

Productivity benefits of urban transportation megaprojects: a general equilibrium analysis of «Grand Paris Express»

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ABSTRACT

«Grand Paris Express», a fast rail transit megaproject planned for 2035, is designed to decongest the City of Paris by circumferentially linking its inner suburbs. A general equilibrium model of travel, labor, real estate and output markets is used to assess the project. The region's spatial distribution of jobs and residences are endogenous in the model. The megaproject reduces public transit travel times, alleviates road congestion and imparts a Marshallian externality on production. This reduces the prices of the region's goods benefitting the region's consumers and those who import from the region. In the short run, nominal prices, wages, rents and income and sales tax revenues fall but wages and rents adjusted by the output price, and outputs rise. In the long run, regional population grows and output rises more. Although Pigouvian tolls on road congestion dent nominal incomes and purchasing power, the revenue from tolls well exceeds the project's direct cost. Tolling recoups 81% of the direct cost plus losses from public revenues in the short run; 66% in the long run. Social welfare gains of the megaproject are 1.25% of the region's average income in the short run, 0.55% with population increase in the long run; falling to 1.07% with congestion tolls in the short run, and rising to 1.42% with congestion tolls in the long run.

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1. Introduction

There are two schools of thought on the social benefits of urban transportation megaprojects. One view is that these, like many other types of mega public projects, are white elephants: costs are out of proportion to social benefits, and the projects are proposed mainly because they are beneficial to politicians (Robinson and Torvik, 2005). A countervailing view is rooted in microeconomic theory and empirical work in urban economics. Accordingly, megaprojects can improve the efficiency of the urban economy by creating travel time savings. A second layer of *wider benefits* can stem from productivity gains that occur as the megaprojects alter the spatial concentration of jobs and their accessibility to each other. This view is inspired by Marshall (1920): that positive external effects in production arise as the spatial agglomeration of labor creates pecuniary or nonpecuniary advantages that reduce the costs of production.

Empirical work has suggested that Marshallian agglomerations do indeed form. Glaeser, Kallal et al. (1992), and Henderson, Kuncoro and Turner (1995) found that job growth in US cities is explained both by the concentration of firms in city-industries as well as by the diversity of industries in a city. Rosenthal and Strange (2003) found that agglomerations of business establishments in the U.S. are statistically observable at the State, County and zip code levels of geographic resolution, and are associated with labor pooling, input sharing and knowledge spillovers. Dekle and Eaton (1990) found that agglomeration is associated with higher rents and wages, and Wheaton and Lewis (2002) with higher wages. These studies relied on single-equation models derived from partial equilibrium analyses.

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We use a computable general equilibrium model to study the effects of the Grand Paris Express (GPE, hereafter), a mega public transport project under construction and slated for completion circa 2035 at a cost of 35 billion €. Our Regional Economy, Land Use and Transportation ([RELU-TRAN](#)) model,² has a microeconomic cause-and-effect structure that treats the accessibility improvements and the reduction in road congestion induced by the GPE, and treats the effects of the GPE on the travel, labor, housing, commercial real estate, and output markets. We use evidence accumulated in the past three decades, to show that the accessibility of a region's jobs to each other and the spatial distribution of job densities do positively affect productivity.³ To capture these wider benefits, the model treats a positive Marshallian agglomeration externality in the total factor productivity (TFP) of competitive firms (TFP externality, hereafter). As in [Chipman \(1965\)](#), in our model too, the externality parametrically enters the TFP of the production function of competitive firms. Hence, the firms are subject to internal constant returns to scale but external scale economies and the social marginal product of labor is higher than the private marginal product.

We identify three economic margins across which the TFP externality affects the spatial distribution of jobs and population and the regional economy. The first is *the intensive margin of worker productivity*. If, in the spirit of Marshall, each job becomes more productive as the accessibility to near-by jobs is improved by a project such as the GPE, then fewer jobs are needed to produce the same amount of output. This may be viewed as an instance of Schumpeterian job destruction in the context of Marshallian agglomeration.⁴

A higher TFP, induced by the GPE, reduces the marginal cost of production causing tentative economic profits. Then, competition and free entry reduce output prices until economic profits fall to zero. The lowered prices cause wages, rents and income and sales taxes to fall too, but adjusted for the lowered prices, real wages and rents rise. A second *extensive margin of demand growth* kicks in as the lowered output price spurs an increase in the quantity demanded for local consumption and export, causing output and jobs to rebound. The second margin dominates over

² See [Anas and Liu \(2007\)](#) for the original model's structure and solution algorithm. Complete details of the version adapted to the Paris region are in [Part I of the Appendix](#) to the present paper.

³ [Graham and Gibbons \(2019\)](#) provide a comprehensive survey.

⁴ [Schumpeter \(1941\)](#) wrote: "The Illinois Central [railroad] not only meant very good business whilst it was built and whilst new cities were built around it and land was cultivated, but it spelled the death sentence for the [old] agriculture of the West." (p. 349). He was, apparently, referring more to an extensive than to an intensive margin of job destruction.

the first when the price elasticity of the demand for output is high enough. And when labor is a normal input, then more jobs are associated with the increased output.

There is a third *super-extensive margin of growth* in the long run. The GPE works similarly to an improvement in the man-made amenity-level of the Paris region. As utility improves due to the bettered accessibility and the lowered output prices, net in-migration from the rest of the world ensues, increasing job densities and further improving productivity. The higher labor supply from this long run population growth causes a downward pressure on wages in the labor market, and a positive effect on rents in the land market. This is consistent with the [Roback \(1982\)](#) model of urban labor markets with migration which did not include a productivity externality, but where higher amenity cities attracted more population, had higher rents and possibly lower wages.

As noted by [Eberts and McMillen \(1999\)](#), one cause of a large city size is the sharing of an extensive urban infrastructure. GPE-like megaprojects increase the metropolitan capacity to accommodate more population and jobs which, in turn, can lower the per capita project costs. In our model, the higher long run population causes more road congestion too, a negative externality. We show that the per capita net cost of the GPE can be greatly reduced by Pigouvian pricing which corrects the road congestion externality and provides revenue for funding the GPE. But, as we shall see, congestion tolls can reduce nominal wages (hence, incomes) and purchasing power, resulting in lower revenues from income and excise taxation.

[Venables \(2007\)](#) provided a simple theoretical model of the third margin. In his model the urban area is open to in-migration and there is a single predetermined central business district where all jobs are located (monocentric city). Working requires commuting by a single travel mode, and does not entail congestion. When travel cost per unit distance is lowered, utility rises temporarily. This induces in-migration until utility falls back to its original outside level as the urban area expands.⁵ The added population increases job density and worker productivity. In Venables' model workers get paid their average products and the larger population induced by the transport improvement generates higher incomes and more income tax revenue. This is because the model does not consider that the higher productivity would reduce the price of output. The urban output in Venables's model is sold at the world market at a numeraire world price. In our model, lower output prices increase the demand for output (our second margin) but also pressure

⁵ [Wheaton \(1974\)](#) distinguished between the open-in-population (long run) and closed-in-population (short run) urban models in a partial equilibrium setting. In his analysis, wages and product prices are implicitly fixed, there is only one travel mode and there are no productivity or road congestion externalities, nor trade with the rest of the world.

competitive wages lower, as workers are paid the value of their private marginal product. This results in lower revenues from sales and income taxes. Another aspect is that the long run immigration causes more downward pressure on wages by increasing labor supply.⁶

Our general equilibrium model is spatially detailed and recognizes the polycentric nature of the Paris region. Jobs can emerge anywhere in the region where firms can make normal profits. At equilibrium there is production everywhere in the metropolitan area but at varying densities, with more production in the more accessible and more congested places. Many firms in each place within the urban area compete in producing unique composite goods that can be shopped by the region's residents and exported to the rest of the world. These location-differentiated goods (Armington, 1969) are imperfect substitutes in the utility function of the consumers who are variety-hungry as in Dixit and Stiglitz (1977) and travel from home to shop the variety of goods but in quantities that attenuate with the price at the place of sale inclusive of consumer transport costs. Consumers and producers are interdependent via forward and backward linkages (Anas and Xu, 1999): consumers, if employed, seek to locate near their jobs to economize on monetary commuting costs and travel times, and near producers, whether employed or not, to economize on the same in shopping (forward linkages), while producers seek to locate near their workers, paying lower wages; and near their customers, charging higher prices (backward linkages).

In such a context which reflects undeniable aspects of reality, how will accessibility improvements such as those of the GPE affect the locational equilibrium? At the margin, consumers will seek residence locations where the GPE has improved access to jobs and to goods. Firms will emerge in such places to benefit from the better access to labor and to customers. As jobs agglomerate in a place, the TFP externality becomes more powerful there. In the closed-in-population short run setting, the GPE induces a reshuffling of jobs and residents, causing a higher (lower) TFP where *accessibility to jobs* improves more (less). A higher TFP lowers the marginal cost of production and by competition and free entry, product prices at such locations fall to maintain normal profits. Meanwhile, as population and jobs adjust to locate accessibly to each other, they end up competing for floor space in buildings. Our model allows the conversion of housing and of commercial buildings to land and of land to buildings, as well as allowing for

⁶ In two other simple theoretical models, Parry and Bento (2001) treated the interaction of congestion pricing with labor supply, but not the TFP externality, and Arnott (2007) treated the interaction of the TFP externality with road congestion. Both papers, like Venables (2007), ignored the effects on the output price, and our second margin. In Section 4, these models are compared to ours in more detail.

endogenously determined vacancy rates. At equilibrium, rents and quantities of floor space in each type of building accommodate the demands of residents and firms. The output of the region's firms is both locally consumed and exported, while firms import their capital and some of their labor and other inputs from outside the region. Prices and incomes prevailing outside the region are taken as exogenous, while all prices within the region are endogenously determined.

A preview of the findings is as follows. In the absence of road congestion pricing, when the region's population is fixed in the short run, then the intensive and extensive margins of the TFP externality nearly offset each other's impacts on job densities. But the super-extensive margin of long run growth is powerful. The model predicts that the GPE would cause the region to increase in population by 1.8% if there were no TFP externality in production, and by about 4.5% with the TFP externality. In the short run, with constant regional population, the GPE lowers nominal wages, rents and product prices, but raises outputs. It raises wages and rents when these are normalized by the price index. In the long run, with in-migration, nominal rents rise. These effects of the GPE are stronger when the TFP externality is present. On the fiscal side, although annual congestion toll revenue is more than three times the annualized direct cost of the project, the losses in nominal income and sales tax revenues caused by the congestion pricing are also large. Congestion pricing recovers 81% of the sum of the project's direct cost plus the public revenue losses in the short run, and 66% in the long run. In the absence of congestion pricing, the welfare gain is 1.25% of consumer incomes in the short run and 0.55% in the long run. With congestion pricing, it is 1.07% of incomes in the short run, and rises to 1.42% in the long run. The short run social benefit-to-cost ratio of the GPE with the TFP externality is 3.54 and falls to 3.00 with congestion pricing. The long run ratio is 1.59 and rises to 4.01 with congestion pricing. The lower output prices caused by the GPE strongly benefit consumers to whom the region's goods are exported, as they do not reside in the region and are not exposed to the local costs of congestion, higher rents and lower wages.

[Section 2](#) is a description of the Paris region and its division into subareas for the purposes of our model, the GPE megaproject and the public transit travel time gains it is projected to realize. [Section 3](#) explains how we model the TFP externality by adapting a standard and widely tested specification from the extant literature. In [Section 4](#) we present the simulation results, the social welfare analysis and the fiscal impacts of the GPE megaproject. Eight simulations of the GPE's effects are juxtaposed: without and with the TFP externality, with fixed-in-the-short-run and variable-in-the-long-run regional population, and without and with road congestion pricing.

Welfare analysis of the GPE's effects, the social benefit-to-cost ratios and the prospects of financing it with Pigouvian road taxes are also discussed in [Section 4](#), as are also the interactions between the TFP externality, congestion pricing and the revenues from the distortionary sales and income taxes. [Section 5](#) addresses the robustness of the results by presenting sensitivity analyses on key model parameters and [Section 6](#) concludes. [Part I of the Appendix](#) presents and explains the equations of the Paris-region version of the [RELU-TRAN](#) model.⁷ Parts [II-IV](#) of the Appendix are on technical details of externality formulas and the welfare analysis, and [Part V](#) is on the model's calibration. Equations in the Appendix are numbered (A.1) - (A.47).

2. The Paris region and the «Grand Paris Express»

2.1 Geography, land use and trips in the region

[Figure 1](#) shows the Paris region and its division into zones for our modeling. The City of Paris (Paris or “the City” hereafter), the economic center, is magnified in the inset of [Figure 1](#) and consists of twenty small zones, each an *arrondissement*. The dark and light pink zones comprise an inner ring of suburbs encircling Paris. Of these, the dark pink zones are the ten Contrats de Développement Territorial⁸ (CDTs), targeted by planners as high priority “poles” for potential future growth. The light pink and yellow zones comprise all other suburbs which are of lower average residential and employment density. We refer to four areas that are beyond the outer ring as exurban: northwest, northeast, southeast, southwest. Some residents of exurban zones work in the City, in the CDTs or suburbs, but they comprise a small percentage of the region's total. [Table 1](#) describes the distribution of land, floor space, residential population, jobs, (and their densities) and the number of daily trips by purpose and by mode among three aggregated areas: Paris, CDTs and suburbs.

[FIGURE 1 HERE]

Road congestion in the region is high and especially in the central area in and around the City. Congestion is mitigated in great part by an existing radial public transit and suburban railroad system that covers the whole region. 31% of the jobs are located in the City and 19% of the population resides there. Public transit trips are almost 55% of all trips. 62% of public transit trips but only 23% of car trips terminate in the City. A noteworthy fact in [Table 1](#) is that average

⁷ The model is solved to a high level of precision, by a combination of algorithms written in GAMS, General Algebraic Modeling System (<https://www.gams.com>). The higher-level convergence algorithm which cycles among the markets is an adaptation of the earlier one ([Anas and Liu, 2007](#); Figure 3, page 442) and is described in [Section I\(f\)](#) of the current paper's [Appendix](#).

⁸ Also often referred to as «Pôles de croissance».

residential population density in the City is 6.62 times that in the CDTs and in the CDTs it is 4.35 times that in the suburbs. Job density in the City it is 10.36 times that in the CDTs, and in the CDTs is 6.10 times that in the suburbs.

[TABLE 1 HERE]

2.2 Representation of the region in the model

The Paris region consists of 8 Departments and our model subdivides the region into 12+4 areas for land use and economic interaction purposes: the City, the 10 CDT zones, and all other suburban zones of [Figure 1](#) comprising the twelfth zone, plus the 4 exurban areas. For transportation purposes, the region is subdivided into 50+4 areas: the 20 arrondissements of the City, the 10 CDT zones and the 20 suburban zones (light pink and yellow zones in [Figure 1](#)) plus the 4 exurban areas. These two layers of zonal definition are bridged by travel time aggregation from the 50+4 level to the 12+4 level, and trip disaggregation from the 12+4 to the 50+4 level, described in [Part I\(h\) of the Appendix](#). While the travel mode choice and network equilibrium modeling takes place at the 50+4 level, the land use and economic equilibrium allocations take place at the 12+4 level.

The 50+4 transportation analysis zones are connected by a road network that in our model is represented by 3,004 network links (or network arcs) and 335 network nodes distributed over the 50 zones and 4 exurban areas. Nodes are points on the network where trips originate and where links meet for drivers to switch from one link to another during their travel. In addition, intrazonal roads and streets are represented by an aggregated road capacity in each zone. A Markovian probabilistic network equilibrium procedure is used to model congested travel on the road network, as described in [Part I\(h\) of the Appendix](#). Congestion on all links of the road network is determined using the flow model of congestion. Intrazonal congestion in each transportation analysis zone is modeled as a function of zonal car traffic accessing or egressing from the network, divided by the area of the zone, similar to [Daganzo and Geroliminis \(2008\)](#).

2.3 The «Grand Paris Express»

Planners recognize that Paris has nearly no vacant land left. Redevelopment in the City at higher structural density would increase congestion and would spoil the skyline dotted with famous monuments. The desire of the planners is that future growth concentrate as much as possible in the CDTs. This would preserve the accessibility of the City to the newly added population and jobs, and would allow that the CDTs and the City agglomerations work well together as a whole

interconnected by the GPE. The GPE, shown in [Figure 2](#), has been proposed in order to facilitate the future economic interaction among the CDTs without burdening the existing infrastructure of the City.

The GPE will consist of fast trains and feeder buses connecting the CDTs circumferentially around the City. It will include some 70 new stations where passengers can embark and disembark. It will enable faster direct transport between the CDTs, reducing the need to travel through the City via connections with the existing public transit lines which are radially arranged. By inducing switches from driving to travelling by rail, the GPE will reduce road congestion which in turn will improve travel times by road as well. A possible criticism of the GPE is that the region is already well served by a rich public transit network and that the GPE could add redundancy at a high cost. Such a criticism is not supported by our results.

[FIGURE 2 HERE]

[TABLE 2a and TABLE 2b HERE]

In [Table 2a](#) we show the projected zone-to-zone average travel time savings on the public transit network in minutes, and in [Table 2b](#) in percentage changes, after the GPE becomes fully operational in 2035. These are provided by the Societe du Grand Paris: zone-to-zone travel times on the public transit network pre- and post-GPE are calculated on a much more detailed zone layer consisting of 3000 communes (small zones) and then averaged to the 50+4 zones level used in our model. Blanks in the tables correspond to no savings or very small savings that have been rounded to zero. These projected savings in public transit times are exogenous to the model and drive our results. Indirect reductions in road congestion induced by the GPE are endogenously calculated by the model as we shall see. Sensitivity analysis on the travel time savings are reported in [Section 5](#).

3. The TFP externality

3.1 Modeling the TFP externality

The production functions of the competitive firms are internal-to-the firm constant returns to scale, given by [Eq. \(A.6\)](#) in [Part I\(c\) of the Appendix](#), abbreviated here using the general form:

$$X_{rj} = A_{rj} F_{rj} (K_{rj}, L_{rj}, B_{rj}) \quad (1)$$

X_{rj} is the output of primary industry r in model zone j . The model treats 12 industries, of which $r = 1, 2$ are the primary industries (private sector and public sector). Goods and services provided by these are either purchased directly by the region's consumers, or exported. The remaining ten

industries are five building construction and five building demolition industries, one of each for each of the two residential and three commercial building types in the model. In each zone, construction produces floor space from land and demolition produces land from floor space. Floor spaces are not exportable. Construction and demolition are discussed in [Part I\(d\) of the Appendix](#).

In [Eq. \(1\)](#), K_{rj} is the capital input supplied perfectly elastically to the region; \mathbf{L}_{rj} is the vector of labor inputs, and \mathbf{B}_{rj} is the vector of floor space types. A_{rj} is the input-neutral total factor productivity coefficient (TFP). It will be kept constant when there is no TFP externality. When there is a TFP externality, A_{rj} will be endogenous. It will be a function of job densities and the accessibility of jobs to each other. [Part I\(c\) of the Appendix](#) explains the firm's profit maximization problem. Here we focus on the specification of the TFP.

To model external-to-the-firm Marshallian productivity effects as a Chipman externality ([Chipman, 1965](#)), we will express the TFP coefficients, A_{rj} , for industries $r = 1, 2$, as a function of the spatial distribution of jobs in the region and the accessibility of this distribution to the firms in zone j .⁹ We briefly review the TFP specification in empirical studies. [Ciccone and Hall \(1996\)](#)

used aggregate job density $A_j = \left(\frac{Jobs_j}{Area_j} \right)^\alpha$ to represent the TFP, where $Jobs_j$ is the number of

jobs in zone j and $Area_j$ is the total land area of zone j . Using whole U.S. Counties as the zones, they estimated $\alpha = 0.06$: a one percent increase in the average job density of a County would result in a 0.06% increase in the productivity of the firms in the County. Using French Departments as the geographic units, [Ciccone \(2002\)](#) found $\alpha = 0.045$.¹⁰ Both studies ignored that productivity in a zone j can be influenced by job density in other zones via the accessibility of those zones to zone

j . This was rectified in the work of [Graham \(2007a, 2007b\)](#) who specified $A_j = \left(\sum_{\forall i} Jobs_i \cdot G_{ij}^{-\beta} \right)^\alpha$.

