The Location Effects of Alternative Road Pricing Policies[1] [2]

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The road pricing policies in the Chicago MSA are analyzed using RELU- TRAN2, a computational general equilibrium (CGE) model. The policies are: a) quasi- Pigouvian tolling of major roads; and b) of major and local roads; (a) and (b) are compared to their revenue-neutral fuel taxes. Qiasi-Pigouvian tolls on all roads and fuel taxes centralize the location of residences and jobs. Quasi-Pigouvian toll on major roads suburbanize these. Rents are increased under all of these policies because the floor spade demands increase of revenue distribution. The firms substitute labor for the building space and the wages are increased. Urban sprawl measured as total developed land increases under all policies. The model also calculates effects on VMT, GPM, aggregate fuel and CO2.

Key Words : *congestion, toll, gas tax, land use, location choice, mode coice.*

1. Introduction

Since the early 1970s, urban economists recognized the importance of a general equilibrium model of the urban economy, but initially developed such models only for monocentric cities in which all jobs are assumed to stay in a central business district (CBD). Thus, although the analytical solution of the monocentric city model yielded many theoretical insights, it remained empirically inapplicable. These early contributions toward the general equilibrium model of a monocentric city included Mills (1972), Dixit (1973), and O'Sullivan (1986), who developed the most complete models all solved numerically.

The general equilibrium theory of a polycentric city with dispersed employment is more recent. Such models have been developed for linearly shaped cities, with jobs endogenously located anywhere in the city. The earliest version of such models was by Anas and Kim (1996), which included traffic congestion and agglomeration economies. The weaker are the agglomeration economies or the higher the traffic congestion, the larger is the number of places where jobs concentrate in equilibrium. The effects of congestion pricing on job and residence location was studied by Anas and Xu (1999), tolls and the urban growth boundary were compared in Anas and Rhee (2006, 2007). Cordon tolls have been studied by Fujishima (2011) who applied the Anas-Xu model and Anas and Hiramatsu (in press). The effects of the gas price on the urban economy using RELU-TRAN2, is studied in Anas and Hiramatsu (2012).

The purpose of this article is to report an empirical application of the CGE model RELU-TRAN (Anas and Liu, 2007) to the analysis of road pricing policies in the Chicago MSA. RELU-TRAN is in the tradition of the Anas-Xu and Anas-Rhee type models and in Hiramatsu (2010) it was extended to calculate gasoline consumption, emissions of CO2, car

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VMT and MPG.

Tolling the traffic congestion externality has two major effects on location patterns. One effect is that residences move closer to employment centers in order to reduce travel distances over which the toll must be paid. The other is that producers/jobs may decentralize and move closer to employees or customers in order to avoid higher wages to attract workers to congested job centers. Since job and residence locations are interdependent the net effect is ambiguous. One of these location choices could drag the other location and it is quite possible that both jobs and residents move to the same direction.

We will focus on the quasi-Pigouvian tolling of all local and major roads and of major roads only. Against these benchmarks, we will compare the effects of a tax on gasoline that is revenue neutral with respect to each quasi-Pigouvian tolling. These policies are introduced and discussed in more detail in section 3 and the results are presented in section 4. The case where consumers can travel only by auto as hypothetical simulations is examined in section 5.

Our results show that in the context of the Chicago MSA where, as in most US cities, congestion is much lower than in large European cities such as London or Paris or third world cities such as Beijing, all of the mentioned policies improve social welfare. Another result is that the comprehensive policies of quasi-Pigouvian tolling or revenue-equivalent fuel taxation would increase the after-toll or after-tax monetary cost of transportation by as much as 115%. By doing so, these policies would achieve reductions in gasoline consumption and CO2 emissions of as much as 13%, in total travel times of 5%, the VMT of 10%, and the GPM of 3%.

One of our main focuses in this paper is the effect of road pricing policies on the location of jobs and residences within the Chicago. The issue is relevant to the inquiry about the impact of road pricing on central city revitalization and whether pricing centralizes or decentralizes land use, jobs and population. Almost two decades ago a special report of the National Research Council (1994) professed ignorance and concluded that:

> "Neither theory nor research on the relationship between the cost of transportation and urban development provides compelling evidence to support whether congestion pricing would have a centralizing or decentralizing effect (Deakin, Vol. 2)."

