How and how much do public transportation megaprojects induce urban agglomeration? The case of the Grand Paris Project

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ABSTRACT

We evaluate the general equilibrium and welfare effects of the Grand Paris Project, a planned public transit megaproject slated to decongest the City of Paris by circumferentially linking the City's inner suburbs. In the model, the megaproject improves the accessibility among jobs, spurring worker productivity directly, by decreasing travel times by public transit; and indirectly by reducing road congestion, and by inducing a redistribution of jobs and residences. The megaproject's impact on job and population densities, on travel metrics, on building prices and rents, on wages, and on gross product and economic welfare are calculated with and without the pricing of congestion on roads. We also calculate by how much the megaproject would increase the population size of the Greater Paris agglomeration.

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Introduction

2. The Greater Paris Metropolitan Area and the Grand Paris Project

The Greater Paris Metropolitan Area (GPMA), also known as Ile-de-France is briefly described here. Figure 1 shows the GPMA and its zonal delineation for modeling purposes. The City of Paris which is the center is shown in the inset and consists of 20 small zones each an arrondissement of the City of Paris. The inner suburbs are in deep or light pink and altogether comprise the inner ring of suburbs encircling the City of Paris. The dark pink zones are known as Contrats de Développement Territorial (CDT, hereafter) and are targeted by planners as “poles” for future growth. The yellow zones comprise the remaining outer suburbs which are generally lower density areas. We refer to areas that are beyond the yellow zones as exurban.

Table 1 describes the distribution of land, floor space, population, jobs, and the number of daily trips by purpose and by mode among the three areas. Road congestion in the region is high and especially in the central area in and around the City. This condition is mitigated in great part by an extensive public transit and suburban railroad system that spans the whole region. Note that public transit trips are more than half of all trips and that 62% of public transit trips but only 23% of car trips terminate in the City of Paris.

The long term planning perspective is that the City of Paris is almost completely developed with essentially no undeveloped land remaining. Redevelopment at higher structural density would increase congestion within an already congested City and would also destroy the beauty of a skyline which is dotted with world famous monuments. Therefore, the desired direction for future growth is to concentrate it as much as possible in the CDTs. This strategy preserves the accessibility of newly added population and jobs to the City, thus allowing that the CDT and the City agglomerations work well together as a whole. In order to reinforce this pattern and to facilitate future economic interaction among the CDTs without burdening the infrastructure of the City of Paris, the Grand Paris Project (GPP) shown in Figure 2 has been proposed with a target completion date of 2035 and an estimated construction cost of about 35 Billion €. The GPP is a public transporation system consisting of fixed guideline fast trains and subways and feeder buses that will connect most of the CDTs circumferentially around the City of Paris. It will include some 70 stations where passengers can board or disembark. An obvious benefit of this proposed system is that it will enable faster direct transport between the CDTs, reducing the need to travel through the City of Paris via the existing public transit lines which are radially arranged. Another benefit is that the GPP will reduce road congestion which in turn will facilitate direct transport by road as well. A possible criticism is that the GPMA is already well served by a rich public transit network and that the GPP could add redundancy.

FIGURE 1: The Greater Paris Metropolitan Area (Ile-de-France).

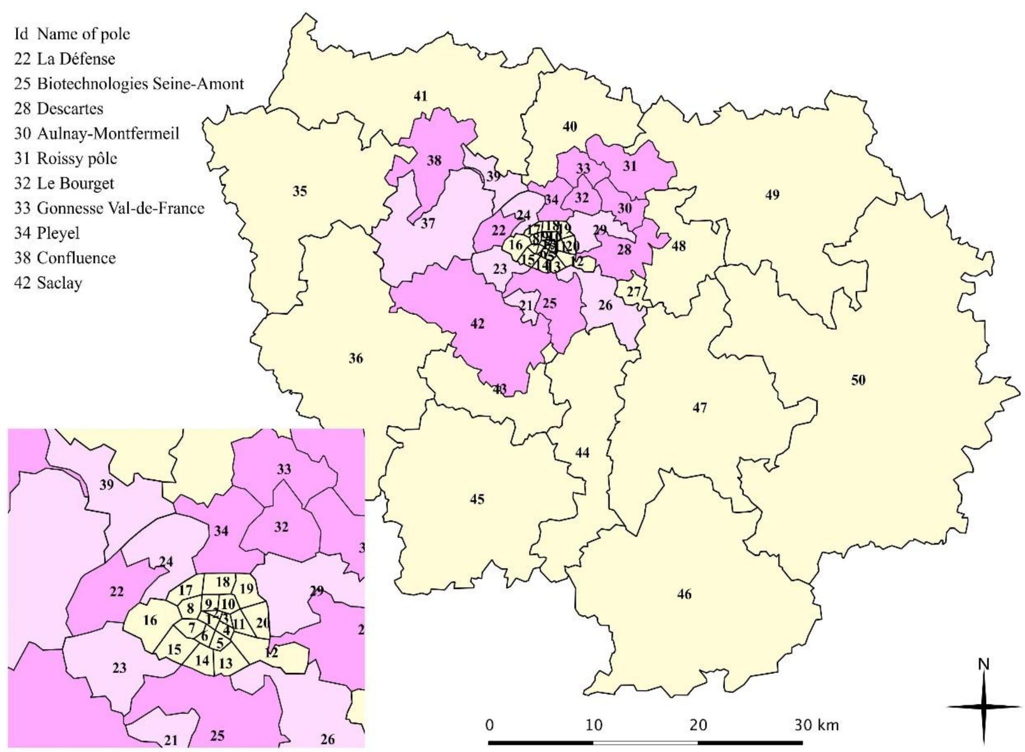

TABLE 1: Land, floor space, population, jobs, and daily trips in the GPMA circa 2005

	Total	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%	
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%	

FIGURE 2: The Grand Paris Project's proposed public transit lines

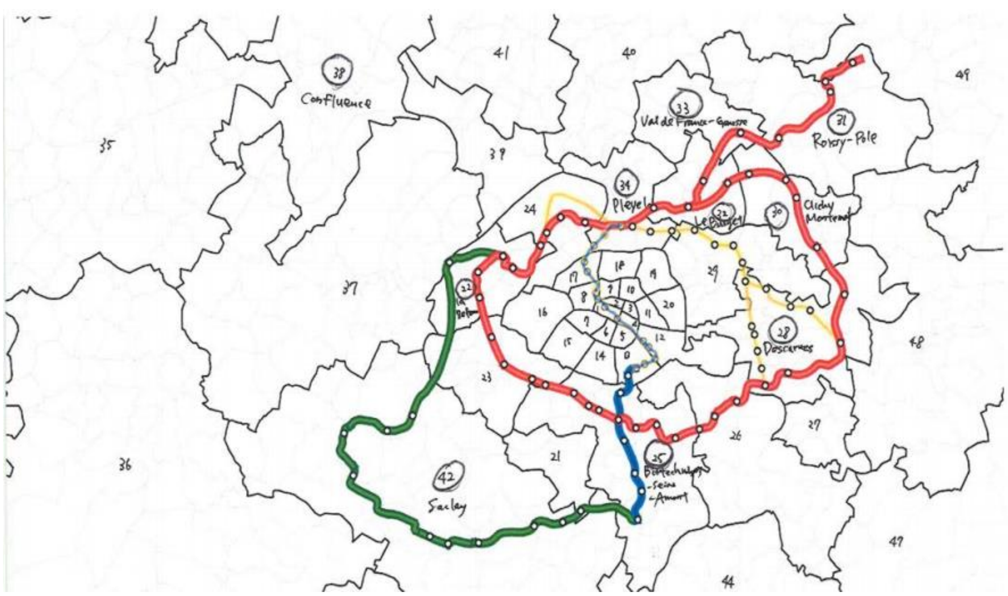

TABLE 2a: Average one-way public transit time savings on the GPP in 2035– Minutes

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
CDTs	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
	Roissy Pole						**12.0**	3.2		0.0			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 GPP 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%
CDTs	La Defense	3.6%	**17.7%**		1.0%	0.6%	0.9%	2.8%	4.7%	8.4%	6.2%		3.3%
	Seinte 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%
	Roissy Pole						**37.6%**	5.7%		0.0%			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%**

Tables 2a and 2b dcoument the projected zone-to-zone travel time savings by public transit in minutes (Table 2a) and in percentage changes (Table 2b) that would result after the GPP is operational in the year 2035. Blanks in the tables correspond to no savings or very small savings that have been rounded to zero.

3. The economics of the productivity externality

The production function of firms in the RELU-TRAN Paris model is as follows (see eq. (A.6) and the associated discussion in the Appendix):

$$X_{rj} = A_{rj} K_{rj}^{\nu_{rj}} \left(\sum_{f=0,1} \kappa_{f|rj} L_{rjf}^{\theta_r} \right)^{\frac{\delta_{rj}}{\theta_r}} \left(\sum_{k=0,3,4,5} \chi_{k|rj} B_{rjk}^{\zeta_r} \right)^{\frac{\mu_{rj}}{\zeta_r}} \tag{1}$$

X_{rj} is the output of firms in industry $r = 1,2$ (private sector, public sector) in model zone j. A_{rj} is the scale factor, or the input-neutral productivity coefficient. K_{rj} is the capital input supplied perfectly elastically; L_{rjf} is the labor input where $f = 0$ represents the workers employed from outside the region by firms in zone *j*, and $f = 1$ stands for workers in the region; B_{rjk} the commercial floor spaces used in production within zone *j* with $k = 0,3,4,5$ denoting floor space outside the region; and in offices, in stores, and in industrial/public buildings respectively. By the assumption of constant returns to scale the outer nest expenditure share parameters sum to one: $\nu_{rj} + \delta_{rj} + \mu_{rj} = 1$, $\forall j, r$. θ_r and ζ_r are the inner nest elasticity of substitution parameters of the CES sub-production function of each type of inputs; $\kappa_{f|rj}$ and $\chi_{k|rj}$ are constants representing the inherent attractiveness of the labor and floor space inputs.