This is a travel-cost-mediated accessibility to jobs or "effective job density" ([Graham, 2007b](#)). G_{ij} is the generalized transport cost between zones i and j , specified as the value of travel time plus the monetary cost of travel. If $\beta = 0$, then the proximity of jobs to zone j does not matter and

⁹ [Fujita and Ogawa \(1982\)](#) and [Lucas and Rossi-Hansberg \(2002\)](#) have utilized such functions in a simplified theoretical setting of single-dimensional continuous space.

¹⁰ A French department is one of the three levels of government below the national level ("territorial collectivities"), between the 27 administrative regions and the commune.

productivity in zone j is affected equally by any job in the entire region. If $\beta > 0$, then job densities in close proximity to zone j affect the productivity of firms in zone j more than do less proximal jobs. Graham used $\beta = 1$. He used U.K. Wards as the zones. He estimated that $\alpha = 0.26$ for England which is 4.3 times higher than the estimate of [Ciccone and Hall \(1996\)](#) for the U.S. and 5.8 times the estimate of [Ciccone \(2002\)](#) for France.¹¹ [Graham and Gibbons \(2019\)](#) reviewed estimates of the elasticity parameter, α , in nearly 50 different studies spanning about 20 countries or a country group (Europe) and using various types of data and estimation methods. These estimates vary from -0.80 to +0.658 with a median of +0.043 and mean of +0.046. The estimates of several different studies for France are from data on zones, workers and plants. These estimates differ, but the only other zone-based estimate for France in [Graham and Gibbons \(2019\)](#) is 0.052 and close to the 0.045 of [Ciccone \(2002\)](#) which we will be using in our zone-based model.

Building on the body of work mentioned above, we use a somewhat modified TFP formula:

$$A_{rj} = C_{rj} \left(\underbrace{\sum_{\forall i} w_i d_i G_{ij}^{-\beta}}_{\equiv A_j} \right)^{\alpha}, \quad \alpha, \beta > 0. \quad (2)$$

The C_{rj} are constants, $d_i \equiv \frac{Jobs_i}{Area_i}$ is the job density in zone i , $w_i \equiv \frac{Jobs_i}{\sum_i Jobs_i}$ is the weight we assign to each zone's density; and G_{ij} is the average of car and public transit travel times from zone i to zone j weighted by the mode-choice probabilities (more below). When $\alpha = 0$, then $A_{rj} = C_{rj}$ and there are no effects on productivity from job agglomeration. When $\alpha > 0$, [Eq. \(2\)](#) reflects that between two equally dense zones i and i' with the same travel time from zone j , the one with more jobs has more influence on the TFP in zone j (because of the higher weight); and between two zones i and i' with the same number of jobs and same travel time to zone j , the one with the higher density has more influence. Between zones of the same job-size and density, the zone with lower travel time, G_{ij} , has more influence.

[Eq. \(A.30\)](#) in [Part I\(i\) of the Appendix](#), repeated here, gives G_{ij} :

¹¹ The 96 Departments in France are fairly comparable in size on average to the 3,142 U.S. Counties. Wards in the U.K. are generally smaller than French Departments. There were 9,196 Wards in Britain at the end of 2015 and 25 in the City of London. The City of Paris is a Department and is the centrally situated zone in our model.

$$G_{ij} = PROB_{CAR|ij} \times (\tau_{ij} + \tau_{ji}) + (1 - PROB_{CAR|ij}) \times (TIME_{PT|ij} + TIME_{PT|ji}) \quad (3)$$

Eq. (3) assumes that travelers from zone i to zone j randomize on each trip between car or public transit with probabilities $PROB_{CAR|ij}$ and $1 - PROB_{CAR|ij}$ respectively. These probabilities are endogenous in the model and calculated from a binary logit explained in [Part I\(i\) of the Appendix](#). $TIME_{PT|ij}$ are travel times from i to j by public transit and these are exogenous to the model, and change as in [Tables 2a](#) and [2b](#) when the GPE is introduced. τ_{ij} are the travel times by car and they are endogenous by the congestion on roads. The details of trips, mode choice and road congestion modeling are explained in [Parts I\(g\), I\(h\) and I\(i\)](#) of the Appendix.

At equilibrium, the number of jobs in a zone which appear in [Eq. \(2\)](#) are endogenously determined and equal the number of workers who choose to work at that zone (equal, at equilibrium, to the number of workers demanded by the firms in that zone):

$$Jobs_j = N \cdot Pr^e \sum_{ikr} P_{ijk}^e(\mathbf{w}, \mathbf{R}, \mathbf{p}, \mathbf{G}, \mathbf{g}), \quad (4)$$

N is the exogenous number of consumers in the region, Pr^e is the exogenous fraction of consumers who are workers, so $N \cdot Pr^e$ is the number of workers. $P_{ijk}^e(\mathbf{w}, \mathbf{R}, \mathbf{p}, \mathbf{G}, \mathbf{g})$ is the multinomial logit model, [Eq. \(A.3a\) in Part I\(a\) of the Appendix](#), that gives the share of workers who choose employment in industry r in zone j , residence in zone i and housing type k . Because consumers maximize utility, the choice probabilities depend on the vector of wages \mathbf{w} , rents \mathbf{R} , prices \mathbf{p} , and composite travel times \mathbf{G} , and monetary travel costs \mathbf{g} , as explained in [Part I\(a\) of the Appendix](#).

From [Eq. \(3\)](#), the public transit travel times, $TIME_{PT|ij}$, changed by the GPE, cause the composite across modes average travel times, G_{ij} , to change directly and also indirectly via the car-choices $PROB_{CAR|ij}$ and the congested car travel times, τ_{ij} . By [Eq. \(4\)](#), the G_{ij} affect job location choices because consumers value travel times. These changes cause all markets to re-equilibrate with new wages \mathbf{w} , rents \mathbf{R} and prices \mathbf{p} . These, in turn, cause secondary changes in monetary travel costs \mathbf{g} , and travel times \mathbf{G} via [Eq. \(3\)](#) and so on. In the general equilibrium solution, all markets clear and all prices, wages, rents, quantities, travel times and costs, job and population distributions and the TFPs given by [Eq. \(2\)](#) converge to their equilibrium values.

3.2 Calibrating the TFP externality

As explained, we adopted $\alpha = 0.045$ from the estimate of [Ciccone \(2002\)](#) for France.¹² The constants C_{rj} are calibrated to match baseline equilibrium conditions for output by sector r in zone j . From [Eq. \(2\)](#), the spot elasticity of $A_j \equiv A_{rj} / C_{rj}$ with respect to a proportional increase by a factor k of the composite travel times G_{ij} is $-\alpha\beta$.¹³ After considerable numerical exploration we set $\beta = 3$ and so $-\alpha\beta = -0.045 \times 3 = -0.135$. General equilibrium differences between $\beta = 1$ and $\beta = 3$ are examined in [Section 5](#) which presents sensitivity analyses. [Table A2](#) in [Section VI of the Appendix](#) shows numerically, how changing β and α out of equilibrium, affects the TFP values of Paris, the CDTs and the suburbs.

3.3 Economic effects of the TFP externality

How do higher TFPs, caused by the GPE, qualitatively affect the output, and the jobs in a zone? In the model, each worker works d days per year and H hours per day. d and H are fixed, but the supply of labor to sector and to job location is endogenous. Dividing aggregate zonal labor hours by Hd gives the zone's jobs. That work hours supplied are inelastic finds support in the empirical literature. [Gutiérrez-i-Puigarnau and van Ommeren \(2010\)](#) find that commute distance, hence travel time, has a negligible effect on hours of labor supplied and on days worked. Other literature, in [Part V of the Appendix](#), claims that hours of labor are insensitive to wages.

We will prove two propositions to strengthen our qualitative understanding of how higher TFPs affect jobs. In the production function, [Eq. \(1\)](#), capital, labor and floor spaces are inputs. The supply of capital is treated as perfectly elastic to all zones, and its price ρ is exogenous. Wages and rents are endogenous in general equilibrium, but we tentatively keep them constant here to prove the propositions. General equilibria in which wages and rents are endogenous require numerical solutions presented in the next section.

Proposition 1 (*Negative productivity effect in the intensive margin*): With constant input prices, when the TFP, A_{rj} , increases, less labor (fewer jobs) are used per output quantity.

¹² For large enough values of α in [Eq. \(2\)](#) multiple general equilibria can exist, but for $\alpha = 0.045$ a unique general equilibrium was confirmed by a battery of numerical solutions of the model. These tests are summarized briefly in [Part I\(j\) of the Appendix](#).

¹³ Proof: $\left. \frac{\partial A_j}{\partial k} \right|_{k=1} = \alpha \left(\sum_i w_i d_i (kG_{ij})^{-\beta} \right)^{\alpha-1} (-\beta) \sum_i w_i d_i (kG_{ij})^{-\beta-1} G_{ij} = -\alpha\beta A_j$, $\eta_{A_j, k|k=1} \equiv \left. \frac{k}{A_j} \frac{\partial A_j}{\partial k} \right|_{k=1} = -\alpha\beta$.

Proof: Eq. (A.11) in Part I(f) of the Appendix is the zero-profit condition of the competitive firm. It says that, with constant internal returns to scale, the output price p_{rj} is equal to the unit cost, which is a function of the TFP and the input prices. Abbreviating notation by $\Gamma(\rho, \mathbf{w}_{rj}, \mathbf{R}_{jk})$ where ρ is the price of capital and $\mathbf{w}_{rj}, \mathbf{R}_{jk}$ are the wage and rent vectors, the zero profit condition is:

$$p_{rj} = \frac{1}{A_{rj}} \Gamma(\rho, \mathbf{w}_{rj}, \mathbf{R}_{jk}) \quad (5)$$

The labor demand functions from Part I(c) of the Appendix are given by Eq. (A.7a) and, abbreviating notation by using a function $\Lambda(\mathbf{w}_{rj})$, they are:

$$L_{rj} = \Lambda(\mathbf{w}_{rj}) \delta_r p_{rj} X_{rj}. \quad (6)$$

Normalizing Eq. (6) by the output X_{rj} and then substituting out the price p_{rj} by Eq. (5):

$$\frac{L_{rj}}{X_{rj}} = \Lambda(\mathbf{w}_{rj}) \delta_r \cdot \underbrace{\frac{1}{A_{rj}} \Gamma(\rho, \mathbf{w}_{rj}, \mathbf{R}_{jk})}_{=p_{rj}}. \quad (7)$$

From the right side of (7), given fixed input prices, the labor demanded per unit of output on the left side decreases as the TFP, A_{rj} , increases. ●

Proposition 2 (*Positive productivity effect in the extensive margin*): With constant input prices, a higher TFP, A_{rj} , decreases the output price causing the demanded quantity of output to increase.

Proof: By Eq. (5), the output price p_{rj} decreases with TFP. Since demand for output is a downward sloping function of output price, output, X_{rj} , increases. ●

Propositions 1 and 2 are the intensive marginal and extensive marginal effects of TFP on jobs discussed in the Introduction. If the demand for the output of zone j were perfectly inelastic, then Proposition 1 expresses a pure Schumpeterian job destruction effect of productivity mentioned in the Introduction, as the extensive marginal effect of Proposition 2 is zero. By Proposition 2, the job destruction effect is more than fully countervailed in the extensive margin, if the demand for the output of zone j is price elastic enough. Then, the extensive marginal effect of Proposition 2 dominates over the intensive marginal effect of Proposition 1 and the higher TFP induced by the lower GPE travel times results in more output, and more labor input (jobs) in zone j .

Both propositions are predicated on constant input prices and only one zone j . But how do input prices change and how would their changes affect the equilibrium distribution of jobs among the zones? Under Proposition 1, the lower labor input quantities caused by the higher TFP, increase the private marginal product of labor. But capital and floor space inputs are similarly lowered by obvious corollaries of Proposition 1. The equilibrium wage equals the value of the private marginal

product of labor: $w_{rj} = \Gamma(\rho, \mathbf{w}_{rj}, \mathbf{R}_{jk}) \left(\frac{\partial F_{rj}(K_{rj}, \mathbf{L}_{rj}, \mathbf{B}_{rj})}{\partial L_{rj}} \right)$. Whether the equilibrium wage increases or decreases, depends on how other wage and rents and capital, floor space and labor inputs change. Then, how much wages and rents change is determined by the demand and supply elasticities in the labor and real estate markets. Therefore, wages and rents need to be determined by numerical solution of the general equilibrium model.

4. General equilibrium results

4.1 The 2035 baseline general equilibrium without the GPE

The baseline general equilibrium is intended as a benchmark forecast for the region in 2035 without the GPE. According to the Societe du Grand Paris, planners believed that the 2035 regional population and jobs without the GPE would be 14.5 % and 17.9% higher than in 2005, reflecting a rise in the labor force participation rate. This forecast did not include any information on what the planners believed would be the economic and demographic drivers of such projected growth. Informed by our discussions, we made our own conjectures about the drivers. We assumed that by 2035 the demand for exports from the region would be 30% more than in 2005 and we supported this by an increase in the income of the representative consumer importing from the region ([Part I\(b\) of the Appendix](#)). Wages and rents in the rest of the world enter the cost functions of firms in the region and are set 25% higher than in 2005 ([Appendix, Part I\(c\)](#)).¹⁴ The building stocks in the City would remain fixed out to 2035 due to the height restrictions and essentially no available developable land, while the rents and market prices of the City's floor spaces are endogenously determined and the 8% baseline vacancy rates adjust downward as firms and consumers choose smaller floor space quantities. For the CDTs and the suburbs where vacant land is available, the floor space and land stocks adjust by construction and demolition while vacancy rates, rents and market prices are endogenous ([Parts I\(d\) and I\(e\) of the Appendix](#)).

4.2 Short run and long run equilibria with the GPE in place

In the 2035 baseline equilibrium without the GPE, it is assumed that the Paris region is in equilibrium with the rest of the world, and a utility level prevails in the region and in the rest of the world so that there is no net in- or out-migration of population in the region. Introducing the

¹⁴ Firms use labor from the region and the rest of the world, as imperfect substitutes. Wages in the rest of the world are exogenous and when they rise, an upward pressure on the region's endogenous wages is created.

GPE lowers the exogenous public transit travel times, $TIME_{PT|ij}$ in Eq. (3). From this, market adjustments and a new general equilibrium follow.

[FIGURES 3a and 3b]

Figure 3a shows the equilibria we study by assuming that the GPE is in place and operating in 2035 without road congestion pricing. Curve *A* shows how consumer utility in the region, measured by the compensating variation (CV), changes with the region’s population before the GPE is introduced.¹⁵ The negative slope is verified by perturbing population around its baseline value at point *a*, solving for a general equilibrium each time, confirming that the region is overpopulated at the short run regional equilibrium of point *a*. Curve *B* is the shift of curve *A* induced by the GPE without the TFP externality. On curve *B*, the TFP is held constant at its calibrated 2035 value. From the 2035 equilibrium *a* (the baseline), with the region closed in population, the GPE raises consumer utility by 162 € to a new equilibrium at *b* on curve *B*. In the long run, population increases by in-migration and consumer utility declines along curve *B* back to its baseline level, until the new long run equilibrium occurs at *b'* where population is 1.8% higher than the baseline. With the TFP externality, the GPE improves not only travel times but also productivity, and Curve *A* shifts to the position of curve *C*. In the short run, utility rises from *a* to *c* by 340 €. In the long run, in-migration increases regional population by 4.53% above the baseline, utility retreating to its baseline level at *c'*.

Figure 3b is interpreted the same way as Figure 3a, but the GPE is introduced together with Pigouvian congestion pricing implemented on all road network links (explained in Part II of the Appendix.) The utility-population curve shifts down from curve *A* to curve *D* when there is no TFP externality, because of the negative income effect of congestion pricing. Consumer utility is 84 € below the baseline in the short run at *d*. Population decreases by 0.3% to reestablish a long run equilibrium with road pricing at point *d'*. With the TFP externality, curve *A* shifts up to position *E*. Consumer utility increases by 130 € above the baseline level in the short run as a new equilibrium occurs at point *e*. In the long run, regional population rises 1.2% above baseline at *e'* and utility declines to its baseline level.

4.3 Total factor productivities

¹⁵ Calculation of the CV is explained in Part III of the Appendix.

Table A3 in Part VI of the Appendix displays the equilibrium TFPs under each simulation and the percentage increase in TFP relative to the baseline. In the long run (region open-in-population) the TFPs are higher than in the short run (region closed-in-population), because as population increases in the long run, so do job densities in Eq. (2) across the region. The higher population causes congestion to rise, and car travel times and composite travel times G_{ij} also rise, causing a secondary countervailing effect on the TFPs, smaller than the effect of the job density increase. Congestion pricing induces switching from car to public transit, reducing car and composite travel times, τ_{ij} and G_{ij} , and the TFPs rise. Thus, congestion pricing and population increase work together to increase the TFPs.

[TABLE 3 HERE]

4.4 Population and job distribution

Table 3 shows the effect of the GPE on the redistribution of the residential population and of jobs among the City, the CDTs, and the suburbs. As explained in the Introduction, consumers seek to reside near their jobs and near shopping to economize on travel costs and times, and firms seek to locate near their workers and customers to pay lower wages and charge higher prices.

Because the GPE connects the CDTs facilitating travel among them, it does shift jobs and residents in the margin to the CDTs in the short run when there is no TFP externality. With the TFP externality, the GPE shifts some population back to Paris and the suburbs and shifts some jobs from the CDTs and from Paris to the suburbs. Proposition 1 is the underlying reason: because the GPE increases TFP in the CDTs, fewer workers are hired per unit of output. The positive extensive marginal effect raises the quantity of labor demanded due to lowered output prices (Proposition 2) but not enough to fully offset the intensive marginal effect. These short run effects are swamped by the super-extensive in-migration effect in the long run.

Congestion pricing in the short run redistributes population from the suburbs into Paris, while decentralizing jobs from Paris and some CDTs, to the suburbs. The population centralizes because, to avoid the congestion tolls, some consumers relocate to Paris and to some CDTs where public transit is more available, or relocate to the higher density Paris and the CDTs to shorten commute and shopping travel times. Jobs adjust to congestion tolls by relocating in the margin to the suburbs where congestion, wages and rents are all lower. The additional job relocations caused by the TFP externality are modest: an additional relocation to the suburbs of about ten percent.

4.5 Transportation

Table A4, in Part VI of the Appendix documents the transportation related effects of the GPE in the simulations. In the short run, trips and travel times by car are reduced as some trips switch to the GPE and as road congestion diminishes. In the long run, with unpriced congestion, although the car share shrinks because of the GPE, car times become longer due to in-migration which increases congestion. The biggest reductions in travel times occur between and within the CDTs. Gasoline consumption is reduced by 7.04% under congestion pricing in the short run, making the region greener. The following results are also noteworthy. In the short run, the GPE lowers the share of car trips for all trip-origin to trip-destination zone pairs, but more significantly for CDT-to-CDT trips (by 1.13%), which see the greatest decrease in the composite travel times and the greatest increase in trips. While we saw that population and jobs increase in the CDTs due to the GPE (Table 3), the commute patterns show that more workers choose to *reside and work* in the CDTs because of the travel time reductions induced by the GPE. In the presence of congestion pricing, such a spatial concentration effect in the CDTs is weakened by the cost of the road pricing borne by the consumers. But the net outcome is still that the GPE brings more resident-workers to the CDTs, in both the short run and the long run. The additional effects that arise from the TFP externality are again not large.

