Pricing urban transport in the Greater Paris Metropolitan Area: A general equilibrium analysis

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ABSTRACT

We examine the general equilibrium and welfare effects of various urban transport pricing policies in the Greater Paris Metropolitan Area (GPMA). We find that switching from the current zone-based transit passes to a flat-fare pass (as was proposed but not implemented) boosts public transit ridership, especially for long-distance trips, resulting in less road congestion and gasoline consumption. The flat-fare induces an income effect that spurs production, and overall welfare improves. We show that making public transit free further improves all these benefits. We then evaluate the effect of congestion pricing on roads under the existing zone-based public transit fare system. The flat-fare policy captures 19% of the welfare benefit of Pigouvian congestion pricing throughout the GPMA. Free public transit captures 80% of the benefit of the Pigouvian tolling. Combining the toll with either the flat-fare or free public transit further increases welfare from tolling alone.

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1. Introduction

The search for the efficient pricing of public transportation services dates back to at least Vickrey (1955). Since then, a body of literature has contributed to our understanding of various aspects of the public transportation market. Studies have found that efficiency can be improved by subsidizing the public transit system. The sources of such efficiency improvements are two:

(a) Economies of scale in public transport: Given fixed service capacity and frequency, the marginal cost of serving an additional passenger is usually very low. High passenger fares could lead to low ridership at which level the marginal benefit of the last passenger is greater than the marginal cost of providing the service. Therefore, increased public transit ridership encouraged by a subsidized fare can be welfare improving (Parry and Small, 2009).

(b) Reduced externalities outside the public transportation system: An increase in public transit ridership indirectly alleviates road congestion (Anas, 2015; Graham and Glaister, 2006) and can mitigate safety externalities associated with high road traffic (Parry and Small, 2009; Basso and Silva 2014). Moreover, public transportation is often more environment-friendly than private transportation.

Other recent studies have considered combinations of the above justifications for public transit subsidies. Parry and Small (2009) presented an aggregate general equilibrium model in which the representative household maximizes utility and takes as given the externalities from various travel modes; while given the travel demand, the transit agency optimizes route density, service frequency, and capacity. Using data from Washington, D.C., Los Angeles, and London, they found that increasing subsidy levels from 50 percent of operating costs improves welfare across cities, transportation modes, and periods (peak and off-peak), peak-time bus service in Washington, D.C. being an exception. In their model, the social benefits of subsidizing public transit come from the scale economies (which occur even during off-peak hours), and from the mitigation of negative externalities such as congestion, pollution, and traffic accidents.

De Borger and Proost (2015) explored the political process of public transportation pricing. They first derived the socially optimal second-best fare (when the first-best congestion toll is not available). They found that such an optimal transit fare is lower than the cost-recovery fare; therefore, a subsidy is required. The difference between the optimal fare and the breakeven fare is the social marginal cost associated with the waiting time. They also found, in their two-group and two-region model, that majority voting in general leads to a fare lower than the breakeven fare. The rationale for this outcome can be explained by dividing the voters into two categories: private vehicle owners (the first voter group) prefer a low passenger fare, in part because the resulting increased public transportation ridership would mitigate road congestion and in part because they themselves are sometimes transit riders; consumers who do not own private vehicles (the second voter group) also prefer a low passenger fare, because they rely heavily on the public transportation system. These voting outcomes are certain unless the majority of local transit service users are from outside the region, in which case local voters would prefer a higher passenger fare because otherwise, voters would have to pay to subsidize a system that they do not sufficiently utilize (Arnott and Grieson, 1981).

These two types of justifications for low passenger fares have ignored potential general equilibrium effects that arise from the interaction between the transportation system and other urban markets. For example, detailed analysis of the interactions between the labor market and transit fare is rare. van Dender (2003), in a highly aggregated model, argued that by differentiating trip purposes, reducing work-related travel costs stimulates the supply of labor and improves welfare. Savage and Small (2010) called for a general-equilibrium analysis of transit pricing in which the labor market is addressed explicitly. Furthermore, the income effect of public transportation pricing and the resultant adjustments in the real output market, the real estate rental and investment markets, and land use patterns have been ignored.

This paper extends the scope of our understanding of the effects of transit pricing by taking into account not only the transportation market, including an elaborate road network, but also a spatially detailed regional economy. Using the RELU-TRAN (Regional Economy, Land Use and Transportation) computable general equilibrium model (Anas and Liu, 2007), calibrated to the Greater Paris Metropolitan Area (Île-de-France), we simulate the general equilibrium and welfare effects of changing from the zone-based (distance-based) transit pass to a flat-fare pass; of free public transit; and of pricing road congestion. We also evaluate the effects of combining these policies.

The simulations conducted in the present study show that the switch to the flat-fare pass boosts public transportation ridership, especially for long-distance commutes, resulting in less road congestion and lower gasoline consumption. other findings of this study relate to the aspects of market adjustments that have been left out of previous studies. We find that, in the long run, in response to the flat fare, some suburban workers relocate to residences in the City of Paris. A bigger labor force in the City causes some suburban firms to relocate to the City. Meanwhile, the income effect of the flat-fare pass stimulates consumer demand and increases aggregate real output. The growth in real output shores up factor demands and factor payments, and the increased rents drive up real estate values. Overall welfare improves. Our findings regarding the welfare effects are consistent with those of previous studies (Small and Gómez-Ibáñez, 1999; Glaister, 2001; Parry and Small, 2009; De Borger and Proost, 2015). Making public transit free has a similar but stronger effects. The simulations show that the combination of a revenue-neutral sales tax or various revenue-neutral property taxes with the flat fare policy would lower the overall welfare, although slightly, compared to the stand-alone flat fare policy.

Section 2 presents the structure of the RELU-TRAN model for the GPMA. Section 3 describes the current zone-based fare structure and the flat-fare structure that was slated for adoption in 2015 but has been shelved since then. Section 4 presents the baseline simulation results with the current zone-based fare system and analyzes the market adjustments that would have followed the implementation of the flat-fare pass. Section 5 explores road congestion pricing and its combination with the flat-fare and the free public transit policies. Section 6 concludes.

2. The RELU-TRAN Model for the GPMA

The GPMA (Île-de-France) consists of 1300 communes. Figure 1 shows the demarcation of the model zones. All our 50 model zones comprising the region are communes or are composed of aggregations of a subset of contiguous underlying communes. The first 20 of our model zones are the communes (arrondissements) that comprise the City of Paris in Figure 1. The ten dark purple zones in Figure 1 are the CDTs (Contrats de Développement Territorial). These are inner suburban subcenters surrounding the city of Paris and are planners' candidates for future economic vitality and job concentration. The remaining 20 zones are also aggregations of communes. The light purple zones in Figure 1 are inner suburbs situated between the City of Paris and the CDTs while the white zones in Figure 1 are suburban areas of low density. In addition to the 50 model zones, there are 4 outside zones representing the exurban areas. Each consumer who works in one of the 50 zones, resides in one of the 54 model zones. In addition to work trips by working consumers, both working and non-working consumers make non-work trips to any of the model 50 zones. Table 1 describes the distribution of land, floor space, population[3], jobs, and the number of daily trips among the four zone types.