To model external-to-the-fim agglomeration effects, we will express the input neutral productivity coefficient as a function of the distribution of jobs and the accessibility of this job distribution to the location of the firms in *j*. Fujita and Ogawa (1982) and Lucas and Rossi-Hansberg (2004) have utilized such functions in a simplified theoretical setting of single-dimensional continuous space. The literature contains only two empirical studies that attempted to estimate the coefficients of such functions. Neither the theoretical, nor the empirical literature has fully fleshed out the implications of modeling agglomeration by means of such functions. The theoretical models are too simple, while the empirical studies focus on estimating the elasticity of production with respect to the agglomeration effect but have not gone as far as examing the equilibrium implications.

Ciccone and Hall (1996) used aggregate employment density $A_j = \left(\frac{Jobs_j}{Area_j} \right)^{\alpha}$ to represent the productivity coefficient, where $Jobs_j$ was 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 *j* they estimated that $\alpha = 0.06$. That is a percent increase in the average job density of a County would result in an approximately 6% increase in the productivity of the firms in the County. Applying the same method to European cities, and using French Departments as geographic units in the case of France, Ciccone (2002) estimated that $\alpha = 0.045$.[1] These authors ignored that productivity in a zone *j* can be influenced not only by job density in that zone but also by job density in nearby or even far away zones.

Graham (2007b) attempted to rectify by assuming $A_j = \left(\sum_{\forall i} \left(\frac{Jobs_i}{Area_i} \right) \cdot T_{ij}^{-\beta} \right)^{\alpha}$. This is a travel-cost-mediated accessibility which Graham named "effective job density". T_{ij} is the generalized transport cost by car between zone *i* and zone *j*. It is the value of travel time plus the monetary cost of travel by car plus any other travel costs converted to monetary units. Note that if one were to assume that $\beta = 0$ then the distribution or proximity of jobs to zone *j* does not matter and productivity in zone *j* is affected equally by the job densities of the zones in the entire region. At the other extreme, as β becomes a large positive number the importance of jobs attenuates exponentially with T_{ij}, hence job densities in close proximity affect much more the productivity of firms in zone *j*. Graham assumed that $\beta = 1$. He used U.K. data and the zones were defined as Wards. 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 5.3 times the estimate of Ciccone (2002) for France. As to the choice of geographical unit, the Departments in France are fairly comparable in size to U.S. Counties. Wards in the U.K. are generally smaller than French Departments. For example, there are 10,780 Wards in Britain and 25 in the City of London. The City of Paris is one Department

[1] In the administrative divisions of France, the department is one of the three levels of government below the national level ("territorial collectivities"), between the 27 administrative regions and the commune. There are 96 departments and one metropole with territorial collectivity status in metropolitan France

and also a zone in our model. The GPMA consists of 8 Departments and our model subdivides the GPMA into 12 model zones.

We propose a new formula in which both job density at the model zones and congestion are taken into account to determine the accessibility of jobs in zone *j* to all other jobs in the region:

$$A_{rj} = C_{rj}\left(\sum_{\forall i}\left(\frac{Jobs_i}{Total\ Jobs}\right)\frac{Jobs_i}{Area_i}\cdot G_{ij}^{-\beta}\right)^{\alpha} \tag{2}$$

where $\frac{Jobs_i}{Area_i}$ is the job density of model zone i and $\frac{Jobs_i}{Total\ Jobs}$ is the weight we assign to each zone's density; and G_{ij} is the travel time from zone *i* to zone *j* which is the average of car and public transit travel times weighted by the mode-choice probabilities. This revised formula implicitly assumes that jobs interact with each other but in such a way that between two equally dense zones *i* located at the same time-distance from zone *j*, the one containing more jobs would have a higher influence on productivity in zone *j*; and between two zones containing the same number of jobs, the higher density zone would have a higher influence on productivity; and, zone size and density being constant, the less time-distant zone would have a higher influence on productivity.

We adopt $\alpha = 0.045$ from Ciccone (2002) since that estimate is for France. From Equation (2), the spot elasticity of $A_j \equiv A_{rj} / C_{rj}$ with respect to all travel times changing simultaneously can be calculated and is $-\alpha\beta$.[1] We set $\beta = 3$ so that the elasticity of the accessibility measure (2) with respect to average travel time is $-\alpha \cdot \beta = -0.045 \times 3 = -0.135$. The coefficients C_{rj} are constants we calibrate to match output by sector *r* in zone *j*. Note that when $\alpha = 0$, then $A_{rj} = C_{rj}$ and there are no effects on productivity from agglomeration. In the sequel we will solve the general equilibrium with the calibrated value of the productivity A_{rj} remaining constant and again by taking into account the changes in $Jobs_i$ and in G_{ij}, thus making endogenous the productivity A_{rj}. We will compare the outcomes in order to understand how the productivity influences wages, output prices, rents, job concentrations, industry output and the equilibrium size of the GPMA.

Eq. (A.30) in the Appendix, repeated here, gives G_{ij}:

[1] Proof available from the authors upon request.

$$G_{ij} = PROB_{CAR|ij} \times \left(\tau_{ij} + \tau_{ji}\right) + PROB_{PT|ij} \times \left(TIME_{PT|ij} + TIME_{PT|ji}\right). \tag{3}$$

The form of (3) hinges on the assumption that travelers from zone i to zone j utilize private car with probability $PROB_{CAR|ij}$ and public transit with probability $1 - PROB_{CAR|ij}$, randomizing with these probabilities the choice of mode on each trip. These probabilities are endogenous in the general equilibrium model. $TIME_{PT|ij}$ are the travel times from i to j by public transit and these are exogenous to the model because the public transit system is treated as not congested. Finally, τ_{ij} are the travel times by car and they are endogenous because road network congestion is treated by the general equilibrium model. For the technical details of the mode choice model, and the route choice equilibrium model the reader is referred to the Appendix.

Table 3 shows the values of the coefficient A_{rj} / C_{rj} from equation (2) which vary only by j under different values of α an β. Then, keeping the distribution of jobs the same, the introduction of the megaproject GPP changes these values by some percentage which is also shown in the Table. The values are highest in the City of Paris, followed by close to Paris CDTs like La Defense, Biotech and Descartes. The values are meaningfully lower in the outer suburbs and the CDTs which are relatively distant to Paris. The values are sensitive to the choice of β and α.

TABLE 3: Percent changes in $A_j \equiv A_{rj} / C_{rj}$ due to the megaproject GPP, with the job distribution fixed at its 2005 values.

α	0.09		0.045		0.045		0.045	
β	1		1		2		3	
Paris	1.62	0.20%	1.27	0.10%	1.073	0.20%	0.905	0.30%
La Defense	1.57	0.52%	1.25	0.26%	1.051	0.76%	0.894	1.53%
Biotech	1.55	0.08%	1.24	0.04%	1.024	0.14%	0.847	0.40%
Descartes	1.55	0.05%	1.24	0.03%	1.024	0.07%	0.844	0.14%
Aulnay-Mont.	1.50	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%	0.820	1.30%
La Bourget	1.54	0.05%	1.24	0.02%	1.016	0.08%	0.837	0.30%
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	0.20%	0.801	0.66%
Saclay	1.50	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%

Let us now discuss how the GPP megaproject would affect the economy in the presence of the accessibility measure (2) appearing in the production function (1) with $\alpha, \beta > 0.$ Although the distribution of jobs among the zones is endogenous in the model, we can start reasoning of how things would work if the distribution of jobs remained unchanged. The megaproject exogenously decreases the public transit travel times, $TIME_{PT|ij}$, for many *ij* zone pairs as was shown in Tables 2a and 2b. This exogenous driver then causes the following changes.

First, because lower-than-before public transit times are now available, the public transit choice probability increases while the car choice probability decreases. As fewer trips are now made by car, road congestion decreases and consequently car travel times τ_{ij} are also reduced. For many zone pairs *ij*, these changes add up to make the mode-probability-weighted-travel-times, the G_{ij}, lower. When G_{ij} are reduced, and initially keeping the distribution of jobs among the zones constant and the total population and jobs in the region also constant, the value of the productivity A_{rj} increases.

This increase in A_{rj} affects the urban economy via two channels:

1. *The productivity effect in the intensive margin*: As the marginal product of labor increases because A_{rj} increases, fewer labor units (and jobs) are needed to produce the same output X_{rj}. *Ceteris paribus*, not only the quantity of labor, but also the quantities of the other production inputs (capital and building floor spaces) in zone *j* would decrease. Thus higher accessibility to jobs caused by lower megaproject travel times reduces jobs and job density in zone *j*, causing a negative feedback on the productivity A_{rj}.
2. *The demand effect in the extensive margin*: From the zero profit condition of a competitive industry under constant returns, p_{rj}, the price of the output produced at *j* is equal to its unit (marginal) cost, and falls as the productivity A_{rj} increases. To see this consider eq. (A.11) in the Appendix, where ρ is the price of capital, w_{rj} is the wage and R_{jk} is the rent for floor space in a type *k* building. This zero profit equation is repeated here:

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

Keeping the wages and the rents constant, as A_{rj} rises, the price p_{rj} falls and the quantity of the output demanded by the consumers in the region and also by those in other regions who import, increases. This then causes the industry *rj* to hire more labor, causing the number of jobs to increase.

