.9	40.9
high-skilled	39.4	40.6	–	–	–	–	39.4	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes. Values for columns (2)–(5) are missing because FAR limits are never binding and changing them will not change the effects of the metro. See the text for more details.

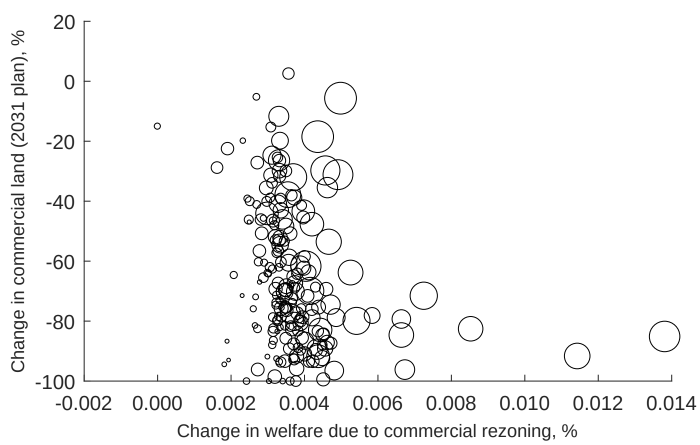
Appendix D Additional Details and Results

D.1 2031 Land Use Plan and Commercial Rezoning

The 2031 Land Use Plan dramatically reduces the land area zoned for commercial use, especially in central wards. What would be the optimal way to rezone the city in light of the introduction of metro? To tackle this question, we run a series of counterfactuals in which, instead of implementing the 2031 plan, we rezone 5,000 square meters of land from residential to commercial use while keeping the total land area fixed in each ward, one by one. We then look at the city-wide welfare gain resulting from commercial rezoning and building the metro in each ward.

Figure D.1 shows that commercial rezoning in the vast majority of wards yields city-wide welfare gains. It also compares the proposed changes in commercial zoning in the 2031 plan with the welfare gains resulting from commercial rezoning in each ward. The results are striking: the correlation between the two variables is −0.25. In other words, the 2031 plan recommended greater *reductions* in commercial land in places that would contribute the most to city-wide welfare if commercial land were *increased*! It also appears that the plan was designed without taking into account the construction of the metro: the mean proposed reduction in commercial land in wards with metro stations is 52%.

Figure D.1: Commercial Rezoning vs. 2031 Land Use Plan



Note: The figure shows the relationship between the change in the land area zoned for commercial use in the 2031 plan and the city-wide welfare gain resulting from rezoning 5,000 sq meters of residential land into commercial in a given ward. The size of a circle is proportional to ward's employment in the benchmark economy.

D.2 Cost-Benefit Analysis

To conduct the cost-benefit analysis of the metro, we convert the increase in workers' welfare and the appreciation of land values that accrue to landowners into a monetary equivalent as follows. In our model, workers spend all of their labor income on consumption and the labor share in output is 0.82. The land share in output is 0.18. Note that our measure of welfare gains is consumption-equivalent.[34] Therefore, a GDP-equivalent gain per worker is the sum of the workers' welfare gain times 0.82 and land appreciation times 0.18.

For example, consider the scenario with the introduction of the metro (column 1 in Table 4) where the welfare gain is 1.3% and land values increase by 4.1%. This gain is equivalent to the one that arises from an increase in output per worker of $0.82 \times 1.3\% + 0.18 \times 4.1\% = 1.8\%$. Once we also take into account that the number of workers goes up by 4%, the growth in total output is 6%. The annual wage bill in Bengaluru is $23,575 million in 2020 prices. With a labor share of 0.82, output is $28,750 million. Thus, a 6% output growth is equivalent to $1,712 million. Construction costs of the metro network are estimated at $7,200 million. At a 5% annual cost of capital, this amounts to $360 million per year.[35] Annual operational cost is $119.3 million (see Section 2), and thus the total annualized cost is $479 million or 1.7% of GDP. Therefore, the metro system results in a net gain of about 4.3% of GDP.[36] Note, however, that most of the increase in GDP is due to the additional 4% of workers moving to Bengaluru from the rest of the country. As a result, the net benefit of the metro *per worker* basis is a mere 0.2% of GDP.