We will show that in our Chicago simulations, Pigouvian tolls and fuel taxes centralize the location of jobs and residences, and more so in the case of the fuel tax. Suburbanization of these is observed under the quasi-Pigouvian taxation of only the major roads. Average rents and wages are increased under all of these policies because the revenue distribution leads the floor demand and rent increase. Firms substitute labor for floor space then the wage increases. Urban sprawl measured as total developed land increase under all policies. A conclusion that emerges from these results is that the all road pricing policies, and especially the fuel tax, can indeed help concentrate jobs and population in the central city and toward the downtown and thus may help central city revitalization and the more land use, but not the more applicable pricing on only major roads.

The summary of the article is as follows. Section 2 and Appendix A explain the structure of the CGE model with a heavier focus on the consumer behavior including travel. More detailed descriptions of the model and how it has been calibrated can be found in Anas and Liu (2007), and Anas and Hiramatsu (2011, 2012). Section 3 describes the road pricing policies to be tested by simulation and section 4 presents and discusses the results of the policy tests. The section 5 tests the hypothetical simulation where only auto is the available travel mode. A few results get the opposite directions. Conclusions are briefly recapped in the last section. Appendix B explains calibration.

2. The RELU-TRAN CGE model

RELU-TRAN is a computable general equilibrium (CGE) model, calibrated and tested for the Chicago MSA, described in Anas and Liu (2007). In RELU-TRAN 2, an extension of RELU-TRAN, the travel behavior of the consumer has been enriched by treating the choice of automobile type by fuel economy level and by adding equations that calculate gasoline consumption and CO2 emissions from automobile travel (Hiramatsu 2010). In the model, the Chicago area is represented by a system of 15 zones covering the entire area and by an aggregation of the major road network and of local roads.

2.1 Representing the Chigcago MSA

Figure 1(a) shows the Chicago MSA in the model. The zones can be grouped into the concentric rings. Ring 1 consists of zone 3 which is the major employment center in the region commonly referred to as the CBD or Central Business District. Ring 2 includes zones 1,2,4,5 which together with the CBD make up the City of Chicago. Ring 3 consists of zones 6-10 which include all of the inner ring suburbs encircling the City. Ring 4 (zones 11-14) are the outer ring.

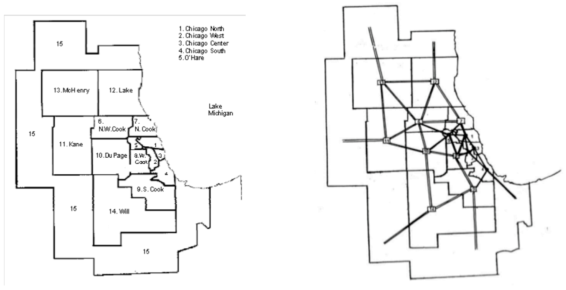

Figure 1(a) (left): RELU-TRAN zones of Chicago MSA
Figure 1(b) (right): RELU-TRAN network of major roads

All trips that originate and terminate within the same zone utilize a *local road* that is an abstract aggregation of the underlying street and minor road system. Trips originating in one zone and terminating in another utilize a path over the inter-zonal road-links of Figure 1(b), a crude aggregation of *major roads and highways*, but they also use the intra- zonal links to access and egress from the inter-zonal road network. Figure 1(b) shows the aggregated inter-zonal road network consisting of two-way road-links connecting the zone system. In the model each local road and each one-way inter-zonal link is represented by a capacity which is crucial in calculating congestion. See Appendix A for the model explanation and Appendix B for the calibration explanation.

