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Faster, taller, better: Transit improvements and land use policies

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FASTER, TALLER, BETTER

TRANSIT IMPROVEMENTS AND LAND USE POLICIES

Liming Chen, Rana Hasan, Yi Jiang, and Andrii Parkhomenko

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ABSTRACT

We study the interaction between transit improvements and land use policies in the context of Bengaluru, one of India's largest cities. The city inaugurated a metro system in 2011. Yet it has low building heights even near metro stations, reflecting low floor-area ratio limits. We construct a rich dataset that includes information on travel times between 198 wards, parcel-level land use, and building heights from satellite images. We then build a quantitative spatial model where heterogeneous workers choose among different commuting modes. The simulations show that the metro system increases citywide output and welfare, even net of costs. However, the net gains are several times larger when floor-area ratio limits are relaxed near metro stations (transit-oriented development) or in the city center. Moreover, the metro and transit-oriented development are complementary—their joint effect on incomes, prices, and welfare is greater than the combined effect of the two policies implemented separately.

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

JEL codes: 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.

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

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 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. 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 et al. 2020; Balboni et al. 2020; Severen 2021; Warnes 2021; Zárate 2022; Tsivanidis 2023; Velásquez 2023; Conwell 2023; Kreindler et al. 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 et al. (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 et al. 2016; Herkenhoff et al. 2018; Hsieh and Moretti 2019; Anagol et al. 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 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.

2 Setting and Data

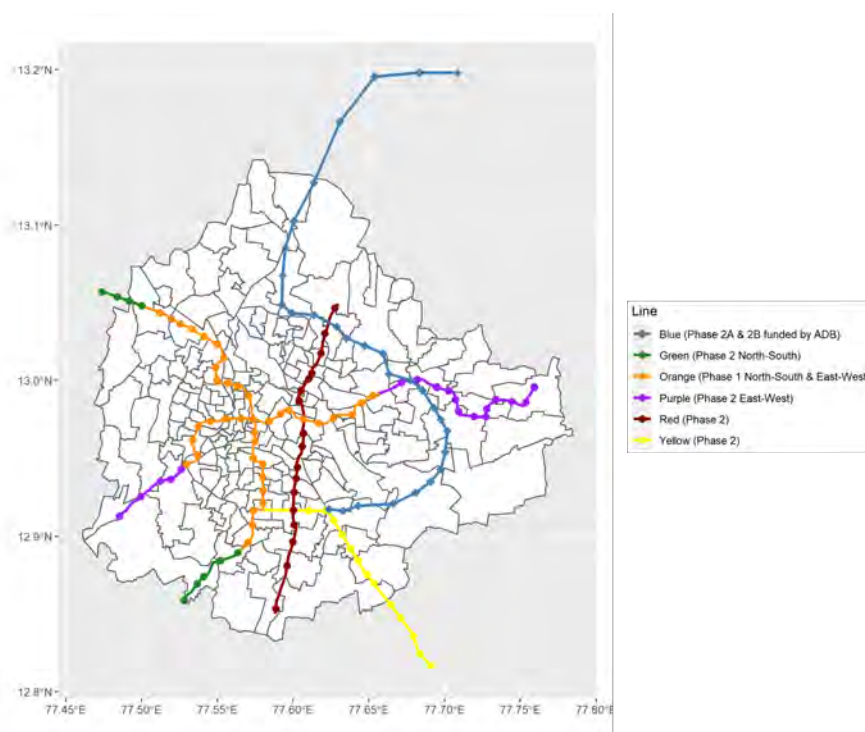
In this section, we describe the city of Bengaluru, its metro network, and FAR policies. We also discuss the data used to document various facts about building heights and land use, and to construct the quantitative model.

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 et al. 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

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.

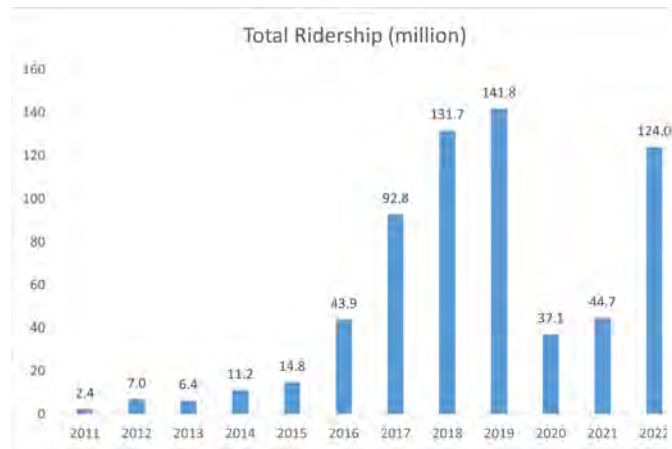
depicts the evolution of the metro network, and Appendix Table A.4 provides more detailed information on each phase.²

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 coronavirus disease (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

²The appendixes are available at <http://dx.doi.org/10.22617/WPS230480-2>.

Figure 2: Metro Ridership



Note: This figure shows annual ridership for the Bengaluru metro.

Source: Bengaluru Metro Rail Corporation Limited.

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 et al. 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.³

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 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 et al. 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.

³Sood (2022) shows that land fragmentation is a key barrier to real estate development in India.

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, see Appendix Section A.

Geography of Bengaluru. We collect data on all 198 wards in Bengaluru.⁴ 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.

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.⁵ 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 2015.⁶ 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

⁴Bengaluru 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.

⁵Workers 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).

⁶The 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.

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.⁷

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.⁸ 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.

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.⁹ 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 2017.¹⁰ Each map outlines land parcels with color-coded land use, such

⁷To 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.

⁸Graduate 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.

⁹Open City: <https://opencity.in> (accessed in June 2021)

¹⁰This 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).

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 et al. 2017, 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 et al. 2021), provide a more accurate prediction of building heights (Amirkolaee and Arefi 2019).¹¹ 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 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.

Employment and Commuting. As shown in Table 1, 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

¹¹Appendix Section A.2 details the methodology and advantages of the ZY-3 building height data.

Table 1: 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

N = number of observations, S.D. = standard deviation, C.V. = coefficient of variation.

Note: This table presents summary statistics for variables that describe residence, workplace, and commuting.

Source: Authors' estimates.

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 2, 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

Table 2: 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	0.02	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

FAR = floor-to-area ratio, N = number of observations, S.D. = standard deviation.