To see more clearly how these effects work, note that the labor demand function of the *rj* industry is:

$$L_{rj1} = \frac{\kappa_{f=1|rj}^{\frac{1}{1-\theta_r}} w_{rj,f=1}^{\frac{1}{\theta_r-1}}}{\sum_{f'=0}^{1} \kappa_{f'|rj}^{\frac{1}{1-\theta_r}} w_{f'jr}^{\frac{\theta_r}{\theta_r-1}}} \delta_r p_{rj} X_{rj} \tag{5}$$

Normalizing both sides of (5) by the output X_{rj} and then substituting out the price p_{rj} by using (4) we get:

$$\frac{L_{rj1}}{X_{rj}} = \frac{\kappa_{f=1|rj}^{\frac{1}{1-\theta_r}} w_{rj,f=1}^{\frac{1}{\theta_r-1}}}{\sum_{f'=0,1} \kappa_{f'|rj}^{\frac{1}{1-\theta_r}} w_{f'jr}^{\frac{\theta_r}{\theta_r-1}}} \delta_r \cdot \underbrace{\frac{\rho^{v_{rj}}}{A_{rj} v_{rj}^{v_{rj}} \mu_{rj}^{\mu_{rj}} \delta_{rj}^{\delta_{rj}}} \left(\sum_{f=0,1} \kappa_{f|rj}^{\frac{1}{1-\theta_r}} w_{jf}^{\frac{\theta_r}{\theta_r-1}} \right)^{\frac{\delta_{rj}(\theta_r-1)}{\theta_r}} \left(\sum_{k=0,3,4,5} \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{\zeta_r-1}} \right)^{\frac{\mu_{rj}(\zeta_r-1)}{\zeta_r}}}_{=p_{rj}} . \tag{6}$$

It is evident from the right side of (6) that, given fixed wages and rents, the labor demanded per unit of output produced decreases as the productivity A_{rj} increases; and this holds for other inputs as well. The reason for this is that although X_{rj} increases with A_{rj}, it is evident from (1) that the increase in X_{rj} is smaller than that of A_{rj} because all demanded input quantities decrease as inputs become more productive because of the higher A_{rj}.

In the above discussion, we assumed that input prices stayed constant in order to reason about the changes that would occur in output and production inputs and therefore in jobs. We found two opposing effects, the intensive margin effect on productivity and the extensive margin effect driven by low output price and higher demanded quantity. Because these effects are opposing each other, their net outcome is especially important to study using general equilibrium analysis which we will do in the sequel. The number of jobs in zone *j* will increase if the extensive marginal effect dominates the intensive marginal effect. Otherwise the number of jobs in zone *j* will decrease if the intensive marginal effect dominates the extensive marginal effect.

But how do input prices change? The lower labor input quantities caused by the higher productivity increase the marginal product of labor, but because capital and floor space inputs are also lowered, the net effect on wages is unclear, because the lowered non-labor inputs decrease the marginal productivity of labor. In a general equilibrium setting, how much the different input prices change is determined by the demand and supply elasticities in the relevant labor and real estate markets.

There is a third effect of the improved accessibility which works in the aggregate by attracting growth to the metropolitan area. We call this the *growth effect*. This effect exists because the megaproject as we saw reduces the cost of travel both on the public transport system, and less directly by decongesting roads. Via these channels, consumers in the region gain utility because their work and non-work trips become less costly. This induces consumers from the rest of the economy to migrate to the GPMA which, in turn, boosts demand for product and floor spaces causing more jobs to emerge. To some extent the in-migration can cause wages to fall because the supply of labor increases.

The resulting higher population and jobs then increase job density in many zones within the metropolitan area, where the value of the productivity coefficient A_{rj} increases by both the higher job density and the better accessibility, offset to some extent by the higher congestion. As we saw, the higher accessibility to jobs has intensive and extensive marginal effects which oppose each other, but the in-migration works with the extensive marginal effect, boosting the region's population and therefore inducing a larger demand for labor to produce more output to serve the larger population. In-migration into the region continues until the initially higher utility dissipates as congestion and rents in the region adjust and as wages might fall too in response to the increased labor supply caused by the in-migration.

In the simulations, we will observe the effects of all three margins: the intensive factor productivity margin, the extensive demand margin and the growth margin of in-migration.

4. General equilibrium effects of the productivity externality

Table A.1 in the Appendix lists the key elasticities of the RELU-TRAN model for GPMA. The calibration of this type of medel for the Chicago MSA has been described in Anas and Hiramatsu (2013); and for Los Angeles in Anas (2017). The calibration strategy followed is to replicate closely the market allocations observed in the base year data. The earlier calibrations did not include specifications in which productivity was a function of the accessibility to jobs. An important issue therefore is how this specification modified the calibration of the model.

The production function (eq. (1)), including the accessibility to jobs given by eq. (2). We first set the values $\alpha = 0.045$ and $\beta = 3$ as explained earlier. Then we calculate the values A_{rj} using eq. (2) and the 2005 base year data for $Jobs_j$ and for G_{ij}; calibrating the constant C_{rj} to match outputs by zone and sector. Once this is done and the rest of the model is calibrated too, there are three kinds of general equilibrium simulations that we will report on in the sequel:

(i) *Exogenous productivity*: We keep the A_{rj} at their 2005 calibrated base year values. In the new equilibrium in 2035, various exogenous changes, such as the introduction of the megaproject or road congestion pricing, cause the values of $Jobs_j$ and expected travel times G_{ij} to change, but we assume that the productivities A_{rj} are not adjusted and remain fixed at their 2005 base year values. This type of simulation means that there are no long term feedbacks between job accessibility and productivity. That is the production function is assumed to be insensitive to the accessibility to jobs. The simulation solves for wages, rents, real estate prices and product prices and all other variables such as travel patterns, congestion levels on the road network and the job and residential population distributions.

(ii) *Endogenous productivity*: This type of simulation differs from (i) in that as the model reaches a new equilibrium due to exogenous changes, the values of $Jobs_j$ and expected travel times G_{ij} change and, by eq. (2), these changes alter the values of the productivities A_{rj} so that in the new equilibrium, both $Jobs_j$ and expected travel times G_{ij} are converged to their endogenously determined values. This type of simulation means that the feedback between job accessibility and productivity is taken into account completely. The equilibrium differs from that in (i), in wages, rents, real estate prices and product prices and in all other variables such as travel patterns, congestion levels on the road network and the job and residential population distributions.

(iii) *Endogenous aggregate population and jobs*: The third type simulation is done with (i) or with (ii). It is intended to make endogenous the region's growth by calculating the in-migration. This is accomplished by placing simulations (i) or (ii) in an inner loop, while the outer loop increases the GPMA's aggregate population until the consumer utility level achieved within the GPMA matches the level of utility that prevailed prior to the exogenous change. So, in the case of the introduction of the GPMA, consumers in the region benefit directly from reduced travel times while also indirectly from enhanced productivity. This raises the region's consumer utility level and in-migration ensues. The in-migration continues until the utility is lowered back to the original level that prevailed prior to the introduction of the GPP. Simulation type (iii), therefore, treats the region as an open economy in the long run, corresponding to the open city model of urban economics), while simulations of type (i) and (ii) treat the region as a closed economy in the short run corresponding to the closed city model of urban economics.

Our simulation results are presented in three groups.

In the first group of simulations, *growth simulations*, the consumer population of the Paris region is increased exogenously to match the population projected for the year 2035 but the GPP project is not introduced. Simulations of type (i) and type (ii) are then performed for 2035 in order to see the effect of making endogenous the accessibility to jobs in the production function. The results are presented in Table 4a -Table 4f.

In the second group of simulations, presented in Table 5a -Table 5g, *GPP simulations*, the GPP is assumed to be operational in 2035 and the type (i) and (ii) simulations are repeated. Thus, these simulations – when compared to those in group one – tell the effect of the GPP travel time improvements on the general equilibrium and on welfare with and without the effects of the accessibility to jobs on production. We also perform the type (iii) simulations which allow us to calculate the effect of the accessibility to jobs on the ultimate 2035 population increment of the GPMA attributable to the GPP. We calculate benefit-to-cost ratios for the GPP.

In the third group of simulations presented in Table 6a-Table 6e, we focus on the effects of implementing congestion tolling on all GPMA roads after the GPP is in place in 2035. These simulations help put the GPP into the context of transport pricing.

4.1 Growth simulations

To do the growth simulations which are intended to capture the region in 2035 in the absence of the GPP, we had to rely on the job and population numbers that French planners believe would prevail in 2035. Planners believed that the 2035 population would be 14.5% more than in 2005 and that jobs would be 17.9% more than in 2005, reflecting a narrowing of the gap between the working and non-working adult populations that is a rise in the labor force participation rate. Unfortunately this forecast by the French planners does not include any information on what would be economic drivers of such projected growth. Therefore, we had to make our own assumptions.

We assumed that by 2035 the demand for exports from each of the region's zones would be 30% higher and we supported this assumption by a corresponding increase in the income level of the importing representative consumer. Outside labor costs were increased by 20% for firms located in the City of Paris, by 30% for firms located in the CDTs and by 25% for firms located in the suburbs. These assumptions are somewhat arbitrary but are meant to reflect the idea that the fastest economic growth would occur in the CDTs and in the suburbs, less in the City of Paris which is relatively growth limited. In tandem with this economic growth limitation, we also assumed that the building stocks in the City of Paris would remain fixed, while the vacancy rates and the rents and market prices of the City's floor spaces are endogenous in the model. For the CDTs and the suburbs the building stocks are adjusting by construction and demolition while vacancy rates, rents and market prices are also endogenous.