3. Road pricing policies: Major Road Congestion tolls, All Roads Congestion Tolls and Its Revenue Neutral Fuel Taxes.

The model calculates two externalities of traffic congestion. One is the delay caused by the volume of traffic, the other is the excess fuel consumption induced by the traffic, that is the fact that when traffic moves more slowly it needs to consume more gasoline per mile as shown in Figure 2. These two externalities are calculated on each mile of road for both major roads and local (intra-zonal) roads, but the model does not distinguish between different times of the day, thus implying that all the travel occurs over a relatively wide rush hour.

The policies we examine in this paper directly or indirectly target these two congestion externalities caused by driving. We consider the following policies:
(a) A quasi-Pigouvian congestion toll, that varies by type of road and is charged on each road link. There are two versions of this: QP1 under which only the major roads are tolled but local (intra-zonal) roads remain un-tolled; QP2 under which all roads (major and intra-zonal) are tolled.
(b) A per gallon fuel tax under which the rate of the tax is calculated so that the fuel tax revenues match the revenues of QP1 or QP2;

Quasi-Pigouvian tolls

In theory, first-best Pigouvian tolling would perfectly internalize both externalities over the entire network. The Pigouvian tolls measure the excess time delay plus the excess fuel consumption imposed by each car-trip on all other car-trips. We call these *quasi*-Pigouvian tolls because they are not first-best. First-best Pigouvian tolls would be very difficult to implement in reality. One reason is the fact that every mile of road is shared by travelers with different values of time. The first-best Pigouvian toll would be calculated by multiplying the marginal time delay experienced by each traveler on each road by the traveler's marginal rate of substitution between travel time and disposable income and then adding up over all travelers on the road. It is unrealistic that road authorities could so distinguish each driver's value of time. Instead, we assume that the road authorities know only the average value of time of the drivers on each road, and even that may not be possible. A second reason that congestion tolls in RELU are quasi-Pigouvian is that consumers can save fuel not only by switching to faster routes (see Figure 2) but also by switching to vehicles with higher fuel economy. The first-best policy would vary the part of the Pigouvian toll aimed to capture the fuel externality, not only according to route but also according to the car types on the road. We assume that road authorities know only the average car on each road and set a toll that is common to all vehicles. The logic of the major roads quasi-Pigouvian tolling is the same. However, this policy is charged only the major roads. Thus the intra-zonal trips would not be charged.

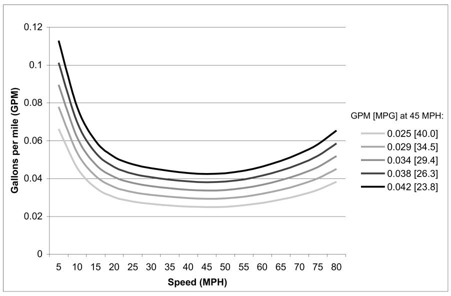

FIGURE 2: Band of gasoline intensity GPM versus speed for the range of cars in RELU-TRAN2

Fuel taxes

The fuel tax also acts globally over the entire network but it is a lower-best instrument since it targets only fuel consumption, thus working on the congestion indirectly. In fact, the fuel tax is, a priori, a crude instrument because it is paid for the fuel consumed on each mile of road regardless of the congestion level on the road. And while from Figure

2 we can see that fuel consumption indeed rises with congestion, the fuel tax would be paid even on a road with zero congestion.

The fuel tax is very easy to implement since all car traffic pays the same fuel tax per gallon of gasoline. Cars with lower fuel economy consume more gasoline and pay higher fuel taxes. Thus, on the one hand, the fuel tax creates an incentive for trips to be made with vehicles that have higher fuel efficiency. On the other hand, the gasoline tax may do a poor job of internalizing the externalities of congestion. It affects congestion only indirectly by raising the monetary cost of travel and thus reducing travel volume and improving speed. In contrast, our quasi-Pigouvian toll directly internalizes the externalities caused by congestion but does not have direct incentive for changing the fuel economy.

Consumer's behavior under the policies

In our general equilibrium model, the effects of these policies will differ according to the way the market agents (consumers, firms and developers) will exercise tax avoidance behavior directly or become influenced by changing prices, rents and wages indirectly. Since the model entails many margins of adjustment, the overall effects are complex and require netting out the various effects across all margins. The most immediate form of adjustment would be made in the transportation behavior; in the choice of route and mode.