Note: This table presents summary statistics for variables that describe land use, building heights, and FARs.

Source: Authors' estimates.

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.

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.

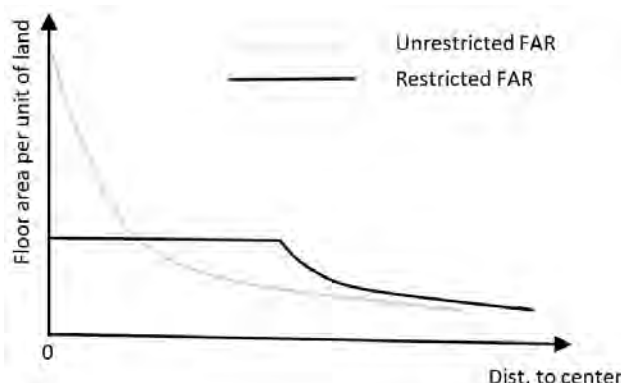
3.1 Building Height Gradient

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 3) show that for the different types of land use, both the parcel's mean and maximum heights increase with 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).¹² Moreover, the coefficients of the interaction between distance to the center and outside-ORR indicator are negative and statistically significant. This indicates that mean

¹²Building 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 3: Height Gradient with Unrestricted and Restricted FAR in a Monocentric City



FAR = floor-to-area ratio.

Note: This figure is adapted Figure 1 from [Bertaud and Brueckner \(2005\)](#).

and maximum heights decrease considerably faster outside the ORR than within the ORR.

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

Table 3: Regressions of Building Heights on Parcel Characteristics by Land Use

	Residential		Commercial	
	Mean log height (1)	Max log height (2)	Mean log height (3)	Max log height (4)
Panel A: Parcel-level height on parcel area and location variables				
Area (log)	0.042*** (0.001)	0.121*** (0.001)	0.015*** (0.002)	0.143*** (0.002)
Distance to city center	-0.012*** (0.004)	0.003 (0.003)	-0.002 (0.005)	-0.001 (0.005)
Squared distance to city center	-0.002*** (0.000)	-0.002*** (0.000)	-0.001** (0.000)	-0.001** (0.000)
Distance to center x Outside ORR	-0.039*** (0.003)	-0.040*** (0.002)	-0.021*** (0.004)	-0.024*** (0.003)
Squared distance to center x Outside ORR	0.002*** (0.000)	0.002*** (0.000)	-0.000 (0.000)	0.001* (0.000)
Constant	0.876*** (0.009)	0.822*** (0.008)	0.928*** (0.018)	0.641*** (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*** (0.001)	0.123*** (0.001)	0.016*** (0.002)	0.143*** (0.002)
Distance to city center	-0.049*** (0.002)	-0.036*** (0.002)	-0.018*** (0.003)	-0.022*** (0.002)
Squared distance to city center	-0.000*** (0.000)	-0.000*** (0.000)	-0.002*** (0.000)	-0.001*** (0.000)
Within 500 meters from metro	0.060*** (0.005)	0.052*** (0.005)	-0.029*** (0.008)	-0.003 (0.006)
Constant	0.942*** (0.007)	0.894*** (0.006)	0.995*** (0.015)	0.712*** (0.013)
Observations	115,370	115,504	43,668	43,700
R-squared	0.109	0.189	0.084	0.182
Panel C: Parcel-level height on the host ward with metro station				
Area (log)	0.044*** (0.001)	0.123*** (0.001)	0.016*** (0.002)	0.143*** (0.002)
Distance to city center	-0.052*** (0.002)	-0.040*** (0.002)	-0.015*** (0.003)	-0.021*** (0.002)
Squared distance to city center	-0.000*** (0.000)	-0.000** (0.000)	-0.002*** (0.000)	-0.001*** (0.000)
In a ward with a metro station	0.003 (0.004)	0.039*** (0.004)	-0.060*** (0.006)	-0.001 (0.005)
Constant	0.970*** (0.006)	0.901*** (0.006)	0.994*** (0.015)	0.711*** (0.013)
Observations	115,370	115,504	43,668	43,700
R-squared	0.107	0.189	0.086	0.182

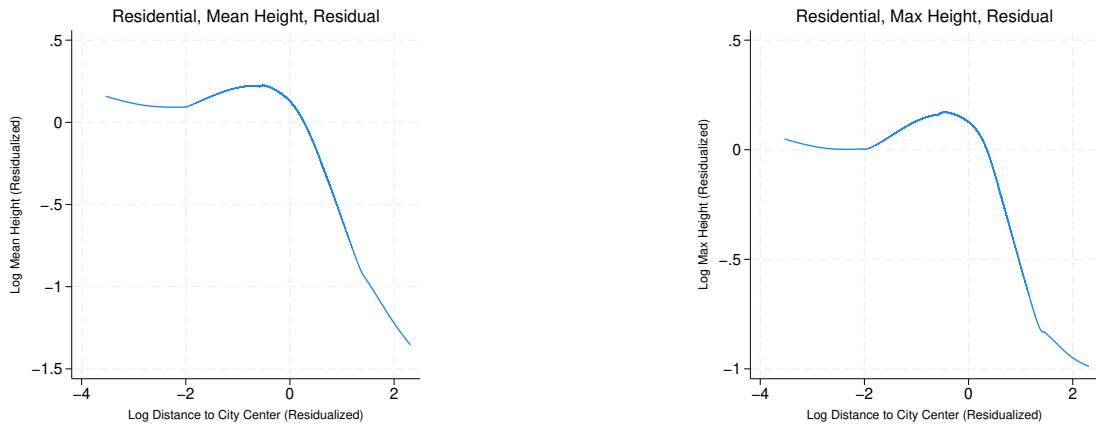
ORR = outer ring road.

