Congestion Tolls Efficiently Reduce CO2 Emissions from Homes in addition to Urban Transportation in the Long Run

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Abstract. Greenhouse gas emissions caused by urban residents' energy consumption arise from the 1) transportation and 2) housing sectors. This energy consumption depends on the population distribution of the city. This study quantitatively examines the effectiveness of congestion tolls, carbon tax, and land use regulations on the social welfare and the reduction of urban CO_2 emissions. Results show that, among the three policies, the congestion toll can increase the social welfare by about 99% of the increase in the first-best scenario, which shows the best among the three policies, and can reduce the amount of total CO_2 emissions by about 22%, which is almost the highest level among the three policies. These results suggest that congestion tolling, which is primarily the Pigovian tax for congestion, does not only internalize congestion externalities but also reduce CO_2 emissions rather effectively through downsizing transportation distances and housing sizes with the spatial change in population density in the city.

Keywords: Carbon tax, Congestion tolls, CO_2 emissions, Land use regulations

JEL classification: R11, R13, R14, R52

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1. Introduction

Global warming is a worldwide problem, which can cause various unpredictable disasters, including the spread of infectious diseases[1]. In 2019, the World Meteorological Organization announced that the world average concentration of major greenhouse gases (GHG, mainly CO_2) in 2018 reached a record high. This is despite the fact that many countries established rather large reduction targets over a decade earlier. At the United Nations Framework Convention on Climate Change (1992), China, India, Japan, and the USA targeted 60-65%, 33-35%, 26%, and 26-28% reductions in greenhouse gas emissions, respectively, from 2005 to 2030 (2025 in the USA). Other countries also set their own targets. To achieve these targets, a lot of endeavors are likely to be required in a vast range of sectors.

While industrial sectors generate CO_2 emissions, urban activities (e.g., households and urban traffic) also generate a large amount of CO_2 emissions. According to the 2017 report by the Ministry of Environment in Japan, about 30% of CO_2 emissions come from urban residential activities. Similarly, the US Environmental Protection Agency (2015) reports that about half of GHG emissions come from urban activities.

CO_2 emissions caused by urban residents' energy consumption arise from the 1) transportation and 2) housing sectors. Pigovian tax is a solution to congestion as well as CO_2 emissions. Pigovian tax on CO_2 emissions is called carbon tax, and it has been introduced by many countries. Carbon tax can directly decrease individual energy consumption, and indirectly decrease energy consumption through a change in the distribution of residents

[1] Indeed, a recent report "Preventing the next pandemic" by the United Nations (2020) says "Climate change is a major factor in disease emergence. The survival, reproduction, abundance and distribution of pathogens, vectors and hosts can be influenced by climatic parameters affected by climate change. Warmer temperatures could also increase the incidence of disease both by increasing the vector population size and distribution and by increasing the duration of the season in which infectious vector species are present in the environment."

within the city. Congestion also depends on the distribution of residents. So, carbon taxes reduce not only CO_2 emissions but also congestion externalities. Similarly, congestion pricing, which is a Pigouvian tax on congestion, can reduce CO_2 emissions through the change in the distribution of residents.

Likewise, change in land use regulations, a typical urban policy, also has effects on energy demand and congestion externalities through the change in the distribution of residents. The change in the distribution of residents changes the total commuting distance and the congestion levels. In addition, as floor space per household increases, household energy consumption from lighting, cooling and heating increases. Land use policies can change CO_2 emissions through changes in floor space per household.

In summary, carbon tax and congestion pricing, which are primarily Pigouvian taxes for the respective externalities, and land use regulations all reduce CO_2 emissions through the change in energy consumption in the 1) transportation and 2) housing sectors by changing the spatial distribution of residents.

Some empirical studies have investigated the relation between urban land use and energy use from various viewpoints. Glaeser and Kahn (2010) compared CO_2 emissions across U.S. cities and within U.S cities with respect to transportation (cars and public transportation), home heating, and household electricity. As a result, they show that denser cities generally have lower CO_2 emissions, and that urban areas, which are denser than suburban areas, generally have significantly lower emissions than suburban areas. Iwata and Managi (2014) have found that land use policies such as taxes and command-and-control regulations can alter city density and may change CO_2 emissions. Waldron et al. (2013) have reported that energy use would change if a group of buildings were relocated. However, forced relocation of buildings cannot result in a long-term equilibrium. In the long-run, residents' utilities are in equilibrium as the equilibrium rents change.

To explore such a long-term effect, urban locational equilibrium models incorporating energy-usage can be used for the quantitative appraisal of the effects of urban policies on CO_2 emissions. Bertaud and Brueckner (2005) numerically calculate the welfare cost of building size regulation at urban location equilibrium. Some studies have shown that floor area ratio (FAR) regulation and urban growth boundary (UGB) policy can substitute as a second-best regime for a first-best toll regime in a congested city (Brueckner, 2007; Kono and Joshi, 2019). Larson et al. (2012) and Larson and Yezer (2015) have shown that gasoline tax, urban greenbelts, and FAR regulation affect energy demand in urban areas in consideration of urban spatial equilibrium; however, they did not consider environmental externality explicitly. Borck (2016) explores the effects of maximum FAR regulations on environments. He does not consider traffic congestion, and does not evaluate optimal FAR regulation, energy policy, or toll regime.

As the first exploration of the effects of energy taxation in an urban setting, Borck and Brueckner (2017) show that considering energy consumption due to transportation and housing in a city, the combination of energy tax, commuting tax, and housing tax makes the city more compact and reduces energy consumption. However, they do not consider traffic congestion, which is a typical externality in a city. If we additionally consider traffic congestion, we can compare the effects of urban policies on the welfare including welfare losses due to congestion. In addition, urban policies affecting the size of housing lots change energy consumption on air conditioning in housing. About 14% of CO_2 emissions come from the household sector, and a quarter of this is due to air conditioning (Energy White Paper 2017, Japan). So, it is necessary to consider the use of air conditioning depending on the size of housing lots[2] as well.

[2] Another difference is that our study evaluates the effect of optimal FAR regulation.

With this background, we study the externalities of congestion and CO_2 emissions and numerically evaluate how urban policies influence the structure of the city, social welfare and CO_2 emissions. In particular, we target the broad impacts of urban policies (i.e. congestion toll regime, FAR regulation) and carbon tax on urban energy structure to clarify the effects of these policies on CO_2 emissions from a long-term view. For this purpose, we use a spatial general equilibrium model which can take account of traffic congestion and global warming externalities.

We extend the spatial general equilibrium model of a congested monocentric city developed by Kono et al. (2012). In our model, residents decide to choose the location where they live, and consumption of housing space. In addition, they select the temperature on their air-conditioner. Indeed, using the U.S. city data, Glaeser and Kahn (2010) show that places with milder Januarys (hotter Julys) have lower (higher) emissions, which is the result of less (more) use of artificial heating (cooling). So, it is important to consider energy consumption for heating and air conditioning.