[34]To see this, note that utility is proportional to composite consumption, $c_G^{1-\gamma} c_H^{\gamma}$, and welfare is proportional to indirect utility (equations 4.1 and 4.9).

[35]The average policy rate of the Reserve Bank of India in 2018–2022 was about 5%. This is also the number that was used in Allen and Arkolakis (2014) to calculate the welfare benefits of the U.S. highway system.

[36]The literature's findings on net benefits of transit improvements vary. While Tsivanidis (2023) finds large net benefits of a BRT in Bogotá, Severen (2021) finds that Los Angeles Metro Rail generates net losses.

Appendix E Sensitivity Checks

Endogenous amenities. In the benchmark model, residential amenities X_i^s are exogenous. However, in the long run, they may adjust to changes in the local population. We endogenize amenities following a specification by Heblich, Redding, and Sturm (2020). Residential amenities for skill s in location i are determined by an exogenous component, x_i^s, and an endogenous component that depends on population density:

$$X_i^s = x_i^s \left(\frac{N_{Ri}}{\Lambda_i} \right)^{\chi}. \tag{E.1}$$

Parameter χ measures the elasticity of amenities with respect to the local density of residents. We set $\chi = 0.172$ following Heblich, Redding, and Sturm (2020), although there is little consensus in the literature about the value of this elasticity.[37] Then we recalibrate the benchmark economy and rerun all counterfactuals.

The results can be found in Table E.2. Most of the results are more pronounced compared to the main counterfactual. For example, welfare gains are larger and population growth is stronger. The main reason for the larger effects is that the influx of residents into Bengaluru increases the amenities in the city, which encourages even more people to move to the city.

Extra utility of riding the metro. In the benchmark model, we assume that commuters have the same utility when they take the metro or the bus, and simply choose the faster mode. However, anecdotal evidence suggests that riding the metro may be a more pleasant experience because metro cars are newer, cleaner, and feel safer than buses. We explore this idea by adding a 5% utility gain for metro rides. In other words, commuters are indifferent between taking a bus or taking the metro and incurring a 5% higher commuting cost.

As can be seen in Table E.3, most of the results are larger than in the main set of counterfactuals. The extra utility of metro rides encourages more people to come to Bengaluru and more transit commuters to choose the metro over the bus.

No migration. Our main counterfactuals allow for migration in and out of Bengaluru. In the counterfactual with the metro only, employment in the city goes up by nearly 4%, while in counterfactuals with the metro and the land use policies employment increases by about 10%. To understand how the implications of metro and land use policies depend on migration, we close the city and maintain fixed city-wide employment in all experiments.

The results are shown in Table E.4. The welfare gains without migration are much larger. In the absence of immigrants from other parts of India, floorspace prices fall, benefiting both firms and workers.

[37] Meta-analysis in Ahlfeldt and Pietrostefani (2019) finds that the density elasticity of amenities largely depends on the type of amenity. Averaged over 67 studies, the estimates vary from −0.04 to 0.24 (categories 5, 6, 8, 9, and 10 from Table 3).

Fixed productivity. In our main counterfactual experiments, we allow local productivity to change endogenously in response to changes in employment. This channel is standard in spatial equilibrium models and has received plentiful empirical support. To understand its role in our results, we mute this channel by setting $\lambda = 0$ (see equation 4.22) and then recalibrate the model.

The results are in Table E.5. Wage growth is slightly lower in all counterfactuals, because the new incoming labor force does not make the city more productive. While welfare gains are somewhat smaller, they are still large enough in counterfactuals with TOD and upzoning in central wards to make the net benefit of constructing the metro positive.

Lower skill substitution and labor informality. For our main counterfactuals, we used the elasticity of substitution between low- and high-skilled labor of 2, as estimated for the U.S. by Card (2009). Due to high levels of labor informality, there may be more segmentation of labor markets in a developing country context and, therefore, the two skill groups may be less substitutable. To understand how our results depend on the skill substitution elasticity, we lowered ξ from 2 to 0.1.[38] Then we recalibrate the model and rerun the counterfactuals.

Table E.6 shows that all of the counterfactual results barely change, which suggests that the elasticity of substitution between skills is not a key parameter that determines the effects of the metro and land use policies.