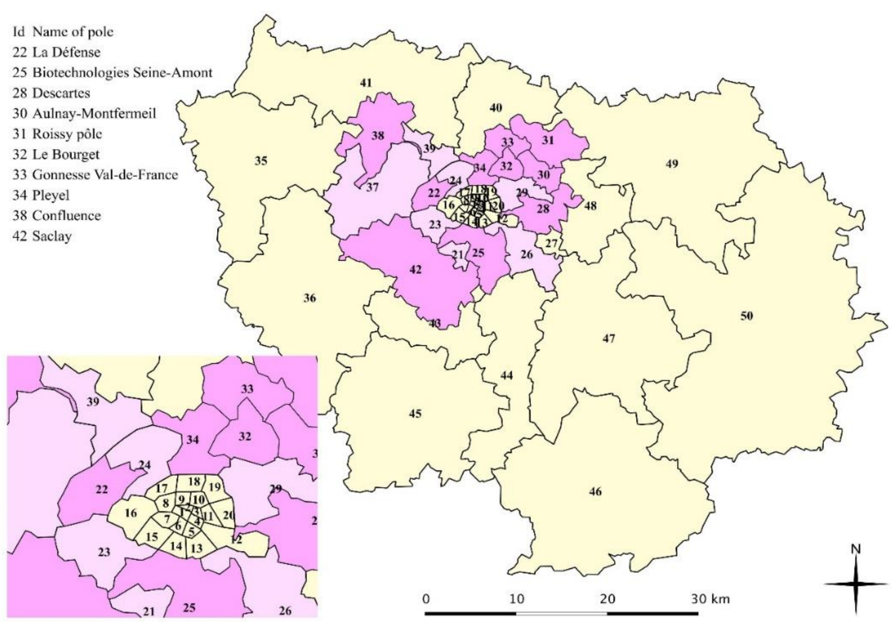
2.1 Consumers in the region: workers and non-workers

In the GPMA version of the RELU-TRAN model, consumers either work or do not work and the split between the two is 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.

Figure 1: The Greater Paris Region (Île-de-France).

The city of Paris: Zone 1-20. The CDTs (deep purple): Zones 22, 25, 28, 30-34, 38, 42

The suburbs: the rest of zones (light purple and yellow).



[3] Population in the model is defined as adult consumers both working and non-working.

Table 1 Distribution of land, floor Space, population, jobs, and trips in the base equilibrium

	Total	City of Paris (20 Zones)	CDTs (10 Zones)	Suburbs (20 Zones)	Exurb (4 Zones)
Vacant 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%
Employment	5,297,752	31%	33%	36%	
Trips by Origin (daily)	21,067,514	22%	31%	44%	3%
Commute Trips	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 Transportation Passenger Trips	11,535,452	28%	32%	40%	0.002%
Trips by Destination (daily)	21,067,514	44%	21%	35%	
Commute Trips	5,297,752	31%	33%	36%	
Non-work Trips	15,769,762	49%	17%	35%	
Car Trips	7,943,385	23%	25%	51%	
Public Transportation Passenger Trips	11,535,452	62%	17%	21%	

A working consumer chooses the most preferred discrete quadruplet (i, j, k, s) where $i = 1,...,54$ are the model's residence zones in which the consumer's housing will be located. The first 50 of these are zones of the GPMA and the remaining four represent outside areas. The zones within the GPMA, $j = 1,...,50$ 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. $s = 1, 2$ is employment 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:

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

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 $j = 1,....50$ 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 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 $\frac{1}{1-\sigma}$, $\sigma < 1$. Meanwhile 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 after taxes and transportation-related monetary costs. A tax rate, t is levied on the purchase of all goods and services from zone z. The income tax rate, τ, is levied equally on all wage and non-wage income. For $j = 0$, the non-working consumers, $\Delta_0 = 0$, and M_{i00} is the after-tax annual nonwage income $(1-\tau)m$ for all residential zones i. For workers, $\Delta_j = 1$ for all $j > 0$ and the annual disposable wage income is $d \cdot H \cdot w_{sj} \cdot (1-\tau)$, where d is the number of work days, H is the hours of work per after-tax work-day, and w_{js} is the hourly wage earned in sector s in zone *z*. For workers, there are deductions from annual after-tax income to obtain the annual after-commuting disposable income. One deduction is the annual value of the expected round-trip monetary cost of travel over all modes of travel, dg_{ij}^{worker}, which includes the gasoline cost when driving. The commuter does not incur a fare cost for public transit trips because we assume that any commuter purchases an annual public transit pass depending on the location of his residence zone, i, and his work, j, which costs C_{ij}^{pass} per year and allows an unlimited number of trips by public transit. A consumer working in zone *j* incurs expected monetary cost $g_{iz|j}^{worker}$ per shopping trip from *i* to *z*. These costs differ according to whether the purchase destination is covered or not by the worker's commuting pass. For non-workers, we assume that they do not buy a transit pass, purchasing tickets for each non-work 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 after-sales-tax-price paid at *z*, $p_{zr}\left(1+t\right)$, plus the monetary cost of travel from i to z. s_{iz} is the assumed quantity bought per non-work trip. A non-working consumer housed in zone *i* and shopping in zone *z* does not own a transit pass, buying a ticket for each non-work trip, which is how the per-trip monetary cost $g_{iz}^{nonworker}$ is determined. The details of how trip costs for working and non-working consumers differ is clarified later when the geographic structure of the fare zones of the public transit system is explained.

The consumer's utility maximization over the continuous quantities yields the Marshallian demands for goods and services,

$$Z_{zr|ijks} = \frac{\iota_{rzi}^{\frac{1}{1-\sigma}} \psi_{rzi|j}^{\frac{1}{\sigma-1}}}{\sum_{\forall r'z'} \iota_{r'z'i}^{\frac{1}{1-\sigma}} \psi_{r'z'i|j}^{\frac{\sigma}{\sigma-1}}} \alpha M_{ijs};\; r=1,2 \text{ and } z=1,...50,$$

where $\psi_{rzi|j} \equiv p_{zr}\cdot\left(1+t\right)+s_{iz}\cdot\left[\Delta_j g_{iz|j}^{worker}+\left(1-\Delta_j\right)g_{iz}^{nonworker}\right]$ is the delivered (after-travel) price of the good or service; and

$$h_{ijks} = \left(1-\alpha\right)\frac{M_{ijs}}{R_{ik}},$$

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*):

$$P_{ijks}^{e} = \frac{e^{\lambda\tilde{U}_{ijks}}}{\sum_{zntr} e^{\lambda\tilde{U}_{zntr}}}, \qquad \sum_{ijks} P_{ijks}^{e} = 1,\; j>0.$$

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

$$P_{ik}^{u} = \frac{e^{\lambda\tilde{U}_{i0k0}}}{\sum_{zt} e^{\lambda\tilde{U}_{z0t0}}}, \qquad \sum_{ik} P_{ik}^{u} = 1,\; j=0,$$

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.