TABLE 4a: Population and job distribution due to growth

	Population				Jobs			
	Exogenous productivity		Change due to endogenous productivity		Exogenous productivity		Change due to endogenous productivity	
Paris	191,515	11.1%	981	0.05%	266,643	16.1%	-445	-0.02%
CDTs	422,066	14.6%	157	0.005%	322,212	18.1%	3	0.00%
Suburbs	725,907	16.6%	160	0.003%	371,145	19.3%	442	0.02%
Exurbs	14,478	6.7%	-1,298	-0.56%				
TOTAL	1,353,965	14.7%	0	0	960,000	17.9%	0	0

TABLE 4b: Wage, rent, price and production changes due to growth

	Wage		Rent		Price		Output		Gross product	
	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity
Paris	6.79%	-0.37%	8.02%	-0.19%	5.50%	-0.78%	8.40%	0.21%	14.90%	-0.55%
CDTs	7.91%	-0.35%	8.64%	-0.13%	6.70%	-0.81%	10.29%	0.35%	18.19%	-0.44%
Suburbs	8.90%	-0.30%	2.90%	-0.12%	6.06%	-0.71%	9.59%	0.27%	16.40%	-0.44%
TOTAL	7.60%	-0.35%	6.27%	-0.15%	6.03%	-0.76%	9.81%	0.28%	16.33%	-0.48%

TABLE 4c: Transportation changes due to growth

Origin (Res.)	Destination (Job)	Auto share of all trips		Auto Time		Average Travel Time		Commute Pattern		Aggregate Gasoline	
		Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity	Exog. prod.	Change due to endo. productivity
Paris	**Paris**	-0.37%	-0.01%	4.23%	0.08%	1.09%	0.02%	13.91%	0.02%		
	CDTs	-0.67%	-0.01%	3.78%	0.07%	0.93%	0.02%	13.58%	0.07%		
	Suburbs	-1.13%	-0.02%	3.82%	0.07%	1.06%	0.02%	16.26%	0.10%		
CDTs	**Paris**	-0.54%	-0.01%	3.74%	0.06%	0.79%	0.01%	16.97%	-0.04%		
	CDTs	-0.27%	-0.01%	2.17%	0.05%	1.13%	0.03%	18.78%	0.02%		
	Suburbs	-1.24%	-0.02%	3.42%	0.06%	1.89%	0.03%	19.12%	0.04%		
Suburbs	**Paris**	-0.79%	-0.02%	3.14%	0.05%	0.59%	0.01%	19.28%	-0.04%		
	CDTs	-1.23%	-0.02%	3.19%	0.06%	1.79%	0.03%	20.34%	0.01%		
	Suburbs	-1.23%	-0.02%	3.12%	0.05%	1.90%	0.03%	20.81%	0.04%		
TOTAL		-0.78%	-0.02%	3.56%	0.06%	1.39%	0.02%	17.91%	0	3.03%	0.27%

TABLE 4d: Welfare and externalities (per consumer)

	2005-2035 change with exo. prod. 2005-2035	Additional change due to endo. prod. in 2035
Welfare	**€ 12,649**	**€ 315**
Consumer CV	€ 2,685	€ 184
Real estate values	€ 2,209	-€ 14
Tax revenue	€ 874	-€ 71
Sales	€ 110	-€ 38
Income	€ 764	-€ 33
Importer CV	€ 6,881	€ 216
Agglomeration externality (2035 level)	€ 408	-€4
Congestion externality (2035 level)	€ 521	+€3

TABLE 4e: The value of productivity A_{rj} under different formulas due to growth

		Our's (eq.(2))			Ciccone's			Graham's		
		Base value 2005	Value after growth 2035	Change	Base value 2005	Value after growth 2035	Change	Base value 2005	Value after growth 2035	Change
Paris		0.903	0.907	0.45%	1.582	1.585	0.20%	1.697	1.812	6.74%
CDTs	La Defense	0.881	0.887	0.65%	1.533	1.536	0.23%	1.621	1.729	6.66%
	Seine Amont	0.843	0.847	0.43%	1.459	1.461	0.19%	1.580	1.674	5.98%
	Descartes	0.843	0.847	0.50%	1.419	1.424	0.30%	1.570	1.669	6.32%
	Aulnay Montfermeile	0.809	0.813	0.52%	1.392	1.396	0.32%	1.502	1.591	5.96%
	Roissy Pole	0.809	0.812	0.38%	1.418	1.420	0.17%	1.487	1.571	5.63%
	La Bourget	0.834	0.839	0.54%	1.395	1.400	0.31%	1.552	1.648	6.20%
	Gonesse	0.819	0.823	0.52%	1.376	1.380	0.31%	1.528	1.619	6.01%
	Pleyel	0.850	0.855	0.55%	1.479	1.483	0.25%	1.577	1.677	6.32%
	Confluence	0.796	0.800	0.53%	1.380	1.382	0.18%	1.461	1.544	5.66%
	Saclay	0.808	0.812	0.43%	1.396	1.399	0.21%	1.518	1.604	5.72%
Suburbs		0.806	0.809	0.45%	1.313	1.316	0.24%	1.470	1.552	5.58%

TABLE 4f: Welfare change under different formulas of the accessibility to jobs (A_{rj})

	Welfare change due to endogenous A_{rj}		
	Our's (eq. (2))	**Ciccone's**	**Graham's**
Welfare	**€ 315**	**€ 379**	**€ 2,227**
Consumer CV	€ 184	€ 204	€ 1,269
Value	-€ 14	-€ 20	-€ 102
Tax Revenue	-€ 71	-€ 111	-€ 595
Sales	-€ 38	-€ 58	-€ 306
Income	-€ 33	-€ 53	-€ 289
Importer CV	€ 216	€ 306	€ 1,655
Agglomeration externality	€ 404	€ 124	€ 548
Congestion externality	€ 524	€ 525	€ 544

From Table 4a we see that under the growth scenario, with exogenous productivity, population by place of residence grows more in the suburbs, less in the CDTs, even less in the City of Paris. Jobs follow a similar pattern. Making endogenous the accessibility to jobs in the production function changes this distribution of population and of jobs very slightly. Note, for example, that the number of jobs located in the City of Paris decrease by a mere 445. This indicates the strength of the intensive margin effect: as the growth increases the value of the accessibility to jobs, workers become more productive and fewer are needed even after the lower price of output increases demand in the extensive margin.

Now note from Table 4b that growth raises wages and rents (the latter much more in the CDTs than in the suburbs, and output prices also rise but more evenly across locations. Production (in real output units) and gross product (value of output in euros) increase and more so in the CDTs. Making the accessibility to jobs endogenous has non-negligible effects on these magnitudes. Wages, rents and output prices all fall, prices falling the most and by 0.81% in the CDTs. Real output is 0.28% higher region-wide and rises by 0.35%, the most, in the CDTs. Output in euro terms defined as price multiplied by real output falls by about half percent.

Combining the results of Tables 4a and 4b, we see that the accessibility to job effect in the CDTs, taking them as an example, exhibits itself in two ways. While output is 0.35% higher, jobs in the CDTs increase by only 3 jobs. This demonstrates that output increases by employing essentially the same number of workers when each becomes more productive. Hence, we see a perfect balancing of the intensive productivity margin with the extensive demand margin. In the City of Paris the intensive margin dominates slightly while in the suburbs the extensive margin dominates slightly. Table 4c shows that growth causes road congestion to rise by 3.56% which causes the share of auto trips to decrease by 0.78%. Gasoline consumption rises by 3.03%. Making the accessibility to jobs endogenous in production has small incremental effects.

Table 4d shows the changes in welfare. Growth increases welfare per consumer from 2005 to 2035 by a total of 12,649 € or an average of about 420 € per year. Note that all components of welfare increase (the compensating variation of consumers, importers, annualized real estate values and income tax and sales tax revenues). Making the accessibility to jobs endogenous increases 2035 welfare by an additional 315 € or 2.5% more than the growth itself with exogenous productivity. Consumer CV increases the most by 6.8% while real estate values fall slightly, and tax revenues fall by 8.1%. The bottom of the table reports the levels of the agglomeration and congestion externalities per consumer. The former is calculated as the gap between the social marginal product and the private average product caused by the addition of one more job, while the latter as the additional aggregate delay caused by one more person-trip.[1]

Finally in the last two tables, Table 4e displays the values of A_{rj} calculated from the alternative specifications (ours, Ciccone's and Graham's); and Table 4f displays the differences in the welfare when the value of A_{rj} are specified accordingly. Note that comparing our specification and that of Ciccone – since we have used his estimate of $\alpha = 0.045$, to our knowledge the only estimate available for France – the difference is mostly due to the fact that he assumed $\beta = 0$ while we assumed that $\beta = 3$. Therefore, Table 4f implies the insensitivity of the results to the choice of β. The results based on our specification and the one based on Graham's formula show a big difference. This difference comes largely from his $\alpha = 0.26$, which is 5.8 times larger than ours and not from his choice of $\beta = 1$.

4.2 The Grand Paris Project

The next group of simulations are focused on the comparison of the impacts of the GPP under exogenous and then endogenously determined accessibility to jobs. From Table 5a we see that the project brings increments of population and jobs to the CDTs in the direction expected by the planners. For example, CDT population increases by 7,065 residents at the expense of mostly the suburbs, but also of Paris and of the exurban areas. The main reason is obvious from Tables 2a and 2b which showed that travel times by public transit within and between the CDTs are lowered by the GPP so some residents relocate there at the margin. Jobs in the CDTs increase by 4,875 at the expense mostly of Paris and to a lesser extent of the suburbs. Making the accessibility to jobs endogenous adjusts these population and job changes rather marginally: CDT jobs are reduced by 438 indicating that the extensive marginal demand effect cannot overcome the intensive marginal productivity effect. These changes, although in the expected direction, are far below the unreasonable expectations of the planners who would like the CDTs to become boom towns.

[1] Calculations are available upon request.