Lower ϵ. The estimated value of the Fréchet elasticity of the residence-workplace shock ϵ is 6.9359. This is within the range of existing estimates but somewhat above the average. A high value of ϵ means that workers, when making location choices, put a relatively high value of location fundamentals and a low value on their idiosyncratic preferences. To evaluate how sensitive our results are to this elasticity, we lowered the value of ϵ to 4, recalibrated the model, and reran counterfactual experiments.

The results can be seen in Table E.7. Lower value of ϵ means that workers, when making location choices, put a relatively low value on location fundamentals and a high value on their idiosyncratic preferences. Therefore, workers choose distant location pairs more often which results in longer commutes (the average commute in the benchmark model is nearly 34 minutes, compared to 23 minutes in the main model). However, because marginal commuting costs are increasing in commute time (equation 4.2), the introduction of metro reduces the average commute, while in the main set of counterfactuals the average commute went up. As a result, welfare gains from introducing the metro are significantly larger. These larger gains lead to higher population inflows and, as a consequence, to higher growth in land and floorspace prices.

Higher σ. The calibrated value of the Fréchet elasticity of the transportation mode shock σ is 1.1878. Very few quantitative spatial models have this elasticity; hence, it is important to understand how much our results depend on its value. We increase σ to 2, recalibrate the model, and rerun the counterfactuals.

[38] With such low substitution, the production function approaches Leontief.

Table E.1: Complementarity of Transportation and Land Use Policies in Sensititivity Checks

	Wages		Resid. prices		Comm. prices		Land prices		Welfare	
	TOD	ORR	TOD	ORR	TOD	ORR	TOD	ORR	TOD	ORR
Main counterfactual	0.05	-0.04	-0.38	-0.09	-1.32	-0.14	0.55	-0.06	0.15	-0.01
Endog. amenities	-0.07	-0.16	-1.40	-0.93	-1.74	-0.70	1.20	0.04	0.37	0.06
Extra utility of metro	-0.01	-0.07	-0.54	-0.09	-1.27	-0.09	0.64	-0.16	0.19	-0.03
No migration	-0.01	-0.01	-0.61	-0.15	-0.86	-0.13	-0.01	-0.01	0.16	0.02
Fixed productivity	0.08	0.00	-0.34	-0.03	-0.83	-0.02	0.57	-0.02	0.15	0.00
Lower skill subst.	0.05	-0.04	-0.38	-0.09	-1.32	-0.14	0.55	-0.06	0.15	-0.01
Lower ϵ	0.07	-0.05	-0.20	0.01	-0.74	0.02	0.65	-0.17	0.17	-0.03
Higher σ	0.06	-0.04	-0.37	-0.09	-1.29	-0.10	0.56	-0.07	0.15	-0.01
Lower h.s. elasticity	0.18	-0.01	-0.25	0.00	-1.77	-0.12	0.86	-0.07	0.20	-0.02

Note: The table shows the complementarity between constructing the metro and two land use reforms: TOD and upzoning within the ORR. The first row shows complementarity for the main set of counterfactuals and reproduces the numbers in Figure 7. The following rows show complementarity for sensitivity checks discussed in this section. The complementarity is calculated using formula (6.1).

Table E.8 shows the results. Higher value of σ implies that workers have weaker idiosyncratic preferences for transportation modes. In the counterfactual where the metro is introduced, the share of transit commutes goes up by 1.9 percentage points, compared to 1.1 percentage points in the main counterfactual. However, all other results, such as welfare gains, population growth, and price changes, are strikingly similar to the main set of counterfactuals.

Lower housing supply elasticity. In our quantitative model, we used the housing supply elasticity of 1.75, as estimated by Saiz (2010) for the U.S. However, it is likely that a large city in a developing country has a lower elasticity. For example, Sturm, Takeda, and Venables (2023) estimate the elasticity of 1.5 for Dhaka, Bangladesh. To evaluate the sensitivity of our results to the value of housing supply elasticity, we reduce it all the way to 1. According to Saiz (2010), this value corresponds to the elasticities observed in the most regulated and land-constrained cities in the U.S.

Table E.9 shows that the results barely change. With lower housing supply elasticity, worker inflows are a little bit smaller than in the main set of counterfactuals. Yet, the welfare gains of the metro and land use reforms are about the same.

