THE EFFECT OF THE FLAT-FARE TRANSIT PASS: AN ANALYSIS USING THE RELU-TRAN COMPUTABLE GENERAL EQUILIBRIUM MODEL[1]

By

Huibin Chang

Department of Economics

State University of New York at Buffalo

Amherst, NY 14260

hc73@buffalo.edu

and

Virtual Co-laboratory for Policy Analysis in Greater Los Angeles

University of California, Riverside

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Abstract

We study the general equilibrium effects of replacing the distance-based transit pass with the flat-fare pass in the Greater Paris Region (Île-de-France). Using the RELU-TRAN (Regional Economy, Land Use and Transportation) computable general equilibrium model (Anas and Liu, 2007), we find that the flat-fare pass boosts public transit ridership, especially for long-distance commutes, resulting in less road traffic and less congestion, and therefore less gasoline consumption. Some suburban workers relocate to the city of Paris where public transit is most accessible. In response to the expanding labor force, some suburban firms also relocate to the city. The income effect of the flat fare stimulates consumer demand; therefore, aggregate output increases. Growing production shores up factor demand and factor prices. Increased rent drives up real estate values. Utility, as well as overall welfare, improves, mainly due to less expensive commutes. Sensitivity analysis shows that these results are robust across a broad range of variation in key elasticities. However, the fare change always results in reduced public transit revenue, even when the choice of transportation mode is assumed highly elastic. We further explore situations in which the transit revenue loss is compensated for by the imposition of various taxes. We report the welfare implications of these tax substitutions and the economic forces behind the results.

Keywords: Computable general equilibrium, welfare analysis, public transit pricing, flat-fare transit pass.

JEL classification: D58, D61, R13, R14, R31, R32, R41, R48, R52.

1. Introduction

The search for efficient pricing of public transportation services can be traced back to at least as early as Vickrey (1955). Since then, a large body of literature has contributed to our understanding of various aspects of the public transportation market. In particular, most studies have found that by subsidizing the public transit system and maintaining low passenger fares, more efficiency can be achieved. The sources of efficiency improvement can be categorized into three strands:

(a) Increased economies of scale in providing the services. Given fixed service capacity and frequency, the marginal operating cost associated with an additional passenger is usually less than the marginal social benefit.

(b) Externalities inside the public transportation market, such as prolonged waiting times, boarding times, and disembarking times induced by the marginal passenger (Mohring, 1972) and discomfort caused by overcrowding (Kraus, 1991; de Palma, Kilani and Proost, 2015).

(c) Externalities outside the public transportation market. For example, the increase in public transit ridership indirectly alleviates road congestion (Anas, 2015; Graham and Glaister, 2006) and mitigates associated safety externalities. 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 externalities from various travel modes, and, 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), with the exception being peak-time bus transit in Washington, D.C. 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 (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 guaranteed unless the majority of local transit services users are from outside the region, in which case local voters would prefer a higher passenger fare. Such interactions between cross-border users and the pricing of a local public good were analyzed by Arnott and Grieson (1981).

Aside from these three types of justifications for low passenger fares, which have been discussed frequently in the literature, several potentially important aspects of transportation market adjustments have been largely ignored. For example, detailed analysis of the interactions between labor supply and transit fare have been conducted only rarely. Van Dender (2003) argued that, by differentiating trip purposes, reducing work-related travel costs encourages the supply of labor and, therefore, improves welfare. However, his model was a highly aggregated one and did not examine the spatial distribution of resources. Savage and Small (2010) also called for a general-equilibrium analysis of transit price in which the labor supply effect was 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 largely ignored.

This paper extends the horizon 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, calibrated to the Greater Paris Region (Île-de-France), we simulate the general-equilibrium effects of changing from the zone-based (distance-based) transit pass to the flat-fare pass.

The simulations conducted in the present study show that the flat-fare pass boosts public transportation ridership, especially for long-distance commutes, resulting in less road traffic and less congestion which, in turn, decreases gasoline consumption. These effects are somewhat well known and can be fit into the three traditional types of justifications for low passenger fares. Nevertheless, other findings of this study relate to the aspects of market adjustments that have been left out of previous studies. For example, we find that in the long run, in response to the fare change, some suburban workers would relocate to the city of Paris, where public transit is most accessible. In response to the expanding labor force, some suburban firms also would relocate to the city. Meanwhile, the income effect of the flat-fare pass would stimulate consumer demand; therefore, aggregate real output would increase. The growth in real output would shore up factor demand and factor payments, and the increased rent would drive up real estate values. Overall welfare also would improve, as a result of the less expensive commute. 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).

Although a low passenger fare is justified on efficiency grounds, other studies have cautioned regarding the hidden costs of providing public subsidies and, therefore, have argued against doing so. The rationale for austerity is that raising funds to provide the subsidies would cause distortions in the economy. In a second-best world, in which there are many taxes, one tax could exacerbate the distortionary effects of other taxes. Parry and Bento (2001) showed that in the presence of distortionary taxes, a Pigouvian congestion toll would discourage labor supply, by amplifying the distortionary effects of income tax, and the net welfare effect of the congestion toll would, therefore, be negative. Van Dender (2003) further explored such effects, by showing that welfare would improve significantly only if the peak-hour congestion toll were combined with a reduction in labor tax. Proost and Van Dender (2008) showed that implementing an optimal congestion toll and an optimal passenger fare in Brussels and London would require increasing both road pricing (e.g., charging higher parking fees) and public transit fares. The explanation for the higher passenger fares in the optimal pricing scheme is that public revenue can directly generate social benefits. In fact, they showed that the "tax premium effect" is as important as the congestion mitigation effect in terms of improving social welfare. Using data and an intermediate-level road network in the Paris area, Kilani, Proost and van der Loo (2014) explored several pricing scenarios and found that an all-time congestion toll levied in the city of Paris, together with an increase in public transportation fare, would produce the largest gain in social benefits. They argued that, once the congestion is mitigated by the congestion toll such that there is little negative externality generated on the roads, the public transportation price should be equal to the social marginal cost of providing the transportation service. In addition, in accounting for the social welfare change, they took into account the change in public revenue collected from public transit riders. Based on these arguments, they claimed that the congestion toll and the fare increase are complements.

In the present paper, we also address the issue of tax interactions. In Section 5, we study cases in which the change in transit fare is coupled with a binding public budget constraint. Because public transit revenue would fall as the zone-based pass is replaced by the flat-fare pass, we simulate scenarios in which the revenue loss from the public transportation sector is compensated for by other taxes such that the aggregate public revenue remains at the same level before and after the fare change. The simulations show that the combination of the flat-fare policy and a revenue-neutral sales tax would achieve more social benefit than would the flat fare alone, although the advantage is marginal. On the other hand, if the flat-fare policy were combined with various revenue-neutral property taxes, social welfare would decrease compared to the standalone flat-fare policy.

Section 2 explains the RELU-TRAN Paris model and the fare structures. Section 3 analyzes the market adjustments following the implementation of the flat-fare pass and presents the baseline simulation results. Section 4 explores in detail the effects of key elasticities and the robustness of the baseline simulation. Section 5 presents the results, including the welfare implications, of the revenue-neutral tax substitutions. The appendix provides additional detail regarding the RELU-TRAN model.

2. The RELU-TRAN Paris Model

The Greater Paris Region (Île-de-France) consists of 50 model zones, each of which belongs to one of the three areas of the region: the city of Paris, the ten CDTs (Territorial Development Contracts, which are subcenters that surround the city of Paris), and the suburbs. In addition to the 50 model zones, there are 4 outside zones representing the exurban areas. Specifically, of the 50 model zones, the city of Paris contains 20 model zones; the CDTs comprise 10 zones, and the suburbs comprise 20 zones. Each employed consumer lives in one of the 54 zones and works in one of the 50 model zones. In addition to work trips, both employed and unemployed consumers can make non-work trips to any of the model 50 zones. All consumers choose between two modes of travel: private car and public transportation. Public transportation riders then face two options: purchasing single-trip tickets and purchasing monthly passes. Figure 1 shows the demarcation of the model zones. Table 1 describes the distribution of land, floor space, population, jobs, and number of daily trips among the four zone types.

RELU-TRAN is a spatially detailed, computable general equilibrium model that incorporates many aspects of the regional economy and transportation, such as the transportation market, mode choice, road network, labor market, production, real estate rental and investment, and land use. The model and its algorithm were developed by Anas and Liu (2007) and have been successfully applied to studies of transportation policy (e.g., Anas and Hiramatsu, 2012, 2013) and the nature of the relationship between the growth of the regional economy and the transportation market (e.g., Anas, 2015). The RELU-TRAN Paris model, used in this paper, adopts the model structure from those articles. Equations, algorithms, and other details are provided in the appendix. Table 2 provides an intuitive description of the model; it explains the *direct linkages* among various markets, from which many *indirect market interactions* arise.

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).

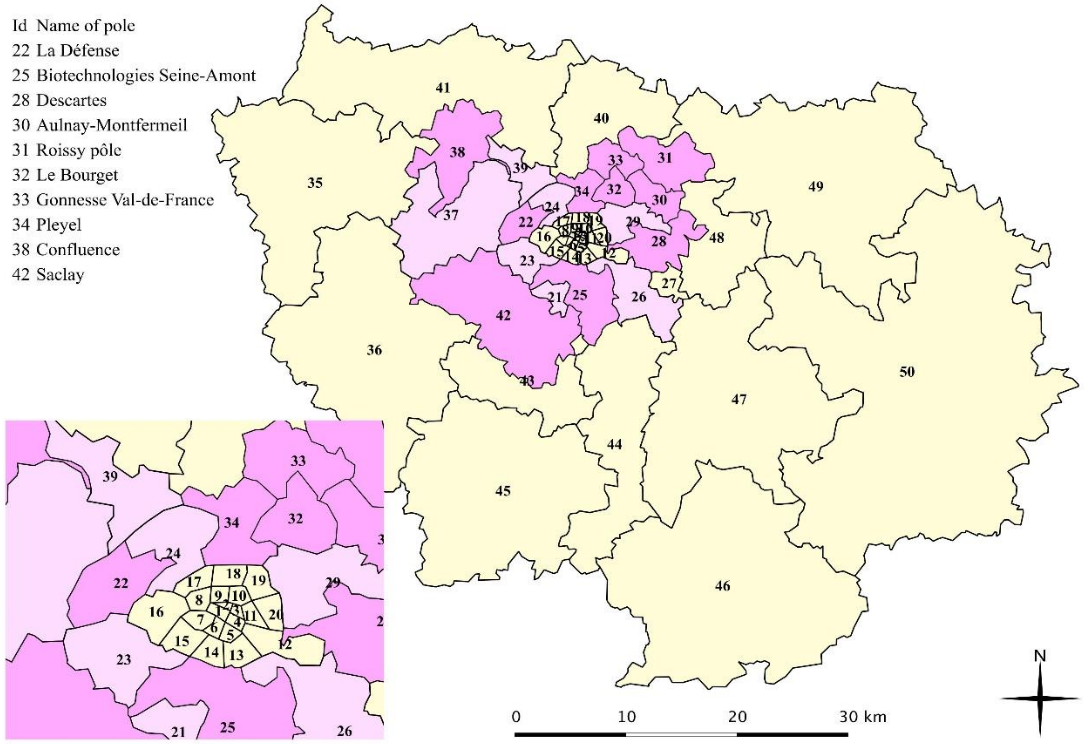


Figure 2: The demarcations based on which the zone-based monthly passes are priced