[TABLE 4 AND TABLE 5 HERE]

4.6 Rents and wages

Table 4 displays changes in nominal wages, in nominal rents, in the prices of zonal outputs and in a regionwide consumer price index. Recall that consumers in the model travel from their residences to all other zones to purchase the imperfectly substitutable zonal goods where they are produced and sold. The prices of these zone-specific composite goods, inclusive of the travel cost of shopping (and of tolls, if any), are weighted by the quantities purchased to arrive at an average regionwide consumer price index explained in Part IV of the Appendix. This price index is used to normalize the nominal wages and rents to arrive at real wage and rent changes shown in Table 5. “Real” here denotes the additional quantity of goods that can be bought per euro of income.

In the short run, without the TFP externality, the introduction of the GPE causes prices at the zone of sale and, hence, the price index to fall (Table 4). The GPE causes prices to fall in the CDTs but not in the City and the suburbs. The regional average price falls, but only slightly. The TFP externality reduces the price index more, since the externality reduces the marginal (unit) cost

of production and hence the prices of the zone-specific composite goods. Under congestion pricing, the price index rises, since the monetary cost of shopping travel includes congestion tolls.

Consider now the changes in the nominal wages and rents and in the prices of the composite goods at their zones of production (sale), in [Table 4](#). The GPE, without the TFP externality, makes nominal wages in the CDTs fall because the shortened travel times draw more labor supply to the CDTs. Since aggregate regional worker population and labor supply are fixed, nominal wages in the City and in the suburbs rise. Since CDTs become more accessible, nominal rents there also rise, while they rise or fall marginally in the City and in the suburbs. With the TFP externality, nominal prices fall more and, as a result, nominal wages and rents also fall. While nominal prices fall due to the lowered unit costs of production, output rises because the GPE enhances the TFP externality. The output increase requires more factor inputs, creating an upward pressure on wages and rents. As a result, nominal wages and rents fall less than output prices do.

In the long run, the population growth increases the supply of labor and the demand for space. Nominal wages fall while nominal rents rise, and nominal prices again fall relatively more than nominal wages and rents. Nominal prices in the long run fall more than in the short run but not more than nominal wages fall: without the TFP externality, prices fall by 0.54% and wages by 1.02%; and with the TFP externality, prices fall by 2.93% and nominal wages by 4.07%. Prices and wages fall more than in the short run because the job densification caused by the in-migration raises the TFPs more, further reducing the private marginal (unit) cost of production.

[Table 5](#) reports real rents and wages and output. Real rents rise and by most in the CDTs, where the accessibility is most improved by the GPE. While the TFP externality raises real rents, congestion pricing lowers them. In the short run with the GPE and no congestion pricing, real wages and real rents rise due to two channels. One is because of the fall in nominal output prices. The other is because output increases, which requires more inputs which tends to support wages and rents. Higher wages, in turn, tend to increase housing rents due to the positive income effect. The higher output causes commercial rents to rise, inducing conversions from residential to commercial buildings at the margin, contributing to higher residential rents. In the long run, real wages fall because the supply of labor increases. Real rents rise more than in the short run because the in-migration causes higher demands for space. Outputs increase and more so in the long run, due to GPE-induced time savings and the higher population. The TFP externality induces even

more output, whereas congestion pricing has a depressing effect on output because of its negative income effect.

[TABLE 6 HERE]

4.7 Social welfare and cost-benefit analysis

Table 6 shows the social welfare and the cost-benefit analysis. Section A of Table 6 shows the aggregate social welfare and its components per consumer per year, the average 2035 after-tax average consumer income, and the social welfare changes from the baseline as a percent of this income. Section B of Table 6 shows the congestion and TFP externalities per consumer. Derivations of these externalities are in Part II of the Appendix. Section C of Table 6 shows the cost, the social benefit-to-cost ratio of the project, and the public cost recovery ratio which is the part of the project's cost plus (minus) the public sector's tax revenue losses (gains) and the public transit system's deficit (surplus) recovered by the congestion tolls.

As explained in Part III of the Appendix, aggregate social welfare change induced by the GPE is the sum of the compensating variations (CV) of the consumers in the region, the CV of consumers in the rest of the world who are importing from the region, the aggregate annualized income from changes in real estate prices that accrue as windfall gains to real estate investors, the changes in the public revenues from the income tax and the sales tax, plus (minus) the change in any surplus (deficit) from the operation of the public transit system, plus the revenue from congestion pricing (if any). Producer profits in the model do not affect welfare since they are zero due to competition and free entry in each of the zonal goods markets.

The salient results on the components of welfare are as follows:

(a) *CV of consumers in the region*: In the short run, when the region is closed in population, the GPE improves consumer utility (CV) because the GPE lowers travel times directly for public transit riders, and indirectly for drivers by alleviating congestion. Without the TFP externality, real wages and real rents rise countervailing each other's effects on the CV. Not only does the GPE make consumers better off via lower travel times, but also shopping travel costs inclusive of the prices of goods are lowered which cause consumer demands and outputs to increase. This shopping channel is ignored in all partial equilibrium models and is also absent in the theoretical models of Parry and Bento (2001), Arnott (2007) and Venables (2007). In the long run, when the region is open in population, consumer CV cannot change by the long run equilibrium no-migration condition.

The gain in CV from the GPE is larger when the TFP externality is present, because the unit cost of production is lowered which by competition and free entry lowers the prices of goods. In [Table 4](#) we saw that the percentage drop in nominal product prices is larger than the percentage drop in wages and rents, and in [Table 5](#) that real wages and rents rose. The balance of these changes works to increase consumer CV. When there is no congestion pricing, real wages increase less than do real rents which works to decrease CV. But what causes the CV to ultimately rise, are the shortened travel times and the decrease in the prices of goods. Congestion pricing reduces consumer CV, because the tolls reduce disposable income and increase the delivered price of the shopped goods. Both effects work to reduce consumer welfare if the travel time gains of congestion pricing are not sufficiently valuable to consumers.¹⁶

(b) *CV of importers*: The CV of the outside-the-region consumer increases because prices of the region's products decrease. Recall from [Table 4](#) that the TFP externality causes prices to fall more, and that prices fall more in the long run because the labor supply increase depresses nominal wages. The lower wages reduce production costs and prices at the zones of sale and because of this, importers gain more in the long run than in the short run. Congestion tolls do not hurt importers since they do not pay the tolls, and the disposable incomes of the importers is not affected by the rent increases caused by the in-migration of population to the region.

(c) *Real estate prices*: Changes in real estate prices are annualized with an interest rate of 4%. Real estate prices change because they capitalize the changes in rents paid by the consumers and the firms and the option values from construction and demolition (parts [I\(d\)](#) and [I\(e\)](#) of [Appendix](#)). In the short run, real estate prices decrease more with the TFP externality, as it decreases nominal wages. In the commercial real estate market, lower nominal wages cause a substitution of labor for floor space decreasing nominal commercial rents. Commercial rents also fall because the lower output prices decrease the value of the marginal product of floor spaces, and hence rents. In the housing market, the lower wages induce a negative income effect, causing nominal residential rents to decrease. In the long run, the population increase overcomes the negative effect on housing rents from the lower wages, causing nominal rents to rise by increasing the competition for floor spaces. Pricing congestion in the long run again causes real estate values to fall as the tolls inhibit in-migration and the negative income effect lowers housing rents directly and commercial rents indirectly.

¹⁶ This result changes if the consumers' valuation of travel time is increased sufficiently.

(d) *Income and sales tax revenues*: Tax revenues are a benefit to the public sector and are composed of the income tax consumers pay on the sum of their wage and non-wage incomes plus the sales tax consumers pay on the goods they shop (but not on housing). [Table 6](#) shows that revenues from the income and sales taxes decrease with the TFP externality, decrease with congestion pricing and are generally lower in the long run than in the short run. This is because the tax bases of aggregate nominal income and aggregate sales are negatively affected by the decreases in nominal wages and in output prices. This is examined in more detail below.

(e) *Public transit operating surplus or deficit*: Fare collections increase as the GPE induces new trips by public transit (see bottom row of [Table A4](#)). Aggregate increase in fare collections minus the cost of operating the GPE benefits public revenues. Without congestion pricing, the GPE increases the operating deficit. With congestion pricing, as trips switch to public transit, the deficit can decrease or turn into a surplus. A surplus also occurs with in-migration in the long run.

4.8 Market distortions and their interaction with congestion pricing

Several market distortions are operative in our model. One is the negative externality of road traffic congestion, and another is the positive TFP externality. Additionally, the income tax and the sales tax are both distortionary taxes. Pigouvian congestion pricing internalizes the congestion externality by charging road trips the gap between their marginal social cost and their average private cost. But because the TFP externality and the tax distortions remain uncorrected, congestion pricing can potentially reduce social welfare if it sufficiently exacerbated the other distortions. It is important therefore to gain insight into how congestion pricing interacts with the TFP externality and with the revenue from the distortionary taxes.

Congestion pricing and the TFP externality

The model by [Parry and Bento \(2001\)](#) treated congestion pricing but did not include a productivity externality, whereas [Venables \(2007\)](#) included a productivity externality but did not treat congestion. [Arnott \(2007\)](#) examined congestion pricing in the presence of a productivity externality when all jobs are in the CBD (Central Business District) and labor supply to the CBD is flexible. All three models are monocentric. As in [Parry and Bento \(2001\)](#) and [Venables \(2007\)](#), Arnott treated only commuting, ignoring consumption-related travel. In Arnott's model, Pigouvian congestion pricing corrects the congestion externality, but discourages labor supply to the CBD, which weakens the productivity externality. Therefore, in Arnott's model, the socially optimal congestion toll depends on the relative magnitudes of the two externalities. When the productivity

externality is sufficiently big relative to the congestion externality, then the socially optimal congestion toll in Arnott's model could even be negative mimicking a Pigouvian wage subsidy.

In our polycentric model with the TFP externality given by Eq. (2), Pigouvian congestion pricing affects TFP along two margins: (i) by redistributing jobs among the twelve job locations; and (ii) by reducing congestion, which enhances the accessibility of jobs to each other. From Table 6, congestion pricing in the short run slightly decreases the TFP externality by 1.46% from 411 € to 405 € per consumer because of the jobs-dispersing effect of tolls. Congestion pricing in the long run reduces central job densities somewhat which works to decrease the TFP externality. But as congestion pricing decreases the composite travel times too, this works to increase the TFP externality (from Eq. (2)). The net effect is only a slight increase in the TFP externality by 1.52% from 395 € to 401 € per consumer (Table 6). In summary, there is a small negative interaction between congestion tolls and the TFP externality in the short run and a small positive interaction in the long run. To our knowledge, ours is the only empirical investigation of the interaction between congestion pricing and the TFP externality.

Congestion pricing and tax revenues

From Table 6, congestion pricing in the short run causes the income and sales tax revenues to decrease and more so in the presence of the TFP externality. In the long run, when there is no TFP externality, congestion pricing reduces the tax revenues less than in the short run. But when the TFP externality is present, congestion pricing reduces tax revenues significantly more in the long run than in the short run. How do these results differ from those in the simple theoretical models of Venables (2007) and Parry and Bento (2001) who included an income tax, but not a sales tax?¹⁷

Venables (2007) models a city open to in-migration which corresponds to our case of long run equilibrium with a fixed level of utility (capturing only our super-extensive margin). In his model all work at the CBD so there are no issues arising from intraurban job redistribution. There is no congestion, but transport improvement entails a costless reduction of the exogenous cost of commuting per mile, making the urban area to gain population and to expand in area. More jobs in the CBD cause the TFP to increase, and since workers are paid their average product, income increases and so do income tax revenues. Unlike our case, the efficiency gain from a higher TFP does not cause lower output prices that can additionally benefit the city's workers.

¹⁷ Arnott (2007) did not include distortionary taxation.

Parry and Bento (2001) treat the short run (fixed aggregate population), have no TFP externality and find a negative interaction between the Pigouvian toll and the distortionary income tax. In their model, the wage rate is exogenous but income is endogenous because the consumer-worker makes a labor-leisure trade off. Pigouvian congestion pricing discourages labor supply, exacerbating the welfare loss from the distortionary tax on income. As in Venables, in their model too the price of output is implicitly fixed.

We recognize that consumers spend about 70% of their after-tax income on the purchase of goods and services which entails consumption related trips. In the Paris region, such non-work trips are about 75% of total trips (Table 1). Because congestion pricing in our model reduces purchasing power, it negatively affects sales tax revenues. Income tax revenues are negatively affected because nominal wages are lowered. Note from Table 4, that when the TFP externality is present, product prices and wages are lowered by congestion pricing in the short run, but are even lower with congestion pricing in the long run. As a result, in Table 6, income tax and sales tax revenues under congestion pricing with the TFP externality are lower in the long run than in the short run.

[FIGURES 4a, 4b HERE]

The TFP externality and tax revenues

Figures 4a and 4b illustrate the effect of the GPE on the sales tax revenue rectangle in the product market, and on the income tax revenue rectangle in the labor market for a jobs center in the presence of the TFP externality.¹⁸ In Figure 4a, the market for product, the supply of product is horizontal because of global constant returns to scale in production. The GPE enhances the TFP externality and lowers unit production cost, and hence the product price. At the same time, there is an increase (shift) in the demand for product because of the increase in real wages and because the GPE lowers travel costs. As seen from the diagram, with the sales tax rate, t , remaining constant, the tax revenue rectangle becomes vertically shorter (tp falls because p falls) and horizontally longer (because output increases), and resulting in lower sales tax revenue overall (smaller area of the tax rectangle). This happens in the eight out of the twelve zones and the sales tax revenue, aggregated across all zones, is also lower. In Figure 4b, the labor market, the demand for labor in nine out of the twelve zones increases (shifts up) because more output must be produced (from Figure 4a), while the supply of labor to the zones also increases (shifts out) because of the increase

¹⁸ Demand and supply are drawn as linear for simplicity.

in real wage and the commuting times lowered by the GPE. The new equilibrium occurs at a higher level of jobs and a lower nominal wage. The income tax rate T remaining constant, the tax revenue rectangle becomes vertically shorter (Tw falls because w falls) and horizontally longer (because jobs increase), but resulting in lower income tax revenue overall. Income tax revenue from five out of twelve zones falls and the aggregate income tax revenue also falls.

4.9 The social benefit to cost ratio and public cost recovery

We annualize the 35 billion € construction cost of the GPE over an infinite horizon with a 4% discount rate to get 1.4 billion € per year.¹⁹ With the 2035 baseline projected population of 10.6 million, the cost is 132 € per consumer per year and changes somewhat under those simulations that affect the long run population (Table 6). The GPE operating cost is projected to be 0.52 billion € annually and the fare structure of the region's public transit system is expected to apply also to trips by the GPE. The annual operating deficit or surplus is included in Table 6.

The social benefit to cost ratio is the social welfare per consumer divided by the project cost per consumer. In the short run, without the TFP externality it is 1.09, rising to 3.54 with the TFP externality. This demonstrates the strong wider benefits of the GPE project. Under congestion pricing, the benefit to cost ratio rises from 1.09 to 1.81 without the TFP externality, but falls from 3.54 to 3.00 with the TFP externality, because congestion pricing reduces tax revenues as we saw. In the long run, without congestion pricing, the social benefit to cost ratios are lowered because consumer utility is at its baseline value, while population growth increases labor supply and reduces wages and incomes which causes lower tax revenues. With congestion pricing the social benefit to cost ratio rises again from 0.02 to 2.45 without the TFP externality and from 1.59 to 4.01 with the TFP externality.

The public cost recovery ratio is the fraction or multiple of the sum of the annualized construction cost and the changes in income and sales tax revenues, plus the change in the annual operating deficit that can be covered by the congestion tolls. In the short run, without the TFP externality, the recovery ratio is 1.01, but with the TFP externality, it falls to 0.81. In the long run, without the TFP externality, the ratio is 1.15 and with the TFP externality it falls to 0.66. The public cost recovery ratio falls because the TFP externality reduces income and prices, for reasons that we saw, causing less revenue from income and sales taxes.

¹⁹ The discount rate consists of a risk-free interest rate of 2.5% plus a risk premium of 1.5% deemed appropriate for urban transportation projects in France [Quinet (2013)].

5. Sensitivity analysis

Table A5 in Part VI of the Appendix, in the same format as Table 6, presents six sensitivity analyses juxtaposed against the baseline equilibrium. In each sensitivity analysis, a parameter is perturbed as shown in the column headings and a new baseline equilibrium is computed with the perturbed parameter value, without the GPE, the region closed in population, the TFP externality present and without congestion pricing. The GPE is then introduced and the simulation repeated. The last six columns of Table A5 show the effects of the GPE under the perturbed new baseline equilibria. For comparison, the first column shows the results of introducing the GPE with respect to the original baseline (same as column 2 of Table 6).

The value of β : The value of the parameter β in the TFP Eq. (2), is lowered from $\beta = 3$ in the baseline to $\beta = 1$. Recall that there are two effects of the lowered β : (i) the elasticity of TFP to a proportional increase in composite travel times is lowered; (ii) the sensitivity to the total regional jobs, rather than to nearer jobs, is increased. Social welfare is 5.5% higher when $\beta = 1$. The TFP externality increases from 411 when $\beta = 3$, to 1060 when $\beta = 1$ and the congestion externality increases from 516 to 772. The reason for the higher congestion is that product prices fall more because of the higher TFP which stimulates demand for goods and, hence, increases consumption related trips. Because of the lower output prices, nominal wages and the average incomes are also lower.

GPE travel time savings: When the public transit time savings in the baseline are 20% higher than in Table 2a, then there is a 14% increase in the social welfare gain and a 17% increase in the consumer CV gain with the TFP externality.

Commute time disutility coefficient, γ : With a more negative γ , workers value the GPE-induced time savings more highly and, therefore, locate more in the CDTs which afford them bigger time savings. Such relocation is associated with more switching to public transit and lower congestion.

Mode choice elasticity: A lowered mode choice elasticity (from the baseline value of -0.7 to -0.5) results in higher CVs and welfare gains. The reason is that when mode choice is less elastic, then there is a stronger tendency for consumers to locate and work in the CDTs to take advantage of the travel time reductions induced by the GPE. This densification in the CDTs is accompanied

by a higher share of public transit use which leads to milder congestion, while consumers also benefit from the GPE and the higher TFP caused by the job densification.

The elasticity of substitution (same as the price elasticity of demand): The sub-utility defined over the region's consumption goods is [Dixit-Stiglitz \(Dixit and Stiglitz, 1977\)](#) so the consumer has a taste for variety and consumes all of the goods produced in the twelve zones. A higher elasticity of substitution among these goods makes the goods of the different zones closer to perfect substitutes and variety becomes less important. This makes the consumers more sensitive to price than to variety: the consumer wants to shop more from the zones with the lower prices (inclusive of monetary travel cost) than shop more comparable quantities from all zones. Because the TFP externality lowers prices across different locations, the consumer benefits more from this price lowering when the taste for variety is weaker.

The last column of [Table A5](#) shows the effect of increasing by 50% the elasticity of substitution of the outside consumer who imports the region's goods. This causes more output to be produced as the TFP externality reduces prices. Labor demand increases, and this in turn increases the wage incomes of the region's consumer-workers. The higher incomes and purchasing power, and the higher output sold cause sales tax and income tax revenues to increase marginally.

6. Conclusions and extensions

Using a detailed general equilibrium model, we found that the GPE would increase social welfare by a considerable amount, surpassing its projected cost. A net effect of the project is that both residential population and jobs densify in the CDTs which are connected by the megaproject. Due to the project, both real income and real rents increase while gasoline consumption, travel times, and the share of driving decrease. In the long run, the GPE would cause the population of the Paris region to increase, while road congestion pricing would suppress most of the increase, while the revenues from the congestion pricing would offset much of the GPE's direct cost and the tax revenue losses caused by the GPE.

The following conclusions can be drawn from this study regarding the economic effects of megaprojects, based on our findings of the effects of the GPE:

(i) Megaprojects that reduce travel times and improve the accessibility of jobs to each other, generate substantial social benefits and output increases. Accessibility improvements are beneficial even in the absence of the TFP externality, but the wider benefits are substantially more when the megaprojects confer a TFP externality (measured and modeled according to the evidence

in the empirical literature.) Based on this finding it is hard to conclude that megaprojects are white elephants unless there are substantial cost overruns.