In our model, residents consume energy for air-conditioning to endogenously set the room temperature of their houses to a comfortable level. Rehdanz and Maddison (2005) demonstrate that there is a close relationship between climate (e.g., temperature, and precipitation) and well-being of the people. Our model supposes that people maximize their own utility through their use of energy. According to Glaeser and Kahn (2010), in most of the U.S. cities, homes in urban areas use lower volumes of electricity than homes in the suburbs. This reflects the difference in energy-efficiency with respect to the size of housing lots[3]. Our

[3] But Glaeser and Kahn (2010) show that this energy consumption tendency between cities and suburbs is not clear with respect to heating-related emissions. It depends on the city. This is probably because the building structure can affect heating-efficiency. The current paper does not consider the difference in building structures. This is for a future study.

endogenous energy consumption mechanisms naturally take account of such a dependency of the energy efficiency on the housing lot size.

The remainder of this paper is organized as follows. Section 2 presents the model. Section 3 presents the explanation of parameters we used for this analysis. Section 4 reports our main findings and explains the mechanisms of the findings. Section 5 provides a conclusion while discussing the broader applicability of the findings. Finally, the Appendix section provides mathematical derivations.

2. Model

2.1. The city

We extend the spatial general equilibrium model of a congested monocentric city developed by Kono et al. (2012). The city is circular, and is symmetric along any radial axis. We consider a closed city accommodating N households. The residential area in the city expands from $x = 0.1$ at the edge of the central business district (CBD) to $x = \bar{x}$ at the urban boundary. Since we focus on only the residential areas, it is not meaningful for the radius of the business area to be set as 0.1. This corresponds to a point CBD assumption. The urban boundary $\bar{x}$ is detemined endogenously. At each location, a constant fraction, ρ_r, of the land is used for a radial road network, and ρ_h is the share of land available for housing. Developers build dwelling units on land rented from the absentee landowners. The total floor supply per unit area of land at x is denoted by $F(x)$, which expresses building height or FAR at x, and is regarded as a continuous function of distance.

2.2. Household behavior

The model introduces environmentally-related factors such as temperature and energy use into a spatial general equilibrium model of a congested monocentric city. Residents use energy for lighting, cooling, heating, etc., to control the temperature of their houses.

For simplicity, one member of a household commutes to the CBD.[4] A household can choose one location within the city to reside. The per-year utility of a household is assumed to be composed of a partial utility function of housing area, denoted q, numeraire composite goods, denoted c, which includes all non-housing consumer goods, and another partial utility of temperatures in summer and winter, denoted $t_c(m)$ for $m \in summer$ and $t_h(m)$ for $m \in winter$. m denotes a month and $m = 1,2,\ldots,12$. The utility function is given by

$$v = c + g(q) + h(\,t_c(m)_{m\in summer}, t_h(m)_{m\in winter}), \tag{1}$$

where $g(q)$ is a concave function of q, and $h(t_c(m)_{m\in summer}, t_h(m)_{m\in winter})$ is a concave function of monthly room temperatures with air-conditioning. We divide a year into two seasons, summer and winter, and assume that residents use cooling or heating.

The household utility is maximized subject to the budget constraint given by

$$c + pq + \Phi(t_c, t_h, q, p_l, p_c, p_h) = y - k(x), \text{ and} \tag{2}$$

$$\Phi(t_c, t_h, q, p_l, p_c, p_h) \equiv p_l q + p_c q \textstyle\sum_{m\in summer}\big(t_o(m) - t_c(m)\big) + p_h q \textstyle\sum_{m\in winter}(t_h(m) - t_o(m)), \tag{3}$$

where $\Phi(\cdot)$ is the expenditure on air-conditioning (cooling and heating) and light in a house. y is the household income per period under consideration, $k(x)$ is the round-trip commuting cost to the CBD from x, which is distance from the CBD, p is the price per square meter of housing, p_l is the energy price per meter for lighting per square meter, p_c is the energy price per square meter to lower the temperature by 1 degree Celsius, p_h is the energy price per square meter to raise the temperature by 1 degree Celsius $t_o(m) - t_c(m)$

[4] Total population is given by multiplying N by household size. If the household size is constant over distance, the number of households is proportional to population density.

and $t_h(m) - t_o(m)$ represent the difference between the room temperature and outside temperature $t_o(m)$[5] in summer and winter, respectively.

The first term of Eq. (3) captures the effect that energy use of lighting increases with an increase in a household's floor space. The second and third terms capture the effect that energy use increases with an increase in the difference between outside temperature and the room temperature. In our model, the temperature at which residents feel most comfortable is assumed to be 23 degrees (hereafter $\bar{a}$), and they choose the room temperature on air-conditioning under a budget constraint to maximize their own utility. Disutility increases as the difference between the set temperature and $\bar{a}$ increases. For example, residents use heating if room temperature is below $\bar{a}$, which we define as winter, and they use cooling if it is above $\bar{a}$, which we define as summer. Floor rent p equals the maximum floor rent bid by a household as a result of the competition among residents.

Substituting the resulting demand functions back into the utility function and equating the result to a parametric utility level at location x, $v(x)$ solves $p(x)$ and $q(x)$ as

$$p(x) = p(y - k(x), v(x)) \text{ and } q(x) = q(y - k(x), v(x)). \tag{4}$$

2.3. Commuting Cost

We assume that automobiles are the only mode of commuting, and that only one radial route extends across the residential zone between the CBD and the urban boundary. Furthermore, the commuting cost is incurred only when commuting to and from the CBD edge. According to most of the prior literature including Brueckner (2007), and Kono et al. (2012), the commuting cost per km at x is given by

[5] We assume that indoor temperature is equal to outside temperature when residents do not use air-conditioning in their homes. We do not consider the thermal insulation performance of housing.

$$T(x) = \eta(1+\delta)\left[\frac{n(x)}{C}\right]^{\zeta}, \tag{5}$$

where η, δ, ζ are positive parameters, $n(x)$ denotes the number of households residing beyond x and C denotes the road capacity. Because commuters from more distant locations increasingly join traffic while moving towards the CBD, the unit cost of commuting from x depends on the ratio of traffic volume to road capacity, expressed by $n(x)/C$.[6]

The term $\delta[n(x)/C]^{\zeta}$ in Eq. (5) denotes congestion, whereas $n(x)$ is expressed as $n(x) = \int_x^{\bar{x}} 2\pi s \rho_h D(s) ds$. Note that $n(0.1) = N$ and $n(\bar{x}) = 0$. When an additional commuter joins traffic at x, the resultant change in congestion cost is given by $\partial T(x) / \partial n(x)$, which, multiplied by $n(x)$, gives the total externality caused by unpriced congestion, expressed as

$$n(x)\frac{\partial T(x)}{\partial n(x)} = \zeta\delta\left[\frac{n(x)}{C}\right]^{\zeta} \equiv \tau_1(x), \tag{6}$$

where $\tau_1(x)$ equals congestion toll at x that fully internalizes congestion externality.