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

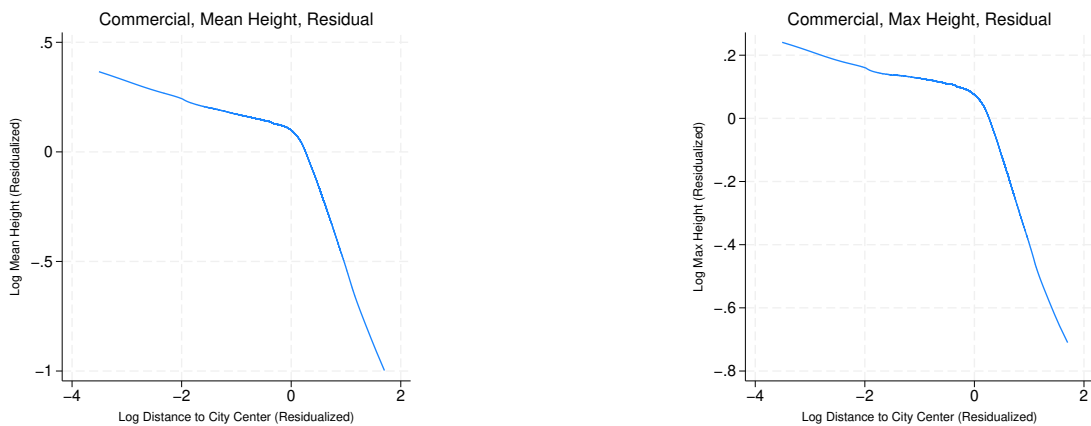
Source: Authors' estimates.

Figure 4: Height Gradients of Bengaluru (Residualized)

Panel (a): Residential



Panel (b): Commercial



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

Source: Authors' estimates.

regulation, involvement of multiple agencies in planning and development of urban infrastructure, land acquisition issues, and insufficient financing (Ramulu et al. 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 Table 2, we present the shares of land area for residential, commercial, and industrial 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%. While it is not clear what the land use mix is for TOD, 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 how much density these locations can sustain, 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 3, 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 considering 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 panel C of Table 3 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 4: 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

ORR = outer ring road.

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.

Source: Authors' estimates.

Table 4 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%.¹³ 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.¹⁴

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

¹³Total 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.

¹⁴For 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.

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.¹⁵

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, 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, v_{ij} , drawn from the Fréchet

¹⁵A canonical example of this model is Ahlfeldt et al. (2015). Sturm et al. (2023) show how such a model can be built for a city in a developing country with minimal data requirements.

distribution with cdf $F(v) = \exp(-v^{-\epsilon})$; (2) shock for the transportation mode, \tilde{v}_m , drawn from the Fréchet distribution with cdf $\tilde{F}(\tilde{v}) = \exp(-\tilde{v}^{-\sigma})$.

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

$$u_{mij}^s(n) = v_{ij}(n) X_i^s E_j^s (c_{G,ij}^s)^{1-\gamma} (c_{S,ij}^s)^\gamma \frac{\tilde{v}_m(n) B_m}{d_{mij}}, \quad (4.1)$$

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_i^s , E_j^s , 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_i^s are exogenous. Later, in Section 6.6, we study how sensitive our results are to this assumption. The budget constraint is

$$w_j^s = c_{G,ij}^s + q_{Ri} c_{H,ij}^s, \quad (4.2)$$

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:

$$d_{mij} = e^{\kappa t_{mij}}, \quad (4.3)$$

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.¹⁶

The demand functions for housing and the consumption good are

$$c_{G,ij}^s = (1 - \gamma) w_j^s \quad \text{and} \quad c_{H,ij}^s = \gamma \frac{w_j^s}{q_{Ri}}. \quad (4.4)$$

The indirect utility function, conditional on idiosyncratic shocks, is

$$v_{mij}^s = X_i^s E_j^s \frac{w_j^s B_m}{q_{Ri}^\gamma d_{mij}}. \quad (4.5)$$

¹⁶The exponential functional form is standard in the literature. See Ahlfeldt et al. (2015), Tsivanidis (2023), Zárate (2022), and many others.

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

$$\pi_{ij}^s = \frac{(v_{ij}^s)^\epsilon}{\sum_{i' \in I} \sum_{j' \in I} (v_{i'j'}^s)^\epsilon}, \quad (4.6)$$

where

$$v_{ij}^s \equiv \left[\sum_{m \in \mathcal{M}} (v_{mij}^s)^\sigma \right]^{\frac{1}{\sigma}} \quad (4.7)$$

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

$$\pi_{mij}^s = \frac{(v_{mij}^s)^\sigma}{\sum_{m' \in \mathcal{M}} (v_{m'ij}^s)^\sigma}. \quad (4.8)$$

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

$$\pi_{mij}^s = \pi_{mij}^s \pi_{ij}^s. \quad (4.9)$$

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

$$V^s = \Gamma\left(\frac{\sigma-1}{\sigma}\right) \Gamma\left(\frac{\epsilon-1}{\epsilon}\right) \left[\sum_{i \in I} \sum_{j \in I} \left[\sum_{m \in \mathcal{M}} (v_{mij}^s)^\sigma \right]^{\frac{\epsilon}{\sigma}} \right]^{\frac{1}{\epsilon}}, \quad (4.10)$$

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

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

$$N_{Ri}^s = \sum_{j \in I} \sum_{m \in \mathcal{M}} \pi_{mij}^s N^s, \quad (4.11)$$

as well as local employment,

$$N_{Wj}^s = \sum_{i \in \mathcal{I}} \sum_{m \in \mathcal{M}} \pi_{mij}^s N^s. \quad (4.12)$$

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 of a location is

$$N_{Ri} \equiv N_{Ri}^L + N_{Ri}^H \quad (4.13)$$

and total employment is

$$N_{Wj} \equiv N_{Wj}^L + N_{Wj}^H. \quad (4.14)$$

Migration. We allow for migration into and out of the city.¹⁷ 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

$$N^s = N_o^s \left(\frac{V^s}{V_o^s} \right)^\zeta. \quad (4.15)$$

Commuter market access. How attractive is a given residential location i to a given worker? Using equations (4.5) and (4.7), we can write the utility of choosing residence i before knowing the value of the workplace-mode shock as

$$v_i^s = X_i^s q_{Ri}^{-\gamma} \left(\mathcal{R}_{mi}^s \right)^{\frac{1}{\epsilon}}, \quad (4.16)$$

where

$$\mathcal{R}_{mi}^s \equiv \sum_{j \in \mathcal{I}} \left(\frac{E_j^s w_j^s}{\tilde{d}_{ij}} \right)^\epsilon \quad (4.17)$$

¹⁷In Section 6.6, we study the sensitivity of our results to the open city assumption.

is the residential commuter market access (CMA), and

$$\frac{1}{\tilde{d}_{ij}} \equiv \left[\sum_{m \in \mathcal{M}} \left(\frac{B_m}{d_{mij}} \right)^\sigma \right]^{\frac{1}{\sigma}} \quad (4.18)$$