Complementarity of metro and land use reforms. Importantly, as Table E.1 demonstrates, none of the modifications that we considered in this section change our conclusion that the construction of the metro is complementary to TOD but not with central upzoning.

Table E.2: Aggregate Effects of Metro and Land Use Policies (Endogenous Amenities)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓

Panel A: Employment, wages, prices, and welfare

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg	7.0	7.0	15.7	6.5	14.1	-22.5	-17.2
low-skilled	6.9	5.9	14.6	5.6	13.2	-22.7	-17.3
high-skilled	7.0	8.4	17.1	7.6	15.3	-22.4	-17.2
Shares, p.p. chg							
residents within ORR	-2.3	5.4	1.7	6.5	3.6	5.8	3.8
jobs within ORR	-2.0	5.7	2.4	6.5	4.0	-3.5	-5.9
residents next to stations	1.5	3.6	5.9	-1.2	0.4	-3.5	-1.6
jobs next to stations	0.7	4.5	5.6	-0.3	0.3	6.8	7.7
Wages, % chg	0.0	3.2	3.1	2.6	2.5	-7.5	-7.4
low-skilled	0.1	2.7	2.9	2.3	2.4	-7.8	-7.4
high-skilled	-0.1	2.9	2.7	2.4	2.2	-7.4	-7.4
Residential floorspace prices, % chg	1.7	7.3	7.7	6.9	7.8	17.9	17.4
Commercial floorspace prices, % chg	3.4	-0.7	1.0	0.3	3.0	32.0	34.3
Land prices, % chg	7.0	10.4	19.3	9.3	17.0	2.8	9.9
Welfare, % chg	2.3	2.3	5.0	2.2	4.5	-8.2	-6.1
low-skilled	2.2	1.9	4.6	1.8	4.2	-8.2	-6.1
high-skilled	2.3	2.7	5.4	2.5	4.9	-8.1	-6.1

Panel B: Commuting patterns

	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.4	21.8	23.5	21.9	23.6	22.0	23.5
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.2	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.8	40.8
bus	39.6	24.7	39.7	24.1	39.6	24.6	39.8	24.5
metro	0.0	16.0	0.0	16.6	0.0	16.1	0.0	16.3
low-skilled	39.8	40.9	39.9	40.9	39.8	40.8	39.9	40.9
high-skilled	39.4	40.6	39.5	40.6	39.4	40.6	39.6	40.7

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.3: Aggregate Effects of the Metro and Land Use Policies (Extra Utility of Metro)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		6.6	5.8	13.4	5.5	12.4	-18.5	-12.3
low-skilled		6.6	4.8	12.5	4.8	11.7	-18.3	-12.1
high-skilled		6.7	6.9	14.5	6.3	13.2	-18.7	-12.5
Shares, p.p. chg								
residents within ORR		-1.1	2.0	0.5	2.7	1.5	-4.5	-6.0
jobs within ORR		-1.6	4.0	1.8	4.7	3.2	-8.9	-11.0
residents next to stations		0.7	1.7	2.7	-0.5	0.2	0.4	1.2
jobs next to stations		0.7	3.7	4.9	-0.4	0.3	6.2	6.9
Wages, % chg		-0.1	2.9	2.8	2.5	2.4	-7.7	-7.7
low-skilled		0.0	2.4	2.5	2.2	2.2	-7.9	-7.7
high-skilled		-0.1	2.8	2.6	2.4	2.2	-7.4	-7.5
Residential floorspace prices, % chg		3.3	0.5	3.2	0.6	3.8	-12.5	-11.1
Commercial floorspace prices, % chg		3.6	-2.7	-0.5	-2.5	0.9	29.9	33.9
Land prices, % chg		6.6	8.8	16.6	8.1	15.1	7.9	16.2
Welfare, % chg		2.2	1.9	4.3	1.8	4.0	-6.6	-4.3
low-skilled		2.2	1.6	4.0	1.6	3.8	-6.5	-4.2
high-skilled		2.2	2.2	4.6	2.1	4.2	-6.7	-4.4
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.4	21.8	23.5	21.8	23.5	22.0	23.8
Private mode use, %	60.4	58.4	60.3	58.3	60.4	58.4	60.3	58.3
Transit use, %	39.6	41.6	39.7	41.7	39.6	41.6	39.7	41.7
bus	39.6	24.5	39.7	24.2	39.6	24.4	39.7	24.2
metro	0.0	17.1	0.0	17.5	0.0	17.2	0.0	17.4
low-skilled	39.8	41.8	39.9	41.8	39.8	41.8	39.9	41.8
high-skilled	39.4	41.5	39.5	41.5	39.4	41.5	39.4	41.5