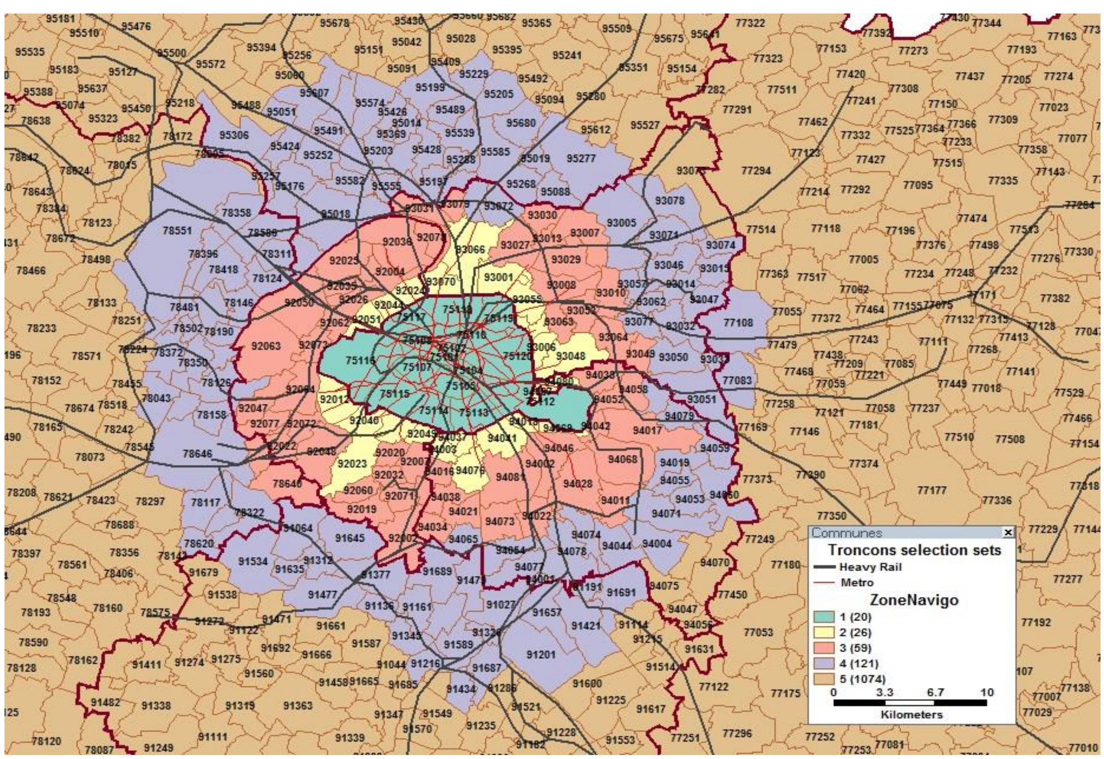


Table 1: Distribution of Land, Floor Space, Population, Jobs, and Trips in the Calibrated Equilibrium

	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	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%	

In Sections 3 and 4 of this paper, we investigate in detail the effects of the public transportation system replacing the zone-based transit pass with a flat-fare pass. Single-trip ticket prices remain unchanged. Before the flat-fare pass, the entire Greater Paris Region is divided into five ring-shaped fare zones (not to be confused with model zones), as shown in Figure 2. For zone-based pass fares, the cost of a transit pass varies based on a rider's origin zone and destination zone, as shown in Table 3. In principle, passes for long-distance rides are more expensive than passes for short-distance rides.[2] In contrast, in flat-fare pricing, all passes cost the same amount (50.7 €, adjusted for 2005) per month no matter where the origin and destination.

Now we examine the difference between the flat fare and zone-based fares. Table 4 shows the percentage difference between the two, defined as $\frac{\text{Zonal Fare - Flat Fare}}{\text{Zonal Fare}} \cdot 100\%$. The negative savings indicate that the flat fare is more expensive than the zone-based fare for those origin-destination pairs. We can see from Table 4 that, in general, passengers who travel for longer distances would be better off under the flat fare system, whereas passengers who travel for shorter distances would be slightly worse off under the flat fare system. For instance, consider a commuter who uses a public transit pass to commute from fare zone 5 to fare zone 1. His or her monthly cost under the zone-based fare is 99.1 €, compared to 50.7 € in the flat fare system. Consider another commuter who commutes within the city of Paris and whose zone-based transit pass costs only 50.4 €, slightly less than the flat fare.

[2] There are exceptions to this principle. For example, a commuter who travels daily within fare zone 4 for a long distance circumferentially only pays 46.6 € for a monthly pass.

Table 2: Structure of the RELU-TRAN Computable General Equilibrium Model – *Direct Linkages* between markets

			Product and Labor Markets		Real Estate and Land Use				Transportation
			Production	Labor	Real Estate Rental Markets		Investment and Land Use		
					Housing Floor Space	Commercial Floor Space	Investment	Construction and Demolition	
Product and Labor Markets	Production		**CRS firms use labor and capital to produce goods that are bought by consumers. Variable solved: the price of goods in each zone.**	Production requires labor input. An increase in output drives up labor demand.	Ceteris paribus, an increase in the price of goods leads to substitution of housing for consumption goods.	Production requires the input of commercial floors. An increase in output drives up demand for floors.			An increase in demand for real output (e.g. driven by lowered price) requires more shopping trips, leads to an increase in travel (non-work) demand.
	Labor		Wage rate affects production cost. Hence, a higher wage rate depresses production and vice versa.	**At the model zone level, labor demand from firms equates labor supply. Variable solved: wage rate in each model zone.**	Wage income is part of the disposable income that determines the demand for housing.	A higher wage prompts firms to substitute capital for labor in production, which drives up demand for floor space.			An increase in wage income drives up demand, which results in more shopping trips. Moreover, consumers' changes of jobs affect commuting pattern.
Real Estate and Land Use	Real Estate Rental Markets	Housing	Ceteris paribus, higher housing rent prompts the consumer to substitute goods for housing, pushing up the demand for goods.		**At the model zone level, demand for housing equates the supply. Variables solved: residential rents and occupancy rates.**		Higher housing rent leads to higher expected investment return that will drive up real estate value.	Higher rent increases the occupancy rate and enables fuller utilization of the stocks.	Higher residential rent prompts the consumer to substitute goods for housing, which leads to higher demand and may result in more shopping trips. Higher rent also incentivizes the consumer to relocate to a more affordable place, which would affect commuting patterns.
		Commercial	Commercial rent affects production cost. Hence, higher rent depresses production and vice versa.	Higher commercial rent encourages firms to substitute labor for capital in the production, causing labor demand to rise.		**At the model zone level, demand for floors equals supply. Variables solved: commercial rents and occupancy rates.**	Higher commercial rent leads to higher expected investment return and higher real estate value.	Higher commercial rent increases occupancy rate of the existing floor space.	
	Investment and Land Use	Investment					**For each building type in each zone, floor price adjusts according to rent. Variable solved: floor price.**	For building type(s) whose value increases relative to others, there will be more construction and less demolition, hence the stock increases.	
		Cons. & Demo.			More housing stock depresses housing rent, and vice versa.	More commercial stock depresses commercial rent, and vice versa.		**Developers make decisions whether to tear down an existing structure and whether to build on a vacant lot. Variable solved: floor space stocks.**	
Transportation			An increase in travel cost (e.g. exacerbated congestion, risen pecuniary cost) discourages shopping activity, especially those long-distance or congested trips, hence would reduce demand for goods.	Risen travel cost discourages long-distance commutes, thereby making jobs closer to the residence more attractive.	An increase in travel expenditure reduces disposable income and demand for housing.				**Given the OD matrix generated from commuting and shopping, mode choice (car, transit) probabilities, and the road network, traffic equilibrium is solved. An increase in the cost (time or pecuniary) of one mode induces passengers to switch to the other. Variables solved: equilibrium time and pecuniary costs of both modes and the mode choice probability for each OD pair.**

Table 3: Zone-Based Fare

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

Table 4: Monthly Savings of the Flat-Fare 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 for this study, we make three important assumptions. The first is that all commuters who commute by public transit always use monthly passes rather than single-trip tickets, both before and after the fare change. This assumption is vindicated by the observation that even for the most expensive zone-based pass, which costs 1,189 € annually, the transit pass is cheaper for an employed worker, on a per-trip basis, than purchasing single-trip tickets. To see this, consider that a typical worker must make 500 one-way work trips per year, in addition to discretionary non-work trips. This calculation implies that even the most expensive per-trip cost in the zone-based fare system is still less than the average single-trip ticket price of 2.04 €. Furthermore, the comparison is even more stark for longer commutes. The second assumption is that all unemployed consumers who use public transit buy tickets rather than monthly passes. This assumption is justified by the calculation that shows that, based on the average number of trips an unemployed person makes, his or her average annual spending on transit tickets is only 316 €, which makes it unnecessary to purchase a transit pass. Finally, we assume that employed workers know the per-trip cost of the transit pass, which is defined as $\frac{12 \cdot \text{Monthly Pass Fares}}{\text{Personal Trips Per Year}}$. The rationale for this assumption is that commuters are aware that with a public transit pass, the more trips they make, the lower the cost per trip. From the perspective of public transit passengers, there exist economies of scale for using the pass, whereas the cost of driving is more linear, if not convex, due to traffic congestion.

Calibration and Simulation with the Flat-Fare Pass

In the calibrated base, which represents the starting equilibrium before the introduction of the flat-fare pass, commuters' per-trip cost of using public transit is calculated according to zone-based pass fares. The per-trip cost of using public transit for an unemployed person, on the other hand, is simply the ticket price, which remains constant despite the pass system change. In subsequent policy simulations, the flat-fare pass replaces the zone-based pass, and commuters' per-trip cost of using public transit is adjusted so that it equals the annual flat-fare pass cost divided by the number of endogenous personal trips made during the year. The adjusted per-trip cost is then read as an input for policy simulations. Facing the flat fare, commuters may make different decisions: they may switch mode of travel, because the relative prices of the modes have changed; they may adjust consumption, because their disposable incomes net of transportation costs have been directly affected by the fare change or the costs of shopping are altered by the flat-fare policy. In each RELU-TRAN cycle of the policy simulation, after the

RELU module converges, the per-trip costs for commuters who make various choices are calculated for the updated number of trips. The TRAN module then uses the updated public transit costs as inputs and updates average travel costs (across modes) and generalized travel costs (taking into consideration both time and pecuniary costs). After TRAN converges (road network equilibrium), the algorithm then goes into the next RELU-TRAN cycle. This process continues until the entire system converges.

3. Market Adjustments to the Flat-Fare Pass

3.1. Mode Choice, Congestion, Travel Cost, and the Commuting Pattern

How would commuters respond to the change in transit fares? The response depends on the perceived difference in travel costs. Table 4 shows the percentage monthly savings after the flat-fare pass is introduced. With the flat-fare pass, short-distance commuters would pay slightly more for public transit than they did in the zone-based system (negative saving). However, the increase in cost for these commuters is relatively small. To see this, note that workers who commute within the vicinity of the city of Paris would experience a monthly pass cost increase of only 0.6%. The largest increase in PT (public transit) fare is for commutes within fare zone 5 and between fare zones 4 and 5, for which the flat-fare pass costs 9.3% more than did the zone-based pass (see Figure 2 and Table 4).