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

$$\mathcal{F}_{mj}^s \equiv \sum_{i \in \mathcal{I}} \left(\frac{X_i^s q_{Ri}^{-\gamma}}{\tilde{d}_{ij}} \right)^\epsilon \quad (4.19)$$

4.2 Production Firms

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

$$Y_j = A_j \tilde{N}_j^\alpha H_{Wj}^{1-\alpha}, \quad (4.20)$$

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,

$$\tilde{N}_j = \left[\omega_j^L \left(N_{Wj}^L \right)^{\frac{\xi-1}{\xi}} + \omega_j^H \left(N_{Wj}^H \right)^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}, \quad (4.21)$$

where ξ is the elasticity of substitution, and ω_j^s 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

$$Y_j - w_j^L N_{Wj}^L - w_j^H N_{Wj}^H - q_{Wj} H_{Wj}, \quad (4.22)$$

where w_j^s 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

$$\frac{w_j^H}{w_j^L} = \frac{\omega_j^H}{\omega_j^L} \left(\frac{N_{Wj}^L}{N_{Wj}^H} \right)^{\frac{1}{\xi}}. \quad (4.23)$$

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

$$w_j^L = \alpha(1 - \alpha)^{\frac{1-\alpha}{\alpha}} A_j^{\frac{1}{\alpha}} (\omega_j^L)^{\frac{\xi}{\xi-1}} q_{Wj}^{-\frac{1-\alpha}{\alpha}} \left[1 + \left(\frac{\omega_j^H}{\omega_j^L} \right)^{\xi} \left(\frac{w_j^L}{w_j^H} \right)^{\xi-1} \right]^{\frac{1}{\xi-1}}. \quad (4.24)$$

The equilibrium demand for commercial floorspace is

$$H_{Wj} = \left(\frac{(1 - \alpha)A_j}{q_{Wj}} \right)^{\frac{1}{\alpha}} \tilde{N}_j. \quad (4.25)$$

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:

$$A_j = a_j \left(\frac{N_{Wj}}{\Lambda_j} \right)^{\lambda}. \quad (4.26)$$

Parameter $\lambda > 0$ measures the elasticity of productivity with respect to local employment density.¹⁸ 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

$$H_{fi} = \phi_{fi} L_{fi}^{\eta} K_{fi}^{1-\eta}, \quad (4.27)$$

¹⁸We do not include spatial spillovers of productivity between locations. These spillovers are highly localized, as found in Ahlfeldt et al. (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.

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:¹⁹

1. Zoning (extensive margin): specifies how much land in each ward can be used for residential or commercial use. In particular, a fraction v_{fi} of land can be used for development of type f , with $v_{Ri} + v_{Wi} = 1$. Thus, the developers' land input must satisfy:

$$L_{fi} \leq v_{fi}\Lambda_i. \quad (4.28)$$

2. Density limit or FAR (intensive margin): given zoning, specifies how much floorspace 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} :

$$h_{fi} \equiv \frac{H_{fi}}{L_{fi}} \leq \bar{h}_{fi}. \quad (4.29)$$

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

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

$$q_{fi}H_{fi} - l_{fi}L_{fi} - K_{fi}, \quad (4.30)$$

subject to constraints (4.28) and (4.29). Since there is no alternative use of land, all land will be developed, i.e., the optimal land input is $L_{fi} = v_{fi}\Lambda_i$. The equilibrium floorspace supply is

$$H_{fi} = \min \left\{ \bar{h}_{fi}v_{fi}\Lambda_i, \phi_{fi}(1-\eta)^{1-\eta} (D_{fi})^{1-\eta} (v_{fi}\Lambda_i)^\eta \right\}. \quad (4.31)$$

In the previous expression, D_{fi} is the total expenditure demand on floorspace of type f in location i . Using equation (4.4), we can solve for total residential expenditure demand,

$$D_{Ri} = \gamma \left(w_i^H N_{Ri}^H + w_i^L N_{Ri}^L \right). \quad (4.32)$$

Using equation (4.25), we can solve for total expenditure demand for commercial floorspace,

$$D_{Wj} = (1-\alpha)^{\frac{1}{\alpha}} A_j^{\frac{1}{\alpha}} q_{Wj}^{-\frac{1-\alpha}{\alpha}} \tilde{N}_j. \quad (4.33)$$

¹⁹The specification of land use regulation in our model is similar to the one in [Acosta \(2022\)](#).

The equilibrium price of type- f floorspace is

$$q_{fi} = \max \left\{ \frac{D_{fi}}{\bar{h}_{fi} v_{fi} \Lambda_i}, \frac{D_{fi}^\eta}{\phi_{fi} (1 - \eta)^{1-\eta} (v_{fi} \Lambda_i)^\eta} \right\}. \quad (4.34)$$

Equations (4.31) and (4.34) 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_{mij}^s is consistent with optimal choices of workers, as specified in equation (4.9);
- (b) A_j is determined according to equation (4.26);
- (c) w_{mj}^s clears the skill-specific local labor market, while N_{Wj}^s is consistent with profit-maximizing choices of firms, as described in equations (4.23) and (4.24);
- (d) q_{fi} clears the local floorspace market, while H_{fi} is consistent with profit-maximizing choices of floorspace developers, as described in equations (4.34) and (4.31); and
- (e) N_s satisfies equation (4.15).

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 5 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 United States (US). The elasticity of productivity with respect to density is set to $\lambda = 0.086$, as estimated by [Heblich et al. \(2020\)](#) for the city of London, UK.²⁰ To calibrate η , the share of land in construction, we use the elasticity of housing supply

Table 5: 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 et al. (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.

²⁰Meta-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 et al. 2020](#)).

estimated by [Saiz \(2010\)](#) for the US. 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) estimator and maximize the following log-likelihood function,

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

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 . Table 6 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.²¹ 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 Section B.1. The calibrated value of B_p is 1.19, which reflects the relative preference for using a private vehicle.

Table 6: 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. Source: Authors' estimates.

²¹Other studies that estimate the commute cost elasticity arrive at similar estimates. For instance, [Ahlfeldt et al. \(2015\)](#) find a value of 0.011 and [Zárate \(2022\)](#) finds 0.009.