(ii) We identified three distinctive margins by which the productivity benefits induced by a megaproject affect the spatial job agglomerations. The super extensive margin of in-migration to the region in the long run is the most important. With fixed population in the short run, the intensive and extensive margins of improved productivity largely offset each other (Propositions 1 and 2). In the short run, therefore, planners should not expect dramatic changes in the intraurban distribution of economic activity.

(iii) Although in the long run, the GPE causes the region to grow bigger in population and jobs, and such a growth is significantly strengthened by the TFP externality, the negative income effect of congestion pricing mitigates the in-migration induced by the project.

(iv) The TFP externality reduces nominal output prices and wages, but increases real wages and rents, measured in purchasing power. Importantly, the TFP externality alters product prices in ways that affect the benefits received by consumers in the region and by consumers who import from the region, and affect the government's revenues from distortionary taxes. More precisely:

(iv-a) The lower nominal output prices of traded goods confer benefits on those who reside elsewhere but purchase goods and services produced in the region. Not counting these benefits can misleadingly and substantially underestimate the social value of the project.

(iv-b) The lower nominal output prices and wages induced by the higher TFP cause the revenue from income and sales taxation to decrease. Not counting these losses can misleadingly and substantially overestimate the value of the project.

(iv-c) Potential revenues from congestion pricing of the road traffic are a substantial part of the social benefits but the negative income effects of congestion pricing on purchasing power cause the revenue from the distortionary taxes to be reduced importantly.

(v) The TFP externality has a minor negative interaction with congestion pricing in the short run (fixed population) and a minor positive interaction in the long run (endogenous population).

On the methodological side, the urban computable general equilibrium model presented here is grounded in microeconomic theory. It provides a framework for evaluating the social benefits and allocative effects of urban transportation projects at a realistic level of detail for an urban setting in which the spatial distributions of population and jobs are endogenously determined. The model, which captures a rich set of interactions among markets in an urban area and the

interactions between the transport sectors and the markets, can be employed to evaluate a broad set of policies and exogenous shocks in different urban areas, and to provide results with theoretical clarification, and with empirical implications, thanks to the ever-improving availability of spatial data. Although we presented sensitivity analyses around the model's calibrated coefficients to investigate the robustness of the results, there is clearly more that can be done to vary functional forms and modify model assumptions in order to see how such changes affect the results. Potential extensions of the model include investigating the effects of alternative travel pricing schemes, modeling in more detail the relationship between non-work trips and the quantity and location of consumption, and modeling delivery services and online shopping. Also important would be a higher degree of sectoral disaggregation, especially distinguishing industries in which the TFP externality is stronger from those in which it is weaker or non-existent.

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FIGURES AND TABLES

FIGURE 1: The Paris Region (Ile-de-France)
 (City of Paris and its 20 arrondissements in inset; Dark pink zones are the 10 CDTs or poles)

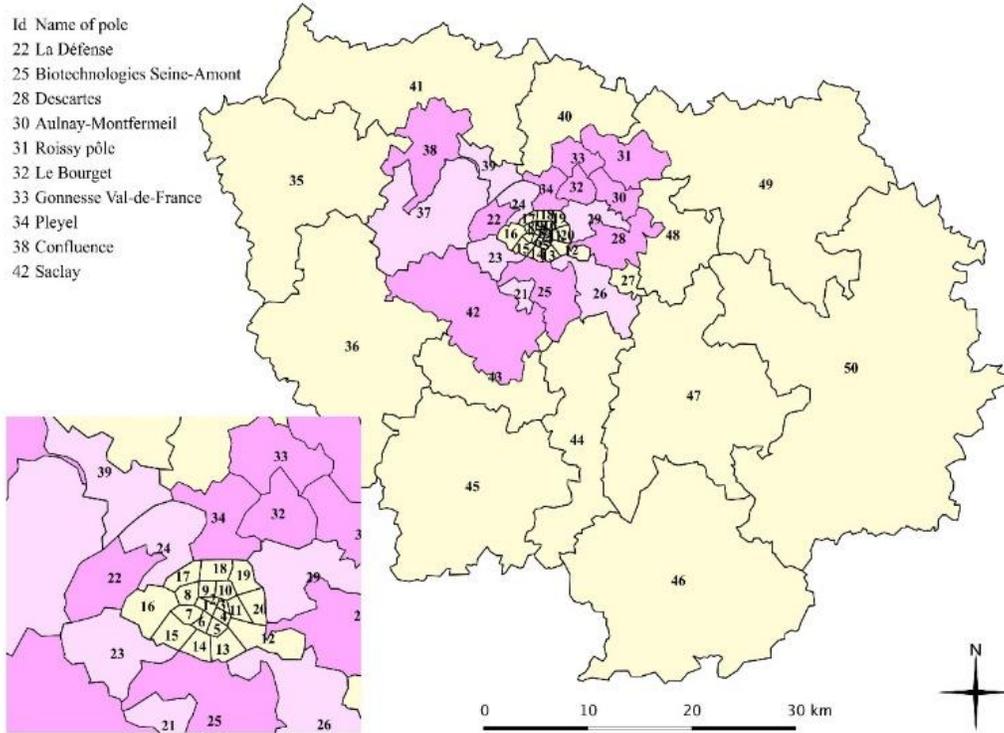


FIGURE 2: The Project du Grand Paris (GPE) proposed public transit lines

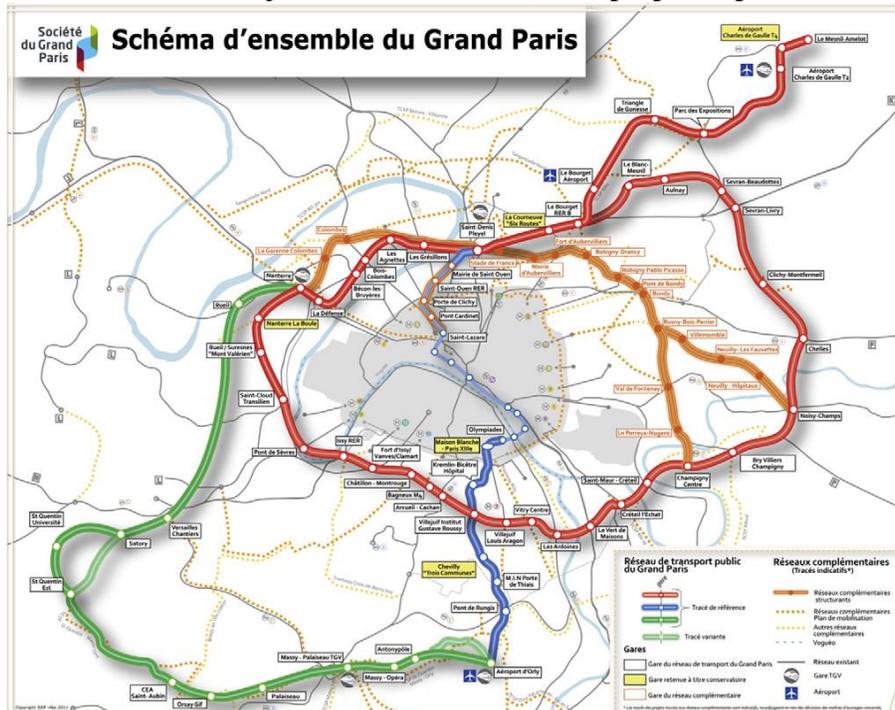


FIGURE 3a: GPE-induced long run growth without congestion pricing

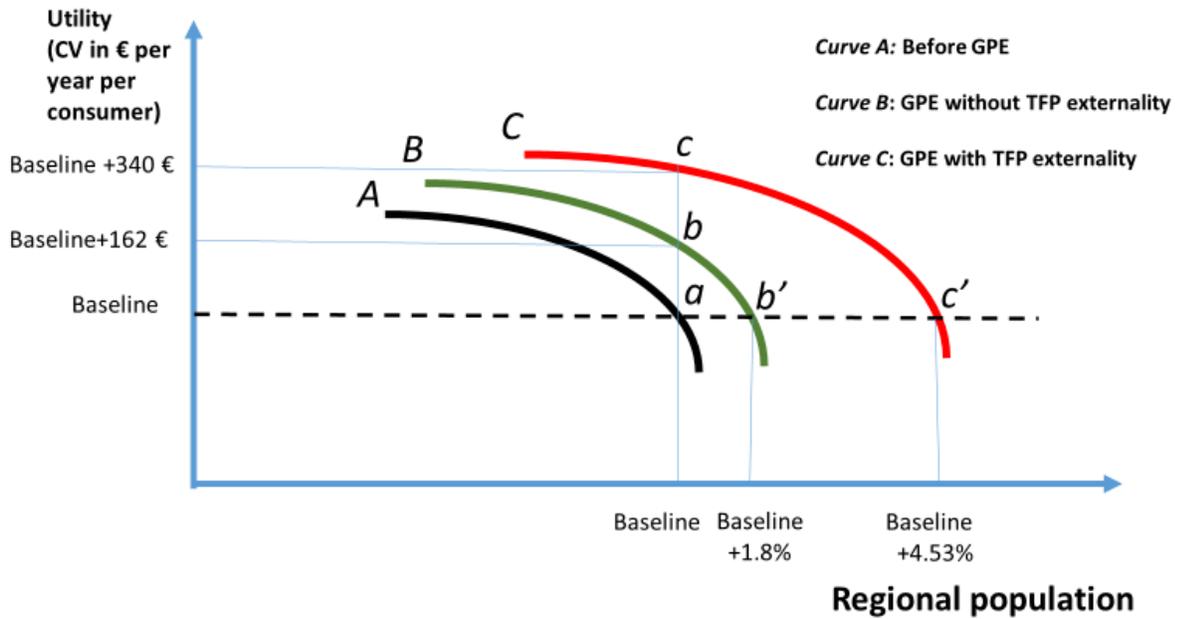


FIGURE 3b: GPE-induced long run growth with congestion pricing

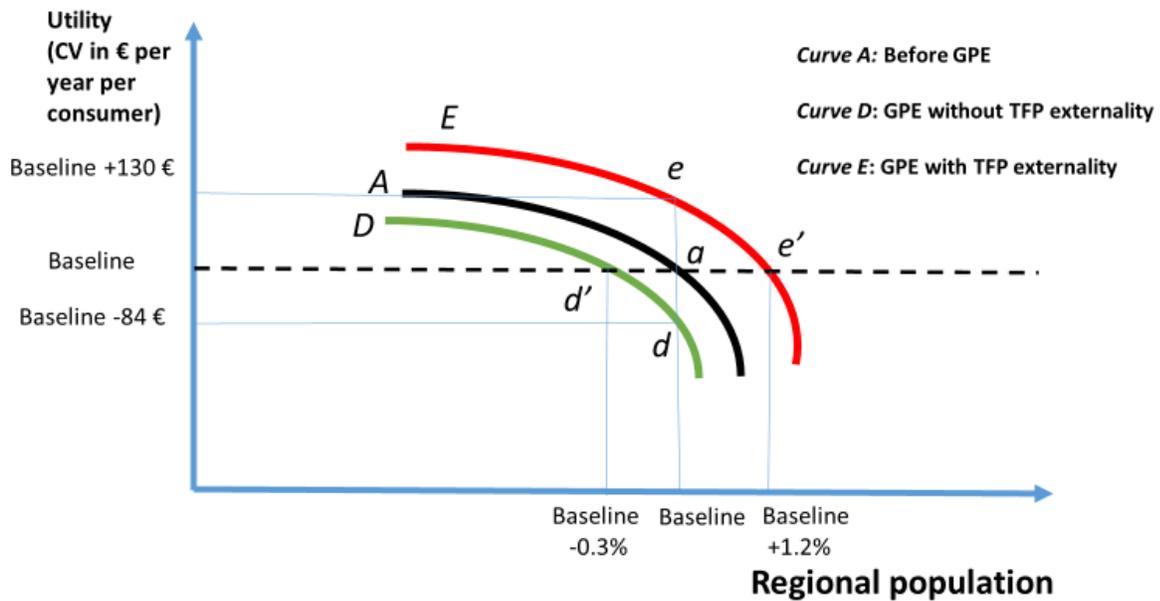


FIGURE 4a: The effect of the GPE (with the TFP externality) on sales tax revenue

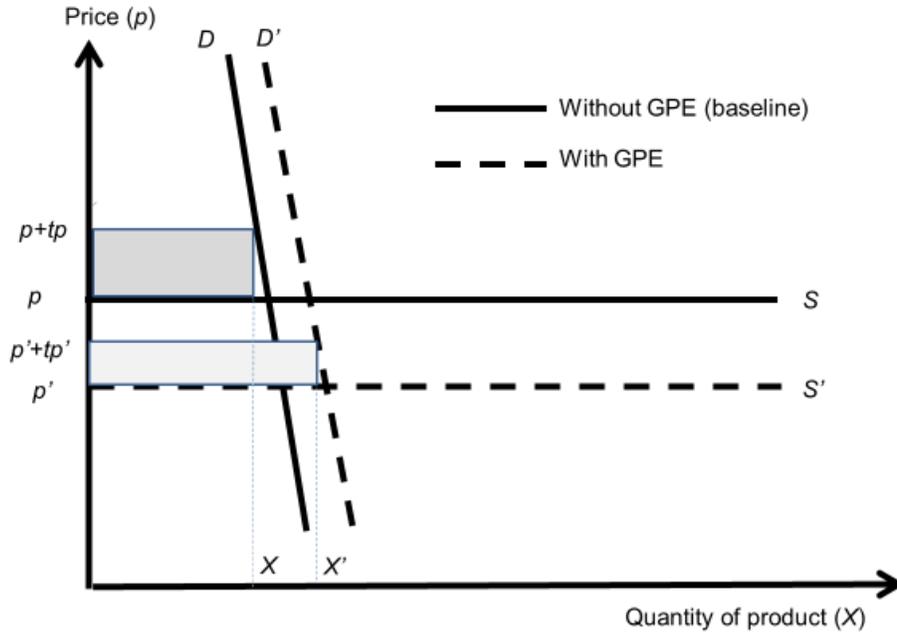


FIGURE 4b: The effect of the GPE (with the TFP externality) on income tax revenue

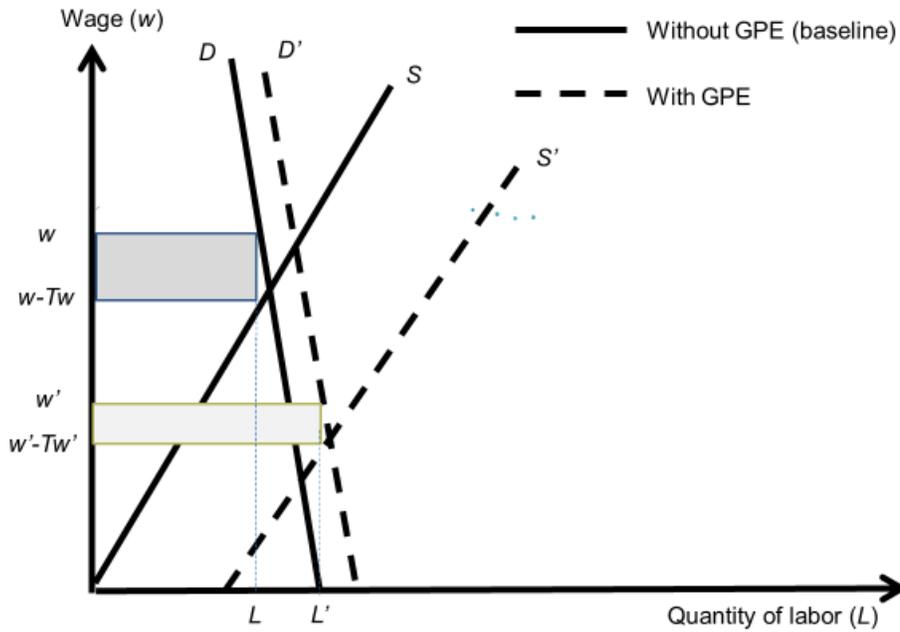


TABLE 1: Land, floor space, population, jobs, densities and daily trips in circa 2005

	Total	Shares (in percentages)			
		City	CDTs	Suburbs	Exurbs
Developable land		0	8	92	
Residential floor space		8	37	55	
Commercial floor space		24	33	43	
Population	9,214,428	19	31	46	4
Jobs	5,297,752	31	33	36	
Population density (person/sq. km)		27,710	4,188	962	
Jobs density (jobs/sq. km)		26,687	2,576	422	
Trips by origin (residence)	21,067,514	22	31	44	3
Work trips (commutes)	5,297,752	21	31	43	4
Non-work trips	15,769,762	22	31	45	2
Car trips	7,943,385	14	30	50	6
Public transport trips	11,535,452	28	32	40	
Trips by destination	21,067,514	44	21	35	
Work trips (commutes)	5,297,752	31	33	36	
Non-work trips	15,769,762	49	17	35	
Car trips	7,943,385	23	25	51	
Public transport trips	11,535,452	62	17	21	

TABLE 2a: Average one-way public transit time savings on the GPE in 2035 – Minutes

TO → FROM ↓	Paris	CDTs										Suburbs
		La Defense	Seinte Amont	Descartes	Aulnay- Montfermeile	Roissy Pole	La Bourget	Gonesse	Pleyel	Confluence	Saclay	
Paris	0.7	1.8	0.0	0.2	0.1		0.1	0.9	1.6	0.2	0.1	0.7
La Defense	1.4	4.4		0.5	0.4	0.7	1.8	3.1	4.8	3.7		1.5
Seine Amont	0.1	2.0	6.4					0.5	2.6		1.1	0.3
Descartes	0.2	0.4		5.0	0.3		2.5	1.5	1.5			0.8
Auinay Montfermeile	0.1	0.4			6.9		0.4	8.4		1.5		0.8
CDTs						12.0	3.2					2.8
La Bourget	0.2	2.6		1.8	0.3	3.6	6.8	4.9		5.3		1.9
Gonesse	0.1	1.8			9.1	0.7	3.3	8.7		7.2	0.2	3.0
Pleyel	1.0	5.0		1.4	3.4	2.9		1.1	5.4	5.8	0.1	2.6
Confluence	0.5	3.4			3.3	6.1	4.8	12.3	5.4	8.4	1.7	0.6
Saclay	0.0	0.4	0.5				0.8	3.3	1.9	7.0	8.9	0.8
Suburbs	0.2	0.6	0.3	0.0	0.9	2.2	1.2	2.9	1.8	1.1	0.8	4.5

TABLE 2b: Average public transit time savings on the GPE in 2035 – Percentages

TO → FROM ↓	Paris	CDTs										Suburbs
		La Defense	Seine Amont	Descartes	Aulnay Montfermeile	Roissy Pole	La Bourget	Gonesse	Pleyel	Confluence	Saclay	
Paris	2.9	4.3	0.1	0.6	0.2		0.2	1.7	4.1	0.3	0.2	1.4
La Defense	3.6	17.7		1.0	0.6	0.9	2.8	4.7	8.4	6.2		3.3
Seine Amont	0.1	3.0	19.1					0.7	3.8		1.9	0.5
Descartes	0.5	0.7		15.3	0.5		4.5	2.4	2.7			1.7
Auinay Montfermeile	0.2	0.5			23.3		1.0	12.5		1.5		1.2
CDTs						37.6	5.7					3.8
La Bourget	0.3	4.0		3.0	0.8	6.8	27.7	10.4		5.9		3.5
Gonesse	0.2	2.3			13.8	1.6	7.0	32.1		7.1	0.2	4.5
Pleyel	2.7	8.7		2.4	6.2	5.0		2.7	19.0	7.2	0.1	4.9
Confluence	0.8	5.4			3.3	5.7	5.4	13.3	7.0	24.2	1.7	1.0
Saclay	0.0	0.7	0.9				0.9	3.5	2.2	7.8	24.1	1.4
Suburbs	0.4	1.3	0.5	0.1	1.3	3.3	2.0	4.6	3.2	1.8	1.3	8.3