2.2 Consumers outside the region (importers)

We assume the presence of a representative outside consumer for each sector, with income $\mathbb{Q}_r$, who imports a quantity $\Xi_{j|r}$ of the goods and services 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 $\frac{1}{1-e_r}$ 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. The utility maximization problem is:

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

and it yields the Marshallian demand functions:

$$\Xi_{j|r} = \frac{\Omega_{rj}^{\frac{1}{1-e_r}} \left[p_{rj}(1+t) \right]^{\frac{1}{e_r-1}}}{\sum_{j'=0}^{J} \Omega_{rj'}^{\frac{1}{1-e_r}} \left[p_{rj'}(1+t) \right]^{\frac{e_r}{e_r-1}}} \mathbb{Q}_r .$$

2.3 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:

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

ν_r, δ_r, μ_r are the cost shares of capital, labor and floor space in sector r, $(\nu_r + \delta_r + \mu_r = 1)$. 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 $\theta_r, \zeta_r < 1$. 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:

$$L_{rj} = \frac{\kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{1}{\theta_r - 1}}}{\kappa_{0|rj}^{\frac{1}{1-\theta_r}} w_{0|rj}^{\frac{\theta_r}{\theta_r - 1}} + \kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{\theta_r}{\theta_r - 1}}} \delta_r p_{rj} X_{rj}; \quad r = 1,2; \quad j = 1,...,50,$$

$$B_{k|rj} = \frac{\chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{1}{\zeta_r - 1}}}{\sum_{k=0,3,4,5} \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{\zeta_r}{\zeta_r - 1}}} \mu_r p_{rj} X_{rj}, \quad k = 0,3,4,5; \quad r = 1,2; \quad j = 1,...,50.$$

2.4 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 00 denotes land that stays undeveloped, 0*n* denotes type-*n* construction and *n*0 type-n demolition. Construction costs including non-random non-financial costs of construction and demolition are $\mathbb{C}_{i0n}$ and $\mathbb{C}_{in0}$ 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:

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

If building type-k, profit is:

$$\Pi_{i0n} = \left(\frac{1}{1+\rho}\right)^5 \left(V_{in} - \mathbb{C}_{i0n}\right) m_{in} + \varsigma_{i0n} - V_{i0} ,$$

If demolishing type-k building, profit is:

$$\Pi_{in0} = \left(\frac{1}{1+\rho}\right)^5 \left(\frac{V_{i0}}{m_{in}} - \mathbb{C}_{in0}\right) + \varsigma_{in0} - V_{in} ,$$

and if keeping type-k building unchanged profit is:

$$\Pi_{inn} = \left(\frac{1}{1+\rho}\right)^5 V_{in} - \mathbb{C}_{inn} + \varsigma_{inn} - V_{in} .$$

The multinomial logit construction probability for land is:

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

and the demolition probability for any building type is :

$$Q_{in0}\left(V_{i0}, V_{in}\right) = \frac{\exp \Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^5 \left(\frac{V_{i0}}{m_{in}} - \mathbb{C}_{in0}\right)\right]}{\exp \Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^5 \left(\frac{V_{i0}}{m_{in}} - \mathbb{C}_{in0}\right)\right] + \exp \Phi_{in}\left[\left(\frac{1}{1+\rho}\right)^5 V_{inn}\right]} ,$$

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

2.5 Landlords

Landlords rent out real-estate floor space and are competitive and risk neutral.[4] 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:

$$q_{in}(R_{in}) = \frac{\exp \phi_{in}(R_{in} - D_{ino})}{\exp \phi_{in}(R_{in} - D_{ino}) + \exp \phi_{in}(-D_{inv})} ,$$

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

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

2.6 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). There are thus 176 equations and unknowns.

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 and zone:

$$p_{rj} = \frac{\rho^{\nu_r}}{A_{rj}\nu_r^{\nu_r}\mu_r^{\mu_r}\delta_r^{\delta_r}}\left(\kappa_{0|rj}^{\frac{1}{1-\theta_r}} w_{0|rj}^{\frac{\theta_r}{\theta_r-1}} + \kappa_{rj}^{\frac{1}{1-\theta_r}} w_{rj}^{\frac{\theta_r}{\theta_r-1}}\right)^{\frac{\delta_r(\theta_r-1)}{\theta_r}}\left(\sum_{k=0,3,4,5}\chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{jk}^{\frac{\zeta_r}{\zeta_r-1}}\right)^{\frac{\mu_r(\zeta_r-1)}{\zeta_r}} \quad r=1,2;\; j=1,\ldots,50.$$

Outputs are the calculated by sector and zone from:

$$X_{rz} = N\left[Pr^e \sum_{iks,\, j>0} P_{ijks}^e Z_{zr|ijks} + \left(1-Pr^e\right)\sum_{ik} P_{ik}^u Z_{zr|ik}\right] + \Xi_{rz}\,;\; r=1,2;\; z=1,\ldots,50.$$

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

$$N\left[Pr^e \sum_{s,\, j>0} P_{ijks}^e h_{ijks} + \left(1-Pr^e\right) P_{ik}^u h_{ik}\right] = S_{ik} q_{ik}\,;\; k=1,2;\; i=1,\ldots,50.$$

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

$$\frac{\chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{1}{\zeta_r-1}}}{\sum_{k=0,3,4,5} \chi_{k|rj}^{\frac{1}{1-\zeta_r}} R_{ik}^{\frac{\zeta_r}{\zeta_r-1}}} \mu_r p_{rj} X_{rj} = S_{jk} q_{jk}\,;\; k=1,2;\;\; j=1,\ldots,50.$$

Labor markets clear in each zone by calculating the wages:

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

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

$$V_{i0} = \sum_{y=1}^{5} \left(\left(\frac{1}{1+\rho} \right)^{y-1} R_{i0} \right)$$
$$+ \frac{1}{\Phi_{i0}} \ln \left[\exp \Phi_{i0} \left(\left(\frac{1}{1+\rho} \right)^{5} V_{i0} - \mathbb{C}_{i00} \right) + \sum_{k} \exp \Phi_{i0} \left(\left(\frac{1}{1+\rho} \right)^{5} (V_{ik} - \mathbb{C}_{i0k}) m_{ik} \right) \right],$$