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

$$\frac{\pi_{Tij}^s}{\pi_{Pij}^s} = \left(\frac{v_{Tij}^s}{v_{Pij}^s} \right)^\sigma. \quad (5.2)$$

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

$$\frac{\partial \ln(\pi_{Tij}^s / \pi_{Pij}^s)}{\partial \ln t_{Tij}} = -\sigma \kappa t_{Tij}. \quad (5.3)$$

Note that the left-hand side can be decomposed into the difference between the own-elasticity, $\partial \ln \pi_{Tij}^s / \partial \ln t_{Tij}$, and the cross-elasticity, $\partial \ln \pi_{Pij}^s / \partial \ln t_{Tij}$. We use available estimates of own- and cross-elasticities of transit ridership with respect to commuting times on transit and by car from [Frank et al. \(2008\)](#): -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_i^s , ω_j^s , ψ_j , ϕ_{fi} , a_j , and E_j^s 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_i^s) and employment (E_j^s) 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.2](#) 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 v_{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 \(4.34\)](#), 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.²² 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 (4.34) 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 (4.34) 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.²³ 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.

²²Twelve out of 66 outside-ORR wards have binding residential FAR limits, and 7 out of 66 wards have binding commercial FAR limits.

²³If 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., $t_{Tij} = \min \{t_{bus,ij}, t_{metro,ij}\}$. 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.

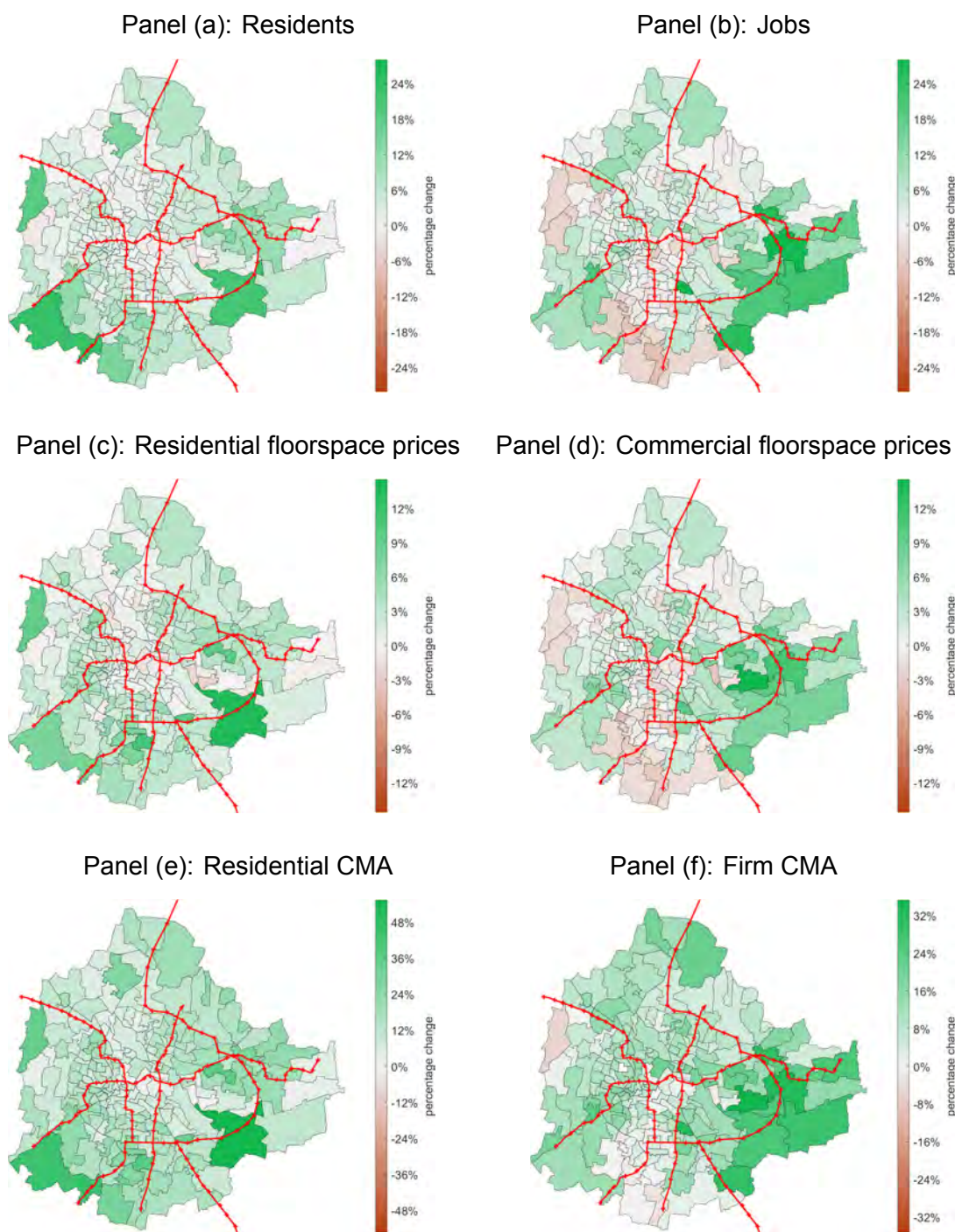
Panels (a) and (b) of Figure 5 show the counterfactual changes in residents and jobs. There is mild decentralization of both: as shown in column (1) of panel A in Table 7, the share of residents in central wards declines by 0.7 percentage points, while the share of jobs declines by 1 percentage point. 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 7 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.²⁴

²⁴CMA is a sufficient statistic for welfare gains, as shown in Tsivanidis (2023), and it also incorporates

Figure 5: Local Effects of Introducing the Metro



CMA = commuter market access.

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.

Source: Authors' estimates.

changes in wages and housing costs, as can be seen from equations (4.17) and (4.19).

Table 7: Aggregate Effects of Metro and Land Use Policies

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

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

FAR = floor-to-area ratio, ORR = outer ring road.

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.

Source: Authors’ estimates.

As panel (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 7 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.²⁵ 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 Figure 6 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.