TABLE 3: GPE-induced changes in the distribution of residential population and jobs
(changes, and percentage changes from the 2035 baseline)

	Closed in population				Closed in population with congestion pricing				Open in population				Open in population with congestion pricing				
	Without TFP externality		With TFP externality		Without TFP externality		With TFP externality		Without TFP externality		With TFP externality		Without TFP externality		With TFP externality		
Population	Paris	-948	-0.05%	-172	-0.01%	11,016	0.58%	12,666	0.67%	30,918	1.62%	79,565	4.16%	3,652	0.19%	33,861	1.76%
	CDTs	7,065	0.21%	7,020	0.21%	-1,356	-0.04%	-1,255	-0.04%	67,243	2.03%	158,221	4.77%	-13,934	-0.41%	38,337	1.14%
	Suburbs	-4,572	-0.09%	-4,205	-0.08%	-9,573	-0.19%	-10,210	-0.20%	89,470	1.75%	230,458	4.51%	-21,059	-0.41%	49,275	0.97%
	Exurbs	-1,545	-0.67%	-2,643	-1.15%	-88	-0.04%	-1,202	-0.58%	4,029	1.75%	10,907	4.73%	-2,477	-1.21%	2,177	1.06%
	Total	0	0	0	0	0	0	0	0	191,661	1.81%	479,152	4.53%	-33,818	-0.32%	123,651	1.17%
Jobs	Paris	-3,061	-0.16%	-3,661	-0.19%	-6,949	-0.36%	-7,898	-0.41%	29,894	1.55%	78,074	4.05%	-15,540	-0.81%	13,684	0.71%
	CDTs	4,875	0.23%	4,437	0.21%	-10,119	-0.48%	-10,915	-0.52%	43,597	2.07%	102,041	4.85%	-18,009	-0.85%	14,388	0.67%
	Suburbs	-1,813	-0.08%	-775	-0.03%	17,068	0.75%	18,813	0.83%	41,131	1.79%	106,441	4.64%	13,324	0.59%	45,878	2.03%
	Total	0	0	0	0	0	0	0	0	114,623	1.81%	286,557	4.53%	-20,225	-0.32%	73,949	1.17%

TABLE 4: GPE-induced changes in nominal wages, rents, prices and in the price index (percentage changes from the 2035 baseline)

		Closed in population		Closed in population with congestion pricing		Open in population		Open in population with congestion pricing	
		Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality
Nominal wage	Paris	0.14	-0.29	-0.61	-1.23	-0.88	-3.84	-0.22	-2.00
	CDTs	-0.22	-0.67	-0.86	-1.48	-1.29	-4.68	-0.43	-2.04
	Suburbs	0.13	-0.20	-2.41	-2.86	-0.83	-3.53	-2.34	-3.54
	Total	0.01	-0.40	-1.31	-1.87	-1.02	-4.07	-1.05	-2.61
Nominal rent	Paris	-0.01	-0.22	-0.25	-0.56	0.51	1.53	-0.35	-0.25
	CDTs	0.06	-0.09	-0.47	-0.71	0.80	2.48	-0.59	-0.43
	Suburbs	0.00	-0.11	-0.81	-0.92	0.67	2.19	-0.87	-0.48
	Total	0.01	-0.15	-0.51	-0.73	0.65	2.04	-0.54	-0.36
Nominal price at place of sale	Paris	0.00	-0.87	-0.46	-1.63	-0.54	-3.00	-0.27	-2.09
	CDTs	-0.18	-1.17	-0.59	-1.84	-0.71	-3.42	-0.42	-2.28
	Suburbs	0.09	-0.59	-1.51	-2.31	-0.39	-2.42	-1.47	-2.70
	Total	-0.02	-0.86	-0.84	-1.91	-0.54	-2.93	-0.71	-2.35
Price index		-0.19	-0.85	1.33	0.50	-0.60	-2.06	1.41	0.17

TABLE 5: GPE-induced changes in real wages, rents, and output
(percentage changes from the 2035 baseline)

		Closed in population		Closed in population with congestion pricing		Open in population		Open in population with congestion pricing	
		Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality
Real wage	Paris	0.33	0.56	-1.92	-1.72	-0.29	-0.96	-1.6	-2.16
	CDTs	-0.03	0.18	-2.16	-1.97	-0.7	-1.39	-1.9	-2.42
	Suburbs	0.32	0.65	-3.69	-3.33	-0.23	-0.67	-3.69	-3.70
	Total	0.2	0.45	-2.6	-2.36	-0.42	-1.04	-2.42	-2.78
Real rent	Paris	0.18	0.63	-1.56	-1.06	1.12	3.13	-1.71	-0.42
	CDTs	0.25	0.76	-1.78	-1.21	1.41	3.82	-1.98	-0.43
	Suburbs	0.19	0.74	-2.11	-1.41	1.28	3.65	-2.26	-0.69
	Total	0.2	0.71	-1.82	-1.22	1.26	3.52	-1.98	-0.52
Real output	Paris	0.04	0.25	-0.76	-0.51	0.8	2.21	-0.83	-0.03
	CDTs	0.13	0.53	-0.9	-0.45	1.12	3.17	-1.02	0.22
	Suburbs	0.02	0.25	-1.37	-1.15	0.91	2.54	-1.46	-0.59
	Total	0.06	0.34	-1.01	-0.70	0.97	2.92	-1.1	-0.11

TABLE 6: Social welfare and benefit-cost analysis of the GPE

	Closed in population		Closed in population with congestion pricing		Open in population		Open in population with congestion pricing	
	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality	Without TFP externality	With TFP externality
A. SOCIAL WELFARE								
(a – f: change from the 2035 baseline, €/person/year)								
Welfare [= a + b + c + d + e + f]	144	467	239	395	3	203	328	525
a. Consumer CV	162	340	-84	130	-1	0	0	0
b. Importer CV	5	241	236	303	147	645	200	653
c. Real estate values	1	-14	-51	-71	61	127	-60	-35
d. Tax revenues	7	-77	-280	-397	-211	-640	-222	-551
<i>Sales tax</i>	3	-41	-145	-204	-107	-320	-117	-281
<i>Income tax</i>	4	-37	-135	-192	-105	-319	-105	-270
e. GPE operating surplus	-31	-23	-4	5	7	71	-11	30
f. Congestion toll revenue			422	425			421	428
Average disposable income (after tax and commuting costs)	37,234	37,500	36,818	36,792	36,364	36,757	37,212	36,914
Welfare gain as a percent of average income	0.39	1.25	0.65	1.07	0.01	0.55	0.88	1.42
B. EXTERNALITIES								
(2035 levels in €/person/year)								
TFP externality		411		405		395		401
Road congestion externality								
Uninternalized	513	516	0	0	520	535	0	0
Internalized	0	0	422	425	0	0	421	427
C. BENEFIT-COST ANALYSIS								
Cost of GPE (€/person/year)	132	132	132	132	130	127	134	131
Benefit-to-cost ratio [= Welfare/GPE cost]	1.09	3.54	1.81	3.00	0.02	1.59	2.45	4.01
Public cost recovery ratio [= f/(GPE cost - d - e)]			1.01	0.81			1.15	0.66

FOR ONLINE PUBLICATION

APPENDIX

Productivity benefits of urban transportation megaprojects: a general equilibrium analysis of «Grand Paris Express»

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The version of the [Regional Economy, Land Use and Transportation \(RELU-TRAN\)](#) model ([Anas and Liu, 2007](#)) modified for this study, is a spatially detailed computable general equilibrium model calibrated to the Paris region. The model treats the combined equilibrium of urban labor and housing markets, production with interindustry trade, imports and exports, durable residential and commercial structures and their construction and demolition, endogenous job and residence location, work and non-work travel, and choices of car and travel route on the road network versus choice of public transit. In this Appendix we describe technical details of the model. [Part I](#) presents the model's equations and the solution procedure used to compute a general equilibrium. [Part II](#) shows how the TFP externality, the congestion externality and the Pigouvian congestion tolls are calculated. [Part III](#) explains the details of the welfare analysis. The calculation of the output price index is explained in [Part IV](#), and [Part V](#) explains how the model is calibrated.

I. The RELU-TRAN Model for the Paris region

(a) Consumers in the region: workers and non-workers

In the [RELU-TRAN](#) model for the Paris region, consumers either work or do not work and the total population and the share of workers and non-workers are exogenously given. Non-workers represent adults who are not in the labor force as well as those who may be looking for work. From an urban transportation standpoint, workers commute, while also making non-work trips, while non-workers make non-work trips but do not commute.

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A working consumer chooses the most preferred discrete quadruplet (i, j, k, s) where, $i = 1, \dots, 16$ are the model's residence zones in which the consumer's housing can be located (these are the 12 zones in the region plus the four exurban areas) and $j = 1, \dots, 12$ are the zones in which the consumer's job can be located. The 12 zones are the City, the 10 CDTs (as explained in [Section 2](#) of the main text) and all other suburban areas. $k = 1$, denotes a single-family house, and $k = 2$, an apartment in a residential multifamily building. Employment is either in the private sector ($s = 1$) or the public sector ($s = 2$), the primary sectors, or in 5 construction and 5 demolition sectors (one of each for each building type in each zone). We set $j = s = 0$ to denote a non-working consumer who chooses only among a subset of bundles (i, k) . Therefore, there are $16 \times 12 \times 2 \times 12 = 4,608$ choices available to working consumers and $16 \times 2 = 32$ choices available to non-working consumers. For each discrete bundle (i, j, k, s) , utility is maximized over the vector of the quantities of goods and services and over housing floor space (all continuous variables), under the consumer's budget constraint for that discrete bundle. The consumer then chooses the discrete bundle with the highest indirect (maximized) utility.

The consumer's 2-stage continuous-discrete utility maximization problem is:

$$\max_{\forall (i, j, k, s)} \left\{ \begin{array}{l} \max_{\forall Z_{ijks}, h_{ijks}} U_{ijks} = a \cdot \ln \left(\sum_{rz} \iota_{rzi} \cdot (Z_{rz|ijks})^\sigma \right)^{\frac{1}{\sigma}} + (1-a) \ln(h_{ijks}) + \gamma \Delta_j \ln(G_{ij}) + E_{ijks} + e_{ijks} \\ s.t. : \underbrace{\Delta_j d(H \cdot w_{sj}(1-T) - g_{ij}) + m(1-T)}_{\equiv \tilde{M}_{ijs}} \geq \sum_{rz} \underbrace{(p_{rz}(1+t) + s_{iz}g_{iz})}_{\text{Delivered price}} Z_{rz|ijks} + R_{ik} h_{ijks} \end{array} \right\} \quad (\text{A.1})$$

The utility function

In the direct utility function U_{ijks} , $Z_{rz|ijks}$ is the quantity of goods and services purchased from sector r in zone z (where $r = 1$ is the private and $r = 2$ is the public sector); h_{ijks} is the quantity of housing floor space of type k rented in zone i , by consumers choosing the discrete bundle (i, j, k, s) , and recalling that $j = 0$, $s = 0$ denotes non-working consumers, $s = 1, 2$ denotes working in the private or public sector and $s = 3, \dots, 12$ denotes working in the construction and demolition industries for each of the five building types. The overall utility is Cobb-Douglas between housing floor space and the sub-utility of product varieties, so that a is the share of disposable income allocated to goods and services, and $1-a$ is the share allocated to housing. The coefficients ι_{rzi}

capture the inherent attractiveness of purchasing goods and services from sector r in zone z by consumers who reside in zone i .

G_{ij} is the across-all-travel-modes (composite) expected commuting time per work day from residence zone i to a workplace zone $j > 0$, given by Eq. (3) in the main text, and captures, by $\gamma < 0$, the marginal disutility of commuting: $\frac{\gamma}{G_{ij}}$. This disutility is not present for non-workers because they do not commute. Hence, we set $\Delta_0 = 0$ for non-workers and $\Delta_j = 1$ for all workers who choose from workplaces $j = 1, \dots, 12$. E_{ijks} are alternative-specific constants (fixed effects) denoting the utility value of all amenities for the quadruplet (i, j, k, s) . e_{ijks} are random utilities for each (i, j, k, s) and have an i.i.d. extreme value Type I distribution over the consumers. Note that each sector r in each model zone z produces a distinct good and service variant. These product variants are imperfect substitutes in the utility function, and the consumer has an extreme taste for variety, inducing the consumer to want to consume all of these available variants. To this end, the C.E.S. sub-utility of goods and services purchased from the two sectors and the 12 zones where they are produced and sold is of the [Dixit-Stiglitz \(1977\)](#) form and has an elasticity of substitution $\frac{1}{1-\sigma}$, $-\infty < \sigma < 1$.²⁰

The budget constraint

In the budget constraint, M_{ijs} is the consumer's annual disposable income and g_{ij} transportation-related composite monetary cost of traveling from zone i to zone j . For $j = 0$, the non-working consumers, $\Delta_0 = 0$, and M_{i00} is equal to the annual nonwage income m for all residential zones i . For workers, $\Delta_j = 1$, for all $j > 0$, the annual disposable wage income is $d \cdot H \cdot w_{sj}$, where d is the number of work days, H is the hours of work per work-day, and w_{sj} is the hourly wage earned in sector s in zone j . T the income tax rate in the zone of employment j and t the sales tax rate paid by consumers on goods other than housing at the zone of sale z . For workers, the expected round-trip monetary cost of travel from zone i to zone j over all modes of

²⁰ When $\sigma = -\infty$, the sub-utility function is Leontief and the zonal goods are perfect complements. When $\sigma = 1$, the sub-utility function is linear and the zonal goods are perfect substitutes, and when $\sigma = 0$, the sub-utility function becomes Cobb-Douglas.

travel, $d \cdot g_{ij}$, includes the gasoline cost when driving. The cost $d \cdot g_{ij}$ is deducted from income to determine the disposable income which is allocated between housing and the 24 zonal goods and services (consumers do not directly buy from the construction or the demolition industries). The delivered price of a unit of goods and services purchased from sector r in zone z , consists of the price paid at z , p_{rz} , plus the monetary cost of travel from zone i to zone z , $g_{iz} \cdot 1/s_{iz}$ is the fixed quantity bought per non-work trip from residence location in zone i to zone z . Therefore, $\psi_{rzi} \equiv p_{rz}(1+t) + s_{iz}g_{iz}$ is the delivered (after-travel) unit price.

Marshallian demands

The consumer's utility maximization over the continuous quantities yields the Marshallian demands for goods and services and for housing quantity (floor space):

$$Z_{rzi|jks} = \frac{t_{rzi}^{\frac{1}{1-\sigma}} \psi_{rzi}^{\frac{1}{\sigma-1}}}{\sum_{\forall r'z'} t_{r'z'i}^{\frac{1}{1-\sigma}} \psi_{r'z'i}^{\frac{1}{\sigma-1}}} aM_{ijs}, \quad (\text{A.2a})$$

and

$$h_{ijks} = (1-a) \frac{M_{ijs}}{R_{ik}}, \quad (\text{A.2b})$$

where R_{ik} is the rent per unit of type k housing floor space in zone i .

Choice probabilities

In the outer stage of utility maximization, the consumer chooses among the discrete bundles. The expected demand for the bundle (i, j, k, s) for a working consumer, and bundle $(i, 0, k, 0)$ for a non-working consumer are the multinomial logit probabilities. For a working consumer, denoted by superscript e :

$$P_{ijks}^e = \frac{e^{\lambda \tilde{U}_{ijks}}}{\sum_{i'j'k's'} e^{\lambda \tilde{U}_{i'j'k's'}}}, \quad \sum_{ijks} P_{ijks}^e = 1, \quad j > 0. \quad (\text{A.3a})$$

For a non-working consumer, denoted by superscript u :

$$P_{ik}^u = \frac{e^{\lambda \tilde{U}_{i0k0}}}{\sum_{i'k'} e^{\lambda \tilde{U}_{i'0k'0}}}, \quad \sum_{ik} P_{ik}^u = 1, \quad j = 0, s = 0. \quad (\text{A.3b})$$

where \tilde{U}_{ijks} are the indirect utilities net of the random utility terms and λ is the dispersion parameter of the random utility distribution.

(b) Consumers outside the region (importers)

We assume the presence of a representative outside-the-region consumer for each sector, with given income Q_r , who imports a quantity Ξ_{jr} of the goods and services produced by sector r from each of the region's zones. The outside consumers' utility function is C.E.S. over the imported varieties with elasticity of substitution $\frac{1}{1-e_r}$, $-\infty < e_r < 1$, and zone-specific utility parameters Ω_{rj} . The outside consumer pays the after-tax price $p_{rj}(1+t)$ and we assume incurs no other costs. To allow for the substitution of the region's products with products produced elsewhere, we assume the existence of an outside location $J+1$ from where the importing consumer can also buy. The utility maximization problem is:

$$\max_{\Xi_r} U_r = \left(\sum_{j=1}^{J+1} \Omega_{rj} \Xi_{jr}^{e_r} \right)^{\frac{1}{e_r}} \quad s.t. : \sum_{j=1}^{J+1} p_{rj}(1+t)\Xi_{jr} = Q_r, \quad (\text{A.4})$$

and it yields the Marshallian demand functions:

$$\Xi_{jr} = \frac{\Omega_{rj}^{\frac{1}{1-e_r}} [p_{rj}(1+t)]^{\frac{1}{e_r-1}}}{\sum_{b=1}^{J+1} \Omega_{rb}^{\frac{1}{1-e_r}} [p_{rb}(1+t)]^{\frac{1}{e_r-1}}} Q_r. \quad (\text{A.5})$$

(c) Firms

The region's production in the private and public sectors of each zone exhibits internal constant returns to scale and uses capital, labor and floor space as inputs. Capital employed by sector r in zone j , K_{rj} , is treated as homogeneous and perfectly elastically supplied to any sector and zone. Labor inputs are of two types: either local labor supplied by the workers of the region, L_{rj} , or labor employed outside the region, $L_{0|rj}$, (such as remote consultants or workers employed in out of the region plants). Similarly, each sector in each zone rents some floor space, $B_{k|rj}$, from the commercial ($k=3$), industrial ($k=4$), and public ($k=5$) floor space stocks, and employs building stocks, $B_{0|rj}$, from outside the region as well ($k=0$). The production function is Cobb-Douglas in the three input types with C.E.S. labor and floor-space sub-production functions:

$$X_{rj} = A_{rj} K_{rj}^{\nu_r} \left(\kappa_{0|rj} L_{0|rj}^{\theta_r} + \kappa_{rj} L_{rj}^{\theta_r} \right)^{\frac{\delta_r}{\theta_r}} \left(\chi_{0|rj} B_{0|rj}^{\zeta_r} + \sum_{k=3,4,5} \chi_{k|rj} B_{k|rj}^{\zeta_r} \right)^{\frac{\mu_r}{\zeta_r}} \quad (\text{A.6})$$

ν_r, δ_r, μ_r are the cost shares of capital, labor and floor space in sector r , ($\nu_r + \delta_r + \mu_r = 1$). Note that A_{rj} is the TFP (Total Factor Productivity) coefficient which is modeled by the function of Eq. (2) in the main text, when a TFP externality is present.