TABLE 5a: Population and job distribution changes in 2035 due to the GPP

	Population				Jobs			
	Exogenous Productivity		Change due to endogenous productivity		Exogenous productivity		Change due to endogenous productivity	
Paris	-948	-0.05%	776	0.04%	-3,061	-0.16%	-600	-0.03%
CDTs	7,065	0.21%	-45	-0.001%	4,875	0.23%	-438	-0.02%
Suburbs	-4,572	-0.09%	367	0.01%	-1,813	-0.08%	1,038	0.05%
Exurbs	-1,545	-0.67%	-1,098	-0.48%				
TOTAL	0	0	0	0	0	0	0	0

TABLE 5b: Wage, rent, price and production changes in 2035 due to the GPP

	Wage		Rent		Price		Production		Gross product	
	Exo. prod.	Endo. prod.	Exo. prod.	Endo. prod.	Exo. prod.	Endo.. prod.	Exo. prod.	Endo. prod.	Exo. Prod.	Endo. prod.
Paris	0.14%	-0.43%	-0.01%	-0.21%	-0.01%	-0.87%	0.04%	0.21%	1.46%	-0.65%
CDTs	-0.22%	-0.45%	0.06%	-0.15%	-0.18%	-0.99%	0.13%	0.40%	-0.69%	-0.57%
Suburbs	0.13%	-0.33%	0.00%	-0.11%	0.09%	-0.68%	0.02%	0.23%	1.04%	-0.45%
TOTAL	0.01%	-0.41%	0.01%	-0.16%	-0.02%	-0.84%	0.06%	0.28%	0.70%	-0.56%

TABLE 5c: Transportation changes in 2035 due to the GPP

Origin (Res.)	Destination (Job)	Auto Share of All Trips		Auto Time		Average Travel Time		Commute Pattern		Aggregate Gasoline	
		Exo. prod.	Change due to endo.prod.	Exo. prod.	Change due to endo.prod.	Exo. prod.	Change due to endo.prod.	Exo. prod.	Change due to endo.prod.	Exo. prod.	Change due to endo.prod.
	Paris	-0.13%	-0.01%	-0.18%	0.08%	-1.10%	0.02%	0.02%	0.01%		
Paris	**CDTs**	-0.09%	-0.01%	-0.14%	0.07%	-0.62%	0.01%	-0.33%	0.03%		
	Suburbs	-0.05%	-0.02%	-0.18%	0.06%	-0.35%	0.02%	-0.31%	0.12%		
	Paris	-0.05%	-0.01%	-0.13%	0.07%	-0.41%	0.01%	-0.28%	-0.05%		
CDTs	**CDTs**	-1.12%	-0.01%	-0.10%	0.05%	-2.83%	0.04%	1.05%	0.00%		
	Suburbs	-0.17%	-0.02%	-0.15%	0.06%	-0.41%	0.03%	-0.42%	0.06%		
	Paris	-0.03%	-0.01%	-0.15%	0.06%	-0.39%	0.01%	-0.29%	-0.05%		
Suburbs	**CDTs**	-0.21%	-0.03%	-0.15%	0.06%	-0.49%	0.03%	-0.60%	-0.01%		
	Suburbs	-0.97%	-0.02%	-0.15%	0.05%	-1.54%	0.03%	0.12%	0.07%		
TOTAL		-0.40%	-0.01%	-0.15%	0.06%	-0.97%	0.02%	0	0	-0.79%	+0.27%

TABLE 5d: Welfare and externalities (per consumer)

	Change due to GPP with exogenous A_j	Change due to GPP with endogenous A_j
Welfare	**€ 175**	**€ 315**
CV	€ 162	€ 178
Real estate values	€ 1	-€ 15
Tax Revenue	€ 7	-€ 84
Sales	€ 3	-€ 44
Income	€ 4	-€ 41
Importer CV	€ 5	€ 236
Agglomeration externality (level)	€ 416	€ 411
Congestion externality (level)	€ 513	€ 516

TABLE 5e: Welfare and externalities after in-migration (open city)

	Change due to GPP with exogenous productivity	Change due to GPP with endogenous productivity
Welfare	**-€ 4**	**-€ 132**
CV	-€ 1	€ 0
Real estate values	€ 61	€ 127
Tax Revenue	-€ 211	-€ 640
Sales	-€ 107	-€ 320
Income	-€ 105	-€ 319
Importer CV	€ 147	€ 645
Population and jobs	+1.8%	+4.5%
Agglomeration externality	€ 410	€ 395
Congestion externality	€ 520	€ 535

From Table 5b we see that the GPP induces marginally lower wages in the CDTs. This is because labor supply to the CDTs increases as consumers use the GPP which improves access to and from and within the CDTs. From Table 5c, travel times decrease by 2.83% within the CDT region. To keep more labor from moving from the City of Paris to the suburbs, wages there increase marginally. For the region as a whole, the average wage remains essentially unchanged. Similarly, the changes in rents are minimal. Output prices fall slightly in the CDTs as wages fall and rise slightly in the suburbs. Production increases in the CDTs and so does gross product because prices fell so slightly. Making accessibility to jobs endogenous induces additional marginal changes. In particular, wages, rents and prices all fall significantly more but the changes are still small. A notable change is that the GPP reduces gasoline consumption by 0.79%, but making the accessibility to jobs endogenous takes back about a third of that.

Tables 5d and 5e present the welfare analysis of the GPP project, before and after the in-migration respectively. Making the accessibility to jobs endogenous, increases the per consumer welfare from 175 to 315 euros per year that is by 1.8 times. Most of the project's welfare gain accrues to the consumers when the accessibility to jobs is exogenous, but because making the accessibility to jobs endogenous lowers prices, the additional benefits mostly accrue to importers from other regions. In addition because the higher productivity causes prices and consequently wages to fall, tax revenues decrease somewhat. The levels of the two externalities are changed little by the endogenous accessibility to jobs.

The social interest rate for public projects in France is reportedly 4%. Using an infinite horizon this gives an annualized megaproject cost of 1.4 billion euros. From Table 5d, with exogenous accessibility to jobs, the model's per consumer total welfare benefit of 175 euros multiplied by the projected 2035 consumer population of 10,568,393 (= 9,214,428 2005 population plus the projected growth of 1,353,965) gives a total annual benefit of 1,849,468,775. This implies a benefit to cost ratio of 1.32. Making the accessibility to jobs endogenous raises the benefit to cost ratio to 2.38. When such benefit-to-cost ratios are presented to planners they are confused because they have an ingrained idea that a project such as the GPP cannot be beneficial unless it attracts a large number of jobs to the CDTs. But such an *idée fixe* seemingly ignores that a job or a consumer does not have to relocate to benefit from the GPP, that the travel time and productivity improvements need not be associated with drastic changes in land use.

From Table 5e, after in-migration, the 2035 GPMA population would be 1.8% larger than 10, 568,393 under exogenous accessibility to jobs and 4.5% larger when making accessibility to jobs endogenous. In this case, however, in-migration has continued until all of the consumer's utility benefit measured by the compensating variation has been dissipated and the total welfare benefit is negative as seen in Table 5e because tax revenues have decreased. We found that as population is increased, the consumer's welfare declines monotonically without initially increasing. This, in turn, means that the GPMA is initially too large, The GPP megaproject makes the GPMA even larger. From Table 5f and 5g, the in-migration has reduced labor supply and therefore wages and also prices, and this is the reason why tax revenues per consumer are euros lower in Table 5e; while the in-migration has increased rents.[1] With the exogenous accessibility, annualized property values are higher by 61 euros per consumer when productivity is exogenous and 127 euros higher when it is endogenous. These higher property values suggest a property tax levy that could help fund the GPP. If productivity were exogenous, such a levy would defray 47% of the cost of the GPP and if it were endogenous, 102% of the cost. Meanwhile the levels of the agglomeration and road congestion externalities are fairly comparable in their magnitudes and are relatively little changed by the in-migration. The in-migration slightly reduces the agglomeration externality and slightly increases the congestion externality.

TABLE 5f: Effects of the GPP with exogenous productivity and in-migration

	Changes with endogenous productivity and +1.8% in-migration								
	Population		Jobs		Wage	Rent	Price	Production	GDP
Paris	30,918	1.62%	29,894	1.55%	-0.88%	0.51%	-0.54%	0.80%	0.30%
CDTs	67,243	2.03%	43,597	2.07%	-1.29%	0.80%	-0.71%	1.12%	0.45%
Suburbs	89,470	1.75%	41,131	1.79%	-0.83%	0.67%	-0.39%	0.91%	0.53%
Exurbs	4,029	1.75%							
TOTAL	191,661	1.81%	114,623	1.81%	-1.02%	0.65%	-0.54%	0.97%	0.42%

TABLE 5g: Effects of the GPP with endogenous productivity and in-migration

	Changes with endogenous productivity and +4.5% in-migration								
	Population		Jobs		Wage	Rent	Price	Production	Gross product
Paris	79,565	4.16%	78,075	4.06%	-2.99%	1.01%	-2.47%	2.21%	-0.18%
CDTs	158,221	4.77%	102,041	4.85%	-3.43%	1.67%	-2.73%	3.17%	0.51%
Suburbs	230,458	4.51%	106,441	4.64%	-2.72%	1.51%	-2.04%	2.55%	0.50%
Exurbs	10,907	4.72%							
TOTAL	479,152	4.53%	286,557	4.53%	-3.08%	1.38%	-2.40%	2.71%	0.24%

[1] This is nothing other than the capitalization effect in urban economics: an improved amenity (in this case the GPP) causes in-migration raising rents and lowering wages.

4.3 Congestion pricing

The last group of tables, Table 6a –Table 6e are focused on the effects and welfare benefits of implementing Pigouvian congestion pricing on all the roads of the GPMA region. In the model this condition is treated by tolling each of the 3004 arcs of the arc-node network as well as tolling congestion within each of the underlying 54 model zones of the GPMA. This congestion pricing policy is implemented in conjunction with the GPP and the projected growth but without calculating the additional effect of in-migration. Our purpose is to find what additional benefits would come from such a policy.

Table 6a, shows the result that congestion pricing would increase the resident population of the City of Paris by about 11,000, about 87% of whom would come from the suburbs and about 13% from the CDTs. The reason for such concentration is that the City of Paris has high land use density and is well served by existing public transit; hence by relocating there consumers can avoid the high after-congestion-toll monetary cost of driving.

Jobs on the other hand (again from Table 6a) react to the congestion pricing by moving from the City and the CDTs to the suburbs but this relocation is about 70% stronger in magnitude, as that of the relocation of the residential population. Among the reasons for such adjustments by firms is that workers facing higher monetary costs of commuting tolls included, and all consumers facing higher monetary costs in non-work travel would demand to be compensated by higher wages and lower output prices. Firms then, can either pay those higher wages and stay put or move to places where wages are lower. As seen from Table 6b congestion tolling causes wages and rents to fall most in the suburbs causing firms to suburbanize to avoid the impact of the tolls on them.