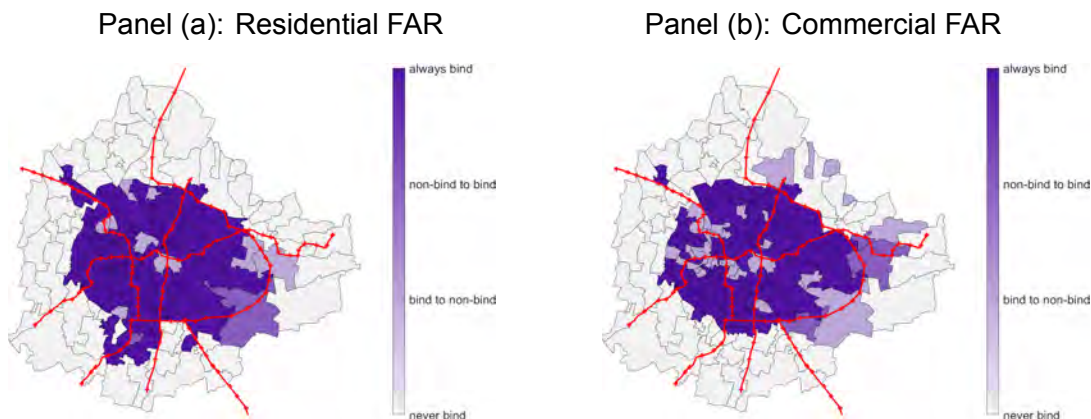
In what follows, we study how changes in land use regulations interact with the introduction of the metro. First, we simulate a policy of TOD by increasing FAR limits near metro stations. Second, we increase FAR limits in all central wards. Finally, we change zoning as envisaged by the 2031 Land Use 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 2.²⁶ This results in varying increases in FARs at the

²⁵The 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%.

²⁶The limit of 2 is below the current limit of 4 near metro stations. However, as discussed in Dhindaw et al. (2021), the FAR of 4 may not be achievable because most land parcels near stations are too small to accommodate tall buildings.

Figure 6: Binding and Nonbinding FAR Limits (Introduction of the Metro)



FAR = floor-to-area ratio.

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").

Source: Authors' estimates.

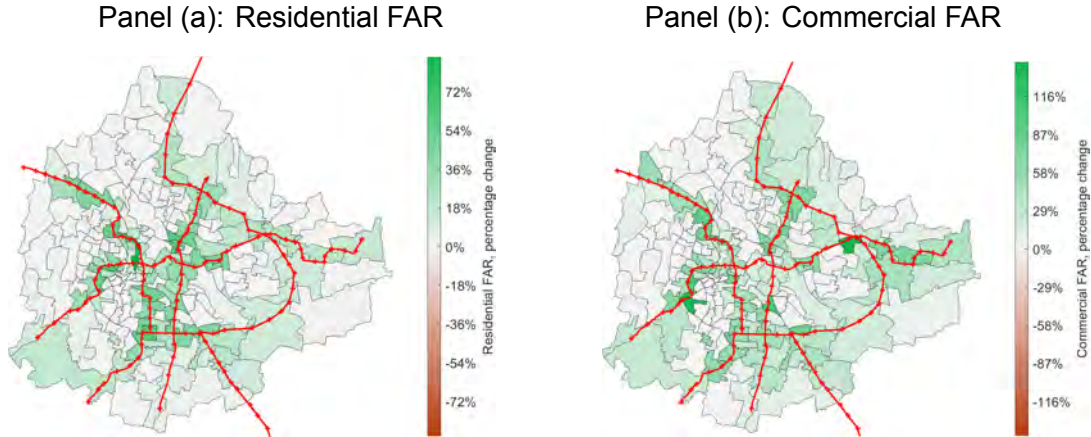
ward level. The affected wards include those with metro stations (70 wards) and those with land parcels within 500 meters of a station. Figure 7 shows the percentage changes in FAR limits in each ward for both residential and commercial development. Within the ORR, where the FAR limits are binding, the average ward sees a 15% increase in residential FAR limits and a 27% increase in commercial FAR limits. Appendix Figure C.7 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 7 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

Figure 7: Transit-Oriented Development



FAR = floor-to-area ratio.

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.

Source: Authors' estimates.

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 7.

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.²⁷ 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.

²⁷This reflects the abundance of high-skilled jobs in the city center in the data.

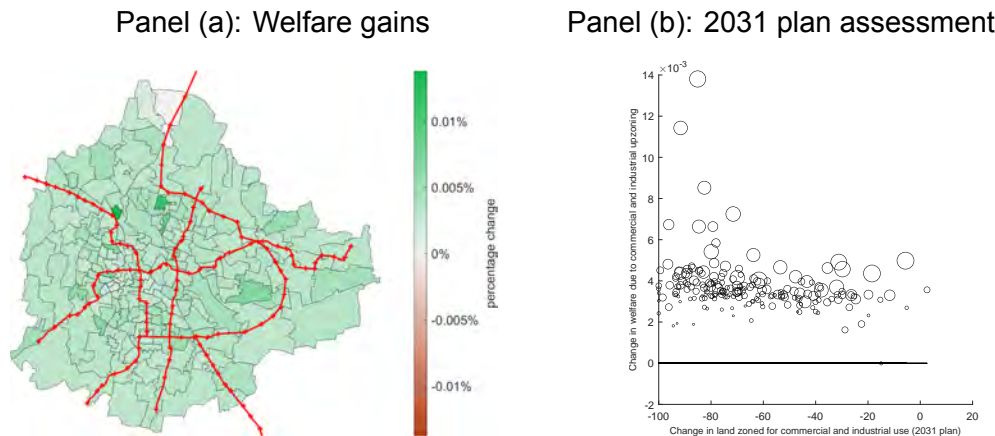
Columns (4) and (5) of Table 7 summarize the results. Many of the outcomes are comparable to the counterfactuals with TOD. One difference is that in this scenario, there is much more concentration of jobs and residents in the city center, which is not surprising since the policy treats only central wards. 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 7 show the results. The economy suffers huge welfare 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.

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 increase the area of land zoned for commercial and industrial use by 5,000 square meters 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. Panel (a) of Figure 8 shows that commercial rezoning in the vast majority of wards yields city-wide welfare gains.

Figure 8: Commercial/Industrial Upzoning vs. 2031 Land Use Plan



Note: Panel (a) shows city-wide welfare gains from increasing commercial/industrial land area by 5,000 sq meters in a single ward. Panel (b) shows the relationship between the percentage change in the land area zoned for commercial/industrial use in 2031 and the city-wide welfare gain resulting from adding 5,000 sq meters of commercial/industrial in a given ward. The size of a circle is proportional to ward's employment in the benchmark economy.

Source: Authors' estimates.

Panel (b) compares the proposed changes in commercial zoning in the 2031 plan with the model-based welfare contributions of 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 seems that the 2031 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%.

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.

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. We measure welfare gains using a consumption-equivalent

Table 8: Cost-Benefit Analysis

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

FAR = floor-to-area ratio, GDP = gross domestic product, ORR = outer ring road.