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.4: Aggregate Effects of the Metro and Land Use Policies (No Migration)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		0.0	0.0	0.0	0.0	0.0	0.0	0.0
low-skilled		0.0	0.0	0.0	0.0	0.0	0.0	0.0
high-skilled		0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shares, p.p. chg								
residents within ORR		-0.2	2.8	2.3	3.3	2.9	-7.0	-7.1
jobs within ORR		-0.4	4.9	4.1	5.5	5.1	-11.9	-12.5
residents next to stations		0.4	1.6	2.2	-0.6	-0.1	0.8	1.0
jobs next to stations		0.5	3.7	4.4	-0.4	-0.1	6.0	6.4
Wages, % chg		0.2	3.0	3.2	2.6	2.9	-8.4	-8.2
low-skilled		0.2	2.2	2.5	2.1	2.3	-8.5	-8.2
high-skilled		0.2	3.5	3.7	3.0	3.2	-8.4	-8.1
Residential floorspace prices, % chg		-0.5	-2.7	-3.8	-2.6	-3.2	-4.1	-4.6
Commercial floorspace prices, % chg		0.4	-6.6	-7.1	-6.0	-5.7	47.1	46.5
Land prices, % chg		0.2	3.0	3.2	2.7	2.9	31.3	31.7
Welfare, % chg		2.0	2.8	5.0	2.7	4.7	-9.3	-7.5
low-skilled		1.8	2.0	4.1	2.1	4.0	-9.0	-7.3
high-skilled		2.1	3.6	6.0	3.3	5.5	-9.7	-7.7
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.4	21.8	23.4	21.8	23.5	21.9	23.7
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.4	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.6	40.8
bus	39.6	25.0	39.7	24.7	39.6	24.9	39.6	24.8
metro	0.0	15.8	0.0	16.1	0.0	15.8	0.0	16.0
low-skilled	39.8	40.9	39.9	40.9	39.8	40.8	39.9	40.9
high-skilled	39.4	40.6	39.5	40.6	39.4	40.6	39.4	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.5: Aggregate Effects of the Metro and Land Use Policies (Fixed Productivity)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		3.4	5.3	9.4	5.2	8.8	-18.9	-15.8
low-skilled		3.3	4.7	8.6	4.7	8.2	-18.4	-15.5
high-skilled		3.5	6.1	10.2	5.8	9.4	-19.4	-16.2
Shares, p.p. chg								
residents within ORR		-0.5	1.9	1.0	2.4	1.8	-5.1	-5.7
jobs within ORR		-0.6	2.8	1.7	3.3	2.7	-10.2	-11.0
residents next to stations		0.4	1.6	2.1	-0.5	-0.1	1.0	1.1
jobs next to stations		0.2	2.7	3.3	-0.3	-0.1	5.1	5.3
Wages, % chg		-0.3	2.2	1.9	2.0	1.7	-9.4	-9.7
low-skilled		-0.3	1.8	1.7	1.8	1.5	-9.6	-9.8
high-skilled		-0.4	2.1	1.7	1.9	1.5	-9.0	-9.4
Residential floorspace prices, % chg		1.5	-0.6	0.5	-0.4	1.0	-16.6	-15.8
Commercial floorspace prices, % chg		2.2	-5.7	-4.5	-5.6	-3.5	47.8	51.0
Land prices, % chg		3.1	7.6	11.5	7.3	10.6	5.4	9.1
Welfare, % chg		1.1	1.8	3.1	1.7	2.9	-6.8	-5.6
low-skilled		1.1	1.5	2.8	1.6	2.7	-6.6	-5.4
high-skilled		1.2	2.0	3.3	1.9	3.1	-6.9	-5.7
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.3	21.7	23.4	21.7	23.4	21.6	23.4
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.4	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.6	40.8
bus	39.6	25.1	39.7	24.8	39.6	25.1	39.6	24.9
metro	0.0	15.7	0.0	15.9	0.0	15.7	0.0	15.9
low-skilled	39.8	40.9	39.9	40.9	39.8	40.9	39.9	40.9
high-skilled	39.4	40.6	39.4	40.6	39.4	40.6	39.3	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.6: Aggregate Effects of the Metro and Land Use Policies (Lower Skill Substitution)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		4.1	5.7	10.5	5.4	9.7	-18.4	-14.6
low-skilled		4.0	4.5	9.3	4.6	8.8	-18.2	-14.2
high-skilled		4.1	7.1	11.9	6.4	10.7	-18.8	-15.0
Shares, p.p. chg								
residents within ORR		-0.7	2.0	1.0	2.7	1.9	-4.5	-5.5
jobs within ORR		-1.0	4.0	2.4	4.7	3.7	-8.9	-10.4
residents next to stations		0.5	1.7	2.5	-0.5	0.0	0.4	0.9
jobs next to stations		0.5	3.7	4.7	-0.4	0.0	6.2	6.6
Wages, % chg		0.0	3.0	3.0	2.6	2.6	-7.7	-7.6
low-skilled		0.1	2.3	2.5	2.1	2.3	-7.9	-7.6
high-skilled		-0.1	2.8	2.8	2.4	2.4	-7.4	-7.5
Residential floorspace prices, % chg		1.9	0.5	2.0	0.6	2.5	-12.5	-11.9
Commercial floorspace prices, % chg		2.8	-2.8	-1.4	-2.6	0.0	29.9	32.8
Land prices, % chg		4.1	8.8	13.8	8.1	12.5	7.9	13.2
Welfare, % chg		1.3	1.9	3.4	1.8	3.2	-6.6	-5.1
low-skilled		1.3	1.5	3.0	1.5	2.9	-6.5	-5.0
high-skilled		1.4	2.3	3.8	2.1	3.5	-6.7	-5.3
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.4	21.8	23.4	21.8	23.5	22.0	23.7
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.3	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.7	40.8
bus	39.6	25.0	39.7	24.7	39.6	25.0	39.7	24.7
metro	0.0	15.7	0.0	16.1	0.0	15.8	0.0	16.0
low-skilled	39.8	40.9	39.9	40.9	39.8	40.9	39.9	40.9
high-skilled	39.4	40.6	39.5	40.6	39.4	40.6	39.4	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.7: Aggregate Effects of the Metro and Land Use Policies (Lower ϵ)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		6.7	6.3	14.0	6.1	13.1	-20.8	-15.2
low-skilled		6.9	5.6	13.6	5.6	12.8	-20.7	-14.9
high-skilled		6.4	7.2	14.4	6.7	13.3	-20.8	-15.6
Shares, p.p. chg								
residents within ORR		-1.0	1.1	-0.2	1.6	0.6	-2.7	-3.7
jobs within ORR		-1.5	2.5	0.5	3.0	1.5	-6.4	-8.1
residents next to stations		0.5	1.3	2.0	-0.3	0.2	0.2	1.0
jobs next to stations		0.4	2.5	3.2	-0.2	0.1	4.9	5.3
Wages, % chg		-0.2	2.7	2.6	2.5	2.2	-8.8	-9.0
low-skilled		-0.1	2.3	2.4	2.2	2.1	-9.1	-9.1
high-skilled		-0.2	2.6	2.5	2.4	2.2	-8.5	-8.7
Residential floorspace prices, % chg		3.2	-0.6	2.3	-0.3	2.9	-14.0	-11.8
Commercial floorspace prices, % chg		3.1	-4.7	-2.5	-4.7	-1.7	54.6	59.1
Land prices, % chg		6.5	9.2	16.9	8.7	15.5	3.4	10.3
Welfare, % chg		2.2	2.1	4.5	2.0	4.2	-7.5	-5.4
low-skilled		2.3	1.8	4.3	1.8	4.1	-7.4	-5.2
high-skilled		2.1	2.3	4.6	2.2	4.3	-7.5	-5.5
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	33.8	33.5	31.8	33.4	31.9	33.4	32.0	33.6
Private mode use, %	60.4	58.3	60.3	58.2	60.3	58.3	60.3	58.2
Transit use, %	39.6	41.7	39.7	41.8	39.7	41.7	39.7	41.8
bus	39.6	20.5	39.7	20.4	39.7	20.6	39.7	20.4
metro	0.0	21.2	0.0	21.4	0.0	21.2	0.0	21.4
low-skilled	39.6	41.8	39.7	41.8	39.7	41.8	39.6	41.8
high-skilled	39.6	41.7	39.8	41.8	39.7	41.7	39.7	41.7