TABLE 6a: Population and job after congestion pricing with the GPP in place

	Population				Jobs			
	Change with exogenous productivity		Additional change with endogenous productivity		Change with exogenous productivity		Additional change with endogenous productivity	
Paris	11,016	0.58%	1,650	0.09%	-6,949	-0.36%	-949	-0.05%
CDTs	-1,356	-0.04%	101	0.00%	-10,119	-0.48%	-796	-0.04%
Suburbs	-9,573	-0.19%	-637	-0.01%	17,068	0.75%	1,745	0.08%
Exurbs	-88	-0.04%	-1,114	-0.54%	0	0		
TOTAL	0	0	0	0	0	0	0	0

TABLE 6b: Wages, rents, prices and production after congestion pricing with the GPP in place

	Wages		Rents		Prices		Output		Gross product	
	Exo. prod,	Endo. prod.	Exo. prod,	Endo. prod.	Exo. prod,	Endo. prod.	Exo. prod,	Endo. prod.	Exo. prod,	Endo. prod.
Paris	-0.61%	-0.62%	-0.25%	-0.31%	-0.46%	-1.18%	-0.76%	0.25%	-1.23%	-0.91%
CDTs	-0.86%	-0.63%	-0.47%	-0.24%	-0.59%	-1.26%	-0.90%	0.45%	-1.48%	-0.79%
Suburbs	-2.41%	-0.46%	-0.81%	-0.11%	-1.51%	-0.81%	-1.37%	0.22%	-2.87%	-0.59%
TOTAL	-1.31%	-0.57%	-0.51%	-0.22%	-0.84%	-1.08%	-1.01%	0.31%	-1.85%	-0.77%

TABLE 6c: Congestion tolling after the GPP is in place: Transportation

Origin (Res.)	Destination (Job)	Auto Share of All Trips		Auto Time		Average Travel Time		Commute Pattern		Aggregate Gasoline	
		Exo. prod.	Change due to endo. productivity	Exo. prod.	Change due to endo. productivity	Exo. prod.	Change due to endo. productivity	Exo. prod.	Change due to endo. productivity	Exo. prod.	Change due to endo. productivity
	Paris	-0.67%	-0.01%	-3.13%	0.08%	-0.58%	0.02%	0.26%	0.02%		
Paris	**CDTs**	-1.17%	-0.02%	-2.94%	0.06%	-0.43%	0.01%	-0.46%	0.06%		
	Suburbs	-2.03%	-0.02%	-2.99%	0.05%	-1.64%	0.02%	1.10%	0.20%		
	Paris	-0.95%	-0.01%	-3.17%	0.07%	-0.32%	0.01%	-0.92%	-0.08%		
CDTs	**CDTs**	-0.51%	-0.01%	-3.00%	0.07%	-0.48%	0.05%	-0.96%	-0.02%		
	Suburbs	-2.40%	-0.02%	-2.87%	0.05%	-2.18%	0.03%	0.78%	0.10%		
	Paris	-1.38%	-0.01%	-2.58%	0.06%	-1.04%	0.01%	-0.86%	-0.11%		
Suburbs	**CDTs**	-2.40%	-0.03%	-2.51%	0.06%	-2.12%	0.02%	0.19%	-0.04%		
	Suburbs	-2.46%	-0.02%	-2.59%	0.05%	-2.79%	0.03%	0.74%	0.09%		
TOTAL		-1.48%	-0.02%	-2.58%	0.06%	-1.65%	0.02%	0	0	-7.31%	0.29%

From Table 6b we also see that congestion pricing reduces output and gross product (though we shall see that welfare is increased), but the decrease in both is somewhat smaller when the productivity is endogenous. From Table 6c congestion pricing is somewhat less effective in reducing car shares, travel times and gasoline consumption when the productivity is endogenous.

This is so because jobs tend to concentrate into a higher density pattern to the benefits of the productivity externality, and by doing so some of the travel time improvements due to the congestion pricing are offset.

The welfare effects are shown in Table 6d. What we see here is that congestion pricing is much more beneficial when the productivity effect is endogenous than when it is exogenous. The clues for this are in Table 6a where we saw significant relocation effects at the margin. By inducing more residents to locate in the City benefits are incurred from higher public transit use in the center and less car use in the suburbs; at the same time the relocation of some jobs to the less congested suburbs adds to the benefits. Note from Table 6d, that the lion's share of the benefits are due to the congestion toll revenue. As shown in Anas (2017) for Los Angeles, redistribution of this revenue would a sizeable second dividend. Notably as well, although Los Angeles and the GPMA are not too differently sized, the benefits of congestion pricing per consumer are much higher in the GPMA which is not too surprising since the GPMA is much more congested although better served by public transportation.

TABLE 6d: Welfare and externalities due to congestion pricing with the GPP in place (in € per consumer)

	Change due to congestion pricing with exogenous productivity	Change due to congestion pricing with endogenous productivity
Welfare	**243**	**804**
Consumer CV	-$84	$214
Property values	-$51	-$20
Tax Revenue	-280	-$117
Sales	-$145	-$59
Income	-$135	-$57
Toll Revenue	422	424
Importer CV	236	303
Agglomeration Externality (level)	412	405
Congestion Externality (level)	422	424

Congestion pricing as a very beneficial complementary policy to the construction of the GPP. Under an exogenous productivity effect, the benefit-to-cost ratio rises from 1.32 to 1.83 and that is without the effect of recycling the congestion toll revenue back into the economy. With endogenous productivity the

The final Table 6e shows that growth, the GPP and congestion pricing all increase the value of A_j, the accessibility to jobs.

TABLE 6e: **Changes in the accessibility to jobs (A_j)**

		Base	Growth		Growth and GPP		Growth and GPP with congestion pricing	
		Value of A	Value of A	Change from Base	Value of A	Change from Base	Value of A	Change from Base
Paris		0.903	0.907	0.45%	0.908	0.58%	0.909	0.64%
CDTs	La Defense	0.881	0.887	0.65%	0.892	1.25%	0.893	1.35%
	Seine Amont	0.843	0.847	0.43%	0.848	0.55%	0.848	0.58%
	Descartes	0.843	0.847	0.50%	0.847	0.55%	0.848	0.66%
	Auinay Montfermeile	0.809	0.813	0.52%	0.814	0.60%	0.814	0.63%
	Roissy Pole	0.809	0.812	0.38%	0.815	0.75%	0.815	0.79%
	La Bourget	0.834	0.839	0.54%	0.840	0.64%	0.840	0.70%
	Gonesse	0.819	0.823	0.52%	0.824	0.65%	0.825	0.76%
	Pleyel	0.850	0.855	0.55%	0.858	0.86%	0.858	0.92%
	Confluence	0.796	0.800	0.53%	0.801	0.73%	0.802	0.78%
	Saclay	0.808	0.812	0.43%	0.813	0.53%	0.813	0.60%
Suburbs		0.806	0.809	0.45%	0.810	0.49%	0.812	0.73%

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APPENDIX

The RELU-TRAN Model for the GPMA

The version of the Regional Economy, Land Use and Transportation (RELU-TRAN) model (Anas and Liu, 2007) used in the study reported in this article, is a spatially detailed computable general equilibrium model calibrated to the Greater Paris Metropolitan Area (GPMA). The model treats the interactions 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 public transit. In this Appendix we describe in technical detail the model’s structure and its solution procedure.

1. Consumers in the region: workers and non-workers

In the GPMA version of the RELU-TRAN model, consumers either work or do not work and the shares are exogenously given. Non-workers include adults who are not in the labor force as well as those who may be looking for work. From an urban transportation standpoint both are important because workers commute, while also making non-work trips, while non-workers make non-work trips but do not commute.

A working consumer chooses the most preferred discrete quadruplet (i, j, k, s) where, in this study, $i = 1,...,12$ are the model's residence zones in which the consumer's housing will be located and $j = 1,...,12$ are also the zones in which the consumer's job is located. Housing is $k = 1$, a single-family house, or $k = 2$ an apartment in a residential multifamily building. Employment is in the private sector ($s = 1$) and public sector ($s = 2$). To evaluate each combined discrete bundle (i, j, k, s), utility is maximized over continuous goods and services and housing floor space, under the consumer's budget constraint for that discrete bundle. Where convenient, we will set $j = s = 0$ to denote a non-working consumer who chooses only among a subset of bundles (i,k). The consumer maximizes utility for each bundle, and then chooses the discrete bundle with the highest indirect (maximized) utility.

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

$$\max_{\forall(i,j,k,s)} \left\{ \begin{array}{l} \max\limits_{\forall Z_{zr},h} U_{ijks} = \alpha \cdot \ln\left(\sum\limits_{zr} \iota_{rzi} \cdot \left(Z_{zr|ijks} \right)^{\sigma} \right)^{\frac{1}{\sigma}} + (1-\alpha)\ln(h_{ijks}) + \gamma\Delta_j \ln\left(G_{ij}\right) + E_{ijks} + e_{ijks} \\ s.t. \; : \; \underbrace{\Delta_j d\left(H \cdot w_{sj}\left(1-\tau_j\right) - g_{ij}\right) + m\left(1-\tau_j\right)}_{\equiv M_{ijs}} \geq \sum\limits_{zr} \underbrace{\left(p_{zr}\left(1+t_z\right) + s_{iz} g_{iz}\right)}_{Delivered\ \ price} Z_{zr|ijks} + R_{ik} h_{ijks} \end{array} \right\} \text{(A.1)}$$

In the direct utility function U_{ijks}, $Z_{zr|ijks}$ is the quantity of goods and services purchased by "shopping" 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), recalling that $j = 0,\ s = 0$ denotes non-working consumers. In the budget constraint, $\Delta_0 = 0$ for non-workers and $\Delta_j = 1$ for $j = 1,....12$ for workers. G_{ij} is the across-all-travel-modes expected commuting time per work day from residence zone i to a workplace zone $j > 0$, and captures, by $\gamma < 0$, the marginal disutility of commuting: $\frac{\gamma}{G_{ij}}$. E_{ijks} is an alternative-specific constant (fixed effect) denoting the utility value of all amenities for the quadruplet (i, j, k, s). e_{ijks} is a random utility that for each (i, j, k, s) and has an i.i.d. extreme value Type I distribution over the consumers. Note that each sector 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 "shop" 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 has an elasticity of substitution $\frac{1}{1-\sigma}$, $\sigma<1$. The overall utility is Cobb-Douglas between housing floor space and the sub-utility of product varieties, so that α is the share of disposable income allocated to goods and services, and $1-\alpha$ 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*.