In addition, the total damage from the CO_2 emissions externality at location x is generated. A commuter at x pays the total commuting cost, denoted by $k(x)$, which is inclusive of the congestion toll, carbon tax and direct costs, and is given by

$$k(x) = \int_{0.1}^{\bar{x}} \{T(s) + \tau_1(s) + \tau_2(s)\} ds, \tag{7}$$

where $\tau_2(x)$ expresses carbon tax at location x.[7]

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[6] Previous studies define road capacity as $2\pi x \rho_r$. Instead of $2\pi x \rho_r$, we set a constant C as road capacity; because we make the model generate the actual congestion level when using congestion parameters set by the Japanese Society of Civil Engineers, we set value C as 175,000 so as to make the congestion level equal to the actual level in the baseline simulation.

[7] $\tau_2(x) = carbon\ price\left(\frac{yen}{tCO_2}\right) \times fuel\ consumption(l) \times emission\ factor\left(\frac{tCO_2}{l}\right)$

$\Leftrightarrow \tau_2(x) = 15{,}000\left(\frac{yen}{tCO_2}\right) \times \frac{231(times)\times 2(round\ trip)\times x(km)}{9.4\left(\frac{km}{l}\right)} \times 0.00232\left(\frac{tCO_2}{l}\right) \quad \therefore \tau_2(x) = 1710x$

When no congestion toll and carbon tax are levied in the city, $\tau_1(x)$ and $\tau_2(x)$ in Eq. (7) are set to zero. Finally, to help set the stage for what will come later, we differentiate $n(x)$ and $t(x)$ with respect to distance x, which yields

$$n'(x) \equiv \frac{dn(x)}{dx} = -2\pi x \rho_h D(x) \quad \text{and} \quad k'(x) \equiv \frac{dk(x)}{dx} = T(x) + \tau_1(x) + \tau_2(x). \quad (8)$$

2.4. Developers' Behavior

Developers are assumed to be perfectly competitive and are therefore price-takers. They combine housing capital (or building materials) and land to produce residential buildings. Housing output per unit of land is expressed as $F(S)$, where F is the housing production (floor area) function, and S is the capital-to-land ratio. Using S as the reverse function of $F(S)$, the total developers' net profit from the total floor space supply in the city, denoted Π, is given by

$$\Pi = \int_{0.1}^{\bar{x}} 2\pi x \rho_h [F(x)p(x) - S(F(x)) - r(x)]dx, \quad (9)$$

where $r(x)$ is the land rent, and the price of capital is normalized at unity. Developers maximize profit per unit of land with respect to $F(x)$. Solving the relevant first-order condition for $F(x)$ provides

$$p(x) - \partial S/\partial F = 0, \quad (10)$$

and solving Eq. (10) for $F(x)$ and $S(F)$ yields

$$F(x) = F(y - k(x), v(x)) \quad \text{and} \quad S(F(x)) = S(y - k(x), v(x)). \quad (11)$$

Substituting this solution into the profit function in Eq. (9), and considering that the developers' profit is zero at any location because of perfect competition among developers,

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The external cost of carbon dioxide emissions is set at 15,000 yen / tCO2, which is the Swedish standard tax rate. Sweden has led the way in terms of carbon tax since 1991 (Japanese Ministry of the Environment, 2017).

the land rent is expressed as

$$r(x) = F(x)p(x) - S(F(x)) = r(y - k(x), v(x)). \tag{12}$$

Finally, population density, denoted by D, equals housing square km per unit of land divided by square km per dwelling, and is expressed as

$$D(x) = \frac{F(S(x))}{q(x)}. \tag{13}$$

2.5. Market Clearing Conditions

The market clearing conditions are given as follows. Equation (14) implies that the total population N is exogenously given and is fixed.

$$\int_{0.1}^{\bar{x}} 2\pi x \rho_h D(y - k(x), v(x))dx = N \tag{14}$$

Equation (15) states that the household utility across all locations should be equal to the equilibrium utility level, which is endogenously determined.

$$v(x) = u \quad \forall x \in [0.1, \bar{x}] \tag{15}$$

The total floor space supplied by developers at a location equals the total floor space consumed by households at that location, which is expressed by

$$F(x) = D(x)q(x) \quad \forall x \in [0.1, \bar{x}]. \tag{16}$$

Finally, Eq. (17) implies that the land rent at the edge of the city is equal to the agricultural rent, denoted by r_a in the case of no urban growth boundary (UGB) regulation.

$$r(y - k(\bar{x}), u)|_{NoUGB} = r_a \tag{17}$$

Note that when a UGB regulation is imposed, $\bar{x}$ is set exogenously; so in such a case, Eq. (17) does not hold.

2.6. Social Welfare Function

The social welfare function is denoted as follows:

$$W = Nu + \int_{0.1}^{\bar{x}} 2\pi x \rho_h [r(x) - r_a]dx + \int_{0.1}^{\bar{x}} n(x)\{\tau_1(x) + \tau_2(x)\}dx$$

$$- e \int_{0.1}^{\bar{x}} n(x)\{E^c(x) + E^r(x)\}dx. \quad (18)$$

In words, the social welfare is composed of money-metric aggregate utility, the differential land rent, tax revenues, and environmental externalities caused by CO_2, where e is monetary-term environmental externalities per CO_2 emission.

3. Model Specification and Calibration

3.1. Setting parameters and data sources

The parameters are set as closely as possible according to real data. The city we target is basically the city of Sendai, Japan, with about 500 thousand households, but it is a hypothetical city in the sense that some parameters do not match those of Sendai. The number of commuters N living in the area is set at 500,000. The ratio of residential area to the whole area, ρ_h, is set at 1/15. The fraction of land available for roads ρ_r is set at 0.2.

Net household income y in Sendai 2005 was JPY 4,046,000 per year. Travel time cost is equal to half the wage rate (Small and Verhoef (2007)), and is set at JPY 19100 per hour. This wage rate (w) is calculated by dividing average monthly gross salary by average monthly working hours. The agricultural land rent r_a is calculated from research of land prices and rents by the Japan Real Estate Institute. We used the average agricultural land rent of paddy fields in Miyagi Prefecture and set it at JPY 5,950,000 per square km.