The production function (A.6) is defined for each sector $r = 1, 2$ but also for each building construction and demolition industry as we will see below. However, it is assumed that in the construction and demolition sectors there is no TFP externality. The elasticities of substitution among sub-input types are $\frac{1}{1 - \theta_r}$ for labor, and $\frac{1}{1 - \zeta_r}$ for floor space with $-\infty < \theta_r, \zeta_r < 1$. $\kappa_{f|rj}$, $\chi_{k|rj}$ are coefficients specific to the sub-input types. The conditional cost minimizing demands for labor and space are:

$$L_{rj} = \frac{\kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r-1}}}{\kappa_{0|rj}^{\frac{1}{1-\theta_r}} w_{0|rj}^{\frac{1}{\theta_r-1}} + \kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r-1}}} \delta_r p_{rj} X_{rj}; \quad r = 1, \dots, 12; \quad j = 1, \dots, 12, \quad (\text{A.7a})$$

Where the w_{rj} are the wages in sector r in zone j and $w_{0|rj}$ is the outside-the-region wage relevant to the rj firms in the region.

$$B_{k|rj} = \frac{\chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{1-\zeta_r}}}{\chi_{0|rj}^{\frac{1}{1-\zeta_r}} R_{0|rj}^{\frac{\zeta_r}{1-\zeta_r}} + \sum_{k=3,4,5} \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{1-\zeta_r}}} \mu_r p_{rj} X_{rj}, \quad k = 3, 4, 5; \quad r = 1, \dots, 12; \quad j = 1, \dots, 12. \quad (\text{A.7b})$$

where R_{jk} is the floor rent for type k floor space in zone j and $R_{0|rj}$ is the outside-the-region rent relevant to the rj firms in the region.

(d) Real estate developers

Developers, in any model zone $i = 1, \dots, 12$, own undeveloped land ($n = 0$) on which they may construct the two residential and the three commercial floor spaces; or own any of these five floor space types in the zone and may either keep as is or demolish the floor space to create undeveloped land. We assume that developers are competitive and risk neutral and that the horizon for a developer's construction or demolition decision is five years with an annual interest rate r . V_{ni} is

the market value for a unit of undeveloped land ($n=0$) or type n ($n=1,\dots,5$) floor space in zone i , where n denotes a construction industry, one for each building type. A transition denoted by $0 \rightarrow 0$ is land that stays undeveloped; $0 \rightarrow n$ with $n=1,\dots,5$ denotes the five construction activities, one for each building type. Demolition is denoted by $n \rightarrow 0$, ($n=1,\dots,5$) one for each building type. Recall that the two primary sectors are private and public production of goods and services. The five construction industries will be ordered from 3 to 7 and the five demolition industries from 8 to 12. Construction prices per unit of floor space in zone i are denoted by $p_{2+n,i}$, and demolition price per unit of type n floor space in zone i are $p_{7+n,i}$. Non-financial costs are random, φ_{0ni} , for construction, and φ_{n0i} for demolition; and are i.i.d. Type-I extreme value distributed over developers for each discrete construction or demolition choice. m_{ni} is the structural density (floor space per unit of land) of the type- n building in zone i . Developer profit, if keeping vacant land undeveloped, is:

$$\Pi_{i,0 \rightarrow 0} = \left(\frac{1}{1+r} \right)^5 V_{0i} + \varphi_{00i} - V_{0i}, \quad (\text{A.8a})$$

If building type- n , profit is:

$$\Pi_{i,0 \rightarrow n} = \left(\frac{1}{1+r} \right)^5 (V_{ni} - p_{2+n,i}) m_{ni} + \varphi_{0ni} - V_{0i}, \quad (\text{A.8b})$$

If demolishing type- n building, profit is:

$$\Pi_{i,n \rightarrow 0} = \left(\frac{1}{1+r} \right)^5 \left(\frac{V_{0i}}{m_{ni}} - p_{ni} \right) + \varphi_{n0i} - V_{ni}, \quad (\text{A.8c})$$

and if keeping type- n building unchanged, profit is:

$$\Pi_{i,n \rightarrow n} = \left(\frac{1}{1+r} \right)^5 V_{ni} + \varphi_{inn} - V_{in}. \quad (\text{A.8d})$$

The multinomial logit construction probability for land is:

$$\mathcal{Q}_{i,0 \rightarrow n}(V_{0i}, V_{1i}, \dots, V_{5i}) = \frac{\exp \Phi_{0i} \left(\frac{1}{1+r} \right)^5 (V_{ni} - p_{2+n,i}) m_{ni}}{\exp \Phi_{0i} \left(\frac{1}{1+r} \right)^5 V_{0i} + \sum_{n'=3}^7 \exp \Phi_{0i} \left(\frac{1}{1+r} \right)^5 (V_{n'i} - p_{2+n',i}) m_{n'i}}, \quad (\text{A.9a})$$

and the demolition probability for any building type n is:

$$Q_{i,n \rightarrow 0}(V_{0i}, V_{ni}) = \frac{\exp \Phi_{ni} \left(\frac{1}{1+r} \right)^5 \left(\frac{V_{0i}}{m_{ni}} - p_{7+n,i} \right)}{\exp \Phi_{ni} \left(\frac{1}{1+r} \right)^5 \left(\frac{V_{0i}}{m_{ni}} - p_{7+n,i} \right) + \exp \Phi_{ni} \left(\frac{1}{1+r} \right)^5 V_{ni}}, \quad (\text{A.9b})$$

where Φ_{0i}, Φ_{ni} are the dispersion parameters of the random costs.

(e) Landlords

Landlords rent out real-estate floor space and are competitive and risk neutral.²¹ Given that the market rent of floor space is R_{in} , and the costs of keeping a unit amount of floor space occupied or vacant are D_{ino} and D_{inv} respectively, the landlord's profit is either $\pi_{ino} = R_{in} - D_{ino} + \xi_{ino}$ or $\pi_{inv} = -D_{inv} + \xi_{inv}$ where ξ_{ino}, ξ_{inv} are i.i.d. type-I extreme value random costs distributed over the landlords in . Then, the profit maximizing occupancy probabilities are binomial logit:

$$q_{in}(R_{in}) = \frac{\exp \phi_{in}(R_{in} - D_{ino})}{\exp \phi_{in}(R_{in} - D_{ino}) + \exp \phi_{in}(-D_{inv})}, \quad (\text{A.10})$$

where ϕ_{in} is the dispersion parameter. The vacancy rates are $1 - q_{in}(R_{in})$.

(f) General equilibrium of RELU: solution procedure

The general equilibrium conditions are that, in each zone, the market for each type of residential and non-residential floor space must clear; that the labor market must clear; that the output produced in each primary industry and zone must meet the demands by consumers who shop in that zone and the demand of importers from that zone. In addition, in each zone, all firms make zero profit and the developer-landlords of each building type make zero expected profit. Finally, in each zone, the floor space stock of each building type that is constructed must equal the floor space stock of that building type that is demolished, and the land depleted by the construction of new buildings must equal the land created by the demolishing of existing buildings. Equations describing these conditions are solved for the vectors \mathbf{p} (prices of goods and services by sector and zone), \mathbf{R} (rents by building type and zone), \mathbf{W} (wages by sector and zone), \mathbf{V} (values by building type and land by zone) and \mathbf{X} (output by sector and zone), \mathbf{S} (stock of land and building type by zone).

²¹ Without any loss of generality, developers and landlords can be assumed to be the same economic agent.

As explained in [Anas and Liu \(2007\)](#), the system of equations that must be solved simultaneously are block-recursive in nature, and the solution is found by cycling from one block of equations to another until all variables converge to the equilibrium and all equilibrium conditions are satisfied. This cyclical procedure is as follows and takes as given the travel times G_{ij} and monetary travel costs g_{ij} which come from the TRAN model:

Step 1: Given wages, and given rents for the commercial buildings, the zero profit equations of firms are used for each zone $j = 1, \dots, 12$, to calculate the unit prices of goods and services of the two primary sectors, $r = 1, 2$; and the unit prices of construction, $r = 3, \dots, 7$, and of demolition, $r = 8, \dots, 12$ industries. These $12 \times 12 = 144$ zero profit equations are:

$$p_{rj} = \frac{\rho^{v_r}}{A_{rj} v_r^{\mu_r} \mu_r^{\delta_r}} \left(\kappa_{0|rj}^{1-\theta_r} w_{0|rj}^{\theta_r-1} + \kappa_{rj}^{1-\theta_r} w_{rj}^{\theta_r-1} \right)^{\frac{\delta_r(\theta_r-1)}{\theta_r}} \left(\chi_{0|rj}^{1-\zeta_r} R_{0|rj}^{\zeta_r-1} + \sum_{k=3,4,5} \chi_{k|rj}^{1-\zeta_r} R_{jk}^{\zeta_r-1} \right)^{\frac{\mu_r(\zeta_r-1)}{\zeta_r}} \quad (\text{A.11})$$

The right side of [\(A.11\)](#) is the unit cost of production as a function of the input prices, and the left side is the unit price.

Step 2: Using the wages, rents and primary output prices, demanded output quantities are then calculated for the two primary sectors in each zone, from the following $2 \times 12 = 24$ equations:

$$X_{rz} = N \left[Pr^e \sum_{iks, j>0} P_{ijks}^e Z_{rz|ijks} + (1-Pr^e) \sum_{ik} P_{ik}^u Z_{rz|ik} \right] + \Xi_{rz}; \quad r = 1, 2; \quad z = 1, \dots, 12, \quad (\text{A.12})$$

where N is the exogenous total number of consumers and Pr^e the exogenous fraction of consumers who are working. Ξ_{rz} are the export demand functions by sector r and zone z , given by [Eq. \(A.5\)](#).

Step 3: Then, the expected zero-profit conditions of developer-landlords are simultaneously solved for building and land values in each zone:

$$V_{0i} = \sum_{y=1}^5 \left(\left(\frac{1}{1+r} \right)^{y-1} R_{i0} \right) + \frac{1}{\Phi_{0i}} \ln \left[\exp \Phi_{0i} \left(\left(\frac{1}{1+r} \right)^5 V_{0i} \right) + \sum_n \exp \Phi_{0i} \left(\left(\frac{1}{1+r} \right)^5 (V_{ni} - p_{2+n,i}) m_{ni} \right) \right], \quad (\text{A.13a})$$

for those who own and rent out vacant land in zone i with the option to develop it, and there are 12 such equations, one for each zone:

$$\begin{aligned}
V_{ni} = & \sum_{y=1}^5 \left(\left(\frac{1}{1+r} \right)^{y-1} \frac{1}{\phi_{ni}} \ln \left\{ \exp[\phi_{ni}(R_{in} - D_{ino})] + \exp[\phi_{ni}(-D_{inv})] \right\} \right) \\
& + \frac{1}{\Phi_{ni}} \ln \left[\exp \Phi_{ni} \left(\left(\frac{1}{1+r} \right)^5 \left(\frac{V_{0i}}{m_{ni}} - p_{7+n,i} \right) \right) + \exp \Phi_{ni} \left(\left(\frac{1}{1+r} \right)^5 V_{ni} \right) \right],
\end{aligned} \tag{A.13b}$$

for those who own and rent out type- n building, with the option to demolish it. there are 5 such equations for each zone, hence $5 \times 12 = 60$ such equations.

Step 4: For the building industries, the outputs are floor spaces for construction, and land for demolition in each zone and are not traded. For the construction industries, floor space output is $X_{2+n,i} = S_{i0} Q_{i,0 \rightarrow n} m_{ni}$, $n=1, \dots, 5$ where S_{i0} is the stock of vacant land in zone i on which floor space can be built. There are $5 \times 12 = 60$ such equations. Land output from demolition is $X_{7+n,i} = S_{in} Q_{i,n \rightarrow 0} / m_{ni}$, $n=1, \dots, 5$, where S_{in} is the stock of type- n floor space that can be demolished to create vacant land. There are $5 \times 12 = 60$ such equations. The $Q_{i,0 \rightarrow n}$ and $Q_{i,n \rightarrow 0}$ are the construction and demolition probabilities in zone i and $n > 0$ is the building type, given by Eqs. (A.9a) and (A.9b).

Step 5: Given the wages and the prices calculated from the zero profit conditions for the primary industries, housing rents clear the residential floor space market by zone and residential building type. These rents are found by solving simultaneously the $2 \times 12 = 24$, Eq. (A.14), which equate demanded and supplied housing floor spaces of the two types in each zone:

$$N \left[Pr^e \sum_{s,j>0} P_{ijks}^e h_{ijks} + (1 - Pr^e) P_{ik}^u h_{ik} \right] = S_{ik} q_{ik}; \quad k=1,2; \quad i=1, \dots, 12. \tag{A.14}$$

Step 6: And given the outputs and prices calculated earlier, rents are similarly found in the three commercial real estate markets by solving simultaneously the $3 \times 12 = 36$, Eq. (A.15), which equate demanded and supplied commercial floor spaces of each type in each zone:

$$\sum_{r=1,2} \frac{\chi_{klrj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{1}{\zeta_r}-1}}{\chi_{0lrj}^{\frac{1}{1-\zeta_r}} R_{0lrj}^{\frac{\zeta_r}{\zeta_r}-1} + \sum_{k=3,4,5} \chi_{klrj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{\zeta_r}-1}} \mu_r p_{rj} X_{rj} = S_{jk} q_{jk}; \quad k=3,4,5; \quad j=1, \dots, 12. \tag{A.15}$$

Step 7: Labor markets clear in each zone and sector by calculating the wages after equating demanded labor with labor supplied in the two primary plus ten construction demolition industries in each zone, thus $12 \times 12 = 144$ such equations solved simultaneously:

$$\frac{\kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r-1}}}{\kappa_{0rj}^{\frac{1}{1-\theta_r}} w_{0rj}^{\frac{1}{\theta_r-1}} + \kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r-1}}} \delta_r p_{rj} X_{rj} = N \cdot Pr^e \cdot d \cdot H \sum_{ik} P_{ijk}^e \cdot \quad (\text{A.16})$$

Step 8: Then, given the total developed and developable land area of a zone, W_i , at equilibrium, the flow of demolished floor space equals the constructed floor space for each building type, Eq. (A.17), and the total land area is conserved, Eq. (A.18):

$$S_{in} Q_{i,n \rightarrow 0} = m_{ni} S_{i0} Q_{i,0 \rightarrow n}; \quad n = 1, \dots, 5; \quad i = 1, \dots, 12 \quad (\text{A.17})$$

$$W_i = S_{i0} + \sum_{\forall n > 0} \frac{S_{in}}{m_{ni}}, \quad i = 1, \dots, 12. \quad (\text{A.18})$$

In each zone, the building and developable land area stocks are solvable from these equations, given the construction and demolition probability functions which are evaluated using the floor and land prices as explained earlier in [Part I\(d\)](#) of this Appendix. There are $6 \times 12 = 72$ such equations.

After this step, the RELU algorithm returns to Step 1, and starts a new cycle with the most recently available variable values. Once RELU converges, then the algorithm starts calculating an equilibrium of the TRAN model as explained in (g)-(i) below. TRAN finds updates of travel times G_{ij} and monetary travel costs g_{ij} and a new cycle of RELU then begins (Steps 1-8 above). The algorithm normally converges fully to a combined RELU and TRAN equilibrium by cycling about eight times between RELU and TRAN. Convergence to an equilibrium is checked by strict convergence criteria so that each endogenous variable in RELU and in TRAN change within a very tight tolerance from one cycle to the next, and also that each equation is satisfied to a very high degree of accuracy.

The TRAN model is explained next.

(g) Person trips

Once RELU converges to an equilibrium conditional on the travel times and costs, then aggregate person-trips pass to TRAN for mode choice and traffic assignment. These person-trips are the sum of work and non-work trips by all commuters per day:

$$TRIPS_{iz} = \underbrace{\sum_{ks} N \cdot Pr^e \cdot P_{izks}^e}_{TRIPS_{iz}^1 \equiv \text{daily work trips (commutes)}} + \frac{1}{365} \left[\underbrace{s_{iz} N \cdot Pr^e \sum_{rks, j>0} P_{ijks}^e Z_{zr|ijks}}_{TRIPS_{iz}^2 \equiv \text{annual non-work trips by workers}} + \underbrace{s_{iz} N \cdot (1 - Pr^e) \sum_{rk} P_{ik}^u Z_{zr|ik}}_{TRIPS_{iz}^3 \equiv \text{annual non-work trips by non-workers}} \right] \quad (A.19)$$

$TRIPS_{iz}$ are split between modes (automobile and public transit) in the TRAN model using a binary mode choice model. Auto trips are spread evenly throughout the travel day because RELU-TRAN ignores intraday traffic dynamics. TRAN assigns auto trips to a version of the region's road network consisting of 3,004 arcs and 335 nodes to calculate equilibrium congested travel times and monetary costs reflecting gasoline consumption, using the flow model of congestion. The congested arc travel times combined with the monetary costs give equilibrium expected generalized costs between any zone pairs, and these combined with the exogenous transit times and fares give the expected across-modes (composite) travel times, G_{iz} , and across-modes (composite) monetary costs, g_{iz} , which are inputs into RELU. By assumption, public transit trips are not subject to congestion or crowding effects and public transit travel times between zone pairs are exogenous.

(h) Trips by car and congested traffic equilibrium times and costs

Auto trips from zone i to zone z (including those originating in i and traveling to z and those originating at z and returning to i) are:

$$AUTOTRIPS_{iz} = \frac{TRIPS_{iz} \times PROB_{CAR|iz} + TRIPS_{zi} \times PROB_{CAR|zi}}{\text{passenger per vehicle}}, \quad (A.20)$$

$PROB_{CAR|iz}$ are endogenous mode choice probabilities to be discussed later. Each zone contains multiple nodes of the road network. Each node is either the start or end of one or more network arc. $AUTOTRIPS_{iz}$ are distributed evenly among the node pair combinations to create node-to-node (NTN) auto trips:

$$NTN_AUTOTRIPS_{o \in i, d \in z} = \frac{AUTOTRIPS_{iz}}{node(i) \cdot node(z)}, \quad (A.21)$$

where $o \in i$ denotes the trip's origin node in zone i , and $d \in z$ the destination node in zone z , and $node(j)$ is the number of nodes in zone j . Each auto trip probabilistically decides which arc of the network to take at every node reached during a journey. Each trip chooses a route that consists of a sequence of arcs giving the lowest expected disutility for the trip. The formulation is an adaptation of the algorithm of [Baillon and Cominetti \(2008\)](#). The multinomial logit probability of choosing an arc a at a node o , while traveling to destination node d is:

$$P_{a|d} = \frac{\exp\left[-\tilde{\lambda}\left(gcost_a + \wp_{\pi(a)d}\right)\right]}{\sum_{a' \in A_o^+} \exp\left[-\tilde{\lambda}\left(gcost_{a'} + \wp_{\pi(a')d}\right)\right]}, \quad \sum_{a \in A_o^+} P_{a|d} = 1, \quad \forall d \quad (A.22)$$

$P_{a|d}$ is the probability of choosing arc a given destination node d . $\pi(a)$ is the end node of arc a , A_o^+ is the set of all roads that are outgoing from node o , $\tilde{\lambda}$ is the dispersion parameter of the idiosyncratic disutility shock experienced at node o ; $gcost_a$ the generalized cost of traveling on arc a , (which will be explained below in [Eq. \(A.25\)](#)), and $\wp_{i(a)d}$ the expected disutility of an auto trip traveling from node i to node d :

$$\wp_{id} = -\frac{1}{\tilde{\lambda}} \ln \left[\sum_{a \in A_i^+} \exp\left[-\tilde{\lambda}\left(gcost_a + \wp_{\pi(a)d}\right)\right] \right]. \quad (A.23)$$

The congested travel time (in minutes) on each arc a is of the BPR-form:

$$time_a = t_a^0 \left[1 + b_a \left(\frac{flow_a}{capacity_a} \right)^C \right], \quad (A.24)$$

where t_a^0 is the free-flow (uncongested) travel time on each road, b_a and C are constants, $capacity_a$ is road capacity and $flow_a$ the vehicle flow choosing arc a . We use $b_a = 0.15$ and $C = 1.2$. The generalized per-person vehicle cost $gcost_a$ is the sum of time and monetary costs:

$$gcost_a = vot \times \frac{time_a}{60} + \underbrace{\frac{(pfuel \times F(speed_a)) \times length_a + toll_a}{passenger \text{ per vehicle}}}_{\equiv mcost_a}, \quad (A.25)$$

where vot is the monetary value of time (\$ per hour), $pfuel$ is the gasoline price, $F(speed_a)$ ²² is gasoline usage per unit distance as a function of speed on arc a , $length_a$ is the length of each road. $toll_a$ is the Pigouvian congestion toll (if any) that equals the difference between the private average cost and the social marginal cost, that is $toll_a = vot \cdot \left(C \cdot t_a^0 b_a \left(flow_a / capacity_a \right)^C \right)$. Each TRAN iteration updates time and monetary costs, arc choice probabilities and flows until an equilibrium is reached. Then, TRAN gives equilibrium times ($time_a$) and monetary costs ($mcost_a$) for arcs, equilibrium expected times τ_{od} and monetary costs μ_{od} for (o, d) node pairs are:

$$\tau_{od} = \sum_a P_{a|d} \times \left(time_a + \tau_{\pi(a)d} \right), \quad (A.26)$$

$$\mu_{od} = \sum_a P_{a|d} \times \left(mcost_a + \mu_{\pi(a)d} \right). \quad (A.27)$$

The zone i to zone z τ_{iz} and μ_{iz} are obtained as averages of the node-to-node $\tau_{o \in i, d \in z}$, $\mu_{o \in i, d \in z}$.