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.8: Aggregate Effects of the Metro and Land Use Policies (Higher σ)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓
Panel A: Employment, wages, prices, and welfare								
		(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg		3.8	5.8	10.3	5.5	9.5	-18.5	-14.8
low-skilled		3.7	4.8	9.3	4.8	8.7	-18.3	-14.7
high-skilled		4.0	6.9	11.5	6.3	10.4	-18.7	-15.0
Shares, p.p. chg								
residents within ORR		-0.6	2.0	1.1	2.7	2.0	-4.5	-5.4
jobs within ORR		-0.9	4.0	2.5	4.7	3.8	-9.0	-10.3
residents next to stations		0.5	1.7	2.4	-0.5	0.0	0.4	0.8
jobs next to stations		0.4	3.7	4.7	-0.4	0.0	6.2	6.6
Wages, % chg		0.0	2.9	3.0	2.5	2.5	-7.7	-7.6
low-skilled		0.1	2.4	2.6	2.2	2.3	-7.9	-7.7
high-skilled		0.0	2.8	2.8	2.4	2.3	-7.4	-7.4
Residential floorspace prices, % chg		1.9	0.5	2.0	0.6	2.5	-12.4	-11.8
Commercial floorspace prices, % chg		2.6	-2.7	-1.5	-2.5	0.0	29.9	32.6
Land prices, % chg		3.9	8.8	13.6	8.1	12.3	7.9	12.9
Welfare, % chg		1.3	1.9	3.4	1.8	3.1	-6.6	-5.2
low-skilled		1.2	1.6	3.0	1.6	2.8	-6.5	-5.1
high-skilled		1.3	2.2	3.7	2.1	3.4	-6.7	-5.3
Panel B: Commuting patterns								
	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.5	23.2	21.6	23.3	21.7	23.3	21.9	23.6
Private mode use, %	60.4	58.5	60.3	58.4	60.4	58.5	60.3	58.4
Transit use, %	39.6	41.5	39.7	41.6	39.6	41.5	39.7	41.6
bus	39.6	25.7	39.7	25.4	39.6	25.6	39.7	25.4
metro	0.0	15.8	0.0	16.2	0.0	15.9	0.0	16.1
low-skilled	40.0	41.7	40.0	41.8	39.9	41.7	40.0	41.8
high-skilled	39.2	41.2	39.4	41.3	39.3	41.2	39.2	41.3