In contrast, for long-distance commuters, the cost of taking PT decreases significantly with the flat-fare pass. For example, for a worker who lives in the city of Paris and commutes by PT to the suburbs, the one-way travel cost would be 49% lower with the flat-fare pass than with the zone-based pass. Workers who commute between the city of Paris and the CDTs also benefit significantly from the flat-fare pass. Specifically, as shown in Table 4, the origin-destination pairs that benefit the most from the flat-fare pass are the ones that are farther apart. Most commutes between the city of Paris and the CDTs and between the city of Paris and the suburbs, fit into this category.

Because the cost savings for long-distance trips with the flat-fare pass are substantially larger, in absolute terms, than the cost increases for short-distance trips, the average PT cost decreases. As a result, some commuters would switch from driving to taking PT, and thus PT ridership would increase. The increase in PT ridership would have two consequences. First, given that the number of trips *by all modes* would remain relatively stable, some commuters switching to PT would mean that some traffic is diverted from the roads to the PT system, which, in turn, implies that road congestion would be mitigated. Consequently, average automobile speed would be faster, and fuel economy would improve. Both the reduced congestion and the improved fuel economy would contribute to aggregate gasoline consumption decreasing by 1.5%. Second, the replacement of the zone-based fares by the flat fare can be thought of as an overall price cut in the public transportation sector, which presumably would lead to a reduction in PT revenue. Indeed, the baseline simulation results confirm that transit revenue would shrink by 14.9%. The loss of PT revenue, however, would not be as large as it would have been if there had not been increased ridership. The traditional elasticity argument applies here: Although the PT fare decreases, demand would increase, due to some workers' decisions to switch to PT, so that some of the PT revenue loss would be recovered. A simple calculation shows that the revenue from sales of transit passes would decrease by 15.9% if PT demand remained constant. Therefore, the increase in ridership would recover 1%, or 18 million euros, potential loss of transit pass revenue. The magnitude of the adjustments in mode choice (ridership), of course, depends on the elasticity of mode choice with respect to travel cost. In Section 4, we examine the simulation results based on mode choice elasticities that differ from the baseline assumption. This sensitivity testing shows that the conclusions derived in this section are robust across a broad range of elasticity values.

Table 5 summarizes the changes in the transportation market after the flat-fare pass is introduced. The column labeled "Change of PT Share" shows the mode choice changes for each origin-destination pair. Apparently, most mode switches would happen for trips between the city of Paris and the CDTs and between the city of Paris and the suburbs, because the cost of these long-distance commutes is considerably less with the flat-fare pass than with the zone-based pass, prompting some commuters to switch to PT. Hence, the number of trips made by PT would increase while the number of trips made by car would decrease. The average car speed would become faster due to mitigated congestion. The average (across modes) travel time between these long-distance origin-destination pairs, however, would increase, because some workers would have switched to the relatively lower-cost but longer travel time mode — PT. Finally, in the long run, workers could choose to relocate or change jobs, and their choices of location would be influenced by commute costs. In the remainder of this section, we look at these adjustments in detail.

The number of daily one-way PT passenger trips between the city of Paris and other areas would increase by 147,273. In contrast, the number of *total* daily PT passenger trips would increase by just 145,546. The latter (the increase in total PT trips) is smaller than the former (the increase in PT trips in and out of the city of Paris), because the number of local PT trips would decrease, which is a result of increasing per-trip pass cost for local trips and changing commuting patterns such that the number of local commutes would decline.

Table 5: Effects of Flat-Fare Pass – Transportation Market

Origin (Res.)	Destination (Job)	Change of PT Share	Number of PT Trips	Auto Time	Average Travel Time	Commute Cost Per Trip	Commuting Pattern (Per Day)	Aggregate Gasoline
Paris	**Paris**	-0.13%	-6,341	-0.83%	-0.25%	-0.01 €	-4,484	
Paris	**CDTs**	2.20%	13,822	-1.46%	0.31%	-0.84 €	3,693	
Paris	**Suburbs**	2.63%	15,275	-0.68%	0.10%	-0.77 €	2,864	
CDTs	**Paris**	1.82%	56,370	-1.75%	0.19%	-0.87 €	3,648	
CDTs	**CDTs**	-0.03%	-1,269	-0.52%	-0.19%	-0.02 €	-2,596	-1.50%
CDTs	**Suburbs**	-0.01%	-165	-0.52%	-0.20%	-0.03 €	-1,197	
Suburbs	**Paris**	1.89%	61,806	-1.05%	0.05%	-0.89 €	4,956	
Suburbs	**CDTs**	0.12%	1,810	-0.53%	-0.13%	-0.05 €	-1,513	
Suburbs	**Suburbs**	0.11%	4,238	-0.34%	-0.01%	-0.03 €	-4,185	
TOTAL or AVERAGE		0.67%	145,546	-0.88%	0.03%	-0.52 €	1,187	

Table 6: Effects of the Flat-Fare Pass – Regional Economy

	Population		Jobs		Wage	Price	Production	GDP	Rent
Paris	2,642	0.15%	3,940	0.24%	-0.27%	-0.14%	0.05%	-0.09%	-0.003%
CDTs	-359	-0.01%	-883	-0.05%	0.07%	0.06%	0.05%	0.12%	0.072%
Suburbs	-1,098	-0.03%	-3,057	-0.16%	0.08%	0.05%	0.04%	0.09%	0.057%
Outside	-1,186	-0.55%							
TOTAL	0		0		-0.02%	-0.02%	0.05%	0.03%	0.036%

The increase in PT ridership and the shift in its distribution from local trips to long-distance trips indicate an efficiency improvement in the public transportation sector. Due to the introduction of the flat-fare pass, the use of PT for local commutes (commutes within the city of Paris, within the CDTs, and within the suburbs) would decrease, while overall PT use, especially for long-distance commutes, would increase. Meanwhile, it is plausible to believe that PT facilities within the center city and within other subcenters are more congested than are PT facilities that serve more sparsely populated areas. Therefore, the shift in the distribution of PT usage implies that PT riders would be shifted away from congested service areas to less congested, or even underused, service areas. The reduced demand for PT in congested service areas would then result in less negative externalities, namely, shorter waiting times, boarding times, and disembarking times (Mohring, 1972), less crowding (Kraus, 1991), and better fuel economy in the case of bus service; while the increased demand for PT in the less congested service areas could promote increased utilization of PT facilities, thus reducing the cost per rider of providing transit services. Indeed, Anas and Timilsina (2015) found that improving PT services in peripheral areas could effectively reduce overall carbon dioxide emissions.

Average travel time (across modes) would become marginally longer. The reason for this is that PT is the relatively slower mode, and by some commuters switching to PT, the average travel time of all commuters actually gets longer even though the average car speed would be slightly faster with less traffic on the roads. The increase in average travel time is most salient for trips made between the city of Paris and the CDTs, for which more than 70,000 passengers would switch to PT, and between the city of Paris and the suburbs, for which more than 77,000 passengers would switch to PT. The average travel time between other origin-destination pairs would decrease, due to the improved automobile speed. Thus, the overall average travel time in the region would increase by 0.03%, but the effect on consumer utility would be negligible. This paper's finding of stable average travel time is consistent with the finding of the recent study by Anas (2015). He observed that the average travel times in U.S. cities remained relatively stable despite economic growth and urban sprawl. He explained that, because consumers and firms chase each other, relocating farther out of the city as economy grows and because some consumers would switch to PT as road congestion worsens, the increase in average travel time would be mild compared to the increase in population and employment. A commuter's average monetary cost per trip, which takes into account the costs of both modes (car and PT), is reduced for three reasons: 1) the average transit fare becomes less expensive, 2) commuters switch to PT, for which the monetary cost is lower than that for traveling by private car, and 3) for commuters still traveling by car, commuting becomes cheaper due to less road congestion.

Finally, an important consequence of the fare change is that, in the long run, some workers may change their residence and employment locations and, when making their choices, they will take into consideration the cost of commuting. This trend would be reflected in the commuting pattern change. Naturally, origin-destination pairs that experience relatively larger cost savings due to the switch to the flat-fare policy would attract more commuters. Daily commutes into and out of the city of Paris would increase by 15,161, while other commuting patterns would decrease by 13,974. In addition, some workers who previously lived in exurban areas would move into the region in order to take the advantage of lower commute costs. The number of daily commutes in the entire region would increase by 1,187. The reallocation of workers would lead to other adjustments in the regional economy; we deal those in Section 3.2 of this paper.

3.2. Labor Market Adjustments and the Effects on Production, Rent, and Welfare

One of the advantages of the RELU-TRAN model for analyzing public policy is that by bringing together the road network equilibrium, land use, and regional economic activities, researchers can use simulations to account for a particular policy's effects on various aspects of the regional economy. Moreover, the spatially detailed nature of the model helps researchers to better understand the geographic nuances of the equilibrium, such as the spatial shifts in population and employment, the relationship between economic activities and travel demand, and the overall welfare effect of public policy. With the introduction of the flat-fare transit pass, the initial change in commute cost would, in the long run, affect workers' choices of location for residence and employment, which, in turn, would have an extensive effect on the economy. We examine the details of the adjustments in the labor market, production, the floor-space rental market, and the real estate investment market. Table 7 lists the estimated key elasticities in the baseline equilibrium.

Table 7: Baseline Elasticities

Baseline Elasticities	
Location w.r.t. Rent	-0.37
Transit Mode w.r.t. Travel Cost	-0.80
Demand w.r.t. Price	-0.18
Labor Demand w.r.t. Wage	-1.47
Labor Supply w.r.t. Wage	1.04
Construction w.r.t. Floor Price	0.22
Location w.r.t. Travel Time	-0.23
Location w.r.t. Travel Cost (IV)	-1.46
Occupancy w.r.t. Rent	0.18

How would the labor market react to the introduction of the flat-fare transit pass? Consider first a consumer who both lives and works outside the city of Paris. Some employment opportunities in the city of Paris, which he or she had previously perceived as just as satisfying as the suburban job, would become more attractive, because commuting to Paris is made cheaper by the flat-fare pass. Such a realization would lead to his or her later decision to work in the city.

After all, the consumer would be better off, in terms of commute cost, by choosing a new job in the city of Paris. Such workers changing their work locations would increase the labor supply for the city of Paris and decrease the labor supply for the CDTs and the suburbs. The increase in labor supply for Paris would increase competition among workers there, reducing the wage rate. Firms, facing an influx of applicants who are willing to accept lower wages, would substitute labor for capital. These firms could then produce at a slightly lower cost and therefore sell their products at slightly lower prices. The increasingly competitive prices offered by these firms in the city of Paris would attract more shoppers, and demand would eventually increase. Facing greater demand, the firms would then hire more workers. This process is the self-reinforcing cycle of agglomeration that this author studies in detail in his dissertation. Paris would gain 3,940 jobs, while the CDTs and the suburbs would lose 883 and 3,057 jobs, respectively (see Table 6).

The increase in Paris' labor supply would exceed the increase in labor demand, resulting in a 0.27% dip in the wage rate. In contrast, in the CDTs and the suburbs, the decrease in labor supply would dominate, and the wage rate would decrease by 0.07% and 0.08%, respectively. Determined by production cost, prices would adjust accordingly. In Paris, the average price would decrease by 0.14%, while in the CDTs and the suburbs, it would increase by 0.06% and 0.05%, respectively (see Table 6).