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

$$V_{ik} = \sum_{y=1}^{5} \left(\left(\frac{1}{1+\rho} \right)^{y-1} \frac{1}{\phi_{ik}} \ln \left\{ \exp\left[\phi_{ik} (R_{ik} - D_{iko}) \right] + \exp\left[\phi_{ik} (-D_{ikv}) \right] \right\} \right)$$
$$+ \frac{1}{\Phi_{ik}} \ln \left[\exp \Phi_{ik} \left(\left(\frac{1}{1+\rho} \right)^{5} \left(\frac{V_{i0}}{m_{ik}} - \mathbb{C}_{ik0} \right) \right) + \exp \Phi_{ik} \left(\left(\frac{1}{1+\rho} \right)^{5} V_{ik} \right) \right],$$

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:

$$S_{ik} Q_{ik0} = m_{ik} S_{i0} Q_{i0k}\,;\; k=1,2,\ldots,5\,;\; i=1,\ldots,54$$

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

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

2.7 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:

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

The three types of trips, $TRIPS^x_{iz},\ x=1,2,3$ 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 the main goal of RELU-TRAN is to capture the longer-term interactions between the regional economy and transportation, ignoring intraday traffic dynamics. TRAN assigns auto trips to an aggregated version of the GPMA road network consisting of about 3,000 arcs 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 $g^{worker}_{iz}, g^{nonworker}_{iz}, g^{worker}_{iz|j}$ which were mentioned earlier as inputs into RELU. Public transit trips are not subject to congestion or crowding effects and the travel times between zone pairs are exogenous.

2.8 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:

$$AUTOTRIPS^x_{iz}=\frac{TRIPS^x_{iz}\times PROB^x_{CAR|iz}+TRIPS_{zi}\times PROB^x_{CAR|zi}}{passenger\ per\ vehicle},\ \ x=1,2,3.$$

$PROB^x_{CAR|iz}$ 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. $AUTOTRIPS^x_{iz}$ are distributed evenly among the node pair combinations to create node-to-node (NTN) auto trips:

$$NTN\_AUTOTRIPS^{x}_{o\in i,d\in z} = \frac{AUTOTRIPS^{x}_{iz}}{node(i)\cdot node(z)},$$

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:

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

$\mathrm{P}_{a|d}$ 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, $\mathbb{Z}$ 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:

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

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

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

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

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

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:

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

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

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

2.8 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 $MCOST_{PT|iz}^x$. The generalized cost is then:

$$GCOST_{PT|iz}^x = vot \times TIME_{PT|iz} / 60 + MCOST_{PT|iz}^x,$$

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

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

$PROBx_{PT|iz} = 1 - PROB_{CAR|iz}^x$. The across-modes expected commute travel times G_{iz} in RELU are then:

$$G_{iz} = PROB_{CAR|iz}^1 \times \left(\tau_{zi} + \tau_{iz} \right) + PROB_{PT|iz}^1 \times \left(TIME_{PT|iz} + TIME_{PT|zi} \right).$$

The across-modes expected monetary costs in RELU depend on whether the traveler is a worker and whether the trip is costless via the worker's public transit pass, or whether the traveler is a non-worker. In general, we have:

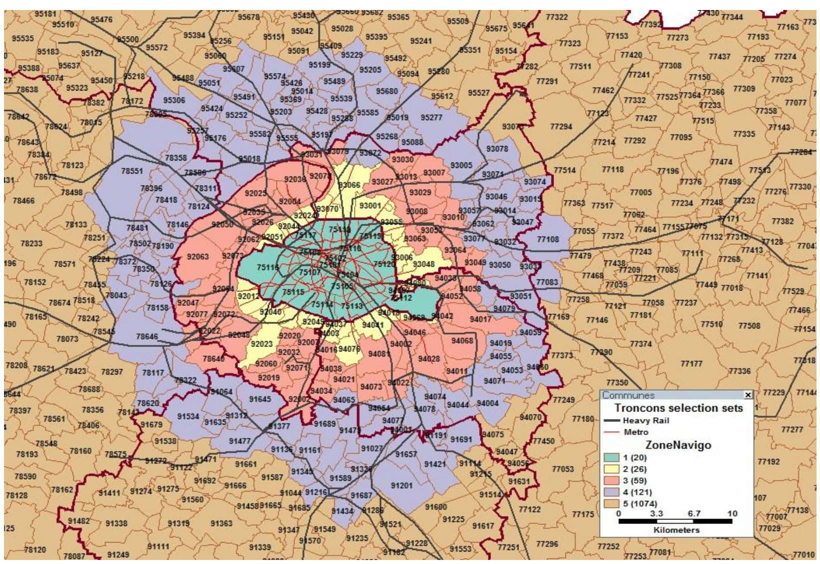
$$g_{iz}^x = PROB_{CAR|iz}^x \times \left(\mu_{zi} + \mu_{iz} \right) + PROB_{PT|iz}^x \times \left(MCOST_{PT|iz}^x + MCOST_{PT|zi}^x \right).$$

For $x = 1$, a worker employed in zone z owns a public transit pass for the pair of the work and residence fare-zones and $MCOST^1_{PT|iz} = MCOST^1_{PT|zi} = 0$. The pass is also valid for any non-work trip between those fare-zones and for such cases $MCOST^2_{PT|iz} = MCOST^2_{PT|zi} = 0$. Workers also do non-work trips that do not belong to the same fare zones covered by their passes and non-workers do not have passes. For those cases $MCOST^x_{PT|iz} = ticket\ \ price,\ x = 2,3.$ The monetary costs which are passed from TRAN to RELU are $g^{worker}_{iz} \equiv g^1_{iz}, g^{nonworker}_{iz} \equiv g^2_{iz}, g^{worker}_{iz|j} \equiv g^3_{iz}$.

3. The switch to the flat-fare public transit pass

As is evident from the description in the previous section, all consumers in the model choose between two modes of travel for each trip they make: private car or public transportation. There are two ways to pay for public transit rides: purchasing a monthly pass that allows an unlimited number of trips in some areas of the region, and purchasing a ticket per individual trip if itis not covered by the pass or if one does not own a pass.

Figure 2: The demarcations based on which the monthly transit passes are priced



Before the flat-fare pass policy is initiated, the GPMA consisted of five roughly concentric public transit fare zones shown in color in Figure 2. Each fare zone was itself was very nearly an aggregation of a subset of the 1300 communes. As seen in Figure 2, the green fare zone 1 is coincident with the City of Paris, surrounded by the yellow fare zone 2 that includes parts of some inner suburbs, then by the orange fare zone 3, then the purple fare zone 4 and finally the outermost and extensive fare zone 5.