In the budget constraint, M_{ijs} is the consumer's annual disposable income and transportation-related monetary costs. For $j=0$, the non-working consumers, $\Delta_0=0$, and M_{i00} is the annual nonwage income m for all residential zones i. For workers, $\Delta_j=1$ for all $j>0$ and 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_{js} is the hourly wage earned in sector s in zone (j) z. is τ_j the income tax rate in the zone of employment *j* and t_z the sales tax at the zone of sale z. For workers, there are deductions from annual income to obtain the after-commuting disposable income. One deduction is the annual value of the expected round-trip monetary cost of travel over all modes of travel, $d \cdot g_{ij}$, which includes the gasoline cost when driving. A consumer working in zone *j* incurs expected monetary cost g_{iz} per shopping trip from *i* to *z*.

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_{zr}, plus the monetary cost of travel from i to z. s_{iz} is the assumed quantity bought per non-work trip. The consumer's utility maximization over the continuous quantities yields the Marshallian demands for goods and services,

$$Z_{zr|ijks}=\frac{\iota_{rzi}^{\frac{1}{1-\sigma}}\psi_{rzi}^{\frac{1}{\sigma-1}}}{\sum_{\forall r'z'}\iota_{r'z'i}^{\frac{1}{1-\sigma}}\psi_{r'z'i}^{\frac{\sigma}{\sigma-1}}}\alpha M_{ijs};\ r=1,2 \text{ and } z=1,...12, \qquad \text{(A.2)}$$

where $\psi_{rzi} \equiv p_{zr}\left(1+t_z\right)+s_{iz}g_{iz}$ is the delivered (after-travel) price; and $h_{ijks}=\left(1-\alpha\right)\dfrac{M_{ijs}}{R_{ik}}$, the Marshallian demand for housing floor space, where R_{ik} is the rent per unit of floor space of type *k* in zone *i*.

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 an employed consumer, and bundle (i,k) for a non-employed consumer are the multinomial logit probabilities. For an employed consumer (superscript, *e*):

$$P^e_{ijks}=\frac{e^{\lambda \tilde{U}_{ijks}}}{\sum_{zntr} e^{\lambda \tilde{U}_{zntr}}}, \qquad \sum_{ijks} P^e_{ijks}=1, \;\; j>0. \tag{A.3a}$$

For a non-employed consumer (superscript *u*):

$$P^u_{ik}=\frac{e^{\lambda \tilde{U}_{i0k0}}}{\sum_{zt} e^{\lambda \tilde{U}_{z0t0}}}, \qquad \sum_{ik} P^u_{ik}=1\,,\; j=0\,, \tag{A.3b}$$

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

2. Consumers outside the region (importers)

We assume the presence of a representative outside consumer for each sector, with income Q_r, who imports a quantity $\Xi_{j|r}$ of the goods and services produced by sector r from each of the region's zones. The outside consumers' utility functions are C.E.S. over the imported varieties with elasticity of substitution $\dfrac{1}{1-e_r}$ and zone-specific utility parameters Ω_{rj}. The outside consumer pays the after-tax price $p_{rj}\left(1+t_j\right)$ and we assume incurs no other costs. The utility maximization problem is:

$$\max_{\Xi_{j|r}} \; \mathrm{U}_r=\left(\sum_{j=0}^{J} \Omega_{rj}\Xi_{j|r}^{e_r}\right)^{\frac{1}{e_r}} \qquad s.t.\;:\; \sum_{j=0}^{J} p_{rj}\left(1+t_j\right)\Xi_{j|r}=Q_r\,,$$

(A.4)

and it yields the Marshallian demand functions:

$$\Xi_{j|r} = \frac{\Omega_{rj}^{\frac{1}{1-e_r}} \left[p_{rj} \left(1+t_j\right) \right]^{\frac{1}{e_r-1}}}{\sum_{j'=0}^{J} \Omega_{rj'}^{\frac{1}{1-e_r}} \left[p_{rj'} \left(1+t_{j'}\right) \right]^{\frac{e_r}{e_r-1}}} Q_r . \tag{A.5}$$

3. Firms

The region's production in the private and public sectors of each zone is constant returns to scale and uses capital, labor and floor space as inputs. Capital, 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 $(f = 1)$ or labor employed outside the region $(f = 0)$. Similarly, each sector in each zone rents some floor space from the commercial $(k = 3)$, industrial $(k = 4)$, and public $(k = 5)$ floor space stock and employs building stocks 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:

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

ν_r, δ_r, μ_r are the cost shares of capital, labor and floor space in sector r, $(\nu_r + \delta_r + \mu_r = 1)$. This production function is defined for each sector $r = 1, 2$ but also for each building construction and demolition industry as we will see below. The elasticities of substitution among sub-input types are $\dfrac{1}{1-\theta_r}$ for labor and $\dfrac{1}{1-\zeta_r}$ for floor space with $\theta_r, \zeta_r < 1$. A_{rj} is the risk neutral productivity coefficient and $\kappa_{f|rj}$, $\chi_{k|rj}$ are coefficients specific to the sub-input types. The conditional cost minimizing demands for labor and space are:

$$L_{rj} = \frac{\kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r-1}}}{\kappa_{0|rj}^{\frac{1}{1-\theta_r}} w_{0|rj}^{\frac{\theta_r}{\theta_r-1}} + \kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{\theta_r}{\theta_r-1}}} \delta_r p_{rj} X_{rj}; \quad r = 1, 2; \quad j = 1, ..., 12 , \tag{A.7a}$$

$$B_{k|rj} = \frac{\chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{1}{\zeta_r-1}}}{\sum_{k=0,3,4,5} \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{\zeta_r}{\zeta_r-1}}} \mu_r p_{rj} X_{rj}, \quad k = 0, 3, 4, 5; \quad r = 1, 2; \quad j = 1, ..., 12 . \tag{A.7b}$$

4. Real estate developers

Developers, in any model zone $i = 1,...,12,$ own undeveloped land ($n = 0$) on which they may construct residential ($n = 1,2$) or commercial ($n = 3,4,5$) floor space; or own any of the five floor space types in the zone and may either keep it as is or demolish it 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 ρ. V_{in} is the market value for a unit of undeveloped land ($n = 0$) or type n $(n > 0)$ floor space in zone i. The transition denoted by the subscripts 00 is land that stays undeveloped, $0n$ denotes type-n construction and $n0$ type-n demolition. Construction and demolition prices per unit of floor space including non-random non-financial costs are p_{i0n} and p_{in0} respectively. Random non-financial costs are similarly ζ_{i0n} for construction, and ζ_{in0} for demolition; and these are i.i.d. Type-I extreme value distributed over developers for each discrete construction or demolition choice. m_{in} is the structural density (floor space units per unit of land) of the type-n building in zone i. Developer profit if keeping vacant land undeveloped is:

$$\Pi_{i00} = \left(\frac{1}{1+\rho}\right)^5 V_{i0} + \varsigma_{i00} - V_{i0}, \tag{A.8a}$$

If building type-k , profit is:

$$\Pi_{i0n} = \left(\frac{1}{1+\rho}\right)^5 \left(V_{in} - p_{i0n}\right) m_{in} + \varsigma_{i0n} - V_{i0}, \tag{A.8b}$$

If demolishing type-k building, profit is:

$$\Pi_{in0} = \left(\frac{1}{1+\rho}\right)^5 \left(\frac{V_{i0}}{m_{in}} - p_{in0}\right) + \varsigma_{in0} - V_{in}, \tag{A.8c}$$

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

$$\Pi_{inn} = \left(\frac{1}{1+\rho}\right)^5 V_{in} - p_{inn} + \varsigma_{inn} - V_{in}. \tag{A.8d}$$

The multinomial logit construction probability for land is:

$$Q_{i0n}\left(V_{i0}, V_{i1}, ..., V_{i5}\right) = \frac{\exp \Phi_{i0} \left[\left(\frac{1}{1+\rho}\right)^5 \left(V_{in} - p_{i0n}\right) m_{in}\right]}{\exp \Phi_{i0} \left[\left(\frac{1}{1+\rho}\right)^5 V_{i0} - p_{i00}\right] + \sum_{k'=1}^{5} \exp \Phi_{i0} \left[\left(\frac{1}{1+\rho}\right)^5 \left(V_{i0n'} - p_{i0n'}\right) m_{in'}\right]}, \tag{A.9a}$$

and the demolition probability for any building type is :

$$Q_{in0}\left(V_{i0},V_{in}\right)=\frac{\exp\Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^{5}\left(\frac{V_{i0}}{m_{in}}-p_{in0}\right)\right]}{\exp\Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^{5}\left(\frac{V_{i0}}{m_{in}}-p_{in0}\right)\right]+\exp\Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^{5}V_{inn}\right]}, \qquad \text{(A.9b)}$$

where Φ_{i0},Φ_{in} are the dispersion parameters of the random costs.

5. Landlords

Landlords rent out real-estate floor space and are competitive and risk neutral.[1] 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:

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

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

6. General equilibrium

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 sector 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 stock of each type of building that is constructed must equal the 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).