Next, consider another consumer who also lives and works outside the city of Paris. Suppose that his or her residence is located in a less populated area and there is no PT station nearby. The consumer commutes by car. After the flat-fare pass has been introduced, he or she will be tempted to move to some other place where PT is accessible, as long as the new home is not too far from work. The city of Paris happens to be the most accessible place in terms of public transportation. Therefore, this worker would later move to the city while keeping the job outside the city. Also contributing to the decision to move to the city of Paris is that shopping in Paris would become less expensive, as already described. In the end, such decisions made by homeowners and renters would result in an increase of 2,642 in the population of the city of Paris. As shown in Table 6, the populations of the CDTs and the suburbs would shrink by 359 and 1,098, respectively. In addition, the region would attract 1,186 new residents from the exurbs.

What would be the change in real output? First, the lowered price in the city of Paris would stimulate consumer demand. Second, shoppers whose residences are located outside the city and who, encouraged by the reduced travel cost, acquire a transit pass would become more likely to make trips to Paris and to shop there. Third, with the flat-fare pass, PT riders would be left with more disposable income and, therefore, would consume more, given that commodities are normal goods. Consequently, as shown in Table 6, real output in the city of Paris, driven by growing demand, would increase by 0.05%. In the CDTs and the suburbs, because wage rate rises and the flat-fare pass has left PT riders with more disposable income, demand would grow and so would real output. The aggregate real output in the region would increase by 0.05%. As both price and output increase, GDP in the CDTs and the suburbs would increase by 0.12% and 0.09%, respectively. GDP in the city of Paris would fall despite the growth in output, because lowered prices reduce the value of the product. Overall, GDP for the entire region would grow by 0.03%.

Table 6 also shows the changes in rent. The average residential rent would increase in all three areas, because the consumer's ability to pay increases with disposable income. Commercial rent would rise in the CDTs and the suburbs, partly because the growth in real output would raise the demand for floor space and partly because the slightly higher wage would trigger producers to substitute floor space for labor, which also would drive up demand for floor space. In Paris, however, commercial rent would fall, because lower product prices would depress the marginal value of floor space so that the factor compensation, or rent, would decrease. In addition, the wage rate drop in Paris would drive firms to substitute labor for floor space, which would provide further downward pressure on commercial rent in Paris. Overall, the average rent in the region would increase by 0.04%.

As average rent rises, the expected returns from real estate investment also rise, leading to higher real estate values. Developers would respond to rising property values by building 155,191 square meters of residential floor space and 30,673 square meters commercial floor space. This construction would convert 39,878 square meters of vacant land to buildings.

Finally, we examine the flat-fare pass's effects on welfare and its components (see Table 10, "Baseline" column). First, as already discussed, the real estate value per person would increase by 6 €. Second, PT revenue per person would decrease by 28 €. Note that the revenue from transit passes would drop by 14.9%, while the revenue from transit tickets would increase by 1.1%. The revenue from tickets would increase because, given that the ticket price is unchanged, ticket buyers, who are unemployed consumers, respond to the lower prices in Paris by shopping there more, which requires more trips. Overall, PT revenue decreases by 9%, or approximately 258 million euros. Finally, compensating variation is positive because A) consumption by the average consumer rises (recall that real output increases), B) the average consumer's dwelling size increases, and C) the average travel cost decreases. Altogether, the changes in property value, PT revenue, and compensating variation mean that welfare per person increases by 82 € due to the introduction of the flat-fare pass.

Table 8: Commuting Pattern, Change of Number of Work Trips per Day.

Origin (Res.)	Destination (Job)	Commuting Pattern (Daily Trips)				
			Mode Elasticity Baseline = -0.8		Travel Cost Elasticity Baseline = 0.2	
		Baseline	**-0.27**	**-2.4**	**0**	**0.6**
	Paris	-4,484	-5,285	-4,021	-1,263	-11,039
Paris	**CDTs**	3,693	3,741	2,847	1,182	8,645
	Suburbs	2,864	2,837	2,054	863	6,828
	Paris	3,648	4,077	2,881	925	11,577
CDTs	**CDTs**	-2,596	-2,983	-1,411	-588	-3,478
	Suburbs	-1,197	-1,433	-644	-294	-9,408
	Paris	4,956	5,269	4,205	1,438	126,517
Suburbs	**CDTs**	-1,513	-1,774	-1,321	-543	-41,552
	Suburbs	-4,185	-3,500	-3,136	-1,199	-86,018
In-and-Out Paris		**15,161**	**15,924**	**11,987**	**4,408**	**153,567**
TOTAL		1,187	948	1,454	521	2,071

Table 9: PT Revenue under Different Choice Elasticities of Transportation Mode with Respect to Travel Cost and PT Revenue Elasticities with Respect to "Transit Price."[3]

	Baseline	**Triple Mode Choice Elast.**	**One Third Mode Choice Elast.**
Price Change	-9.4%	-9.4%	-9.4%
Pass Revenue	-14.9%	-13.8%	-15.5%
Ticket Revenue	1.1%	2.3%	0.4%
Total Revenue	-9.0%	-7.9%	-9.6%
Revenue Elasticity with respect to Price	0.96	0.84	1.02

[3] The row "Price Change" is calculated using fixed trip matrix. The rest are calculated using endogenous trip matrix generated by the model.

Table 10: Welfare

Welfare	Baseline	Mode Choice Elast.		Location Choice Elasticity	
	Baseline	-0.27	-2.4	0	0.6
CV	105 €	80 €	130 €	41 €	236 €
Value	6 €	10 €	3 €	12 €	-8 €
Revenue	-28 €	-30 €	-25 €	-28 €	-28 €
Welfare	82 €	61 €	109 €	25 €	199 €

4. Effects of the Key Elasticities

4.1. The Elasticity of Mode Choice with Respect to Travel Cost

In Section 3, we mentioned that the magnitude of the market adjustments and the change in PT revenue caused by the introduction of the flat-fare pass would depend on the mode choice elasticity, which is defined as the percentage change in the share of PT riders given a 1% change in public transit cost. Consider first the case in which it is very difficult for consumers to switch transportation mode, likely due to poor accessibility to PT in suburban areas. For example, if most of the city population are already taking PT, and if most suburban residents do not have access to PT, then the introduction of the flat-fare pass, or more generally, a PT price reduction, would not appeal to those suburban residents who commute by car. The only way they could take advantage of the less expensive commute would be by moving to the city, where there are PT stations. Thus, only when mode choice is *inelastic* would consumers substitute location for travel. As a result, if mode choice is inelastic, the commuting pattern shift due to lowering the transit fare would be larger. On the other hand, when changing mode is difficult, the introduction of the flat-fare pass would be met with very little increase in ridership; therefore, the loss of PT revenue would be greater than in the case when mode choice is *elastic*.

Given the importance of mode choice elasticity, the first question we ask ourselves is how robust the results are with respect to elasticity changes. To what extent can we generalize the understanding from the current model to models of other metropolitan areas where PT is less accessible, as is typically the case in U.S. urban areas? Alternatively, can we apply our findings from Paris to other places where PT is more accessible? Furthermore, how sensitive is PT revenue to mode choice elasticity? To answer these questions, we change the calibrated value of the mode choice elasticity and simulate the introduction of the flat-fare pass.

Table 11 shows the simulation results when (a) mode choice elasticity is tripled and (b) when mode choice elasticity is reduced to one-third of its baseline value. When mode choice is three times as elastic as the baseline value, more workers would switch to PT, which would cause the overall share of PT riders to rise by 1.35%, about twice the rise in PT share in the baseline simulation (0.67%). Noticeably, because the flat-fare pass favors long-distance rides, PT's share would increase by 6.57% for Paris-to-suburbs trips and by 5.36% for Paris-to-CDTs trips. These increases are more than double the increases in the baseline simulation (2.63% and 2.2%, respectively). At the same time as PT is becoming more popular for long-distance trips, its shares for local trips would decrease by more than in the baseline simulation. In particular, PT share would decrease by 0.84% for Paris-to-Paris trips and by 0.44% for CDT-to-CDT trips. This outcome is not surprising, because the flat-fare pass makes some local PT trips more expensive. In short, when mode choice is very elastic, switching between PT and car would become more polarized, which suggests a more balanced and efficient use of PT facilities. In addition, given further reduced road congestion, the average auto time would decrease (-1.33%) by more than in the baseline simulation. Gasoline consumption would decrease by 2.98%, approximately twice as much as in the baseline simulation. On the whole, the changes in the magnitude of market adjustments are moderate given the drastic changes in mode choice elasticity.

Another important question is what would be the change in PT revenue when mode choice is more elastic. Because the increase in PT ridership is greater with the higher mode choice elasticity than with the baseline mode choice elasticity, part of the PT revenue loss would be compensated for by the increased demand for PT. Similarly, when mode choice elasticity is reduced to one-third of its baseline value, PT revenue would drop by more than in the baseline simulation, because PT demand is less sensitive to the fare. Although the directions of the changes are hardly surprising, what concerns policymakers is the magnitude of the changes. Table 9 shows the changes in PT revenue given various mode choice elasticities. Before we look at the results, a clarification is in order. How do we define the change in price that is caused by the introduction of the flat-fare pass? The difficulty is that, before the flat-fare pass, the cost of PT varies by location. To overcome this issue, we use the fixed-base trip matrix to calculate the PT revenue from the zone-based pass and the PT revenue from the flat-fare pass, and we then calculate the percentage difference between those (-9.4%) as the average price change. Except for this calculation of average price change, all other revenue changes shown in Table 9 are calculated using the origin-destination matrix that is endogenously generated by the model.

As shown in Table 9, under all three elasticities, the introduction of the flat-fare pass causes PT revenue to fall. Moreover, the directions of the change agree with intuition: revenue loss is the smallest when the mode choice is the most elastic and is the largest when the mode choice is the least elastic. Nonetheless, the variation in PT revenue caused by varying elasticities is small, from -7.9% in the most elastic scenario to -9.6% in the least elastic scenario. The point elasticity of PT revenue with respect to fare, the percentage change in PT revenue in response to a 1%

change in fare, also varies very slightly with respect to mode choice elasticity. The change in revenue is not sensitive to the change in fare, because PT demand is *inelastic*. These comparisons suggest that the results of this study are robust across a wide range of mode choice elasticities and that PT revenue would always fall as a result of lowering the fare.

Why is demand for PT so inelastic with respect to fare? In particular, it may seem paradoxical that the elasticity of choosing PT with respect to own *generalized cost* is 0.8, which means that a 1% decrease in generalized cost would lead to a 0.8 percent increase in the share of PT ridership. The explanation is that both monetary cost and time cost are valued by riders. Given that PT is the slower mode of transportation, a consumer's willingness to use PT is constrained by the desire to save time, even when the monetary cost of riding is reduced. Therefore, policymakers should realize that lowering the monetary cost is most likely insufficient to promote PT ridership. To achieve substantial increase in PT ridership, service time must be shortened, either by increasing service frequency in the short run or by improving route density and infrastructure investment in the long run, to motivate more consumers to switch.