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Table E.9: Aggregate Effects of the Metro and Land Use Policies (Lower Housing Supply Elasticity)

Introduce metro:	–	✓	–	✓	–	✓	–	✓
Increase FAR next to stations:	–	–	✓	✓	–	–	–	–
Increase FAR within the ORR:	–	–	–	–	✓	✓	–	–
2031 land use plan:	–	–	–	–	–	–	✓	✓

Panel A: Employment, wages, prices, and welfare

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Residents, % chg	3.8	5.4	10.1	5.4	9.4	-19.1	-15.9
low-skilled	3.7	4.5	9.0	4.7	8.5	-19.1	-16.0
high-skilled	3.9	6.6	11.4	6.3	10.4	-19.1	-15.8
Shares, p.p. chg							
residents within ORR	-0.5	2.0	1.2	2.5	1.9	-4.9	-5.6
jobs within ORR	-0.8	3.6	2.3	4.3	3.6	-7.5	-8.4
residents next to stations	0.4	1.5	2.2	-0.5	-0.1	0.6	1.1
jobs next to stations	0.4	3.5	4.5	-0.4	-0.1	6.4	6.8
Wages, % chg	0.0	2.8	3.0	2.6	2.5	-8.4	-8.4
low-skilled	0.0	2.3	2.6	2.2	2.2	-8.8	-8.6
high-skilled	-0.1	2.7	2.7	2.4	2.3	-8.1	-8.2
Residential floorspace prices, % chg	2.1	0.7	2.6	0.7	2.8	-15.9	-14.7
Commercial floorspace prices, % chg	3.0	-2.3	-1.2	-2.4	0.4	37.5	40.7
Land prices, % chg	3.7	8.4	13.3	8.1	12.1	6.3	10.6
Welfare, % chg	1.2	1.8	3.3	1.8	3.1	-6.8	-5.6
low-skilled	1.2	1.5	2.9	1.5	2.8	-6.8	-5.6
high-skilled	1.3	2.2	3.7	2.1	3.3	-6.8	-5.6