The utility function is specified as

$$v(c,q,t_c,t_h) = c - \alpha q^2 + \beta q - \frac{\gamma}{2}\left\{\sum_{m\in summer}\left(\bar{a}-t_c\right)^2 + \sum_{m\in winter}\left(\bar{a}-t_h\right)^2\right\}, \quad (19)$$

where α, β, and γ are positive multiplicative factors. We set the value of α and β such that in equilibrium, the inequality of $0 < q < \frac{\beta}{2\alpha}$ holds for all distances in the city. We set parameters $\alpha = 116.9,$ and $\beta = 28866.5,$ for the utility function in equation (19) using data for unit floor rent (p) and floor space per household (q).[8] Outside temperatures (monthly mean temperature) $t_o(m)$ are given exogenously. Similarly, we set $\gamma = 12846.5$ using Eq. (A8) and data for floor space per household (q). The room temperatures $t_c(m)$ and $t_h(m)$ which residents determine, are given in Eqs. (A13) an (A14), respectively.

3.2. Calculation method of CO_2 emissions

Sources of CO_2 emissions are from commuting and residences in this model. CO_2 emissions from commuting and residences are defined as follows.[9]

$$E^c(x) = \frac{231(times) \times 2(\text{roundtrip}) \times x(\text{km})}{9.4\left(\frac{km}{l}\right)} \times 0.00232\left(\frac{\text{t}CO_2}{l}\right) = 0.11x \tag{20}$$

and

$$E^r(x) = q(x)\{\delta_l + \delta_c \textstyle\sum_{m \in summer}\big(t_o(m) - t_c(m)\big) + \delta_h \sum_{m \in winter}\big(t_h(m) - t_o(m)\big)\}. \tag{21}$$

For calculation of CO_2 emissions caused by commuting $E^c(x)$, multiplying the distance of the residence from the center x by 231 working days and by 2 (round trips) gives total mileage (km) per year. Dividing it by average fuel consumption (9.4 km/liter) gives total fuel consumption per year. Furthermore, multiplying it by average emissions 0.00232 tCO_2/liter of gasoline cars gives CO_2 emissions from commuting.[10] The calculated value is 0.11.

For calculation of CO_2 emissions caused by residences $E^r(x)$, we use the value of

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[8] We use only data of studio apartments for estimating this, due to data constraints.

[9] We use conversion factors $\delta_l = 0.0185 \times 0.16$, $\delta_c = 0.00139 \times 0.16$, and $\delta_h = 0.00071 \times 0.081$. This value is set so that the average values in the baseline simulation are equal to 0.15GJ (cooling), 3.88GJ (heating), and 0.81GJ (lighting), which are obtained from data of Sendai, compiled by Tonooka et al. (2005). The unit is GJ/year/household.

[10] In the Japanese Greenhouse Gas Emissions Calculation and Reporting Manual, CO_2 emissions from commuting is defined as $E^c(x) = \text{fuel consumption}(l) \times \text{emission factor}(\text{tCO}_2/l)$.

0.16 tCO_2/GJ for electricity for lighting and cooling.[11] For heating in residences, various kinds of fuel are used: electricity, city gas, liquefied petroleum gas (LPG), and kerosene. We use the weighted average of these (16% electricity, 5% city gas, 0.6% LPG, 78% kerosene). Hence, we use the value 8.1×10^{-2} tCO_2 /GJ.[12] Finally, the external cost of CO_2, e in Eq. (18), is set at 15,000 JPY/tCO_2 (=119EUR/tCO_2), which is the standard tax rate for tCO_2 used in Sweden. Sweden is one of the leading countries which introduce carbon taxes. Actually, the rate is relatively high, compared to other countries' rates (e.g., 62 EUR/tCO_2 in Finland, and 44.6 EUR/tCO_2 in France in 2018).

3.3. Calibration of p_c, p_h, p_l

The first term of Eq. (3) represents expenses for lighting, the second is for cooling, and the third represents expenses for heating. Tonooka el al. (2005) analyzed detailed energy demand estimation and CO_2 emissions of residences by prefecture and housing type in Japan. Among energy use in residences, energy consumption of heating, cooling, and lighting may change with the increase/decrease of floor space in buildings. Therefore, we focus on energy consumption of heating and cooling, and estimate it as follows.

First, among data of energy consumption by fuel (e.g., electricity, utility gas, liquefied petroleum gas, and kerosene)[13], we calculate the total energy consumption for heating and cooling, considering the use ratio. Second, we obtain expenses for heating and lighting (e.g., electricity, utility gas, liquefied petroleum gas, kerosene) from the Housing Survey in Japan. Third, we multiply the utility costs by the percentage of heating and cooling in total energy

[11] The Federation of Electric Power Companies of Japan estimate it as 0.00057 t-CO_2/kwh for electricity. Considering 1kwh=0.0036GJ, we use the value 0.16t-CO_2/ GJ.

[12] $(0.00057\times0.16)+(0.00018\times0.05)+(0.000213\times0.06)+(0.000244\times0.78)=0.00029$ t-CO_2/kwh.

[13] Detailed data comes from Tonooka et al. (2005).

consumption by fuel.[14] Finally, we set the most comfortable temperature as 23 degrees Celsius. Data for outside temperatures are monthly average temperatures, obtained from the Japan Metrological Agency. In our model, residents use the energy to increase the room temperature from the outside temperature to the temperature of their choice. The energy consumption necessary to increase the temperature by one degree Celsius increases according to the housing consumption. Data for housing consumption is obtained from the Land General Information System (www.land.mlit.go.jp/webland/). Thus, we set p_c=231, p_h=95, and $p_l = 230$.

3.4. Calibration of transportation cost function

For the transportation cost function, Eq. (5), we use a pair of congestion exponent parameter $\zeta = 2.82$ and multiplicative factor $\delta = 0.48$, which are set by the Japanese Society of Civil Engineers (2003). This parameter set expresses an average urban road function. Parameter η expresses the travel cost incurred while driving 1 km in the case of no congestion. We set η at JPY 25,586.[15] The road capacity C is set as 175,000.

3.5. Estimation of the housing production function

We specify the housing production function as $F = \theta S^{v}$, where S is the capital for buildings, v and θ are positive multiplicative factors, and $0 < \theta < 1$. We estimate the parameters, using data of construction costs, the area of the site, and total floor area, which are shown in Urban

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[14] For example, in the case of cooling (electricity), the ratio of use for cooling in total energy consumption (2.1%) × electricity cost (JPY 141,646)= JPY 2,952. Energy use for cooling is only electricity, while that for heating is electricity, utility gas, liquefied petroleum gas, and heating oil.

[15] This is because 231 (working days) ×2 (round trip) ×[1.0 (km) /30 (km/h)]×{1905.6 (yen/h) /2+23.62 (yen/km) ×30 (km/h) }= 25,586 yen where the value within [ ] expresses the average time to travel 1 km. 1906 (yen/hour) = 31.76 (wage rate) ×60 (min) .