Table 8 shows the commuting pattern changes for various mode choice elasticities. These results reveal the substitution of travel and location. Consider the case in which switching mode is easy, that is, when mode choice is most elastic. Some suburban residents who previously drove to work would simply switch to PT in order to save money, because the introduction of the flat-fare pass lowers the cost of taking PT. In doing so, they would not need to change work or residential locations. This is likely to be the case when workers have good access to the PT system, namely, when there are stations near both the residential location and the workplace, and the travel time via PT is not too long compared to the travel time via car. Such is the situation in which many consumers could benefit from the flat-fare pass without relocating. On the other hand, consider the case in which mode choice is least elastic. Suppose a consumer lives and works in the CDTs, and there are PT stations near the consumer's home but not near his or her workplace. In this circumstance, the consumer may consider finding a new job at a location that can be reached by PT. Alternatively, consider another consumer whose job is close to a PT station and who lives in a sparsely populated area where there is no PT service. In order to save commute costs by taking PT, the consumer would need to move to a location where there is convenient access to PT. Because the city of Paris is the most accessible location in terms of PT, the first consumer in the inelastic mode choice case may end up finding a new job in the city, while the second consumer may move to live in the city. Thus, when mode choice is inelastic, the change in commuting pattern caused by the change in fare would be greater, and when mode choice is elastic, the opposite is true. The above reasoning is substantiated by the simulation results shown in Table 8, which show that commutes into and out of the city of Paris increase the most when mode choice is inelastic, and vice versa.

4.2. The Elasticity of Location Choice with Respect to Travel Cost Disutility

In the RELU-TRAN Paris model, consumer utility is affected by travel cost in three ways: (a) consumption — when travel is less expensive, the consumer shops and consumes more; (b) income — when travel is less expensive, employed consumers have higher disposable income after paying commute expenses; (c) shorter commute time and lower commute cost. The travel cost disutility — the average cost that takes into account both the time cost and the pecuniary cost of PT or car — directly enters into the RELU utility function. In this subsection, we study the last of the above three ways in which consumer welfare is affected by the transit fare change. In particular, we examine the robustness of the model's results with regard to consumer sensitivity to travel cost. At one extreme, suppose that an employed worker does not care about travel cost per se and that transit fare affects the consumer through only disposable income and consumption. Would the introduction of the flat-fare pass still improve such a consumer's welfare?

To answer this question, we set to zero the elasticity of the consumer's location choice with respect to commute cost. In this case, the worker's location preference does not directly depend on commute cost. Therefore, when PT is made cheaper by the flat-fare pass, instead of moving or relocating, many workers would choose to stay put, at least initially. As in the baseline simulation, with the introduction of the flat-fare pass, those workers who can easily switch to PT, without relocating, would do so in order to save commute costs. Such savings would leave them with higher disposable income, which, in turn, would boost demand for goods and residential floor space. Unlike in the baseline simulation, in which workers' moving to Paris would lead to a slight drop in the wage rate overall, the lack of consumer sensitivity to commute costs in this simulation would blunt the spatial shift in employment, and growing consumption would increase labor demand and thus increase the wage rate. Moreover, the increase in real estate value per person in this simulation is double that in the baseline simulation. With the weaker reshuffling of the labor market and, therefore, an increase rather than a decrease in the wage rate, the income effect is stronger in this simulation than in the baseline simulation. Such an increase in income would cause demand for floor space to rise, which would then drive up rents and floor-space prices. The changes in average wage rate, rent, production, and output price as for various travel cost elasticities of location choice are reported in Table 12.

Table 11: Effects of (Transit) Mode Choice Elasticity with Respect to Own Travel Cost

Origin (Res.)	Destination (Job)	Change of PT Share			Number of PT Trips			Auto Time			Average Travel Time			Aggregate Gasoline		
		Mode Elasticity			Mode Elasticity			Mode Elasticity			Mode Elasticity			Mode Elasticity		
		Baseline	-0.27	-2.4	Baseline	-0.27	-2.4	Baseline	-0.27	-2.4	Baseline	-0.27	-2.4	Baseline	-0.27	-2.4
Paris	Paris	-0.13%	-0.01%	-0.84%	-6,341	-3,890	-32,670	-0.83%	-0.44%	-0.96%	-0.25%	-0.09%	-0.67%			
Paris	CDTs	2.20%	0.83%	5.36%	13,822	6,921	28,859	-1.46%	-0.50%	-3.08%	0.31%	0.16%	0.83%			
Paris	Suburbs	2.63%	0.97%	6.57%	15,275	6,823	34,404	-0.68%	-0.30%	-0.36%	0.10%	0.04%	0.52%			
CDTs	Paris	1.82%	0.66%	4.47%	56,370	24,709	131,502	-1.75%	-0.67%	-3.69%	0.19%	0.08%	0.60%			
CDTs	CDTs	-0.03%	0.02%	-0.44%	-1,269	-185	-9,476	-0.52%	-0.24%	-0.41%	-0.19%	-0.03%	-0.56%	-1.50%	-0.67%	-2.98%
CDTs	Suburbs	-0.01%	0.02%	-0.54%	-165	497	-8,338	-0.52%	-0.21%	-0.65%	-0.20%	-0.04%	-0.52%			
Suburbs	Paris	1.89%	0.69%	4.64%	61,806	27,617	142,365	-1.05%	-0.43%	-1.18%	0.05%	0.03%	0.28%			
Suburbs	CDTs	0.12%	0.07%	-0.20%	1,810	1,158	-3,532	-0.53%	-0.20%	-0.70%	-0.13%	-0.02%	-0.35%			
Suburbs	Suburbs	0.11%	0.05%	0.13%	4,238	2,690	5,335	-0.34%	-0.13%	-0.44%	-0.01%	0.02%	-0.01%			
TOTAL or AVERAGE		0.67%	0.27%	1.35%	145,546	66,340	288,450	-0.88%	-0.36%	-1.32%	-0.06%	0.05%	0.020%			

Next, Table 10 shows that when the travel cost elasticity of location choice is zero, the positive compensating variation and the gain in real estate value would offset the decrease in PT revenue, resulting in a 25 € average welfare gain on a per person basis. Thus, when travel cost is absent from the worker's utility function, welfare would still improve following the drop in transit fare. The important implication of this sensitivity analysis is that the validity of the prediction that the flat-fare pass improves welfare does not depend on strong consumer preference for inexpensive travel per se. Therefore, the merit of the introduction of a flat-fare pass, or more generally, the merits of inexpensive PT, is reminiscent of that of a cut in the personal income tax rate. It would leave the consumer with higher disposable income, and therefore would boost demand, production, and real estate values.

At the other extreme, if the consumer is very sensitive to travel cost disutility, namely, if the travel cost elasticity of location choice is very high, would the model's predictions change drastically? To answer this question, we triple the travel cost elasticity from its baseline value. That is, for an employed consumer, the effect of travel cost on utility, given the worker's choice of residence location and workplace, is three times as large as in the baseline simulation. Under these conditions, when the flat-fare pass is introduced, more workers would respond to the policy by moving or finding a new job, by which they could save commute costs. Because the flat fare favors long-distance trips and causes the costs of some local trips to rise, commutes into and out of the city of Paris would increase by ten times as much as in the baseline simulation. This can be seen in Table 8, which shows the changes in commuting pattern in various scenarios. The average wage rate in Paris would fall by 0.81%, precisely three times as much as in the baseline simulation. Because Paris accounts for roughly one-third of all jobs in the region, the region's average wage rate would also decrease more than in the baseline simulation, offsetting the positive income effect associated with lower travel cost. Demand for floor space and demand for final goods, therefore, would decrease, although only slightly. Furthermore, in Paris, commercial rents would decrease, because firms would substitute low-cost labor for capital, thereby reduce the demand for floor space. Residential rents in Paris would also fall, because the declining disposable income would depress demand for housing. Real estate values would fall due to the reduction in rents. Thus, when location choice is very elastic with respect to the travel cost, the very factor that causes greater spatial shift in the labor market would also make inexpensive travel more valuable to the consumer. The compensation of the lowered fare to consumer utility would offset the negative income effect of the reshuffling of labor markets. In this sense, the effect of location choice elasticity with respect to travel cost is self-stabilizing: The adverse outcomes caused by the flat fare are always compensated for by the satisfaction it provides. A less expensive commute, therefore, improves welfare in its own right.

Table 12: Effects of the Location Elasticity w.r.t. Travel Cost

	Wage			Price		
	Location Elasticity w.r.t. Travel Cost			Location Elasticity w.r.t. Travel Cost		
	Baseline	0	0.6	Baseline	0	0.6
Paris	-0.27%	-0.02%	-0.81%	-0.14%	0.00%	-0.47%
CDTs	0.07%	0.06%	0.06%	0.06%	0.05%	0.09%
Suburbs	0.08%	0.08%	0.09%	0.05%	0.05%	0.06%
TOTAL	-0.02%	0.05%	-0.16%	-0.02%	0.03%	-0.13%

	Production			GDP			Rent		
	Location Elasticity w.r.t. Travel Cost			Location Elasticity w.r.t. Travel Cost			Location Elasticity w.r.t. Travel Cost		
	Baseline	0	0.6	Baseline	0	0.6	Baseline	0	0.6
Paris	0.05%	0.07%	0.00%	-0.09%	0.07%	-0.47%	0.00%	0.05%	-0.14%
CDTs	0.05%	0.06%	0.01%	0.12%	0.11%	0.09%	0.07%	0.08%	0.05%
Suburbs	0.04%	0.08%	-0.02%	0.09%	0.13%	0.04%	0.06%	0.07%	0.02%
TOTAL	0.05%	0.07%	-0.01%	0.03%	0.10%	-0.13%	0.04%	0.06%	-0.03%

5. Revenue-Neutral Tax Substitution for Public Transit Revenue

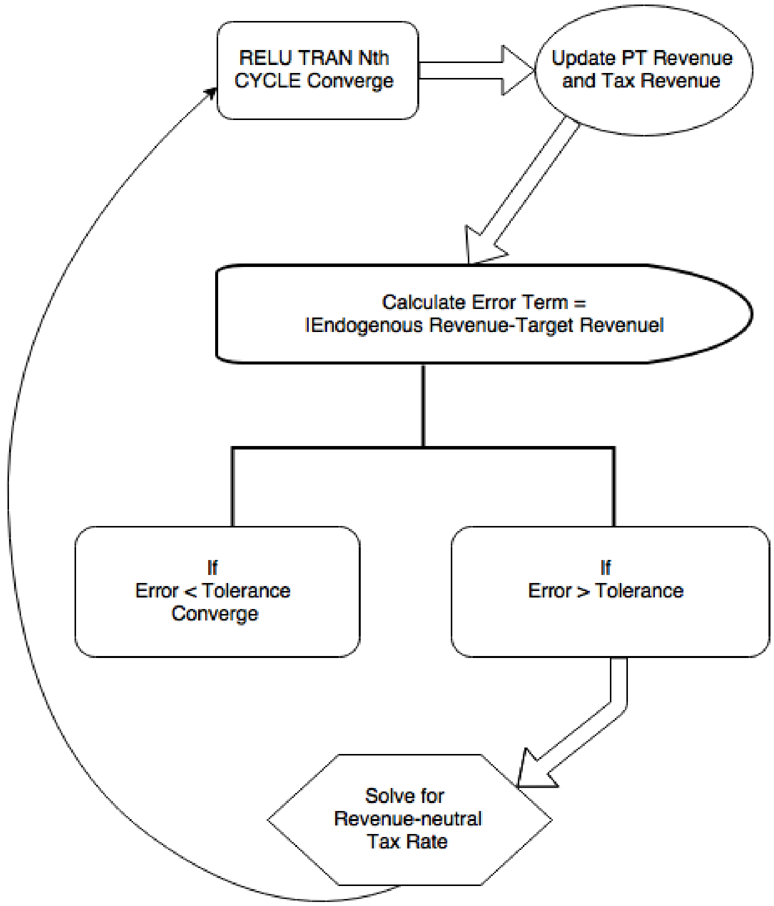
What if, when the flat-fare pass is introduced, the loss of PT revenue is compensated for by sales tax or property tax? Would a revenue-neutral tax substitution improve consumer welfare? In this section, we simulate scenarios in which the loss of PT revenue is compensated for by one of five tax instruments: (a) a regional sales tax, (b) a regional uniform property tax, (c) a property tax in the city of Paris, (d) a property tax in the CDTs, and (e) a property tax in the suburbs. In the remainder of this section, we first report the algorithm for the tax substitutions and then explain the welfare implications associated with them.