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

Source: Authors' estimates.

measure.²⁸ Therefore, a GDP-equivalent gain per worker is equal to 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 7) where the welfare gain is 1.3% and land values increase by 4.1%. This is equivalent to an increase in output per worker of $0.82 \times 1.3\% + 0.18 \times 4.1\% = 1.8\%$. If we take into account that the number of workers goes up by 4%, the growth in total output is almost 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 are estimated at \$7,200 million. At a 5% annual cost of capital, as in Allen and Arkolakis (2014), this amounts to \$360 million per year. 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.²⁹ Note, however, that most of the GDP increase 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 on a per-worker basis is only 0.2% of GDP.

Table 8 shows the cost-benefit analysis for other counterfactuals using the same calculation. In scenarios with TOD and central upzoning, the net gains are much larger:

²⁸To 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 4.10).

²⁹The 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.

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.³⁰ However, the construction of the metro could have much 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

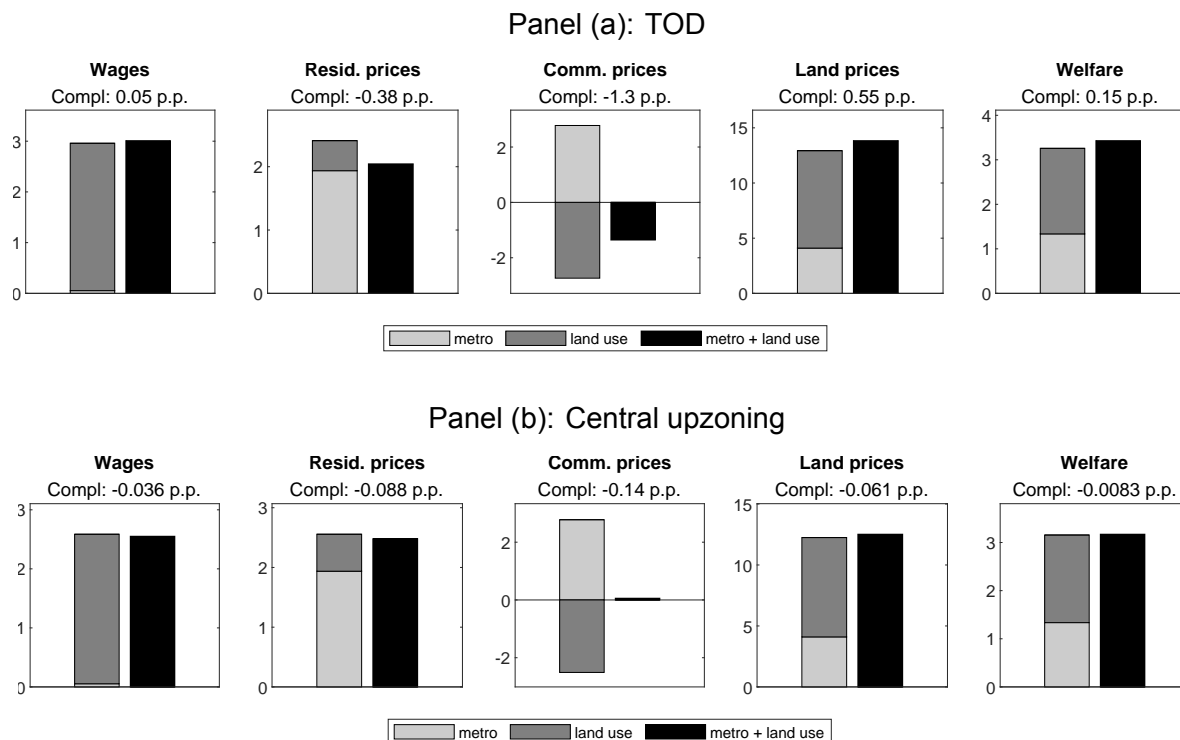
The results in Sections 6.1 and 6.2 suggest that both transit improvements, such as the construction of the metro, and land use reforms, such as TOD or upzoning in central areas, can increase welfare and improve various outcomes. However, it is equally important to understand whether or not these policies 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

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

³⁰In 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.

Figure 9: Complementarity of Transportation and Land Use Policies



TOD = transit-oriented development.

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.

Source: Authors’ estimates.

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.³¹ “Land use” can represent any of the three land use policies studied above.

We study the complementarity between the metro on the one hand, and TOD and central upzoning on the other.³² The results are reported in Figure 9. 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

³¹For 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 $C(Z) = (1.03 - 1) - (1.01 \times 1.01 - 1) \approx 0.01$. That is, the complementarity between the two policies leads to a 1 percentage point larger effect on variable Z .

³²Because the 2031 Land Use Plan results in large welfare losses, we do not study the complementarity between the metro and the 2031 plan.

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 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.³³

The results can be found in Appendix Table D.1. 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 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

In this section, we study how sensitive our results are to values of key parameters and to some assumptions we have made.

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 et al. \(2020\)](#). 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:

$$X_i^s = x_i^s \left(\frac{N_{Ri}}{\Lambda_i} \right)^\chi. \quad (6.2)$$

Parameter χ measures the elasticity of amenities with respect to the local density of residents. We set $\chi = 0.172$ following [Heblich et al. \(2020\)](#), although there is little

³³Counterfactuals 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.

consensus in the literature about the value of this elasticity.³⁴ Then we recalibrate the benchmark economy and rerun all counterfactuals.

The results can be found in Appendix Table D.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 Appendix Table D.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 Appendix Table D.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.

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 4.26) and then recalibrate the model.

³⁴Meta-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).

The results are in Appendix Table D.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 US 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 0.1.³⁵ Then we recalibrate the model and rerun the counterfactuals.

Appendix Table D.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 Appendix Table D.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 4.3), 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.

³⁵With such low substitution, the production function approaches Leontief.

Table 9: Complementarity of Transportation and Land Use Policies in Sensitivity 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

ORR = outer ring road, TOD = transit-oriented development.

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 9. The following rows show complementarity for sensitivity checks discussed in this section. The complementarity is calculated using formula (6.1).

Source: Authors' estimates.

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.

Appendix Table D.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 US. However, it is likely that a large city in a developing country has a lower elasticity. For example, Sturm et al. (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 US.

Appendix Table D.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 9 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.