The monthly cost of the transit pass varied based on fare-zone combinations covered by the pass, according to Table 2. Note that there were 10 possible passes. In 2005, if one paid 99.1€ per month, one owned the most comprehensive pass enabling unlimited travel anywhere in the region (combined area of fare-zones 1-5) with zero additional cost per trip. Owning the pass costing 82.6€ per month, one could freely travel only in the combined area covered by fare-zones 1-4; with a pass costing 74.7€ per month one could travel freely in fare-zones 2,3,4,5 and so on as shown in Table 2. With the introduction of the flat-fare pass in 2014, this was drastically simplified, the ring-shaped fare zones of Figure 2 ceased to exist, and a pass cost the same per month for any trip in the entire region: 50.7 in 2005 euros.[5] Negative numbers in Table 2 indicate that for some origin-destination pairs the flat-fare pass is a bit costlier than the pass before the change. On average, passengers who traveled longer distances would be better off under the flat-fare pass, whereas passengers who traveled shorter distances would be somewhat worse off. For example, a commuter who used a pass to travel anywhere in the region was paying 99.1 €, compared to 50.7 € under the flat-fare pass, a 48.8% cost saving. One who commuted within the City of Paris, was paying 50.4€, 0.6% less than the 50.7 € under the flat-fare pass.

Table 2 Zone-based pass monthly cost, in €

Fare Zone	1	2	3	4	5
1	50.4	50.4	66.6	82.6	99.1
2	50.4	50.4	47.9	61.8	74.7
3	66.6	47.9	47.9	46.6	58.7
4	82.6	61.8	46.6	46.6	46.4
5	99.1	74.7	58.7	46.4	46.4

[5] Because the model's data is for the year 2005, both fare-zone based and flat-fare based pass costs were converted to 2005 euros. Therefore, our simulations examine what would have been the consequences if the flat-fare-pass had started in 2005.

Table 3 Monthly percent savings due to the flat-fare pass replacing the zone based pass

Fare Zone	1	2	3	4	5
1	-0.6%	-0.6%	23.9%	38.6%	48.8%
2	-0.6%	-0.6%	-5.8%	18.0%	32.1%
3	23.9%	-5.8%	-5.8%	-8.8%	13.6%
4	38.6%	18.0%	-8.8%	-8.8%	-9.3%
5	48.8%	32.1%	13.6%	-9.3%	-9.3%

In the simulations, because we have no data on the pass purchase choices and socioeconomic characteristics of travelers, we make two important assumptions about who buys a pass and who pays per trip. Our first assumption is that all *workers* – before and after the change to the flat-fare pass – acquired passes that covered their transit trips spanning the concentric fare zone rings between the fare-zone of their residence commune and the fare-zone of their job commune, and used these passes for their commutes and any other trips in the same area. This assumption, although admittedly rough, is vindicated by observing that even the most expensive pass, which cost 99.1€ × 12 = 1,189 € annually, was cheaper for a worker, on a per-trip basis, than would be purchasing a ticket for each trip. To see this, according to our base simulation, a typical worker makes 500 one-way work trips per year, in addition to an average of 1,286 one-way non-work trips. Suppose that the typical worker used public transit for 55% of all his trips which is the aggregate market share in the region, and given the 2005 average ticket price of 2.04 € per trip, the cost of using public transit without a pass is (500 + 1,286) × 55% × 2.04 € = 2,004 € annually. Then, for workers, even the most expensive pass was cheaper than purchasing tickets.

Our second assumption is that, before and after the change to the flat fare, all non-working consumers who use public transit buy tickets rather than monthly passes. This assumption is justified by observing that, in the base year, a non-worker in our model makes an average of 274 one-way trips, and even supposing that public transit is used for all these trips, the ticket cost is bounded by 274 × 2.04 € = 559 € annually, making it relatively uneconomical to buy pass.

Under our first assumption, commutes by public transit have zero marginal monetary cost for all workers because they purchase a pass that covered their commutes. If the worker made a non-work trip that was not covered by the pass, we assume that a ticket was bought for such a trip.

After the flat-fare, because all workers own passes, all transit trips have zero marginal monetary cost for workers.

The switch to the flat-fare pass induces a worker to experience an income effect from the change in the cost of the pass, and a substitution effect for those non-work trips for which the marginal monetary cost of a trip drops to zero. These effects induce passengers to make various adjustments: they switch mode of travel because the relative cost of travel modes changes directly; they adjust consumption bundles as their disposable incomes net of pass costs change directly, and because the monetary costs of traveling for shopping are altered. Indirectly, they relocate (residence or job). We will study these adjustments in detail in the next section. Recall that travelers also incur the time costs of trips that change indirectly due to altered road congestion and relocation effects induced by the flat-fare pass.

4. General equilibrium and welfare effects of pricing regimes

4.1 Effects of the switch to the flat-fare pass

Table 4 shows the effect on public transit revenue which falls by 22%. Pass revenue falls by 16% and revenue from tickets by 32%. Since all workers own passes, the number of passes sold does not change but revenue from passes falls because on average the cost of a pass decreases. Revenue from tickets falls because, although the price of a ticket remains unchanged, workers buy no tickets, since they can now use their passes to make all their trips at zero additional cost. Non-workers do not own passes, but make slightly fewer non-work trips by public transit, because the prices of goods and services increase slightly (table 6) and travel times and gasoline costs by car decrease inducing more non-work trips by car (table 5). The same substitution effects also exist for the non-work trips of workers but the income effect of the lower pass costs dominates for them. We can see from Table 5 that non-work trips increase overall because of the income effect of the pass cost savings on workers.

Table 4 Change in annual public transit revenue (in million €) due to the flat-fare pass

	Baseline Revenue	Change in Revenue due to the Flat Fare Pass	Percent Change in Revenue due to the Flat Fare Pass
Pass Revenue	1,817	-288	-16%
Ticket Revenue	1,054	-341	-32%
Total Revenue	2,871	-630	-22%

The changes in the transportation market shown in Table 6 are small but clear. Public transit trips increase and car trips decrease. This reduces congestion and hence the times of travel by car and reduces aggregate gasoline consumption by 2.23%, making the region greener. Most importantly the switch to the flat fare increase commutes that are longer as in the case of those starting from homes in Paris and ending in the suburbs or the CDTs, or those starting in the suburbs or the CDTs and ending in Paris. These changes happen at the expense of shorter trips such as those within Paris, the CDTs or the suburbs. The longer trips are as expected since the flat-fare pass is cheaper on average than were the previous passes. Table 5 shows that the number of commutes within the region increases by 1,160 because that many workers relocate their residence inside the region from the four outside zones in order to take advantage of the lower cost of the flat-fares. Notably, the table also shows that the across-commutes average travel time also decreases for all trips region wide even though the cheaper passes induce a shift to the slower public transit mode.

Table 6 shows that both residents and jobs increase in the City of Paris at the expense of both the CDTs and the suburbs. As City residents increase, so does labor supply and real wages fall slightly in the City of Paris rising slightly elsewhere. Real rents rise slightly everywhere because of the income effects of the cheaper passes. Prices of goods and services increase very slightly because of the higher demands induced by the income effect of the cheaper passes, and the cheaper monetary costs of travel. Real output and Gross Regional Product also rise slightly.