5.1 Determining the Revenue-Neutral Tax Rate

We now describe the algorithm for the revenue-neutral tax substitutions. First, we calculate PT revenue based on the base-year trip matrix and the zone-based transit fares. Then, because all tax rates are zero in the baseline simulation, we simply set the base-year PT revenue — the pre-flat-fare PT revenue — as the target revenue for the tax substitutions.

Figure 3 shows how a particular revenue-neutral tax rate is solved for iteratively. In the first RELU-TRAN cycle, as in every cycle of the RELU-TRAN algorithm, the mode choice probabilities for all origin-destination pairs are updated based on the updated travel costs of each mode. Similarly, the trip matrix and other model variables are updated based on the changes in commuting pattern consumer demand. Based on the updated trip matrix and mode choice probabilities, the updated PT revenue from passes and tickets can be computed.

Figure 3: Revenue-neutral Simulation



Next, at the beginning of the second cycle, the tentative revenue-neutral tax rate is determined as $tax\ rate_T = \dfrac{\overline{\text{target revenue}} - \text{transit revenue}_{T-1}}{\text{tax base}_{T-1}}$, in which the subscript T represents the number of the cycle, $\overline{\text{target revenue}}$ is the target revenue for tax substitution that equals pre-flat-fare PT revenue, and transit revenue is the endogenous post-flat-fare PT revenue. At the end of the second cycle, transit revenue_T and tax base_T are computed based on the updated model variables. This process continues until all of the model variables, including total revenue, converge.[4] The convergence criterion for total revenue (tax revenue and transit revenue) is as follows: $\frac{\left|\overline{\text{target revenue}} - \text{ transit revenue}_T - \text{tax base}_T \times \text{tax rate}_T\right|}{\overline{\text{target revenue}}} < Tolerance$.

5.2. The Relative Sizes of Tax Bases and Public Transit Revenue

Before proceeding to the results of the tax substitution simulations, it is important to understand the relative size of PT revenue vis-a-vis other potential tax bases. Table 13 compares, before and after the institution of the flat-fare pass, PT revenue, base aggregate consumption value, and base aggregate real estate value. With the zone-based fare, PT revenue would be 2.87 billion euros, with 1.82 billion from sales of passes and the remainder from sales of tickets. With the flat-fare pass, as described in Section 3 (see Table 9), when the regional economy and transportation market reach a new equilibrium, revenue would fall by 9%, or 0.26 billion euros. On the other hand, the value of annual consumption (before the fare change) in the region is 246 billion euros, or 65% of GDP. The aggregate real estate value, which serves as the base for property taxation, is 2,240 billion euros. Noticeably, the base PT revenue is only 1.1% of the value of consumption and only 0.13% of the aggregate real estate value.

Due to its relative small size, the loss of PT revenue could be compensated for by marginally raising the rate for any of the five taxes examined here. For this reason, the overall effects of these tax substitutions are small. It is important, however, to understand the directions of the changes in the model variables and the welfare implications of the policies. In particular, this study's findings confirm this author's findings, in his dissertation, in applying RELU-TRAN to

[4] For details of the convergence criteria, see the appendix.

the Greater Los Angeles Area: Sales tax is more efficient than property tax in a second-best environment, at least for modest ranges of the tax rates.

Table 13: Tax Bases, PT Revenue and Revenue Neutral Tax Rates

	CONSUMPTION	PROPERTY	PT REVENUE	
			BASE	FLAT-FARE
Tax Base or Revenue	0.246 Trillion	2.243 Trillion	2.87 Billion	2.61 Billion
% Change of PT Revenue	----------------	----------------	--------------	-9%
Revenue-Neutral Rate	0.107%	0.011%	--------------	--------------

Table 14 shows the changes due to the tax substitution, in terms of annual welfare and its components. The change in welfare is defined as the difference between the welfare level after the introduction of the flat-fare pass but before the tax substitution and the welfare level after the tax substitution. In other words, the change in welfare and its components measures the *pure effect of the tax substitution.* Throughout this section, welfare change refers to the difference between the results from the baseline simulation and the results from the tax substitution simulation. Recall that overall welfare consists of three components: (a) compensating variation, (b) real estate value, and (c) public revenue, which consists of PT revenue and tax revenue. However, by the nature of revenue-neutral tax substitutions, total public revenue remains at its pre-flat-fare level regardless of which of the tax instruments is used to compensate for the PT revenue loss. Namely, the tax substitution policy always increases the revenue component of overall welfare, compared to its level after the introduction of the flat-fare pass but before the tax substitution. The other two components of welfare, in contrast, always decrease due to the tax substitution policy.

Table 14 shows that only the regional sales tax improves overall welfare; each of the four property tax scenarios lowers welfare. As shown in Table 14, all taxes, to varying extents, reduce consumer utility, which is reflected in negative compensating variations, and depress real estate values. In the remainder of this section, we examine each tax substitution scenario in detail.

Table 14: The Pure Effect of Revenue-Neutral Tax Substitutions - Welfare

WELFARE CHANGE	BASELINE	Welfare Changes ***Against Baseline***				
		PROPERTY TAX WHOLE REGION	PROPERTY TAX PARIS	PROPERTY TAX CDTS	PROPERTY TAX SUBURBS	SALES TAX
CV Per Person	104.65 €	-2.05 €	-0.66 €	-4.46 €	-3.25 €	-0.08 €
Value Change Per Person	5.79 €	-29.44 €	-33.70 €	-24.91 €	-25.45 €	-1.43 €
PT Revenue Change	-28.10 €	0.005 €	0.002 €	0.011 €	0.005 €	-0.43 €
Tax Change	0.00 €	28.43 €	28.42 €	28.44 €	28.43 €	28.52 €
Welfare Change	82.34 €	-3.06 €	-5.94 €	-0.92 €	-0.26 €	26.58 €

5.3. Sales Tax

Recall that in the baseline simulation introducing the flat-fare pass would cause PT revenue to fall by 9%. This reduction in revenue, however, could be compensated for by an increase of only 0.107% in the sales tax rate (see Table 13).

Table 15: **The Pure Effect of Revenue-Neutral Tax Substitutions – Public Transit Revenue and Trips (All Purposes)**

	PROPERTY TAX	SALES TAX
ALL TRIPS	0.002%	-0.019%
PT TRIPS	0.002%	-0.021%
Pass Revenue	0.002%	-0.012%
Ticket Revenue	0.002%	-0.020%
Total PT Revenue	0.002%	-0.015%

Because the increase in sales tax elevates the gross prices of consumption goods, consumer demand would drop. Less shopping, in turn, would require fewer trips. As Table 15 shows, the number of non-work trips would decrease, which would reduce the total number of trips by 0.019%. In addition, the percentage reduction in the number of PT trips would be slightly greater than the percentage reduction in the number of total trips (by all modes). The reason for this result is that with less travel demand, road congestion would be alleviated, and therefore the cost of traveling by private car would be reduced. At the margin, some consumers would switch from PT to car. Fewer PT trips would also lead to less PT revenue. Table 15 shows that the revenue from passes and tickets would decrease by 0.012% and 0.02%, respectively. The overall percentage decrease in PT revenue, however, would be smaller than that the percentage decrease in the number of PT trips. The reason for this result is that transit riders who acquire flat-fare passes and who make fewer trips due to the higher sales tax would have two margins of adjustment: the number of trips, given that they continue to use the passes, and the choice of whether to switch to back to car transportation, because less frequent use of the flat-fare pass makes it uneconomic. The adjustments in the first margin would not affect PT revenue, because those consumers would still purchase the passes. Only the adjustments in the second margin would reduce PT revenue. This decrease in PT revenue would be inconsequential in the present model, because, by design, the tax substitution is revenue-neutral. In general, though, when public revenue is not intentionally maintained at a certain level, such a decrease—however small—in PT revenue would reflect a *tax-interaction effect* in a second-best world in which more than one distortionary tax is at work.

We now turn to the effects of the sales tax increase on the regional economy. Because the increase in the sales tax would dampen consumer demand, production would decrease. From a different perspective, one could say that production would decrease because consumers and firms would share the burden of the sales tax increase. The reduced production would lead to less factor demand, which, in turn, would drive down wage rates. With regard to rents, forces would work in opposing directions. As the higher sales tax causes the gross prices of goods to rise, consumers would substitute residential floor space for consumption. The increase in housing demand then would cause rents to rise, and, over time, the value of residential buildings to rise. In the long run, the higher rent would encourage more construction of apartment buildings and houses. Some of the residential construction would be done by demolishing commercial buildings and replacing them with apartments and houses. Such indirect conversions would slightly reduce the supply of commercial floor space and would shore up commercial rents, which otherwise would be depressed by the lowered factor demand. Moreover, the initial increase in residential rents would be constrained by the decrease in disposable income caused by decreased wages. Eventually, these opposing forces would cancel out each other, and the net change in rents would be negligible.

Table 16: The Pure Effect of Revenue-Neutral Tax Substitutions – Wage and Real Output

WAGE	PROPERTY TAX	SALES TAX
PARIS	0.006%	-0.013%
CDT	0.009%	-0.015%
SUBURBS	0.005%	-0.012%
OVERALL	0.006%	-0.013%
OUTPUT		
PARIS	0.003%	-0.013%
CDT	0.001%	-0.017%
SUBURBS	0.002%	-0.020%
OVERALL	0.002%	-0.016%

In Table 14, the rightmost column shows the pure effect of the sales tax substitution. Although the fall in consumption lowers consumer utility (-0.08 €), the drop in rents reduces real estate value (-1.43 €), and the decline in travel demand decreases PT revenue (-0.43 €), these negative effects are relatively small compared to the public revenue generated by the sales tax increase (+28.52 €). Therefore, among the five tax substitution scenarios, the policy of increasing the regional sales tax to compensate for lost PT revenue yields the only positive welfare gain (26.58 €).

5.4. Uniform Regional Property Tax

Suppose that a uniform property tax were implemented or increased to maintain public revenue at its pre-flat-fare pass level. How would the market adjust? As in the case of a sales tax increase, because the base for property taxation is also very large compared to the reduction in PT revenue, the required increase in the property tax would be tiny (0.011%). The small rate increase indicates that its overall effect on the equilibrium would be small. Even so, it is meaningful to understand the consequential changes in the model variables and the reasons for those changes. After the property tax increase is introduced, in the short run, because buildings are durable, there would not be enough time to complete demolition and new construction; therefore, real estate investors would bear the full burden of the property tax increase. In the long run, because buildings bear heavier tax burdens than does vacant land, the rise in investment cost would cause the floor-space price to fall relative to the land price. Over time, more buildings would be demolished than would be built, and the building stock would decrease. Table 17 shows the change in building stock in each of the four property tax scenarios. Note that floor space in the city of Paris cannot change, because demolition is not allowed in the city and no vacant developable land is available for new construction. Due to the regional property tax increase, both residential and commercial floor space would decrease in the CDTs and in the suburbs. Because the total population in the region remains constant and the production level is initially unaltered by the property tax increase, demand for floor space would be unchanged initially. Given the shrinking supply of and the stable demand for floor space, rents would rise. The increasing residential rent would cause consumers to substitute goods for housing, which would increase consumer demand and the number of shopping trips (see Table 15). Similarly, the increasing commercial rent would cause firms to substitute labor for floor space. Thus, the wage rate would increase slightly. Real output, driven by growing consumer demand, would grow, again slightly. Although the consumer would enjoy a small increase in consumption, the increased rent would affect consumer utility more strongly and directly so that the compensating variation would become negative (-2.05 €). More importantly, the regional property tax would cause annual real estate income to fall by more than the gain in tax revenue. Unlike the sales tax scenario, in the regional property tax scenario the welfare cost of the tax increase would be greater than the associated tax revenue. Therefore, compensating for the lost PT revenue by levying or increasing uniform regional property tax would make consumers worse off.