A first margin of adjustment would be the route choice. As an example of this is that a quasi-Pigouvian congestion toll would increase the monetary cost of travel, inducing consumers with low values of time to choose longer but less congested routes entailing lower tolls. Commuters with higher time values would pay higher taxes and travel on the faster routes. Note roads going through the CBD are congested and the toll is high, while roads circumvent the CBD are less congested and the toll is low. These adjustments would not work as well under fuel taxation since in that case fuel taxes would be more correlated with distance traveled than with congestion.

A second margin of adjustment would entail switching between car and transit. While higher tolls or taxes would induce consumers with lower values of time to switch to the slower but cheaper transit mode, as the tolls or taxes reduce congestion and speed up driving, consumers with high values of time would switch from transit to car.

A third margin of adjustment would entail adjusting by changing one's car fuel efficiency. The higher monetary cost of the fuel tax, for example, would induce consumers to switch to more fuel efficient cars.

A fourth margin of adjustment would be to change the destination, number and length of one's non-work trips from the locations that involve a high tax or toll layout to other locations that involve less. All of these effects are treated in the model.

Consumer's behavior is affected by the toll revenue distribution. Consumer would demand more goods and larger housing floor space. The increment in goods demand again effects on non-work trip behavior. In the longer term, the increment of housing space demand effects not only on the housing floor market but also the industrial floor space market since the amount of the land in each zone is limited and the developers demolish and construct the buildings according to the market demand.

Changing job or residence locations require longer term adjustments. The quasi-Pigouvian toll is more expensive where are congested and less expensive where are not congested, say roads in CBD and in suburb, respectively. Some examples of residence location changes would be for a CBD-worker who commutes into the CBD to move his residence to the CBD to reduce the travel distance, reducing housing size at the same time in response to the higher CBD rents. Such a choice would be favored by those disliking transit, or those who reside in suburban areas that are transit inaccessible. Others may indeed switch to transit but to do so may have to move from the suburbs to the city where transit is more easily accessed. Still others may reject the above options and prefer to switch to a suburban job from one in the CBD.

Firms meanwhile would also respond to tolls or taxes. An example would be a firm located in the congested CBD and employing many employees who drive to the CBD but dislike switching to transit or moving their residences into the CBD. Such a firm faces the choice between paying higher wages to induce its employees to keep their CBD jobs, and relocating outside the CBD to lower the tolls and taxes incurred for long distance driving by its employees. But the CBD may attract more firms if enough consumers are willing to locate residence within it or switch to transit, if such shifts increased the supply of labor within the CBD sufficiently so as to lower wages. Such shifts could also induce demolishing commercial real estate to replace it with residential. This would drive up commercial rents per square foot inducing firms to leave the CBD.

Moving out of the CBD would entail higher costs of procuring certain intermediate inputs for manufacturers or business service providers, or less customer-accessibility for retailers. No strong conclusions can be made about whether the road pricing policies entail the revival or decline of certain real estate markets within the city center. This will depend on whether the total demand for residential or commercial floor space within the CBD increases or decreases which is ambiguous in general but would be driven by whether the jobs and residences within the CBD increased or decreased.

In realistic schemes only major roads are proposed for tolling. If the quasi-Pigouvian toll is levied on major roads only, the differences between quasi-Pigouvian tolling and gasoline taxation are magnified, because drivers on local roads (i.e. traveling intra- zonally) would not be charged under quasi-Pigouvian tolling but would pay the fuel tax. Under such quasi-Pigouvian tolling, the inter-zonal trips and congestion would decrease while intra-zonal trips and congestion would increase.

The quasi-Pigouvian toll will be higher than the fuel tax on highly congested roads. On the other hand, the fuel tax would be expensive where drives consumed more fuel. Hence drivers would recognize that the expenditure on fuel is too high on long distance routes. Under the fuel tax to make dentures is not be very helpful for drivers to since all roads would be impacted.