Table 5 Effects of flat-fare pass – transportation market

Origin (Res.)	Destination (Job)	Change of PT Share	Change in Number of PT Trips	Change in Auto Time	Change in across-Mode Average Travel Time	Change in Non-Work Trips	Change in Commutes	Aggregate Gasoline
Paris	Paris	0.23%	13,704	-0.99%	-0.27%	11,428	-3,811	
	CDTs	1.51%	10,739	-0.99%	-0.26%	1,194	3,098	
	Suburbs	1.90%	12,783	-0.66%	-0.23%	1,779	3,089	
CDTs	Paris	1.64%	55,337	-1.66%	-0.22%	7,269	3,329	
	CDTs	1.33%	28,762	-0.77%	-0.36%	3,369	-2,765	-2.23%
	Suburbs	1.34%	22,706	-0.34%	-0.24%	4,489	-1,096	
Suburbs	Paris	1.75%	61,871	-1.02%	-0.21%	8,682	4,280	
	CDTs	1.21%	21,991	-0.49%	-0.34%	3,805	-1,157	
	Suburbs	1.04%	49,988	-0.11%	-0.10%	9,643	-3,806	
TOTAL or AVERAGE		1.18%	277,882	-0.71%	-0.20%	51,658	1,160	

Table 7 summarizes the effects on welfare. Per consumer utility as measured by the compensating variation increases by 95€ for the consumers in the region; and decreases by 7€ for the consumers importing the region's products, the latter being due to the slight increases in prices noted earlier. Aggregate property values increase by 24€, and the revenue from the sales and income taxes by 27€. The total welfare increase from the switch to the flat-fare is 71€/consumer per year. The table also shows that the annual road congestion externality decreases by 33€ per consumer. However, public transit revenue decreases by 68€.

Table 6 Effects of flat-fare pass – regional economy

	Population		Jobs		Real wage	Real rent	Price index (GPMA)	Real Output	GDP
Paris	2,303	0.13%	3,621	0.22%	-0.08%	0.07%		0.19%	0.21%
CDTs	-663	-0.02%	-1,281	-0.07%	0.06%	0.08%		0.12%	0.21%
Suburbs	-485	-0.01%	-2,340	-0.12%	0.02%	0.07%		0.10%	0.16%
Outside	-1,156	-0.54%							
TOTAL	0		0		0.04%	0.06%	0.05%	0.15%	0.19%

Table 7 Effects of flat-fare pass – welfare change

	Flat fare
Welfare Change	**€ 71**
CV	€ 95
Value	€ 24
PT Revenue	-€ 68
Tax Revenue	€ 27
Sales	€ 17
Income	€ 10
Importer CV	-€ 7
Congestion Extn.(Base € 689)	€ 656

5. Congestion pricing and free public transit

In this section we report simulation results from 4 additional scenarios other than flat-fare pricing. We compare the general equilibrium effects of these five different pricing regimes: (i) the flat-fare pass (as already described in section 3.1), (ii) congestion pricing, (iii) free public transit, (iv) flat-fare pass with congestion pricing, and (v) free public transit with congestion pricing. Lastly we report on the welfare analytic comparisons of these policies.

With congestion pricing, each of the 3004 arcs in the GPMA road network is levied with a Pigouvian congestion toll. While investment in public transportation has long been considered as a more implementable substitute for Pigouvian congestion toll, Table 13 shows that the effect of congestion pricing is significantly stronger than that of the flat-fare. On average, transit ridership increases by 3.5% due to the toll whereas the flat-fare only increases the ridership by 1.18%. The increase in ridership is higher for longer trips such as trips from the City of Paris to the suburbs, or trips between the CDTs and the suburbs. This is because longer trips are more vulnerable to the monetary cost imposed by the toll. Note also that the ridership increase for trips originated from the suburbs to the City of Paris is smaller than that of the trips in the opposing direction. This is due to the fact that public transit facility is sparsely located in the suburbs and it is difficult for suburban consumers to switch to transit.

Table 13 Comparing different pricing schemes – transportation market

Variables	Origin (Res.)	Destination (Job)	Flat fare	Toll	Free public transit	Flat fare + toll	Free public transit +toll
Change of the transit share of all trips	Paris	Paris	0.23%	2.02%	0.42%	2.18%	2.39%
		CDTs	1.51%	4.43%	1.77%	5.65%	5.91%
		Suburbs	1.90%	5.03%	2.23%	6.67%	7.01%
	CDTs	Paris	1.64%	3.49%	2.14%	4.80%	5.26%
		CDTs	1.33%	3.57%	1.93%	4.84%	5.47%
		Suburbs	1.34%	5.18%	1.85%	6.47%	7.02%
	Suburbs	Paris	1.75%	3.51%	2.28%	4.92%	5.41%
		CDTs	1.21%	5.51%	1.74%	6.61%	7.18%
		Suburbs	1.04%	3.41%	1.65%	4.42%	5.07%
	AVERAGE		1.18%	3.50%	1.71%	4.55%	5.08%
Public transit trips	Paris	Paris	13,704	78,356	45,413	90,143	122,651
		CDTs	10,739	22,809	15,065	32,338	36,785
		Suburbs	12,783	26,469	17,333	37,891	42,643
	CDTs	Paris	55,337	98,066	96,376	144,289	185,327
		CDTs	28,762	76,053	48,957	103,358	124,870
		Suburbs	22,706	81,769	37,368	103,140	119,309
	Suburbs	Paris	61,871	100,941	105,035	153,542	196,458
		CDTs	21,991	92,980	38,363	113,133	130,950
		Suburbs	49,988	154,194	93,389	202,339	248,885
	TOTAL		277,882	731,637	497,297	980,172	1,207,879
Average travel time	Paris	Paris	-0.27%	-0.94%	-0.32%	-1.17%	-1.18%
		CDTs	-0.26%	-0.58%	-0.31%	-0.79%	-0.82%
		Suburbs	-0.23%	-1.14%	-0.26%	-1.46%	-1.47%
	CDTs	Paris	-0.22%	-0.40%	-0.25%	-0.59%	-0.59%
		CDTs	-0.36%	-0.78%	-0.37%	-1.10%	-1.07%
		Suburbs	-0.24%	-0.69%	-0.29%	-1.05%	-1.07%
	Suburbs	Paris	-0.21%	-0.64%	-0.24%	-0.82%	-0.83%
		CDTs	-0.34%	-0.46%	-0.37%	-0.79%	-0.81%
		Suburbs	-0.10%	0.06%	-0.10%	-0.17%	-0.17%
	AVERAGE		-0.20%	-0.52%	-0.22%	-0.74%	-0.74%
Commute pattern	Paris	Paris	-3,811	3,431	-4,733	-343	-1,451
		CDTs	3,098	451	3,393	3,554	3,819
		Suburbs	3,089	736	3,292	3,833	4,008
	CDTs	Paris	3,329	562	2,990	3,848	3,521
		CDTs	-2,765	592	-1,485	-2,187	-833
		Suburbs	-1,096	-1,471	-827	-2,564	-2,295
	Suburbs	Paris	4,280	1,180	4,079	5,409	5,227
		CDTs	-1,157	-2,666	500	-3,810	-2,107
		Suburbs	-3,806	-3,988	-2,333	-7,722	-6,156
	TOTAL		1,160	-1,173	4,876	17	3,734
Gasoline consumption			-2.23%	-11.52%	-2.56%	-13.39%	-13.55%