Re-development in Japan No. 1-7.[16] However, the data include commercial buildings, which might be constructed decoratively. Hence, we estimate the parameters of the production function with data in which the building is smaller than the maximum floor area ratio regulation in the residential areas of Sendai (about 500%), and estimate parameters. We used 113 data samples. As a result of parameter estimation with OLS, parameter v is set at 0.75, and the multiplicative factor θ is set at 0.28 (See Table 3 in the Appendix).

v=0.75 expresses the elasticity of housing production with respect to construction materials, where housing is produced from land and construction materials. The housing production function depends on the country, but Combes et al. (2017) estimate this as 0.80 using French data. Our estimation is close to this. υ = 0.75 implies that the cost of building per-square-meter housing space increases to the power of 1/0.75 (=1.3) as the per-square-meter housing space (this is, roughly, the height of buildings) increases.

4. Numerical simulation

This section describes the procedures for numerical calculations and simulations of the equilibrium.

4.1. The setup

For numerical calculations, the distance from the CBD is discretized and indexed by i. This represents rings and $i=1$ at the CBD edge. The inner radius of ring i is given by $x_i = 1+\varepsilon[i-1]$, where x_i represents a distance variable for the corresponding ring. The width of each ring, ε, is set at 0.1 km.

4.2. Steps of the numerical simulation

Income y is exogenously set. The total commuting cost from ring i, t_i, is derived as

[16] The Urban Renewal Association of Japan compiled this data.

$$t_1 = 0;\ t_{i+1} = t_i + \varepsilon t'(x) = t_i + \varepsilon[T_i + \tau_{1i} + \tau_{2i}]. \tag{24}$$

T_i, τ_{1i} and τ_{2i} are set per km, using Eq. (5) and Eq. (6), as

$$T_i = \eta + \delta\left[\frac{n_i}{C}\right]^\zeta,\ \tau_{1i} = \zeta\delta\left[\frac{n_i}{C}\right]^\zeta, \tag{25}$$

where n_i denotes the total population beyond ring i, which is given by

$$n_i = \sum_{k=i}^{i*} \rho_h \pi[x_{k+1}^2 - x_k^2]D_k\,, \tag{26}$$

where i^* denotes the outermost ring such that $n_{i*} = 0$. Finally, the social welfare is expressed as

$$W = \sum_{i=1}^{i*} \rho_h \pi[x_{i+1}^2 - x_i^2][D_i u + r_i - r_a] + n_i(\tau_{1i} + \tau_{2i}) \tag{27}$$

where τ_{1i}, τ_{2i} are set to zero when no congestion toll or carbon tax are levied.

The iterative process starts at $i = 1$ with $t_1 = 0$ and $n_1 = N$, and is conducted conditional on the value of u that should satisfy the equilibrium conditions. In the *laissez-faire*, *toll-regimes*, and *carbon tax* regimes, the iteration stops when i reaches a value i^* such that $n_{i*} \geq 0$ but $n_{i*+1} < 0$, indicating that the population N is just accommodated within the radius of $\bar{x} = x_{i*}$; the increment in n_i is expressed, using Eq. (7), as

$$n_{i+1} = n_i + \varepsilon n'(x_i) = n_i - \varepsilon C D_i. \tag{28}$$

We then check the equilibrium condition stated in Eq. (17) – that is, the land rent at the urban boundary should be equal to the agricultural rent. Until the result shows $r_{i^*} = r_a$ within a reasonable degree of accuracy, the iteration process is repeated by adjusting u.

In the FAR regulation regime, the floor space supply on each ring i is set exogenously. Equations (12) and (13) are rewritten as

$$r_i = F_i p_i - S_i,\ \text{and}\ D_i = \frac{F_i}{q_i}, \tag{29}$$

where p_i and q_i are defined in Eqs. (A7) and (A8), respectively.

4.3. Numerical results

We present five numerical results: (i) the laissez faire equilibrium (baseline), (ii) the equilibrium under the congestion toll regime, (iii) the equilibrium under the carbon tax, (iv) the equilibrium under the congestion toll regime and carbon tax (first best), (v) the equilibrium under FAR regulation and UGB regulation. In regime (v), the city is divided into four zones with equal widths (zone 1 to zone 4 from the city center to the suburbs), and the optimal regulatory level is selected by changing the floor area ratio in every zone. City boundary is set to be the same value as the city radius of the first best regime (regime (iv)). As Kono et al. (2012) and Pines and Kono (2012) prove, the optimal regulation should impose a minimum floor area ratio regulation (i.e., a larger floor area ratio than the market ratio) in at least one zone in the center[17]. In the current simulation model, the optimal regulations are obtained with 15% up in zone 1, 50% down in zone 2, 60% down in zone 3, and 70% down in zone 4 from the market equilibrium floor area ratio. We obtained this optimal combination of floor area ratios by changing the ratios by 5 % in all the zones.

We measure the impact of urban policies, such as congestion toll regime and carbon tax regime, on urban energy structure to clarify the relationship between these policies and the effects on the urban environment. The numerical results are presented in Tables 1, 2 and Fig. 1.

The results of social welfare and welfare gains are shown in the first and second columns of Table 1, respectively. Welfare gains are calculated assuming the first best regime (iv) as 100%. Social welfare in regime (ii) is the second largest, at 2.09017×10^{12} yen, and welfare

[17] Intuitively, the combination of "maximum FAR in one part of the city" with "minimum FAR in another part of the city" is more efficient than "FAR regulation imposed in only one part of the city" to minimize total deadweight loss, which is the cost of reducing negative externality. In a monocentric city with transportation congestion, minimum FAR should be imposed in the central areas of the city. See related discussion in Kono et al. (2010) or Kono and Joshi (2019) for an intuitive explanation.

gain is 98.5%. In regime (v), FAR regulation and UGB regulation regime, welfare gains are 54.4%. On the other hand, in regime (iii), the carbon tax regime, welfare gain is only 13.4%. The radius of the city decreases from the equilibrium boundary in every regime and it is the smallest in the first best regime (iv), at 8.7 km.

Table 2 shows the results of CO_2 emissions and difference in total CO_2 emissions from the laissez-faire regime (i) under each policy. In the five regimes, the amount of total CO_2 emissions is the smallest (268,353 tCO_2/year) in the FAR regulation regime (v), which is 24.9% smaller than that of the laissez-faire regime (i) (357,160 tCO_2/year). In the first best regime (iv) (the congestion toll and carbon tax regime), the amount of total CO_2 emissions is the second smallest (268,944 tCO_2/year), which is 22.4% smaller than that of the baseline. In the congestion toll regime (ii), the amount of total CO_2 emissions is the third smallest (277,075 tCO_2/year), which is 22.4% smaller than that of the laissez-faire regime (i). On the other hand, in the carbon tax regime (iii), it is only 3.3% (345,326 tCO_2/year) smaller than that of the baseline.