Table 17: The Pure Effect of Revenue-Neutral Property Taxes – Floor Spaces

Change of Floor Spaces	BASELINE SIMULATION	Change in Building Stocks ***Against Baseline***			
		PROPERTY TAX WHOLE REGION	PROPERTY TAX PARIS	PROPERTY TAX CDTs	PROPERTY TAX SUBURB
HOUSING					
CDT	73,220	-26,283	0	-145,653	9,999
SUBURBS	81,970	-32,818	0	10,675	-95,174
TOTAL	155,190	-59,101	0	-134,978	-85,175
COMMERCIAL					
CDT	16,623	-47,342	0	-248,426	595
SUBURBS	14,050	-47,597	0	1,790	-136,662
TOTAL	30,673	-94,939	0	-246,636	-136,067

5.5. Local Property Taxes

We now turn to the local property tax scenarios. The revenue-neutral property tax can be levied in only one of the three areas at a time; therefore, there are three scenarios: (a) property tax only in the city of Paris, (b) property tax only in the CDTs, and (c) property tax only in the suburbs. Although the differences in results among these three scenarios are subtle, it is important to examine how the characteristics of each area give rise to such differences.

In the city of Paris, because construction and demolition are not allowed, real estate investors would bear the full burden of the tax. Therefore, levying a local property tax in Paris would yield the largest decrease in annual real estate income. In addition, because the building stock cannot adjust in response to the change in floor-space price, the tax burden cannot be passed on to the real estate rental market and therefore would not cause rents to rise. Thus, the Paris property tax scenario would generate the smallest decrease in consumer utility. Therefore, in terms of consumer utility alone, a city property tax would be neutral because of the inelasticity of the supply of floor space. However, as shown in Table 14, after taking into account the other components of welfare, the relatively sharp fall in real estate value would dominate, which makes the Paris property tax scenario the least efficient.

In the CDTs and suburbs, the supply of floor space can change over time, because existing buildings can be demolished to create vacant land and new buildings can be constructed on vacant land. Because the local property tax would lower the floor-space price relative to the price of vacant land, more buildings would be demolished, because real estate investors would rather invest in vacant land in order to avoid the higher property tax. At the same time, less new floor space would be built. Table 17 shows that in the scenarios for local property tax in the CDTs or the suburbs, the reductions in floor space would be the largest of the five tax substitution scenarios. In particular, if the property tax were levied in the CDTs, floor space would decrease in the CDTs but would increase in the suburbs. The reason for this result is that the tax would cause building stocks in the CDTs to shrink, which would drive up rents in the CDTs. Facing increasing rent in the CDTs, some residents and firms would move to the city or the suburbs. Such a shift in labor supply and production, in turn, would boost the demand for floor space in the suburbs and cause suburban rents to rise as well. In response to increasing rents, investors would invest more in construction in the suburbs and suburban floor space would increase. Similarly, if the local property tax were levied in the suburbs, floor space would decrease in the suburbs but increase in the CDTs.

Because the local property tax in the CDTs or the suburbs would drive up rent everywhere, a portion of the tax burden would be shifted from real estate investors to renters. Therefore, the decreases in real estate values in these scenarios would be smaller than those in the other two property tax scenarios. In addition, due to the rent increase, consumer utility would suffer more in the CDTs and suburbs property tax scenarios than in the other two property tax scenarios. The changes in real estate value and consumer utility are shown in Table 14. Therefore, to compensate for the PT revenue lost by the introduction of the flat fare, a property tax in the CDTs or in the suburbs would be more efficient than a regional property tax or a property tax in the city of Paris. The main reason for this result is that when the elasticity of construction with respect to real estate value is higher, as in the case of property tax in the CDTs and property tax in the suburbs, the negative effect of the tax on real estate value would be mitigated by the adjustments in floor space. In other words, the tax would be "smoothed over" by the shift of a portion of the tax burden from real estate investors to renters.

Appendix: The RELU-TRAN Paris CGE Model (Table 2)

While Table 2 has given us an intuitive description of the model structure of RELU-TRAN, it remains to detail the economic agents and their profit/utility maximization behaviors (for a most detailed introduction of the model, see Anas and Liu, 2007). The players in the economy include consumers, competitive firms and competitive real estate developers, and the government, which could raise taxes and determine the public transit fares exogenously. RELU (regional economy and land use submodels) generates the locational patterns of residences and firms, and the trip matrix that includes both commute and shopping. RELU then passes the trip matrix to the TRAN submodel in which the traffic equilibrium, mode choice, congested travel time and cost are calculated for each OD pair. Then, RELU takes the output of TRAN as input and re-equilibrates; subsequently a new locational pattern and a trip matrix are generated. Such RELU-TRAN cycle goes on until a global equilibrium is reached.

A.1. Consumers, Demand for Goods, Housing, and Travel

Consumers maximize utility in two steps. First they choose the discrete bundle (i, j, k, s), where $i = 1,...,54$ residence zones, $j = 0,1,...,50$ employment zones and $j = 0$ stands for being unemployed, $k = 1,2$ housing types (single family, multiple family structure), and $s = 1,2$ employment sectors (private, public). Conditional on choosing the discrete bundle, consumers choose the continuous consumption bundle to maximize utility:

$$\max_{\forall(i,j,k,s)} U_{ijks} = \alpha_{ik} \cdot \ln\left(\sum_{zr} \iota_{rzi} \cdot \left(Z_{zr|ijks} \right)^{\sigma} \right)^{\frac{1}{\sigma}} + \beta_{ik} \ln(h_{ijks}) + \gamma_1 \ln\left(G_{ij}\right) + \gamma_2 IV_{ij} + e_{ijks}$$

$$s.t. \quad \left(d \cdot H \cdot w_{js} + m_i - d \cdot g_{ij} \right) \geq \sum_{zr} \left(p_{zr} + s_{iz} \cdot g_{iz} \right) Z_{zr|ijks} + R_{ik} h_{iks}$$

where $Z_{zr|ijks}$ is the Marshallian demand for goods produced by industry r in zone z from a consumer who chose the bundle (i, j, k, s); ι_{zri} the constant effects of goods produced by industry r in zone z on consumers live in zone i; h_{ijks} the Marshallian demand for housing floor space; α_{ik} and β_{ik} the expenditure shares of goods and housing, with $\alpha_{ik} + \beta_{ik} = 1$; σ the parameter of the elasticity of substitution of the CES sub-utility of consumption goods; G_{ij} the over-mode average travel time between i and j; IV_{ij} the distance disutility which takes into account both time and monetary costs; e_{ijks} the idiosyncratic taste bias for the discrete bundle; d and H the number of days and hours an employed person works in one year; w_{js} the hourly wage rate; m_i the nonwage income and g_{ij} the over-mode average monetary cost of travel; p_{zr} the mill prices and s_{iz} the number of trips required for the purchase of each unit of goods.

The budget constraint says that, on a yearly basis, the sum of the wage income and nonwage income less commute cost is no less than the sum of the expenditure on goods purchased from all places in both industries and the expenditure on housing. Note that for an unemployed person, both wage income and commute cost are zero.

The Marshallian demand for goods hence can be derived:

$$Z_{zr|ijks} = \frac{\iota_{rzi}^{\frac{1}{1-\sigma}} p_{rzi}^{\frac{1}{\sigma-1}}}{\sum_{\forall s,n} \iota_{sni}^{\frac{1}{1-\sigma}} p_{sni}^{\frac{\sigma}{\sigma-1}}} \alpha_{ik} M_{ijs}$$

in which $p_{rzi} = p_{zr} + s_{iz} \cdot g_{iz}$ is the unit price inclusive of travel cost and $M_{ijs} = d \cdot H \cdot w_{js} + m_i - d \cdot g_{ij}$ the annual disposable income. Similarly, the Marshallian demand for housing is:

$$h_{ijks} = \beta_{ik} \frac{M_{ijs}}{R_{ik}}$$

We can then derive the indirect utility $\tilde{U}_{ijks}$ and assuming $e_{ijks} \sim$ i.i.d. Gumble with dispersion parameter λ, it follows that the probability of choosing a particular discrete bundle can be given by:

$$P_{ijks} = \frac{e^{\lambda \tilde{U}_{ijks}}}{\sum_{zntr} e^{\lambda \tilde{U}_{zntr}}}, \qquad \sum_{ijks} P_{ijks} = 1$$

Finally, the travel demand is given by:

$$TRIP_{iz} = d \sum_{ks} NP^e P_{izks} + s_{iz} N \left[P^e \sum_{rks,\, j>0} P_{ijks} Z_{zr|ijks} + \left(1 - P^e\right) \sum_{rks,\, j=0} P_{ijks} Z_{zr|ijks} \right]$$

in which N and P^e are the exogenous population, and the portion of the employed, respectively. The first term on the right-hand side is travel demand arises from commuting; the $N \cdot [\bullet]$ part of the second term is the quantity demanded for goods sold in zone z from consumers live in zone i, multiplied by the number of trips required per unit of goods s_{iz}, the second term on the right-hand side is the annual shopping trips.