Panel B: Commuting patterns

	(0)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Mean time to work, min.	22.7	23.3	21.8	23.4	21.8	23.4	22.1	23.8
Private mode use, %	60.4	59.3	60.3	59.2	60.4	59.3	60.4	59.2
Transit use, %	39.6	40.7	39.7	40.8	39.6	40.7	39.6	40.8
bus	39.6	25.0	39.7	24.7	39.6	25.0	39.6	24.7
metro	0.0	15.7	0.0	16.1	0.0	15.7	0.0	16.1
low-skilled	39.8	40.9	39.9	40.9	39.8	40.9	39.9	40.9
high-skilled	39.4	40.6	39.5	40.6	39.4	40.6	39.4	40.6

Note: Panel A shows the counterfactual changes in employment, wages, prices, and welfare. Panel B shows commuting patterns. Column (0) shows results for the benchmark economy. Other columns show counterfactual results. The header indicates which of the four adjustments are considered in a given counterfactual. "% chg" refers to percentage changes, and "p.p. chg" refers to percentage point changes.

Appendix F Extensions

Below we discuss a number of additional factors that may be considered when studying transit improvements and land use reforms, and that we leave for future research.

Traffic congestion. In our model, commuting speeds do not change in response to changes in traffic volumes. How would our results change if we took into account this margin of adjustment? On the one hand, the introduction of the metro takes 15.7% of commuters off roads although, as shown in column (1) of panel B in Table 4, most of the switchers are previously bus riders and buses presumably contribute less to traffic congestion than private vehicles.[39] On the other hand, more workers are moving to the city, adding to the pressure on the existing road network. Finally, any improvement in speed may lead to more trips in the long run (Duranton and Turner, 2011). Therefore, whether or not the introduction of metro in Bengaluru leads to less road traffic depends on which of the above-mentioned channels dominate.

Environmental effects. The metro produces less greenhouse gas emissions than private vehicles and buses, and taller buildings tend to be more energy-efficient due to economies of scale. As a result, the introduction of the metro is likely to bring environmental benefits that are likely to be amplified by land use policies such as TOD and central upzoning. On the other hand, these benefits may be mitigated by population inflows.

Dynamic effects. The static nature of our model does not allow us to distinguish outcomes for incumbent residents and newcomers. However, increases in land prices in all counterfactuals suggests that welfare gains for the incumbents are larger. The absence of dynamics also prevents us from evaluating potential costs of new real estate development on existing residents. In a comparable context of Mumbai, Gechter and Tsivanidis (2023) find that even though the redevelopment of former textile mills in the city center led to significant citywide gains, it imposed large losses on the relocated slum dwellers.

Informal housing. We treat all housing in the model as homogeneous. Yet Bengaluru, as many other large Indian cities, has a nontrivial amount of informal housing. An alternative way to view our counterfactuals where the FAR limits are relaxed is an increase in the share of formal housing which tends to be taller, and not an increase in the legal height limit. However, understanding how the introduction of metro interacts with formalizing the housing stock would require a dynamic model with segmented housing markets and property rights, such as Henderson, Regan, and Venables (2020).

Population growth. Bengaluru is a rapidly growing city that more than doubled its population from 1991 to 2011. At the same time, in our counterfactual experiments we do not incorporate population growth except via migration from other cities, as is standard in the literature. Thus, our results should be viewed as the effects of building the metro and reforming land use isolated from the effects of population growth.

[39] First, buses allow for a denser layout of passengers inside a vehicle. Second, some streets in Bengaluru have dedicated bus lanes.