Looking at the sources of CO_2 emissions, the reduction rate in emissions from commuting is larger in all policies. In particular, in the congestion regime (ii) and the first best regime (iv), the reduction rate of emissions from commuting is about 2 times larger than that from housing. This is because the congestion toll increases the number of residents living near the CBD, and the total commuting distance of the whole city is shortened. On the other hand, the reduction rate of emissions of residents in the FAR regulation and UGB regulation regime (v) is the largest of the five regimes. This is because the housing size per household is reduced by the FAR regulation and UGB regulation regime (v).

Figure 1 shows the results of population density in each regime. The population densities in the laissez-faire regime (i) and the carbon tax regime (iii) are almost the same, and those in the congestion tax regime and the first-best regime are almost identical. In the congestion tax regime (ii) and the first-best regime (iv), a larger FAR than the baseline is obtained from the city center up to 0.5km, and a smaller FAR is obtained beyond this. This is because many households move closer to the city center to avoid paying high congestion taxes.

Table 1. Social welfare and main variables

Regime	Social welfare (10^{12} yen)	Welfare gains (%)	Residents' utility (10^{6} yen/person)	Urban boundary (km)
(i) Laissez-faire (No-regulation)	2.07123	-	4.096	10.0
(ii) Congestion toll	2.09017	98.5%	3.981	9.1
(iii) Carbon tax (15000 yen/tCO_2)	2.07382	13.4%	4.091	9.5
(iv) Congestion toll + Carbon tax (first best)	2.09046	100.0%	3.979	8.7
(v) FAR regulation + UGB regulation	2.08169	54.4%	4.073	8.7

Table 2. CO_2 emissions

Regime	Total emissions (tCO2)	Difference (%)	Sources of emissions			
			Commuting (tCO2)	Difference (%)	Residences (tCO2)	Difference (%)
(i) Laissez-faire (No-regulation)	357160	-	122975	-	234185	-
(ii) Congestion toll	277075	-22.4%	81694	-33.6%	195380	-16.6%
(iii) Carbon tax (15000 yen/tCO_2)	345326	-3.3%	116525	-5.2%	228800	-2.3%
(iv) Congestion toll + Carbon tax (first best)	268944	-24.7%	77811	-36.7%	191134	-18.4%
(v) FAR regulation + UGB regulation	268353	-24.9%	80117	-34.9%	188235	-19.6%

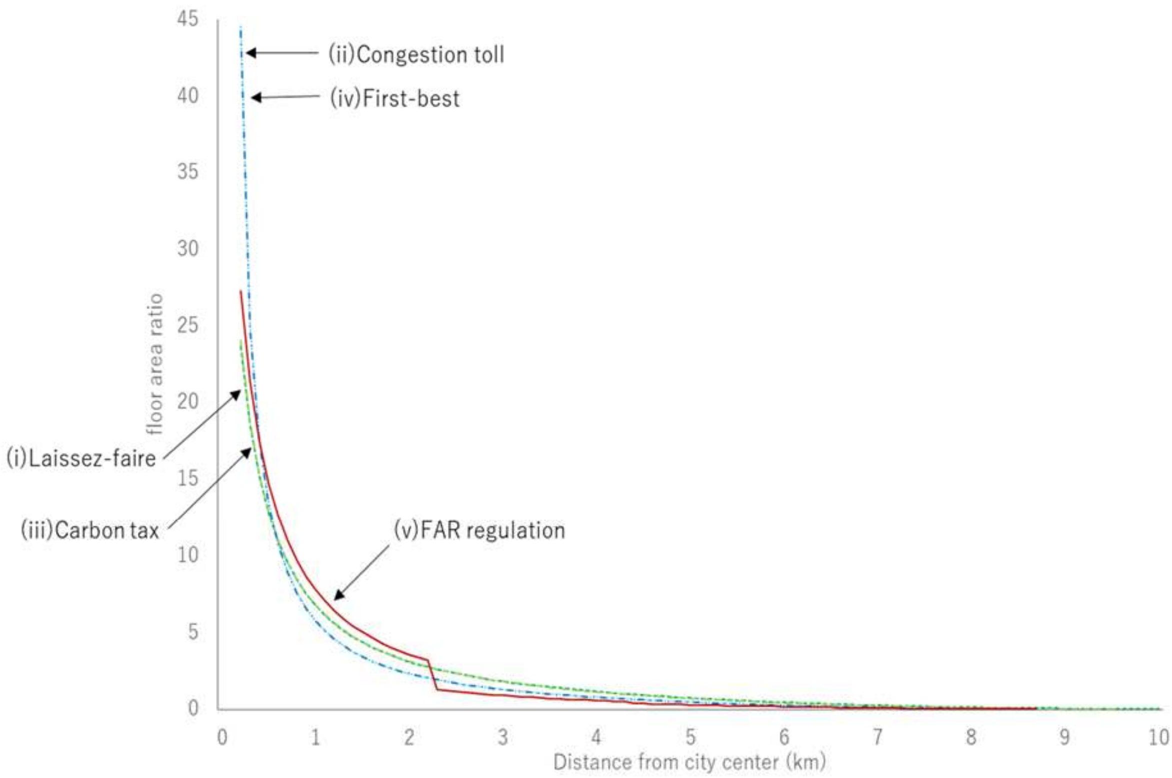

Figure 1. Population density in each regime

4.4 Sensitivity analysis

To check the robustness of the results, we perform sensitivity analyses. We change the road capacity, which affects congestion externalities, by increasing or decreasing it by 10%. With this change, we can change the relative importance between congestion externalities and CO_2 emissions.

The social welfare and the reduction in CO_2 are shown in Figures 2 and 3, while the results of main endogenous variables are shown in Tables 4-7 in the Appendix. As Figure 2 shows, the results of social welfare in both cases of -10% and +10% are not so different from the original simulations. When the road capacity is increased (reduced), residents migrate to the suburbs (the center). As a result, CO_2 emissions from transportation are increased (reduced). Furthermore, the migration increases (decreases) per-household housing space. Accordingly,

CO_2 emissions from houses are also increased (reduced). In this situation, imposition of carbon tax has only large (limited) effects on the increase in social welfare because the amount of CO_2 is large (small) in the small (large) road capacity case.

Although such changes are observed, the general tendency is not changed much from the original simulation. In particular the relative impacts of the policies are not changed. So, the results we obtain in the original simulation are likely to be robust.