(i) Public transit monetary costs and travel times

The public transit (PT) travel times in minutes from zone i to zone z are $TIME_{PT|iz}$, and the monetary cost is $MCOST_{PT|iz}$. The generalized cost is then:

$$GCOST_{PT|iz} = vot \times TIME_{PT|iz} / 60 + MCOST_{PT|iz}, \quad (A.28)$$

where vot is the value of travel time in \$/hour (same as in A.25). The mode choice probabilities and average across-modes travel costs with dispersion parameter Θ are:

$$PROB_{CAR|iz} = \frac{\exp\left\{\Theta\left(\wp_{zi} + \wp_{iz}\right) + K_{CAR|iz}\right\}}{\exp\left\{\Theta\left(\wp_{zi} + \wp_{iz}\right) + K_{CAR|iz}\right\} + \exp\left\{\Theta\left(GCOST_{PT|iz} + GCOST_{PT|zi}\right) + K_{PT|iz}\right\}} \quad (A.29)$$

$PROB_{PT|iz} = 1 - PROB_{CAR|iz}$. The across-modes expected commute travel times G_{iz} and monetary costs g_{iz} passed to RELU are then:

²² $F(s) = 0.12262 - 0.0117211s + 6.413 \times 10^{-4} s^2 - 1.8732 \times 10^{-5} s^3 + 3.0 \times 10^{-7} s^4 - 2.472 \times 10^{-9} s^5 + 8.233 \times 10^{-12} s^6$ where s is speed in miles per hour. We convert gallon/mile to liters/km by gallon/mile*(3.78541/1.60934). We use $s = 0.621371 * \text{km/h}$ to get miles/hour [Davis and Diegle (2004)].

$$G_{iz} = PROB_{CAR|iz} \times (\tau_{zi} + \tau_{iz}) + PROB_{PT|iz} \times (TIME_{PT|iz} + TIME_{PT|zi}). \quad (A.30)$$

$$g_{iz} = PROB_{CAR|iz} \times (\mu_{zi} + \mu_{iz}) + PROB_{PT|iz} \times (MCOST_{PT|iz} + MCOST_{PT|zi}). \quad (A.31)$$

(j) Checking for multiple equilibria

The **RELU-TRAN** model without the TFP externality, described above, was subjected to a battery of tests to observe that starting from many different starting points, the model converges to a unique equilibrium. With the TFP externality present, and a high enough value of α in the TFP Eq. (2), non-unique equilibria cannot be ruled out. However, with the empirically justified value of $\alpha = 0.045$, explained in Section 3 of the main text, the equilibrium appears to be unique.

To check this numerically we performed many perturbations of the model. We perturbed the calibrated starting point values (baseline equilibrium) of the vectors of variables \mathbf{w} (wages), \mathbf{p} (output prices), \mathbf{R} (rents), \mathbf{X} (output), \mathbf{V} (floor space values), and \mathbf{S} (floor space stocks) individually, by increasing these variables to twice their calibrated values, and then by decreasing them to half their calibrated values. All such simulations converged to the original equilibrium. We also did perturbation runs to mimic a quasi-random setting of initial values: 1) Doubling \mathbf{w} , \mathbf{X} , \mathbf{S} ; reducing to half \mathbf{p} , \mathbf{R} , \mathbf{V} . 2) Doubling \mathbf{w} , \mathbf{p} , \mathbf{R} ; reducing to half \mathbf{X} , \mathbf{V} , \mathbf{S} . 3) Doubling \mathbf{p} , \mathbf{V} , \mathbf{X} ; reducing to half \mathbf{R} , \mathbf{S} , \mathbf{W} . 4) Doubling \mathbf{R} , \mathbf{S} , \mathbf{V} ; reducing to half \mathbf{p} , \mathbf{w} , \mathbf{X} . These 4 runs also converged to the original calibrated equilibrium. Based on these tests, the equilibria under the current parameter structure appear to have a robust uniqueness.

II. Congestion pricing, the congestion externality and the TFP externality

In calculating endogenous congestion prices, we consider only the monetary value of the time delay since that is the bulk of the congestion externality, ignoring the effect of congestion on the excessive use of gasoline due to lower speeds. Even though the **RELU-TRAN** model does include this effect, the gasoline use externality is significant only if the average speed is very low or very high, which are unlikely to happen in most places.

The Pigouvian congestion toll on arc a is specified as the gap between the marginal social cost of the delay caused by the flow on that arc, MSC_a less the average private cost of the delay APC_a :

$$toll_a \equiv MSC_a - APC_a = vot \cdot C \cdot t_a^0 b_a \left(\frac{flow_a}{capacity_a} \right)^c, \quad (A.32)$$

This toll function is added to the monetary cost of traveling on arc a , whenever congestion is priced in the model, so that when the equilibrium flows are calculated, the equilibrium tolls on the arcs are according to (A.32). The total externality on the arc is $toll_a \times flow_a$ and the total congestion externality reported in the region reported in section B of Table 6 is:

$$CONGESTION_EXT = vot \cdot C \cdot \sum_a t_a^0 b_a \frac{(flow_a)^{C+1}}{(capacity_a)^C}. \quad (A.33a)$$

To derive the TFP externality reported in part B of Table 6, recall first that the production function is of the form $X_{rj} = C_{rj} A_{rj} F_{rj}(K_{rj}, \bar{L}_{rj}, \bar{B}_{k|rj})$. The private marginal product of labor is

$$PMP_{rj} = A_{rj} \frac{\partial F_{rj}}{\partial L_{rj}} p_{rj}. \text{ The social marginal product is } SMP_{rj} = A_{rj} \frac{\partial F_{rj}}{\partial L_{rj}} p_{rj} + \sum_{si} \frac{\partial A_i}{\partial L_{rj}} F_{si} p_{si}. \text{ Then,}$$

$$SMP_{rj} - PMP_{rj} = \sum_{si} \frac{\partial A_i}{\partial L_{rj}} \cdot F_{si} p_{si}. \text{ The TFP externality is:}$$

$$TFP_EXT = \sum_{rj} (SMP_{rj} - PMP_{rj}) L_{rj} = \sum_{rj} \left(\sum_{si} \frac{\partial A_i}{\partial L_{rj}} F_{si} p_{si} \right) \times (Jobs_{rj}) Hd, \quad (A.33b)$$

$$\text{where } \frac{\partial A_i}{\partial L_{rj}} = 2\alpha \left(\frac{1}{Hd} \right) \left(\sum_j w_j d_j G_{ji}^{-\beta} \right)^{\alpha-1} \frac{G_{ji}^{-\beta}}{Total\ Jobs} d_j$$

III. Welfare analysis

We calculate the change in welfare from the 2035 baseline as the aggregate CV (compensating variation) for working and non-working consumers, plus: (i) the aggregate CV of the representative consumer importing from the region, (ii) the annualized aggregate income from the changes in real estate values, (iii) the change in aggregate tax revenue from income and sales taxes, (iv) the change in the public transit system's operating surplus or deficit (fare revenue minus operating cost) and (v) any congestion tolling revenue. These components of welfare are reported on a per-consumer basis in section A of Table 9 in the main text:

$$\begin{aligned} \Delta W = & CV_{cons.} + CV_{imp.} + \frac{\rho}{N} \left[\sum_{i,k=0,\dots,5} (S_{ik} V_{ik} - S_{ik}^{Base} V_{ik}^{Base}) \right] \\ & + \frac{1}{N} (\Delta Tax\ Rev. + \Delta GPE\ Operating\ Surplus\ or\ Deficit + Toll\ Rev.) \end{aligned} \quad (A.34)$$

The change in public revenues and the annualized change in property values are not distributed to the consumers. The CV is what a consumer would pay in monetary units for the increase, or require

as compensation for the decrease, in expected utility arising from the congestion tolling policy, or from the increase in expected utility caused by the GPE. From the multinomial logit calculus, the expected utility of a worker in the base equilibrium is:

$$W^{e,Base} = \frac{1}{\lambda} \ln \left(\sum_{ijks} \exp(\lambda \tilde{U}_{ijks}^{e,Base}) \right). \quad (\text{A.35})$$

Post-policy indirect utility is $\tilde{U}_{ijks}^{e,Policy} = \tilde{u}_{ijks}^{e,Policy} + \ln M_{ijs}^{e,Policy}$, where $M_{ijs}^{e,Policy}$ is the equilibrium disposable income and $\tilde{u}_{ijks}^{e,Policy}$ is the rest of the indirect utility. The CV of the worker is then solved from:

$$W^{e,Base} = \frac{1}{\lambda} \ln \left(\sum_{ijks} \exp \lambda \left[\tilde{u}_{ijks}^{e,Policy} + \ln \left(M_{ijs}^{e,Policy} - CV^e \right) \right] \right), \quad (\text{A.36})$$

and similarly for CV^u , of a non-worker. The weighted-average per capita CV is then:

$$CV_{cons.} = Pr^e \cdot CV^e + (1 - Pr^e) \cdot CV^u, \quad (\text{A.37})$$

where Pr^e is the exogenous share of workers. The $CV_{imp.}$ of the importers, per consumer in the region, are solved similarly. [Herriges and Kling \(1999\)](#) compared the calculation of CV by this method to its calculation by microsimulation, an approach that was later formalized by [Dagsvik and Karlstrom \(2005\)](#), and they found that the two approaches give similar results.

IV. The output price index

Recall that the delivered price facing a consumer who resides in zone i and buys product from zone z is $\psi_{rzi} = p_{rz} (1+t) + s_{iz} g_{iz}$ where p_{rz} is the at-source price for goods sold in zone z by

industry r . The price index for a consumer in zone i is $PI_i = \sum_{rz} \left(t_{rzi}^{1-\sigma} \psi_{rzi}^{\sigma} \right)^{\frac{\sigma-1}{\sigma}}$. We calculate the

region-wide price index as $PI = \sum_{iz} \frac{\left(\sum_{rjks} Z_{zr|ijks} \right) PI_i}{\sum_{iz} \left(\sum_{rjks} Z_{zr|ijks} \right)}$ where the weights $Z_{zr|ijks}$ (given by [Eq. \(A.2a\)](#),

are the quantities of output of industry r in zone z purchased by consumers who choose the (i, j, k, s) bundle. Real rents and wages (that is rents and wages adjusted for purchasing power in terms of the prices of the consumption goods, are obtained by using PI as the divisor of rents and

wages. The last row of [Table 4](#) shows how much the region-wide price index changes in each of the simulations.

V. Calibration of the model

(a) The general approach

Model variables and parameters are calibrated so as to represent as realistic an initial equilibrium as possible. At the starting point variables are either set directly to observed values or derived from relevant observable datasets. In most cases, parameters are calibrated to match model predictions with observed values, and to match model elasticities with target values of those elasticities taken from the empirical literature. If a parameter cannot be derived from observed data, nor there exists a target value which we can extract from previous studies, we make reasonable assumptions and set values accordingly.

An important property of the multinomial logit (MNL) model of the consumer choice probabilities plays a key role in calibration. This property is the well-known fact that the choice alternative specific fixed effects of the MNL model, the E_{ijks} in [Eq. \(A.1\)](#) which represents unobserved choice-specific effects in utility, can be set so that the predicted choice probabilities at the calibrated equilibrium from [Eqs. \(A.3a\)](#) and [\(A.3b\)](#) replicate the relative frequencies observed in the data. Such values of the E_{ijks} are known to be consistent with the likelihood maximization.²³ So the approach we use, taking [Eq. \(A.1\)](#) as an example, is to calibrate the coefficients a and γ in [Eq. \(A.1\)](#) and λ in [Eqs. \(A.3a\)](#) and [\(A.3b\)](#) to match specific elasticity values from the literature (or which we estimate), while the E_{ijks} in [Eq. \(A.1\)](#) are set to match observed relative frequencies in the data. We will use \tilde{P}_{ijks}^e , \tilde{P}_{ik}^u to denote such observed relative frequencies corresponding, in calibration, to the choice probabilities in [Eqs. \(A.3a\)](#) and [\(A.3b\)](#). A similar approach is followed for all other choice probability functions in the model.

(b) Elasticities

Labor supply and factor demands

Estimates of the labor supply elasticity in the empirical literature vary from negative values ([Bourguignon and Magnac, 1990](#)) to greater than +3 ([Imai and Keane, 2004](#)) depending on specific definitions of the elasticity, data used, and the estimation method. For our purpose, within-

²³ [Anas \(1983\)](#) provided a proof of the property.

period elasticities (as opposed to the elasticities estimated from intertemporal life cycle models) are appropriate. Even with the static-model elasticities, both the specifications of the model and the estimation results can still differ drastically. Most of the empirical studies of the within-period labor supply elasticity can be categorized into two broad branches. One branch estimates the elasticity of aggregate hours supplied by *employed* consumers (the intensive margin) while the other branch measures labor supply by the labor force participation rate (the extensive margin). The former often gives estimates that are close to zero (Heckman, 1993) while the latter results in bigger values.²⁴ In a study that considers both the extensive and the intensive margins, Kimmel and Kniesner (1998) found that the aggregate employment elasticity and the conditional (on being employed) hours supplied elasticity with respect to wage are +1.55 and +0.51, respectively. The former estimate corresponds to the extensive margin of labor supply, while the latter excludes any adjustments in participation. Recall that in the consumer’s utility maximization problem, Eq. (A.1), hours supplied by each *working* consumer is fixed at Hd per year with $d = 250$, $H = 8$. That is, labor supply adjustments in the RELU-TRAN Paris region model are restricted to the extensive margin at the model zone level. In the base equilibrium, given regional population, labor supply to each model zone changes in response to changing wages at that particular location while aggregate regional labor supply, days and hours worked by each worker, and regional participation remain fixed. We therefore come to the conclusion that the elasticity we shall adopt in the model should lie between an extensive-margin estimate of +1.55 and the estimate of the conditional hours supplied of +0.51. We settled on an elasticity value of +1.04 because, as we shall see in the rest of this Part, the calibrated parameter λ (the dispersion coefficient of the consumer’s choice probability, Eqs. (A.3a) and (A.3b)) simultaneously affects the labor supply elasticity and the residential location demand elasticity with respect to rent which we estimated specifically for our model. Our calibration of the value of λ yields a location demand elasticity with respect to rent that matches exactly our target value and produces a labor supply elasticity that is within the range provided by the empirical findings. From the worker’s multinomial logit choice model, Eq. (A.3a), the weighted average elasticity of the choice probability of working in a zone with respect to wage can be derived as follows:

²⁴ For surveys of the estimation models and their results, see Blundell and Macurdy (1999) and Ljungqvist and Sargent (2011).

$$\eta^{LS} = \lambda \sum_{ijks} \check{P}_{ijks}^e \frac{Hd(1-T)w_{sj}}{M_{ijk}} (1 - \check{P}_{ijks}^e), \quad (\text{A.38})$$

From which, given $\eta^{LS} = +1.04$, λ is calibrated.

Using a meta sample covering 151 previous studies across different countries and time periods, [Lichter et al. \(2015\)](#) found that the mean labor demand elasticity with respect to own wage is -0.551 with a large standard deviation -0.747 . Depending on the specifications and samples selected, this elasticity varies from positive values to -0.75 . In our model, the own-wage labor demand elasticity of sector- r firms in zone j derived from the factor demand equation [\(A.7a\)](#) is:

$$\frac{\partial \ln L_{rj}}{\partial \ln w_{rj}} = -\frac{1}{1-\theta_r} \left(1 - \theta_r \frac{\frac{1}{\kappa_{rj}^{1-\theta_r}} w_{rj}^{\frac{\theta_r}{\theta_r-1}}}{\frac{1}{\kappa_{0|rj}^{1-\theta_r}} w_{0|rj}^{\frac{\theta_r}{\theta_r-1}} + \kappa_{rj}^{1-\theta_r} w_{rj}^{\frac{\theta_r}{\theta_r-1}}} \right). \quad (\text{A.39})$$

We calibrate θ_r from [\(A.39\)](#) to match the target elasticity. It is plausible that labor demand of firm r in zone j can be quite sensitive to wage shocks than labor demand at the regional level. We settled on an average labor demand elasticity value of -0.95 , which is more elastic than those estimates in [Lichter et al. \(2015\)](#) because [RELU-TRAN](#) treats labor demand at a granular scale whose variations may not be captured by samples that are typically more aggregated. Moreover, we set $\zeta_r = 0.7$ so that the elasticity of substitution among building types in production is $+3.33$. This is reasonable because the definition of the non-housing building floor spaces in the data are malleable enough that the floor spaces should be considered highly substitutable.

Substitution among consumption goods

From the consumer's utility function [\(A.1\)](#) we know that the elasticity of substitution among consumption goods is $1/(1-\sigma)$ and that the demand elasticity with respect to consumption price can be expressed as:

$$\frac{\partial \ln Z_{zri}}{\partial \ln \psi_{zri}} = -\frac{1}{1-\sigma} \left(1 - \sigma \frac{\frac{1}{t_{zri}^{1-\sigma}} \psi_{zri}^{\frac{\sigma}{\sigma-1}}}{\sum_{z'r'} \frac{1}{t_{z'r'i}^{1-\sigma}} \psi_{z'r'i}^{\frac{\sigma}{\sigma-1}}} \right). \quad (\text{A.40})$$

Because the second term in the parentheses in Eq. (A.40) is small, the demand elasticity is approximately $-\frac{1}{1-\sigma}$ (that is the negative of the elasticity of substitution).²⁵ In general, given the change in relative gross price, a high elasticity of substitution hence a high demand elasticity tends to induce more salient adjustments in consumption-related travel behavior. We settled on $\sigma = -0.3$ (elasticity of substitution = $0.77 \approx -\text{demand elasticity}$).²⁶ A sensitivity analysis using an elasticity of substitution 20 percent larger than that in the calibrated base shows that our numerical results are not very sensitive to the value of σ because of two reasons. First, the effects of different margins cancel each other out;²⁷ and, second, the changes in gross price caused by the GPE and the toll are small in magnitude.

We assume that the demand of the outside-the-region consumer is more elastic than that of the consumers residing inside the region. Recall that the demand of the outside-the-region consumer for the output produced in the region is given by Eq. (A.5). We set the value of e_r such that the elasticity of the outside demand for goods produced inside the region is -1.8 .

Residential location demand and the disutility of commuting

The weighted average residential location elasticity with respect to rent is derived from Eqs. (A.3a) and (A.3b):

$$\eta^{\text{rent}} = -\lambda(1-a) \left[Pr^e \cdot \sum_{ijks} \check{P}_{ijks}^e R_{ik} (1 - \check{P}_{ijks}^e) + (1 - Pr^e) \cdot \sum_{ik} \check{P}_{ik}^u R_{ik} (1 - \check{P}_{ik}^u) \right] \quad (\text{A.41})$$

Indra (2014) estimated that this elasticity in Los Angeles lies between -0.39 and -0.62 for different income groups. Our maximum likelihood estimate for the Paris region is -0.37 . We solve a from (A.41) to match the right-hand side with this target elasticity, having obtained λ from (A.38).

²⁵ Indeed, in the Dixit-Stiglitz (1977) model, it is *assumed* that the consumption variety is so large that the price change of a single good has no effect on the price index, and the price elasticity of demand is approximated as $-1/(1-\sigma)$.