Table 14 Comparing different pricing schemes – regional economy

Variables		Flat fare	Toll	Free public transit	Flat fare + toll	Free public transit +toll
Jobs	Paris	3,621	5,351	1,595	8,911	6,729
	CDTs	-1,281	-1,161	488	-2,450	-591
	Suburbs	-2,340	-4,190	-2,083	-6,461	-6,139
Population	Paris	2,303	4,352	1,251	6,778	5,341
	CDTs	-663	-385	-11	-1,180	-411
	Suburbs	-485	-5,137	3,614	-5,581	-1,213
	Outside	-1,156	1,169	-4,854	-17	-3,716
Real rent	Paris	0.07%	0.11%	0.19%	0.18%	0.29%
	CDTs	0.08%	0.00%	0.43%	0.08%	0.42%
	Suburbs	0.07%	-0.07%	0.40%	0.00%	0.33%
	Total	0.06%	0.02%	0.28%	0.09%	0.30%
Real wage	Paris	-0.08%	-0.17%	0.11%	-0.25%	-0.06%
	CDTs	0.06%	-0.01%	0.13%	0.05%	0.12%
	Suburbs	0.02%	0.05%	-0.04%	0.07%	0.01%
	Total	0.04%	-0.04%	0.11%	0.00%	0.02%
Price index	GPMA	0.06%	-0.11%	0.36%	-0.05%	0.26%
Real output	Paris	0.19%	0.03%	0.57%	0.22%	0.58%
	CDTs	0.12%	-0.22%	0.77%	-0.10%	0.57%
	Suburbs	0.10%	-0.37%	0.75%	-0.26%	0.40%
	Total	0.15%	-0.13%	0.66%	0.03%	0.53%

Our simulation results also show that congestion pricing drives both workers and firms toward the City of Paris. Table 14 shows that the toll causes both jobs and population to increase in the City of Paris at the expense of the CDTs and suburbs. Jobs increase by 5,351 and the population by 4,532 in the City of Paris. The increase in labor supply and population also causes real wages to fall and real rents to rise in the City of Paris. This also can be seen from the change in commute pattern shown in Table 13. Real output rises slightly in the City of Paris while decreases in the CDTs and suburbs. Because the Pigouvian toll revenue is not redistributed, congestion pricing imposes a negative income effect on consumers which lead to weakened demands, lowered output prices, and lowered real output in the CDTs and suburbs. The negative income effect would also reduce travel demands, but the number of daily transit trips increases (Table 13) because the domination of switching from driving to public transit. Some consumers relocate to the center, i.e., the City of Paris, to be closer to shopping destinations, to shorten commutes, and to take advantage of dense public transit facilities. The increase of labor supply in the City of Paris also causes some firms to relocate to the center, and causes real output to increase in the City of Paris albeit the negative income effect induced by the toll. The across-modes average travel times decrease everywhere even though consumers switch to the slower mode of travel. This is due to the dominating effect of shorter auto times after the toll is imposed. Gasoline consumption drops by 11.52% as consumers try to avoid costly driving.

Table 15 Summary of welfare changes under different policies

	Flat fare	Toll	Free PT	Flat fare + toll	Free PT +toll
Welfare Change	**71 €**	**377 €**	**302 €**	**419 €**	**648 €**
CV	95 €	-94 €	390 €	2 €	294 €
Value	24 €	-19 €	129 €	5 €	111 €
PT Revenue	-68 €	7 €	-312 €	-70 €	-312 €
Tax Revenue	27 €	-42 €	148 €	-14 €	109 €
Sales	17 €	-26 €	92 €	-9 €	68 €
Income	10 €	-16 €	56 €	-6 €	41 €
Importer CV	-7 €	17 €	-53 €	11 €	-39 €
Toll	0 €	508 €	0 €	485 €	484 €
Congestion Extn.(Base € 689)	656 €	508 €	651 €	485 €	484 €

Table 13 and 14 also show the effect of setting the public transit price to zero where both the monthly pass cost and ticket cost vanish. With free public transit, many of the market adjustments are parallel to, but stronger than, that of the flat-fare pricing. On average, transit ridership increases by 1.71% (1.18% under flat-fare), and the increases are bigger for longer trips between the City of Paris and the suburbs. Average across-modes travel times are shorter because trips are diverted from diving, mitigating congestion. The shorter auto times again dominate the effect brought about by the switch to the slower transit mode. Making public transit free will also increase daily transit trips by 497,297. Gasoline consumption decreases by 2.56%. Like the flat-fare policy, free transit also has a positive income effect because workers no longer have to pay for their transit pass. This income effect is the driver for higher demands, higher real output, and higher output prices. As can be seen from Table 13, both output prices and real wages increase the most among all five policies. Interestingly, although the free transit policy in most cases has similar but stronger results compared to the flat-fare policy, relocating to central locations is weaker with free public transit than with the flat-fare. Jobs in the City of Paris increases by 1,595 with free transit, less than half of the jobs increase with the flat-fare. Population in the City of Paris also increases by around half of the increase under the flat fare policy. Meanwhile, in the suburbs, population increases by 3,614 while with the flat fare it decreases by 485. The reason is that the positive income effect induced by the free transit policy prompt some consumers to relocate from the center to peripheral locations. This income effect also leads to a 0.66% growth in real output in the GPMA.

The last two columns of Table 13 and 14 compare the effects of combing congestion pricing with different public transit pricing schemes. Unsurprisingly, the combination of free transit and toll produces the biggest increase in ridership. Share of transit trips are up by 5.08% because of the combined policy. The switch again is the strongest for trips originated from the City of Paris to the suburbs, and for trips between the CDTs and the suburbs. 1,207,879 more daily transit trips are induced due to this combined policy. In comparison, the combination of the flat-fare and toll causes daily transit trips to increase by 980,172, about 19% less than the increase under the free transit-toll combination. Across-modes average travel times shorten under both combinations. Although the switch to transit is slightly bigger with the free transit-toll combination than with flat-fare-toll combination, the shortenings in across-modes travel times are very similar under these two scenarios as faster auto trips and more consumers taking the slower transit mode largely cancel each other out. Free transit with toll causes gasoline consumption to fall by 13.55%, slightly bigger than the 13.39% decrease with the flat-fare-toll policy. As explained earlier, the free transit policy induces a greater income effect than does the flat-fare. This is also true under the combined policies: free public transit with toll leads to a stronger positive income effect than does flat-fare with toll. Consequently, the centralization of jobs and population is weaker with the free transit-toll combination than with the flat-fare-toll combination, as higher disposable incomes prompt some consumers to relocate from central locations to the suburb. Furthermore, the positive income effect would strengthen demand for goods, drive up output prices and real output. In the case of flat-fare with toll, the positive income effect of the flat-fare and the negative income effect imposed by the toll work in the opposite directions, leading to slightly lowered output prices and slightly reduced real output. Real wages remain nearly unchanged due to the opposing income effects. On the other hand, with free transit and toll, the positive income effect dominates, causing both output prices and real output to increase.