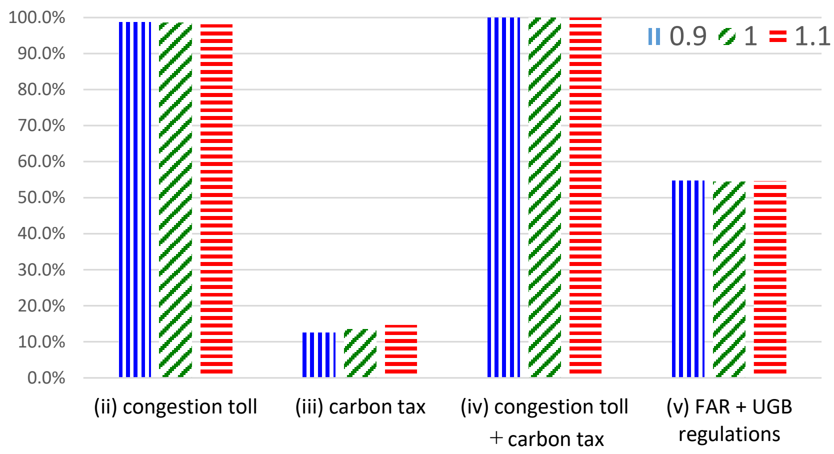

Figure 2. Sensitivity analyses (Social welfare levels compared with the first best)

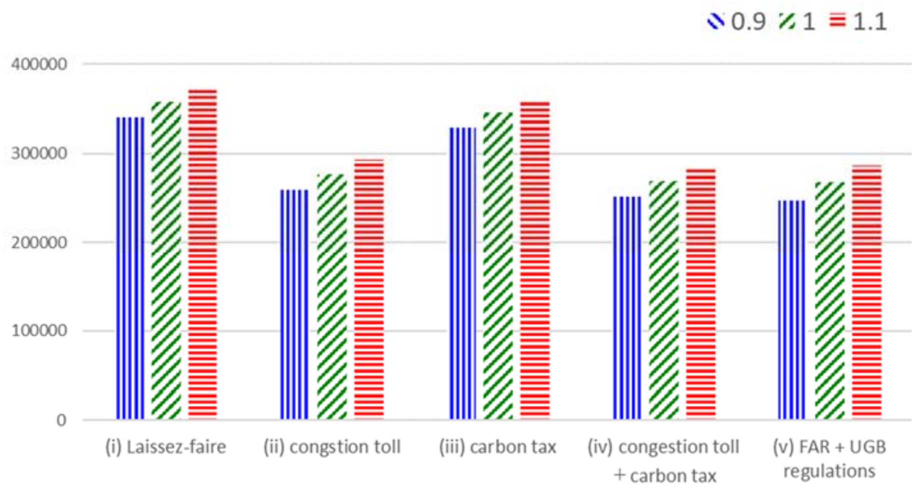

Figure 3. Sensitivity analyses (CO_2 emissions)

5. Conclusion

This study quantitatively examines the effectiveness of congestion tolls, carbon tax, and land use regulations on the social welfare and the reduction of urban CO_2 emissions. Our model incorporates the energy consumption of air conditioning as an endogenous variable.

Our numerical results show that each policy has different impacts on residents, land owners, and CO_2 emissions. The carbon tax (resp. congestion toll) scenario increases social welfare by about 13% (resp. 99 %) of the increase in the first-best scenario, and the amount of total CO_2 emissions is about 3% (resp. 20%) smaller than those of the laissez faire equilibrium. In the floor area ratio regulation scenario, social welfare increases by about 55% of the increase in the first-best scenario, and the amount of total CO_2 emissions is about 20% smaller than that of the laissez faire equilibrium.

These results suggest that congestion tolls are very similar to the first-best policies in terms of social welfare. FAR regulation is also rather socially-efficient. Regarding the reduction of CO_2 emissions, congestion tolls and FAR regulation are both rather effective. From these results, we can conclude that congestion tolling, which is primarily the Pigovian tax for congestion, not only internalizes congestion externalities but also reduces CO_2 emissions effectively through downsizing commuting distances and housing sizes with the spatial change in population density in the city. So, the congestion toll can work as a measure against CO_2 emissions arising from homes as well as transportation from the viewpoints of social welfare and CO_2 emissions.

Our results show that congestion tolls are very useful for reducing CO_2 emissions through the spatial change in the population distribution. Actually, besides congestion tolls, there are multiple car-related taxes such as car usage tax, ownership tax, and purchase tax, which increase personal costs related to cars. Hayashi et al. (2001) simulate the effects of these car-related taxes on reducing CO_2 emissions, and demonstrate which taxes are effective without considering a city space explicitly. Actually, since each of these taxes differently affect the population distribution in a city, a future study should combine Hayashi et al.'s model with ours in order to take account of the relationship between multiple car-related taxes and the population distribution. Furthermore, in this combined model, we should take account of marginal costs of public funds to measure the social welfare because each tax generates a different deadweight loss. To do this, this future work can use the framework of Kono et al. (2019) which optimize multiple car-related taxes simultaneously to reduce the total tax deadweight losses.

Appendix

A.1. First-order conditions of the residents' behavior

The Lagrangian function representing resident's behavior is set as follows.

$$L = c - \alpha q^2 + \beta q - \frac{\gamma}{2}\left\{ \sum_{m \in summer} \left(\bar{a} - t_c\right)^2 + \sum_{m \in winter} \left(\bar{a} - t_h\right)^2 \right\}$$
$$+\lambda\{y - k(x) - c - q[p + p_l + p_c \textstyle\sum_{m \in summer}(t_o(m) - t_c) + p_h \sum_{m \in winter}(t_h - t_o(m))]\} \quad \text{(A1)}$$

The first order conditions are as follows.

$$\frac{\partial L}{\partial c} = 1 - \lambda = 0 \quad \text{(A2)}$$

$$\frac{\partial L}{\partial q} = -2\alpha q + \beta - \lambda(p + p_l + p_c \textstyle\sum_{m \in summer}(t_o(m) - t_c(m)) + p_h \sum_{m \in winter}(t_h(m) - t_o(m))) = 0 \quad \text{(A3)}$$

$$\frac{\partial L}{\partial t_c} = -\frac{\gamma}{2}\left\{2\left(\bar{a} - t_c\right)\cdot(-1)\right\} - p_c q \lambda \cdot (-1) = 0 \quad \text{(A4)}$$

$$\frac{\partial L}{\partial t_h} = -\frac{\gamma}{2}\left\{2(\bar{a} - t_h)\cdot(-1)\right\} - p_h q \lambda = 0 \quad \text{(A5)}$$

$$\frac{\partial L}{\partial \lambda} = y - k(x) - c - q[p + p_l + p_c \textstyle\sum_{m \in summer}(t_o(m) - t_c(m)) + p_h \sum_{m \in winter}(t_h(m) - t_o(m))] = 0 \quad \text{(A6)}$$

A.2. Detailed simulation setup

The main endogenous variables are derived from the model as below.