A.2. Firms, Demand for Labor and Commercial Floor Space

The production function of competitive firms is given by:

$$X_{rj} = A_{rj} K_{rj}^{\nu_{rj}} \left(\sum_f \kappa_{f|rj} L_{jf}^{\theta_r} \right)^{\frac{\delta_{rj}}{\theta_r}} \left(\sum_k \chi_{k|rj} B_{jk}^{\varsigma_r} \right)^{\frac{\mu_{rj}}{\varsigma_r}} ,$$

where X_{rj} is the output of firms in industry $r = 1, 2$ (private, public) in model zone $j = 1, ..., 50$; A_{rj} the local TFP; $K_{rj}^{\nu_{rj}}$ the capital of which supply is perfectly elastic; $L_{jf}^{\theta_r}$ the labor input ($f = 0$ represents the workers employed from outside the region by local firms); $B_{jk}^{\varsigma_r}$ the commercial floor space used in production with $k = 0, 3, 4, 5$ (floor space from outside the region, offices, stores, and industrial/public); $\nu_{rj} + \delta_{rj} + \mu_{rj} = 1$ the outer nest expenditure share parameters of the CRS Cobb-Douglas production; θ_r and ζ_r the inner nest elasticity of substitution parameters of the CES production of each type of input; $\kappa_{f|rj}$ and $\chi_{k|rj}$ the constants representing inherent attractiveness of inputs. Firms minimize cost taking as given demand from consumers and factor prices. Therefore, factor demand for labor and commercial floor space can be solved from cost minimization problem:

$$LD_{js} = \frac{\kappa_{sj, f=1}^{\frac{1}{1-\theta_s}} w_{js, f=1}^{\frac{1}{\theta_s - 1}}}{\sum_f \kappa_{f|sj}^{\frac{1}{1-\theta_s}} w_{fjs}^{\frac{\theta_s}{\theta_s - 1}}} \delta_s p_{sj} X_{sj} \quad ,$$

$$FD_{jk} = \sum_{s=1,2} \frac{\chi_{k|sj}^{\frac{1}{1-\zeta_s}} R_{ik}^{\frac{1}{\zeta_s - 1}}}{\sum_{k=0,3,4,5} \chi_{k|sj}^{\frac{1}{1-\zeta_s}} R_{ik}^{\frac{\zeta_s}{\zeta_s - 1}}} \mu_s p_{sj} X_{sj} \quad ,$$

A.3. Developers, Construction and Demolition of Floor Space

Developers are assumed to have perfect foresight in the sense that they look forward five years at a time, and the values at the end of the five-year period fully reflect the future. This is a simplified version of Anas and Arnott (1997). Developers behave as profit-maximizing firms in a perfectly competitive market. The developers who own undeveloped land face the binary choice of either keeping the property as it is, or building it into one of the five types of structures in the model; the developers who own structures also face a binary choice of either keeping the structure, or tearing it down so that the property will become vacant developable land that may or may not be developed in the future. The profit function for developers who own vacant lot is given by:

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

$$\Pi_{i0k} = \left(\frac{1}{1+\rho}\right)^5 \left(V_{ik} - p_{i0k}\right) m_{ik} - \mathbb{C}_{i0k} + \varsigma_{i0k} - V_{i0} ,$$

where Π_{i00} is the profit of developers in zone i who choose to keep the undeveloped land as it is; ρ the interest rate; V_{ik} the per square meter value of the type-k property, and $k=0$ stands for undeveloped (vacant) land; $\mathbb{C}_{i0k}$ the financial cost of construction; p_{i0k} the construction cost of type-k structure; m_{ik} the exogenous structure density, otherwise known as the floor to area ratio; and finally ς's the idiosyncratic random costs that follow i.i.d. Gumbel distribution with location parameter equals zero and the dispersion parameter Φ_{i0}. The equation of Π_{i00} states that the profit of keeping vacant land equals the present value of the floor-space price, less the acquisition (this can be thought of as developers purchase the property at the beginning of each period at the cost of V_{i0}, or that the opportunity cost of owning the property is V_{i0}) and financial costs and plus the idiosyncratic random effect. The equation of Π_{i0k} states that the (per square meter) profit of converting a vacant lot into type-k structure equals the present value of the floor space less the costs plus the random effect, only now the floor-space price is $(V_{ik} - p_{i0k})m_{ik}$. This is because for each square meter of the type-k floor, it costs p_{i0k} to build, and each unit of vacant land will be converted into m_{ik} unit(s) of floor. Similarly, the profit function of the developers who own existing buildings is given by:

$$\Pi_{ik0} = \left(\frac{1}{1+\rho}\right)^5 \left(\frac{V_{i0}}{m_{ik}} - p_{k0}\right) - \mathbb{C}_{ik0} + \varsigma_{ik0} - V_{ik}$$

$$\Pi_{ikk} = \left(\frac{1}{1+\rho}\right)^5 V_{ik} - \mathbb{C}_{ikk} + \varsigma_{ikk} - V_{ik},$$

in which Π_{ik0} is the profit of choosing to demolish an existing structure and Π_{ikk} the profit of keeping the structure. Note that after demolition, each unit of building structure will become $1/m_{ik}$ unit(s) of vacant land. The equation of Π_{ik0} says that the profit of demolition equals the present value of the converted vacant land less the acquisition cost (or opportunity cost) V_{ik} and the financial cost $\mathbb{C}_{ik0}$ plus the random effect. The equation of Π_{ikk} defines the profit of keeping an existing structure in a similar fashion. With the profit of each choice situation properly defined, a developer who owns vacant land at the beginning of each period will choose to build a type-k building if $\Pi_{i0k} \geq \Pi_{i0t}$, $t = 0,...,5$ and $t \neq k$. The probability that this will occur is given by the polynomial logit:

$$Q_{i0k}\left(V_{i0},V_{i1},...,V_{i5}\right)=\frac{\mathrm{e}^{\Phi_{i0}\left(\left(\frac{1}{1+\rho}\right)^{5}\left(V_{ik}-p_{0k,i}\right)m_{i0k}-\mathbb{C}_{i0k}\right)}}{e^{\Phi_{i0}\left(\left(\frac{1}{1+\rho}\right)^{5}V_{i0}-\mathbb{C}_{i00}\right)}+\sum_{s=1}^{5}e^{\left(\left(\frac{1}{1+\rho}\right)^{5}\left(V_{is}-p_{0s,i}\right)m_{i0s}-\mathbb{C}_{i0s}\right)}} ,$$

where Q_{i0k} is the probability of a unit of vacant land being converted into type-k structure. Note that for any given building, $Q_{i00}+\sum_{k=1}^{5}Q_{i0k}=1$. A developer who owns an existing building at the beginning of each period will choose to demolish if $\Pi_{ik0}>\Pi_{ikk}$, and the probability that this will occur is given by:

$$Q_{ik0}\left(V_{i0},V_{ik}\right)=\frac{e^{\Phi_{ik}\left(\frac{1}{1+\rho}\right)^{5}\left(\frac{V_{i0}}{m_{ik}}-p_{k0}\right)-\mathbb{C}_{ik0}}}{e^{\Phi_{ik}\left(\frac{1}{1+\rho}\right)^{5}\left(\frac{V_{i0}}{m_{ik}}-p_{k0}\right)-\mathbb{C}_{ik0}}+e^{\Phi_{ik}\left(\frac{1}{1+\rho}\right)^{5}V_{ik}-\mathbb{C}_{ikk}}}$$

This is the probability of a type-k building being demolished. By definition, $Q_{ik0}+Q_{i00}=1$.

A.4. General Equilibrium

With the behaviors of all the agents in the economy properly defined, we can put together all the pieces to drive the market equilibrium conditions. The equilibrium conditions in this subsection correspond to the diagonal cells in Table 2.

(A)Rental real estate markets. In each model zone and for each residential type $k=1,2$ demand for housing floor space equals supply:

$$N\left[P^{e}\sum_{s,j>0}P_{ijks}h_{ijks}+\left(1-P^{e}\right)\sum_{s,j=0}P_{ijks}h_{ijks}\right]=S_{ik}q_{ik}$$

in which S_{ik} is the stock of type-k floor space in zone i; q_{ik} the corresponding endogenous occupancy rate that increases with rent. For commercial floor types $k = 3,4,5$ the equilibrium condition is given by:

$$FD_{jk} = S_{jk} q_{jk}$$

in which FD_{jk} is the (factor) demand for type-k floor space in zone j as defined in A.2

(B)Labor markets. While total population in the region is exogenous, workers can choose to work at different locations hence the disaggregated labor supply to each model zone varies with other model variables accordingly:

$$LD_{js} = NP^e dH \sum_{ik} P_{ijks}$$

Local labor demand LD_{js} is derived in A.2. The right-hand side of the equation is the annual local labor supply. $N \cdot P^e$ denotes the number of employed workers in the region and $d \cdot H$ is the annual labor-hour supply of each worker. The summation of consumer choice probabilities over residential location i and residence type k gives us the probability of an employed person in the economy to choose work at zone j for a firm belongs to industry s.

(C)Output markets. The output market equilibrium is given by:

$$X_{rz} = N\left[P^e \sum_{iks, j>0} P_{ijks} Z_{zr|ijks} + \left(1 - P^e\right) \sum_{iks, j=0} P_{ijks} Z_{zr|ijks} \right] + \Xi_{rz} .$$

Notice that the Marshallian demand is derived in A.1, and the conditional supply (of firms located in zone z from industry r) is derived by substituting the factor demands back to the production in A.2. Note that due to CRS technology, the number of firms is arbitrary. Ξ_{rz} is the exogenous demand from outside the region. The Marshallian demand $Z_{zr|ijks}$ is a consumer's demand for goods produced by firm r in zone z conditional on the consumer's choice of the discrete bundle (i, j, k, s). The output equilibrium condition states that at the zone-industry level, total output equals the sum of the demand from consumers in the region and the demand from outside the region.

(D)Stationary-state construction-demolition flows. In stationary equilibrium, stock adjusts so that the construction flow of each type of building in each zone during each period equals the demolition flow:

$$S_{ik}Q_{ik0} = m_{ik}S_{i0}Q_{i0k};$$

by definition, the construction flow is defined as the multiplication of the stock of vacant land S_{i0}, the construction probability Q_{i0k} derived in A.3, and the structural density m_{ik}; the demolition flow is defined in the same spirit as the product of the existing type-k stock in zone i and the demolition probability Q_{i0k} derived in A.3. Moreover, it must hold that in each zone the land taken by all buildings and vacant land add up to the total amount of land J_i that is exogenously given:

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

(E)Zero-profit conditions. Free entry and exit ensures that all producers make zero economic profit so that the mill price offered by firm r in zone j equals unit production cost:

$$p_{rj} = \frac{1}{A_{rj} v_{rj}^{v_{rj}} \mu_{rj}^{\mu_{rj}} \delta_{rj}^{\delta_{rj}}} \left(\sum_f \kappa_{f|rj}^{\frac{1}{1-\theta_r}} w_{jf}^{\frac{\theta_r}{\theta_r - 1}} \right)^{\frac{\delta_{rj}(\theta_r - 1)}{\theta_r}} \left(\sum_k \chi_{k|rj}^{\frac{1}{1-\varsigma_r}} R_{jk}^{\frac{\varsigma_r}{\varsigma_r - 1}} \right)^{\frac{\mu_{rj}(\varsigma_r - 1)}{\varsigma_r}} .$$

Developers in the competitive investment market also make zero profit:

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

where R_{i0} is the exogenous annual rent of vacant land collected at the beginning of each year; $\frac{1}{\Phi_{i0}} \ln[\bullet]$ is the well-known expected present value from logit calculus (see, for example, Small and Rosen, 1981; Train, 2009). This equation states that the value of vacant land equals the present value of its rent income plus its expected present value, so that the developers make zero *ex ante* expected profit regardless of the construction decision. For developers who own an existing type-k building, the zero-profit condition is given by:

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

This equation states that for each type of building in each zone, the value equals its present rent income (collected at the beginning of each year) plus the expected present value $\frac{1}{\Phi_{ik}} \ln[\bullet]$, so that the developers who own existing buildings make zero *ex ante* expected profit regardless of the demolition decision.

The above equilibrium of RELU consists of 1,050 simultaneous equations that are solved by commercial solvers CONOPT and CPLEX using the GAMS system for all model variables including R_{ik}, w_{js}, V_{ik}, p_{js}, S_{ik}, and X_{js}. The endogenous trip matrix $TRIP_{iz}$ is then calculated as described in A.1 and passed on to the traffic equilibrium model TRAN to calculate the average travel time G_{iz} and the monetary cost g_{iz}. RELU then reads g_{iz} and G_{iz} as updated inputs and re-equilibrates. Such RELU-TRAN cycles continue until all model variables converge. For a detailed description of the nested looping algorithms, see Anas and Liu (2007).

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