²⁶ The “approximately equal to” sign is valid here since the number of varieties is a constant ($= 24$) in our model, whereas the number of varieties is determined endogenously in the standard Dixit-Stiglitz model, hence the large variety assumption does not hold in our model. For a detailed discussion of this issue, see Yang and Heijdra (1993).

²⁷ For example, the GPE initially reduces the average across-modes monetary travel costs, g_{ij} , and, hence, the per-quantity delivered price per unit of the good due to consumers switching to public transit, but the increase in travel demand induced by the GPE offsets part of the initial impact on the delivered price. Similar offsetting also happens under congestion tolling.

A key factor that affects the welfare benefits of the GPE and of congestion pricing is the parameter γ (< 0) which is the coefficient associated with the disutility of commute time in (A.1). Meanwhile, γ also determines the elasticity of residential location demand with respect to *commute time*. Recall from (A.1) that for an employed consumer, $\Delta_{j>0} = 1$. Then, from (A.3a), the weighted average location demand elasticity with respect to commute time is given by:

$$\eta^{\text{commute time}} = \gamma \cdot \lambda \sum_{ijks} \check{P}_{ijks}^e (1 - \check{P}_{ijks}^e) \quad (\text{A.42})$$

Indra (2014) found the maximum likelihood estimate for this elasticity in Los Angeles to be -0.05 . Applying the same estimation method to RELU-TRAN for the Paris region, we found $\eta^{\text{commute time}} = -0.46$. Given λ , whose value is calibrated from matching the wage elasticity of labor supply by Eq. (A.38), we then calibrate the value of γ such that the right-hand side of (A.42) equals -0.46 . Moreover, the marginal rate of substitution between disposable income, M_{ijs} , and across-modes average commute time, G_{ij} , is:

$$MRS(M_{ijs}, G_{ij}) = \frac{\partial \tilde{U}_{ijks} / \partial G_{ij}}{\partial \tilde{U}_{ijks} / \partial M_{ijs}} = \frac{\gamma M_{ijs}}{G_{ij}}. \quad (\text{A.43})$$

In the calibrated baseline, the probability-weighted average marginal willingness to pay, $\sum_{ijks} P_{ijks}^e \cdot MRS(M_{ijs}, G_{ij})$, for one hour of time saved in commute is 26.66 €, or 1.43 times the average hourly wage rate.

Mode choice

The mode choice elasticity is important because it is the key factor that determines how sensitively the equilibrium shares of modes will respond to a change in the relative cost between driving and public transit. Indra (2014) found that the maximum likelihood estimate for the elasticity of choosing car with respect to its own cost is -0.1 in the Los Angeles region. Applying the same method, we found that the same elasticity is -0.7 in the Paris region. The fact that mode choice is much more elastic in the Paris region than in Los Angeles is expected since the spatial distribution of population, jobs, and business establishments are significantly denser as compared to Los Angeles. Also, the Paris region is served by a high density transit network with well-developed facilities. Our value of -0.7 is consistent with Chan and Ou (1978, p.43) who found

that the elasticities of demand for vehicle trips with respect to time and monetary costs in Boston are -0.82 and -0.49 , respectively. The same elasticities are -0.39 and -0.12 in Louisville. They point out that the elasticities are sensitive to the service levels, which is consistent with our observation of the difference between Los Angeles and the Paris region. [Small and Verhoef \(2007, p.11\)](#) documented that the demand for car trips with respect to fuel cost (which is expected to be smaller than the elasticity with respect to the full cost) typically lies between -0.1 and -0.3 . From the logit mode choice probability, [Eq. \(A.29\)](#), the elasticity for a given (i, z) zone pair is:

$$\frac{\partial \ln \text{PROB}_{CAR|iz}}{\partial \ln(\phi_{iz} + \phi_{zi})} = \Theta(\phi_{iz} + \phi_{zi})(1 - \check{\text{PROB}}_{CAR|iz}). \quad (\text{A.44})$$

We calibrate the value of $\Theta < 0$ from [\(A.44\)](#) so that the trip-weighted mode choice elasticity equals -0.7 .

Short run and long run floor space supplies

In the short run, housing and commercial floor space supplies adjust to rents as landlords of existing structures decide whether or not to rent out or keep vacant their properties, as shown in the occupancy choice equation [\(A.10\)](#). The occupancy elasticity with respect to rent is therefore:

$$\eta_{in}^{\text{occupancy}} = \phi_{in} R_{in} (1 - \check{q}_{in}) \quad (\text{A.45})$$

[Anas and Arnott \(1993\)](#) estimated that in the Chicago MSA this elasticity is 0.10 for single-family housing and 0.11 for multi-family housing. [Indra \(2014\)](#) found the same elasticity to be 0.1 in Los Angeles. Our estimates for residential housing in the Paris region is 0.25. In the long run, the supply of floor spaces adjusts to real estate values due to developers building or demolishing structures. This elasticity is zero in the City since construction is not allowed and we assume no demolitions. The elasticities in the CDTs and the suburbs vary from 0.01 (single-family housing in the CDTs) to 0.97 (stores in the suburbs).

(c) Value of travel time

tot , the value of time in travel, is another critical parameter in the model as it converts the time costs of car and public transit into pecuniary costs in calculating the generalized costs of the two modes of travel, which, in turn, determine the equilibrium shares of car and public transit. Moreover, the monetary values of both the Pigouvian toll and the congestion externalities depend

on vot . We set $vot = 10$ euros/hour, which is 54% of the average hourly wage rate. This value is consistent with a long line of empirical research on the value of travel time (For comprehensive surveys on the topic, see, for example, [Small and Verhoef, 2007](#); [Abrantes and Wardman, 2011](#); [Small, 2012](#)).

(d) Congestion

In the Bureau of Public Roads (BPR) function [\(A.24\)](#), $b_a = 0.15$, a customary value, for all arcs a and the exponent is $C = 1.2$. Arc road capacities, $capacity_a$, are calibrated to minimize the Mean Squared Prediction Error (MSPE) for all trip-origin to trip-destination zone pairs

$$ij : \quad MSPE = \sqrt{\sum_{ij} weight_{ij} \left(\frac{\tau_{ij}^{observed} - \tau_{ij}^{model\ prediction}}{\tau_{ij}^{observed}} \right)^2}, \quad (A.46)$$

$$capacity^{calibrated} = \underset{capacity_a > 0, \forall a}{arg\ min} (MSPE), \quad (A.47)$$

where $\tau_{ij}^{observed}$ and $\tau_{ij}^{model\ prediction}$ are the observed and model generated driving times between i and j , given all other calibrated parameters. For the $weight_{ij}$ assigned for a particular (i, j) pair, we use the share of observed vehicle flow. We are able to find a vector $capacity^{calibrated}$ that produces a $MSPE$ as small as 0.103. In calculating the monetary cost of driving [\(A.25\)](#), the gasoline price $pfuel$ is set to 1.21 € per liter and the *passenger per vehicle* is set to 1.2. According to the European Environment Agency, the average vehicle occupancy is about 1.45 in the year 2005 in the EU countries. We adjusted our value downward because the occupancy rate has been declining steadily over the past several decades due to increasing car ownership. [Table A1](#) presents the values of the calibrated coefficients.

[TABLE A1 HERE]

Table A1: Calibration

Value of time for travel on the network (€/hr)	10					
Occupancy rate of car (person/car)	1.2					
Congestion exponent in the BPR function	1.2					
Average wage (€/hr)	18.63					
MRS (after-tax disposable income and commute time, €/hr)	26.66					
Expenditure share of housing (%)	29.2					
Tax rates (%)						
Sales	20					
Income	30					
COST SHARES IN PRODUCTION						
Capital	0.11					
Labor	0.47					
Floor spaces	0.42					
ELASTICITIES						
Residential location demand						
with respect to average travel time	-0.46					
with respect to housing rent	-0.37					
Labor						
supply with respect to wage	1.04					
demand with respect to wage	-0.95					
Substitution among consumption goods						
regional residents	0.77					
outside-the-region importer	1.80					
Substitution between in-region and out-of-region labor						
	0.90					
Substitution among building types in production						
	3.33					
Mode (car) choice with respect to car cost						
	-0.7					
Floor space supply						
		Single-family	Multi-family	Office	Store	Industrial
Floor space occupancy with respect to rent	0.25	0.25	0.5	0.5	0.5	
Floor space construction with respect to price						
Paris	0	0	0	0	0	
CDTs	0.01	0.13	0.33	0.65	0.30	
Suburbs	0.04	0.42	0.68	0.97	0.70	

VI. Supplementary tables (A2 – A5)

Table A2 shows how calculations of the TFP coefficient $A_j \equiv A_{ij} / C_{ij}$ of Eq. (2) vary by j under alternative α and β . In the table, the distribution of jobs, the mode choice probabilities and the congested road travel times are kept as in 2005, to focus on the direct out-of-equilibrium effects of the changes in the $TIME_{PTij}$ on the TFPs via the G_{ij} in Eq. (3). The GPE reduces the public transit travel times as shown in Table 2 and increases the TFPs by the percentages shown in Table 3. For each β , the TFP is highest in Paris which – by its central location – is highly accessible to jobs. Paris is followed by CDTs like La Defense and Pleyel that are well-served by the GPE and/or have high job densities or job shares. TFPs are lower in the outer suburbs and in the CDTs that are distant to the City. For each value of β , the TFP of La Defense increases the most when the GPE is introduced, and the suburbs increase the least, in almost all cases. In only a few cases, the CDTs of Saclay and Aulnay-Montfermeil have TFPs lower than those of the suburbs. With $\alpha = 0.045$, the percent increase in the TFP of La Defense divided by that of the suburbs, increases from a ratio of 8.7 when $\beta = 1$, to 15.2 when $\beta = 2$, to 19.1 when $\beta = 3$. Thus, when $\beta = 3$, the GPE favors the CDTs more than when β is smaller. The GPE increases the TFPs by 1.53% in La Defense, by 1.3% in Roissy-Pole, by 0.78% in Pleyel, less elsewhere and negligibly in the suburbs. Because the GPE mostly links the CDTs it has a smaller positive effect on the TFP of the City.

TABLE A2: TFP coefficients and percent changes in TFP coefficients due to the GPE with the job distribution, mode choice and car travel times fixed at 2005 values

α	0.09	Percent	0.045	Percent	0.045	Percent	0.045	Percent
	1	change due	1	change due	2	change due	3	change due
β	1	to GPE	1	to GPE	2	to GPE	3	to GPE
Paris	1.62	0.2	1.27	0.1	1.073	0.2	0.905	0.3
La Defense	1.57	0.52	1.25	0.26	1.051	0.76	0.894	1.53
Seine Amont	1.55	0.08	1.24	0.04	1.024	0.14	0.847	0.4
Descartes	1.55	0.05	1.24	0.03	1.024	0.07	0.844	0.14
Aulnay-Mont.	1.5	0.03	1.23	0.01	0.995	0.06	0.811	0.23
Roissy	1.49	0.07	1.22	0.03	0.991	0.28	0.82	1.3
La Bourget	1.54	0.05	1.24	0.02	1.016	0.08	0.837	0.3
Val de France	1.51	0.07	1.23	0.04	1.002	0.12	0.822	0.39
Pleyel	1.56	0.31	1.25	0.15	1.031	0.37	0.857	0.78
Confluence	1.48	0.11	1.22	0.06	0.984	0.2	0.801	0.66
Saclay	1.5	0.04	1.23	0.02	0.995	0.09	0.811	0.26
Suburbs	1.51	0.05	1.23	0.03	0.995	0.05	0.806	0.08

Table A3, below, shows the changes in the TFPs from the baseline under each of the eight general equilibrium simulations discussed in Section 4.

TABLE A3: GPE-induced general equilibrium changes in TFP (Eq. (2) with $\alpha = 0.045$, $\beta = 3$) (percent changes from the 2035 baseline.)

		Baseline	Closed in population		Closed in population with congestion pricing		Open in population		Open in population with congestion pricing	
		Value of TFP	Value of TFP	Percent change	Value of TFP	Percent change	Value of TFP	Percent change	Value of TFP	Percent change
Paris		0.907	0.908	0.13	0.909	0.19	0.909	0.27	0.913	0.68
	La Defense	0.887	0.892	0.59	0.893	0.69	0.894	0.77	0.899	1.4
	Seine Amont	0.847	0.848	0.13	0.848	0.16	0.849	0.26	0.852	0.62
	Descartes	0.847	0.847	0.05	0.848	0.16	0.849	0.2	0.853	0.7
	Auinay-Mont.	0.813	0.814	0.08	0.814	0.12	0.815	0.23	0.819	0.68
CDTs	Roissy Pole	0.812	0.815	0.37	0.815	0.41	0.816	0.51	0.819	0.83
	La Bourget	0.839	0.84	0.1	0.84	0.15	0.841	0.25	0.845	0.74
	Gonesse	0.823	0.824	0.13	0.825	0.24	0.825	0.28	0.83	0.8
	Pleyel	0.855	0.858	0.31	0.858	0.37	0.859	0.46	0.863	0.97
	Confluence	0.8	0.801	0.2	0.802	0.25	0.803	0.35	0.807	0.82
	Saclay	0.812	0.813	0.09	0.813	0.17	0.814	0.23	0.817	0.64
Outer suburbs		0.809	0.81	0.04	0.812	0.28	0.811	0.17	0.815	0.77

TABLE A4: GPE-induced transportation changes
(percentage changes from the 2035 baseline)

	Origin	Destination	Closed in population		Closed in population with congestion pricing		Open in population		Open in population with congestion pricing	
			Without TFP externality	Change due to TFP externality	Without TFP externality	Change due to TFP externality	Without TFP externality	Change due to TFP externality	Without TFP externality	Change due to TFP externality
Auto share of all trips	(Res.)	(Job)								
		Paris	-0.13	-0.14	-0.67	-0.68	-0.16	-0.22	-0.66	-0.71
	Paris	CDTs	-0.09	-0.10	-1.17	-1.19	-0.15	-0.27	-1.15	-1.23
		Suburbs	-0.05	-0.07	-2.03	-2.05	-0.17	-0.37	-2.00	-2.13
		Paris	-0.05	-0.06	-0.95	-0.96	-0.11	-0.20	-0.94	-1.01
	CDTs	CDTs	-1.12	-1.13	-0.51	-0.52	-1.14	-1.19	-0.50	-0.54
		Suburbs	-0.17	-0.19	-2.40	-2.42	-0.30	-0.53	-2.37	-2.53
		Paris	-0.03	-0.04	-1.38	-1.39	-0.11	-0.25	-1.37	-1.46
	Suburbs	CDTs	-0.21	-0.24	-2.40	-2.43	-0.34	-0.57	-2.36	-2.53
		Suburbs	-0.97	-0.99	-2.46	-2.48	-1.10	-1.33	-2.42	-2.58
	AVERAGE		-0.40	-0.41	-1.48	-1.50	-0.48	-0.62	-1.46	-1.56
Auto time		Paris	-0.18	-0.10	-3.13	-3.05	0.24	0.96	-3.17	-2.83
	Paris	CDTs	-0.14	-0.07	-2.94	-2.88	0.24	0.90	-2.98	-2.68
		Suburbs	-0.18	-0.12	-2.99	-2.94	0.20	0.84	-3.04	-2.75
		Paris	-0.13	-0.06	-3.17	-3.10	0.22	0.84	-3.21	-2.92
	CDTs	CDTs	-0.10	-0.05	-3.00	-2.93	0.12	0.52	-2.98	-2.84
		Suburbs	-0.15	-0.09	-2.87	-2.82	0.18	0.75	-2.91	-2.66
		Paris	-0.15	-0.09	-2.58	-2.52	0.16	0.69	-2.61	-2.38
	Suburbs	CDTs	-0.15	-0.09	-2.51	-2.45	0.17	0.71	-2.54	-2.30
		Suburbs	-0.15	-0.10	-2.59	-2.54	0.15	0.68	-2.62	-2.39
		AVERAGE		-0.15	-0.09	-2.59	-2.53	0.17	0.72	-2.62
Average travel time		Paris	-1.10	-1.08	-0.58	-0.56	-0.99	-0.80	-0.60	-0.51
	Paris	CDTs	-0.62	-0.61	-0.43	-0.42	-0.52	-0.36	-0.44	-0.37
		Suburbs	-0.35	-0.33	-1.64	-1.62	-0.25	-0.08	-1.65	-1.59
		Paris	-0.41	-0.40	-0.32	-0.31	-0.34	-0.22	-0.34	-0.28
	CDTs	CDTs	-2.83	-2.79	-0.48	-0.43	-2.71	-2.50	-0.47	-0.36
		Suburbs	-0.41	-0.38	-2.18	-2.15	-0.23	0.08	-2.20	-2.07
		Paris	-0.39	-0.38	-1.04	-1.03	-0.33	-0.24	-1.04	-1.01
	Suburbs	CDTs	-0.49	-0.46	-2.12	-2.10	-0.32	-0.03	-2.13	-2.02
		Suburbs	-1.54	-1.51	-2.79	-2.76	-1.36	-1.06	-2.80	-2.69
		AVERAGE		-0.97	-0.95	-1.65	-1.63	-0.84	-0.61	-1.66
Commute pattern		Paris	0.02	0.03	0.26	0.28	1.68	4.16	-0.08	1.36
	Paris	CDTs	-0.33	-0.30	-0.46	-0.40	1.41	4.11	-0.94	0.77
		Suburbs	-0.31	-0.19	1.10	1.30	1.49	4.32	0.42	2.55
		Paris	-0.28	-0.33	-0.92	-1.00	1.43	3.92	-1.38	0.13
	CDTs	CDTs	1.05	1.05	-0.96	-0.98	2.90	5.73	-1.44	0.22
		Suburbs	-0.42	-0.36	0.78	0.88	1.41	4.22	0.59	2.04
		Paris	-0.29	-0.34	-0.86	-0.97	1.45	3.97	-1.42	0.19
	Suburbs	CDTs	-0.60	-0.61	0.19	0.15	1.20	3.90	0.11	1.29
		Suburbs	0.12	0.19	0.74	0.83	1.98	4.84	0.73	2.00
		TOTAL		0.00	0.00	0.00	0.00	1.81	4.53	-0.32
Gasoline consumption			-0.79	-0.52	-7.31	-7.04	0.80	3.54	-7.50	-6.17
Public transit trips			0.94	1.34	2.30	2.79	2.86	6.29	1.95	4.09

TABLE A5: Sensitivity analysis: social welfare and benefit-cost of the GPE
(Region closed in population (short run), no congestion pricing, with TFP externality)

	Baseline GPE	$\beta = 1$	20% more time saving	50% higher marginal disutility of travel time	Mode choice elasticity, -0.5 (Baseline, -0.7)	Consumer's elasticity of substitution (40% higher)	50% higher elasticity of substitution for outside consumer
A. SOCIAL WELFARE							
Welfare [= a + b + c + d + e]	467	502	537	622	662	486	722
a. Consumer CV	340	311	397	437	470	362	484
b. Importer CV	241	257	246	303	335	244	248
c. Real estate values	-13	-5	-13	-12	-16	-14	2
d. Tax revenues	-78	-46	-74	-84	-105	-84	9
<i>Sales tax</i>	-41	-20	-39	-48	-53	-43	6
<i>Income tax</i>	-37	-25	-35	-36	-52	-40	3
e. GPE operating surplus	-23	-15	-19	-21	-23	-22	-21
Average income (after tax and commute costs)	37,500	32,220	37,176	34,769	37,034	37,331	39,681
Welfare gain as a percent of average income	1.25	1.6	1.4	1.8	1.8	1.3	1.8
B. EXTERNALITIES							
Productivity externality	411	1060	412	394	407	418	521
Road congestion externality	516	772	514	491	259	527	511
C. BENEFIT-COST ANALYSIS							
Benefit-to-cost ratio [= Welfare/GPE cost = (a + b + c + d + e)/132 €]	3.54	3.81	4.07	4.71	5.01	3.68	5.47