Unit floor rent, $p_i = \sqrt{\kappa_i}\left(\frac{\mu_1}{\gamma} - 2\alpha\right) + \beta - \mu_2$ (A7)

Floor space per household, $q_i = \sqrt{\kappa_i}$ (A8)

Capital-to-land ratio, $S_i = \left\{\upsilon\theta\left[\sqrt{\kappa_i}\left(\frac{\mu_1}{\gamma} - 2\alpha\right) + \beta - \mu_2\right]\right\}^{\frac{1}{1-\upsilon}}$ (A9)

Unit land rent, $r_i = \left(\frac{1-\upsilon}{\upsilon}\right)\left\{\upsilon\theta\left[\sqrt{\kappa_i}\left(\frac{\mu_1}{\gamma} - 2\alpha\right) + \beta - \mu_2\right]\right\}^{\frac{1}{1-\upsilon}}$ (A10)

Population density, $D_i = \frac{F_i}{q_i} = \frac{\left\{\upsilon\left[\sqrt{\kappa_i}\left(\frac{\mu_1}{\gamma} - 2\alpha\right) + \beta - \mu_2\right]\right\}^{\frac{\upsilon}{1-\upsilon}} \theta^{\frac{1}{1-\upsilon}}}{\sqrt{\kappa_i}}$ (A11)

Total unregulated floor space per unit of land,

$$F_i = \left\{\upsilon\left[\sqrt{\kappa_i}\left(\frac{\mu_1}{\gamma} - 2\alpha\right) + \beta - \mu_2\right]\right\}^{\frac{\upsilon}{1-\upsilon}} \theta^{\frac{1}{1-\upsilon}} \quad \text{(A12)}$$

Preset temperature of cooling, $t_{ci} = \bar{a} + \frac{p_c}{\gamma}\sqrt{\kappa_i}$ (A13)

Preset temperature of heating, $t_{hi} = \bar{a} - \frac{p_h}{\gamma}\sqrt{\kappa_i}$ (A14)

CO_2 emissions from commuting $E_i^c = 0.11 i\varepsilon$ (A15)

CO_2 emissions from residences

$$E_i^r = \sqrt{\kappa_i}\left\{\delta_l + \delta_c \sum_{m \in summer} (t_o(m) - t_c) + \delta_h \sum_{m \in winter} (t_h - t_o(m))\right\} \quad \text{(A16)}$$

where $\kappa_i = \frac{2\gamma}{2\alpha\gamma - \mu_1}(u - y + k_i)$, $\mu_1 = p_c^2 C_{summer} + p_h^2 C_{winter}$

$$\mu_2 = p_l + p_c \sum_{m \in summer} \left(t_o(m) - \bar{a}\right) + p_h \sum_{m \in winter} \left(\bar{a} - t_o(m)\right), \quad \mu_3 = p_c C_{sumer} + p_h C_{winter}$$ [18]

where C_{summer} and C_{winter} represent the numbers of months of summer and winter seasons, respectively.

A.3. Estimation of parameters of the floor space production function

Arranging $F = \theta S^{\upsilon}$ with logarithm transformation, we obtain $lnF = ln\theta + \upsilon lnS$. Using this, we estimate the parameters. The result is shown below. Estimation results are statistically significant. In addition, as the main text in Subsection 3.5 shows, the estimated elasticity is close to the elasticity recently estimated by Combes et al. (2017) using French data.

Table 3: Estimation of the floor space production function

	Coefficient	Standard Error	t-value
$ln\theta$	-5.879	0.3482	-16.885
υ	0.7497	0.0343	21.873
Observations		113	
Adjusted R^2		0.810	

Note: The construction costs are calculated using the discount rate of 4%.

A.4. Results of the sensitivity analyses

The results of main variables in the sensitivity analyses are shown in Tables 4-7.

[18] The values of μ_1, μ_2, and μ_3 are 196972, 13384.6, and 1412, respectively.

Figure 4. Social welfare (10% reduction in road capacity)

Regime	Social welfare (10^{12} yen)	Welfare gains (%)	Residents' utility (10^6 yen/person)	Urban boundary (km)
(i) Laissez-faire (No-regulation)	2.06030	-	4.073	9.8
(ii) Congestion toll	2.08184	98.7%	3.944	8.9
(iii) Carbon tax (15000 yen/tCO_2)	2.06301	12.4%	4.069	9.3
(iv) Congestion toll + Carbon tax	2.08212	100.0%	3.943	8.5
(v) FAR regulation + UGB regulation	2.07224	54.8%	4.050	8.5

Figure 5. Social welfare (10% increase in road capacity)

Regime	Social welfare (10^{12} yen)	Welfare gains (%)	Residents' utility (10^6 yen/person)	Urban boundary (km)
(i) Laissez-faire (No-regulation)	2.08056	-	4.115	10.1
(ii) Congestion toll	2.09686	98.1%	4.008	9.3
(iii)Carbon tax (15000 yen/tCO_2)	2.08300	14.7%	4.109	9.7
(iv) Congestion toll + Carbon tax	2.09717	100.0%	4.006	8.7
(v) FAR regulation + UGB regulation	2.08963	54.6%	4.093	8.7

Figure 6. CO_2 emissions (10% reduction in road capacity)

Regime	Total emissions (tCO2)	Difference (%)	Sources of emissions			
			Commuting (tCO2)	Difference (%)	Residences (tCO2)	Difference (%)
(i) Laissez-faire (No-regulation)	340544	-	113334	-	227210	-
(ii) Congestion toll	259365	-23.8%	73926	-34.8%	185439	-18.4%
(iii) Carbon tax (15000 yen/tCO_2)	329433	-363%	107501	-5.1%	221932	-2.3%
(iv) Congestion toll + Carbon tax	251871	-26.0%	70476	-37.8%	181395	-20.2%
(v) FAR regulation + UGB regulation	246871	-27.5%	71580	-36.8%	175292	-22.9%

Figure 7. CO_2 emissions (10% increase in road capacity)

Regime	Total emissions (tCO2)	Difference (%)	Sources of emissions			
			Commuting (tCO2)	Difference (%)	Residences (tCO2)	Difference (%)
(i) Laissez-faire (No-regulation)	371120	-	131519	-	239601	-
(ii) Congestion toll	293491	-20.9%	89289	-32.1%	204203	-14.8%
(iii) Carbon tax (15000 yen/tCO_2)	358750	-3.3%	124592	-5.3%	234157	-2.3%
(iv) Congestion toll + Carbon tax	284543	-23.3%	84800	-35.5%	199742	-16.6%
(v) FAR regulation + UGB regulation	286658	-22.8%	88511	-32.7%	198147	-17.3%

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