6.7 Discussion

In this section, we discuss a number of additional factors that may be considered when studying the interaction of 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 7, most of the switchers are previously bus riders and buses presumably contribute less to traffic congestion than private vehicles.³⁶ 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 certainly produces much 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

³⁶First, buses allow for a denser layout of passengers inside a vehicle. Second, some streets in Bengaluru have dedicated bus lanes.

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 et al. \(2020\)](#).

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.

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 particularly 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 Barr, J. (2022). The economics of skyscrapers: A synthesis. *Journal of Urban Economics*, 129(C):S0094119021001017.
- Ahlfeldt, G. M. and Pietrostefani, E. (2019). The economic effects of density: A synthesis. *Journal of Urban Economics*, 111:93–107.
- Ahlfeldt, G. M., Redding, S. J., Sturm, D. M., and Wolf, N. (2015). The economics of density: Evidence from the Berlin Wall. *Econometrica*, 83(6):2127–2189.
- Akbar, P., Couture, V., Duranton, G., and Storeygard, A. (2023a). The fast, the slow, and the congested: Urban transportation in rich and poor countries. Working Paper.
- Akbar, P., Couture, V., Duranton, G., and Storeygard, A. (2023b). Mobility and congestion in urban India. *American Economic Review*, 113(4):1083–1111.
- Allen, T. and Arkolakis, C. (2014). Trade and the topography of the spatial economy. *The Quarterly Journal of Economics*, 129(3):1085–1140.
- Allen, T., Arkolakis, C., and Li, X. (2016). Optimal city structure. Working Paper.
- Amirkolaee, H. A. and Arefi, H. (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., Ferreira, F. V., and Rexer, J. M. (2021). Estimating the economic value of zoning reform. Working Paper 29440, National Bureau of Economic Research.
- Balboni, C., Bryan, G., Morten, M., and Siddiqi, B. (2020). Transportation, gentrification, and urban mobility: The inequality effects of place-based policies. Working Paper.
- Bank, W. (2013). *Urbanization Beyond Municipal Boundaries: Nurturing Metropolitan Economies and Connecting Peri-Urban Areas in India*. The World Bank.
- Barr, J. and Jedwab, R. (2023). Exciting, boring, and nonexistent skylines: Vertical building gaps in global perspective. *Real Estate Economics*, n/a(n/a).
- Bertaud, A. and Brueckner, J. K. (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 Sridhar, K. S. (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., Glaeser, E., and Tsivanidis, N. (2020). Cities in the developing world. *Annual Review of Economics*, 12(1):273–297.
- Bryan, G. and Morten, M. (2019). The aggregate productivity effects of internal migration: Evidence from Indonesia. *Journal of Political Economy*, 127(5):2229 – 2268.
- Cao, Y. and Huang, X. (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., Kumaraswamy, S. K., Prakash, V. S., Chanchani, R., and Deb, A. (2021). Synergizing land value capture and transit-oriented development: A study of Bengaluru metro. Practice Note. World Resources Institute India.
- Dingel, J. I. and Tintelnot, F. (2021). Spatial economics for granular settings. Working Paper.
- Duranton, G. and Puga, D. (2022). Urban growth and its aggregate implications. Working Paper.
- Duranton, G. and Turner, M. A. (2011). The fundamental law of road congestion: Evidence from US cities. *American Economic Review*, 101(6):2616–52.
- Frank, L., Bradley, M., Kavage, S., Chapman, J., and Lawton, T. (2008). Urban form, travel time, and cost relationships with tour complexity and mode choice. *Transportation*, 35(1):37–54.
- Frantz, D., Schug, F., Okujeni, A., Navacchi, C., Wagner, W., van der Linden, S., and Hostert, P. (2021). National-scale mapping of building height using sentinel-1 and sentinel-2 time series. *Remote Sensing of Environment*, 252:112128.
- Gechter, M. and Tsivanidis, N. (2023). Spatial spillovers from high-rise developments: Evidence from the Mumbai mills. Working Paper.
- Geshkov, M. V. and DeSalvo, J. S. (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., Redding, S. J., and Sturm, D. M. (2020). The making of the modern metropolis: Evidence from London. *Quarterly Journal of Economics*, 135(4):2059–2133.

- Henderson, J. V., Regan, T., and Venables, A. J. (2020). Building the city: From slums to a modern metropolis. *The Review of Economic Studies*, 88(3):1157–1192.
- Herkenhoff, K. F., Ohanian, L. E., and Prescott, E. C. (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 Moretti, E. (2019). Housing constraints and spatial misallocation. *American Economic Journal: Macroeconomics*, 11(2):1–39.
- Jain, D. and Singh, E. (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., Gaduh, A., Graff, T., Hanna, R., and Olken, B. A. (2023). Optimal public transportation networks: Evidence from the world’s largest bus rapid transit system in Jakarta. Working Paper.
- Lall, S., Lebrand, M., Park, H., Sturm, D., and Venables, A. (2021). Pancakes to pyramids. World Bank Publications - Reports 35684, The World Bank Group.
- Li, M., Koks, E., Taubenböck, H., and van Vliet, J. (2020a). Continental-scale mapping and analysis of 3D building structure. *Remote Sensing of Environment*, 245:111859.
- Li, X., Zhou, Y., Gong, P., Seto, K. C., and Clinton, N. (2020b). Developing a method to estimate building height from sentinel-1 data. *Remote Sensing of Environment*, 240:111705.
- Liu, C., Huang, X., Wen, D., Chen, H., and Gong, J. (2017). Assessing the quality of building height extraction from ziyuan-3 multi-view imagery. *Remote Sensing Letters*, 8(9):907–916.
- Liu, C., Huang, X., Zhu, Z., Chen, H., Tang, X., and Gong, J. (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., Sankar, K., and Randhawa, A. (2021). Challenges of transit oriented development (TOD) in Indian cities. *Institute of Town Planners, India Journal*, 18(2):37–55.
- Roy, S. and Shah, A. (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*, pages 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., Takeda, K., and Venables, A. J. (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 Herrendorf, B. (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.
- 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.

Faster, Taller, Better

Transit Improvements and Land Use Policies

This paper examines how the effects of transit improvements vary with land use policies using the case of Bengaluru, one of India's largest cities with a metro system and subject to low floor-area ratios. We build a quantitative spatial model and show that the metro system increases citywide output and welfare, even net of costs. However, the net gains are several times larger when floor-area ratio limits are relaxed near metro stations (transit-oriented development) or in the city center.

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