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

Given wages and rents for the commercial buildings, the zero profit equations of firms are used to calculate the prices of goods and services by sector $r=1,2$ and zone $j=1,...,12$:

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

Outputs are calculated by sector and zone from:

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

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 as described by equation (A.5). In each zone, eq. (A.11) defind for each of the two sectors $r=1,2$ but also for the construction and demolition of each of the five building types are defined as ten additional sectors with their own production functions, that is for $r=3,...,12.$. The outputs of the construction and demolition industries are not used as intermediate inputs by the other sectors but become the flows of constructed and demolished floor spaces.

Given the wages and the prices just calculated, rents clear the residential floor space market by zone and residential building type by solving:

$$N\left[Pr^e\sum_{s,j>0}P_{ijks}^e h_{ijks}+\left(1-Pr^e\right)P_{ik}^u h_{ik}\right]=S_{ik}q_{ik};\ k=1,2;\ i=1,...,12. \qquad \text{(A.13)}$$

And given the outputs and prices calculated earlier, rents are found in the commercial real estate markets by solving:

$$\sum_{r=1,2}\frac{\chi_{k|rj}^{\frac{1}{1-\zeta_r}}R_{ik}^{\frac{1}{\zeta_r-1}}}{\sum_{k=0,3,4,5}\chi_{k|rj}^{\frac{1}{1-\zeta_r}}R_{ik}^{\frac{\zeta_r}{\zeta_r-1}}}\mu_r p_{rj}X_{rj}=S_{jk}q_{jk};\ k=1,2;\ \ j=1,...,12. \qquad \text{(A.14)}$$

Labor markets clear in each zone and sector by calculating the wages:

$$\frac{\kappa_{rj}^{\frac{1}{1-\theta_r}}w_{rj}^{\frac{1}{\theta_r-1}}}{\kappa_{0|rj}^{\frac{1}{1-\theta_r}}w_{0|rj}^{\frac{\theta_r}{\theta_r-1}}+\kappa_{rj}^{\frac{1}{1-\theta_r}}w_{rj}^{\frac{\theta_r}{\theta_r-1}}}\delta_r p_{rj}X_{rj}=N\cdot Pr^e\cdot d\cdot H\sum_{ik}P_{ijkr}^e\ . \qquad \text{(A.15)}$$

The zero-profit conditions of developer-landlords are solved simultaneously for building and land values in each zone:

$$\begin{aligned} V_{i0} &= \sum_{y=1}^{5}\left(\left(\frac{1}{1+r}\right)^{y-1} R_{i0}\right) \\ &+\frac{1}{\Phi_{i0}}\ln\left[\exp\Phi_{i0}\left(\left(\frac{1}{1+r}\right)^{5} V_{i0}-p_{i00}\right)+\sum_{k}\exp\Phi_{i0}\left(\left(\frac{1}{1+r}\right)^{5}(V_{ik}-p_{i0k})m_{ik}\right)\right], \end{aligned} \tag{A.16a}$$

for those who own and rent out vacant land in zone i with the option to develop it, and

$$\begin{aligned} V_{ik} &= \sum_{y=1}^{5}\left(\left(\frac{1}{1+r}\right)^{y-1}\frac{1}{\phi_{ik}}\ln\left\{\exp\left[\phi_{ik}(R_{ik}-D_{iko})\right]+\exp\left[\phi_{ik}(-D_{ikv})\right]\right\}\right) \\ &+\frac{1}{\Phi_{ik}}\ln\left[\exp\Phi_{ik}\left(\left(\frac{1}{1+r}\right)^{5}\left(\frac{V_{i0}}{m_{ik}}-p_{ik0}\right)\right)+\exp\Phi_{ik}\left(\left(\frac{1}{1+r}\right)^{5} V_{ik}\right)\right], \end{aligned} \tag{A.16b}$$

for those who own and rent out type-*k* building, with the option to demolish it.

Then, given the total developed and developable land area of a zone, J_i, the flow of demolished floor space equals the constructed floor space for each building type, and the total land area is conserved:

$$S_{ik}Q_{ik0} = m_{ik}S_{i0}Q_{i0k};\ k=1,2,...,5;\ i=1,...,12 \tag{A.17}$$

$$J_i = S_{i0} + \sum_{k=1}^{5}\frac{S_{ik}}{m_{ik}}\,. \tag{A.18}$$

In each zone, the building and developable land area stocks are from these equations, given the construction and demolition probability functions.

7. 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:

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

$TRIPS_{iz}$ are split between modes (automobile and public transit) in the TRAN model using a binary mode choice model. Auto trips spread evenly throughout the travel day because RELU-TRAN is designed to capture the longer-term interactions between the regional economy and transportation, ignoring intraday traffic dynamics. TRAN assigns auto trips to a version of the GPMA road network consisting of about 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 travel times, G_{iz}, and across-modes monetary costs, g_{iz}, which are inputs into RELU. Public transit trips are not subject to congestion or crowding effects and public transit travel times between zone pairs are exogenous.

8. 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:

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

$PROB_{CAR|iz}$ 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:

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

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 (2006). The multinomial logit probability of choosing an arc a at a node *o*, while traveling to destination node *d* is:

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

$\mathrm{P}_{a|d}$ is the probability of choosing arc a. $\pi(a)$ is the end node of arc a, A_o^+ is the set of all roads that are outgoing from node o, λ is the dispersion parameter of the idiosyncratic disutility shock experienced at node o; $gcost_a$ the generalized cost of tarveling on arc a, and $\wp_{i(a)d}$ the expected disutility of an auto trip traveling from node i to node d:

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

The congested travel time on each arc a is of the BPR-form:

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

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 vehicle cost $gcost_a$ is then the sum of time and monetary costs:

$$gcost_a=vot\times\frac{time_a}{60}+\frac{\left(pfuel\times F(speed_a)\right)\times length_a+toll_a}{passenger\ per\ vehicle}, \tag{A.25}$$

where vot is the monetary value of time, $pfuel$ is the gasoline price, $F(speed_a)$ 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 on arcs until an equilibrium is reached. Upon convergence of TRAN, which only gives equilibrium times ($time_a$) and monetary costs ($mcost_a$) for arcs, the equilibrium expected vehicle times τ_{od} and monetary costs μ_{od} for each (o,d) pair of nodes are:

$$\tau_{od} = \sum_a \mathrm{P}_{a|d} \times \left(time_a + \tau_{\pi(a)d} \right), \tag{A,26}$$

$$\mu_{od} = \sum_a \mathrm{P}_{a|d} \times \left(mcost_a + \mu_{\pi(a)d} \right). \tag{A.27}$$

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

9. Public transit monetary costs

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:

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

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

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

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

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

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

10. Calibration of the model

TABLE A.1 : Baseline Elasticities

Cost shares in production	
Elasticity of	
Residential location demand with respect to average travel time	-0.46
Residential location demand with respect to housing rent	-0.37
Labor supply with respect to wage	1.04
Labor demand with respect to wage	-0.95
Mode (car) choice with respect to car cost	-0.70
Export demand with respect to price	-1.80
Substitution between in-region and out-of-region labor	0.90

Substitution among building types in production	3.33

	Building types				
	Single Family	Multi-Family	Office	Store	Industrial
Floor space supply with respect to rent (short-run)	0.25	0.25	0.50	0.50	0.50
Construction with respect to floor price by county					
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

11. Welfare analysis

Welfare analysis is done by calculating the aggregate CV (compensating variation) for working and non-working consumers; adding to this the aggregate CV of the representative consumer to whom the GPMA's output is exported; and adding to this the change in aggregate tax revenue including any congestion tolling revenue; then adding the annualized aggregate income from all the changes in real estate values. All of these components of welfare are reported on a per-consumer basis in the relevant tables of the main text. Relatedly, in the welfare tables the per consumer values of the agglomeration externality and the congestion externality are also reported.

. In calculating endogenous congestion tolls, we include 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 the effect on gasoline (see Anas and Hiramatsu (2013).

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, less the average private cost of the delay:

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

This toll function is added to the monetary cost of traveling on arc *a*, so that the equilibrium tolls on the arcs are socially optimal. The total externality on the arc is $toll_a \times flow_a$ and the total externality in the GPMA is:

$$Total\ \ externality = vot \cdot c \cdot \sum_a t_a^0 b_a \frac{(flow_a)^{c+1}}{(capacity_a)^c} . \tag{A.33}$$

Total welfare is then:

$$W = CV_{cons,} + CV_{imp.} + \frac{\rho}{N}\left[\sum_{i,k=0,\ldots,5}\left(S_{ik}V_{ik} - S_{ik}^{Base}V_{ik}^{Base}\right)\right] + \frac{1}{N}\left(\boldsymbol{\Delta} Toll\ Rev. + \boldsymbol{\Delta} Tax\ Rev.\right). \quad \text{(A.34)}$$

The change in pubic revenues from a policy run and the annualized change in property values are not distributed to the consumers, but are included in the welfare change as shown in (A.37). The CV is what a consumer would pay in monetary units for the increase, or require as compensation for the decrease, in utility arising from the congestion tolling policy. From the multinomial logit calculus, the expected utility of a worker in the base equilibrium is:

$$W^{e,Base} = \frac{1}{\lambda}\ln\left(\sum_{ijks}\exp\left(\lambda\,\tilde{U}_{ijks}^{e,Base}\right)\right). \quad \text{(A.34)}$$

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

$$W^{e,Base} = \frac{1}{\lambda}\ln\left(\sum_{ijks}\exp\lambda\left[u_{ijks}^{e,Policy} + \ln\left(M_{ijs}^{e,Policy} - CV^{e}\right)\right]\right), \quad \text{(A.35)}$$

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

$$CV_{cons.} = P^{e}\cdot CV^{e} + \left(1 - P^{e}\right)\cdot CV^{u}, \quad \text{(A.36)}$$

where P^{e} is the exogenous share of workers. The $CV_{imp.}$ of the importers, per consumer in the region, are solved similarly.