Finally, Table 15 shows the welfare effects of different pricing schemes. It is shown that the combined policies produce bigger welfare benefits than any of the single pricing schemes, with free public transit with toll being the most beneficial tool followed by flat-fare with toll. The Pigouvian toll ranks the third and is the most beneficial among stand-alone policies, followed by free public transit. The flat-fare policy ranks the last in terms of welfare benefits.

The welfare effect of the flat-fare has already been examined in section 4.1 (Table 7). We now look at the other 4 policies. With congestion pricing, the negative income effect hurts the consumer, causing a negative 94€ compensating variation. Property values are down by 19€ due to lower rents induced by weakened consumer demands. Tax revenue per capita decreases by 42€ as both bases for the income tax and sales tax shrink because of the toll. Importers of the goods produced in the region are better off due to lower output prices. Public transit revenue increases by 7€. The revenue from congestion pricing is 508€, dominates other negative effects. The overall welfare benefit of the congestion toll is 377€.

With free public transit, the welfare effect is a magnified version of that with the flat-fare. As a result of the income effect, compensating variation is positive 390€; real estate value increases by 129€, the revenue from the taxes are up by 148€. Public transit revenue decreases by 312€ and the importers' welfare are lowered by 53€. The overall welfare increase with free public transit is 302€.

With the combination of the flat-fare and toll, the positive income effect of the flat fare and the negative income effect of the toll work against each other, the changes in welfare components are therefore small. Compensating variation is higher by 2€, and real estate value by 5€. The revenue from the taxes decreases by 14€ and the revenue from public transit decreases by 70€. The consumers importing from the region are slightly better off due to reduced output prices. The revenue from congestion pricing is 485€, which dominates, resulting in a 419€ increase in overall welfare.

With free public transit combined with toll, which is shown to be the most beneficial policy, the positive income effect induced by zero transit cost dominates the negative income effect of the toll. Compensating variation increases by 294€, and property values by 111€. The revenue from the taxes increases by 109€. The public transit revenue loss is 312€, and the consumers importing from the region a worse off by 39€ as output prices in the region were driven up by higher disposable incomes. The revenue from congestion pricing is 484€, and the overall welfare of free transit combined with toll is 648€. If we were to treat the welfare benefit of congestion pricing as a benchmark, then the flat-fare captures 19% and free public transit captures 80% of the welfare benefits of the Pigouvian congestion toll. On the other hand, the flat-fare with toll, and free public transit with toll, gain 111%, and 172%, respectively, of the benefit of congestion pricing.

6. Conclusion

We examined the effects of different urban transport pricing policies in the context of a general equilibrium model in which not only the consumer's travel behaviors, but also various markets in the regional economy as well as the interactions between them are rigorously treated. It was shown that in the GPMA, switching from a zone-based pass system to the flat-fare improves transit ridership, diverts auto trips, alleviates congestion, reduces gasoline consumption, and spurs real output production. However, making public transit free would lead to stronger effects across the board and is more beneficial. Furthermore, we showed that the flat-fare would capture 19% of the benefit of congestion pricing while free public transit would capture 80%. Combining the Pigouvian toll with the flat-fare or with free public transit would further improve welfare compared to congestion pricing alone.

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Appendix

A.1 Calibration of the RELU-TRAN Paris Model

Table 1 lists the baseline elasticities in the RELU TRAN Paris model. Kimmel and Kniesner (1998) estimated using the U.S. national data between 1983 and 1986 that the average labor supply elasticity is +0.51. In Anas and Hiramatsu (2012, 2013) and Anas (2015), in which the RELU-TRAN model is applied to the Chicago MSA, the labor elasticity is between +0.63 and +1.60 for suburban workers and between +1.20 and +2.82 for city workers. Our value (Table 1) lie within the ranges of these authors.

Table 1 Calibrated Elasticities in RELU-TRAN Paris

Elasticity of location demand with respect to average travel time		-0.46				
Elasticity of location demand with respect to housing rent		-0.37				
Elasticity of substitution between goods		0.63				
Elasticity of labor supply with respect to wage		1.04				
Elasticity of labor demand with respect to wage		-0.95				
Elasticity of mode choice (pubic transit) with respect to own cost		-0.8				
Elasticity of export demand with respect to price		-1.8				
		Building Types				
		Single Family	Multi-Family	Office	Store	Industrial
Elasticity of floor space supply with respect to rent (short-run)		0.25	0.25	0.5	0.5	0.5
Elasticity of construction with respect to floor price by county						
	Paris	0	0	0	0	0
Areas	CDTs	0.01	0.13	0.33	0.65	0.3
	Suburb	0.04	0.42	0.68	0.97	0.7

In a technical report, Anas and Indra (2011) estimated specifically for the RELU-TRAN Paris model the elasticity of location demand with respect to residential rent to be +0.37. They also estimated specifically for the RELU-TRAN model the elasticity of location demand with respect to average travel time to be -0.46 in Paris. This is close to the values used in Anas and Hiramatsu (2012, 2013) that ranges from -0.55 to -0.62 for different income groups. Anas and Indra (2011) also estimated for the RELU-TRAN model that the elasticity of choosing driving mode with respect to own cost to be -0.7 in Paris. Note that this elasticity is -0.1 in LA because the availability of public transportation is much better in Paris than in LA, and consequently, as driving cost increases, consumers in Paris could switch to public transportation more easily that those in the Greater LA Region.

Anas and Arnott (1993) found that the short run elasticity of housing floor space supply is +0.10 for single-family housing and +0.11 for multi-family building. In Anas and Hiramatsu (2012, 2013), the elasticity is +0.10 and +0.23, respectively. In our case, we use +0.25 for housing and +0.5 for commercial floor spaces. Blackley (1999) found that the construction elasticity is between +1.0 and +1.2, while the elasticity of long-run housing supply with respect to asset value ranges from +1.6 to +3.7. In Anas and Hiramatsu (2012, 2013) and Anas (2015), the construction elasticity in the Chicago MSA ranges from +0.03 (single family housing) to +0.79 (industrial).