4. The impacts of the policies

The results of the road pricing policy simulations are presented in Tables. Table 1 focuses on how consumer utility changes by income group and for consumers who work and who do not. Table 2 juxtaposes the effects of the policies on the distribution of jobs and residences by geographic area within the MSA: the CBD, the rest of the City of Chicago and suburbs. Table 3shows the change in different types of building stocks. Table 4 shows the effects of the policies on driving related aggregates such as VMT, GPM, fuel consumption and CO2.

An observation from TABLE 1(a) is that the revenue raised by the quasi-Pigouvian tolling of all roads (QP2) is a more than the revenue raised by that of all major road (QP1). The revenue raised by the quasi- Pigouvian tolling of all roads (QP2) is more than four times the revenue raised from the tolling of the major roads only. The fuel tax rate that corresponds to QP1 is 56% and that which corresponds to QP2 is 286%.

Consider now the numbers in Table 2(a) which show how the spatial distribution of jobs and residences changes under each policy. A positive number is an increase and a negative number is a decrease. In the model the total number of consumers is fixed and they may choose whether to work or not. Therefore, in addition to changes in job locations, the model also tells us whether a particular policy increases or decreases the number of consumers that are in the labor force. That is why the positive and negative job changes do not sum to zero. Note, however, that each consumer has housing whether in the labor force or not. Therefore, the residential location increases and decreases sum to zero (net of rounding).

Several results are seen from a systematic examination of Table 2(a). Under the tolling of the major roads (QP1), jobs and residences move to the suburbs. However, under other policies jobs and residences move to the cities. What explains this opposite movement? Since only major roads are taxed by QP1, two toll avoidance margins become dominant. The inter-zonal commuters by auto would switch the mode to transit. For them the city is the convenient location. If other inter-zonal commuters by auto want to keep commuting by auto, the suburbs are convenient locations. The roads are not congested and the toll prices in suburban zones are not expensive. The second choice is more popular among them.

Change the viewpoint and introduce the second criteria of location choice where the only the outer-suburban zones are defined as the suburb. All of other inner ring zones are considered as centers. According to this second criteria, both QP1 and QP2 make residences and jobs centralized and its revenue neutral fuel taxes make them suburbanized. Again, QPs are expensive near the center where the roads are more congested and its revenue neutral fuel tax are more expensive in suburbs where requests more fuel.

Next consider the effects of the fuel tax that achieves revenue neutrality with QP1. Recall that the fuel tax is paid by all car travel whether on major roads or not. It is therefore much harder to avoid to make the intra-zonal trips that was important under QP1. Under the higher fuel price, the margin of switching to transit becomes much more important and there is a powerful relocation of residences away from the suburbs and to the City including the CBD. Recall that the City is the convenient location for the transit users. Of course another margin preferred by some consumers is to stay with driving but shorten the length of their trips, and this means that some of those who worked in the City but resided in the suburbs would move their residences to the City.

Now looking at QP2 and its revenue neutral fuel tax, we see that both jobs and residential locations are relocated from the suburbs to the City. Access to transit is again a factor as is also the fact that a toll on all roads is harder to avoid than a toll on major roads only. We also see that the effects of the fuel tax in this case are closer in magnitude to the effects of the quasi-Pigouvian tolling of all roads, since both taxes fall fairly ubiquitously on all roads. As well, we see that the fuel tax produces a considerably bigger centralizing effect than does the congestion tolling, again because the fuel tax induces more distance-shortening and by switching to transit. Since the city roads are congested, the quasi-Pigouvian toll is expensive. However, the fuel tax cost for the driver would not be expensive on the city roads because the driving distance is short and not much fuel is consumed. On the other hand, on the suburban roads where is not congested, the quasi-Pigouvian toll would be cheap. However, to drive the long distance suburban roads requests more fuel consumption and the payment on fuel tax would be expensive. Thus fuel tax has stronger centralization effects than the quasi-Pigouvian toll.

TABLE 3(a) shows the results of developers behavior. Developer would construct the high value buildings and demolish the low value buildings. One of the direct effects of the road pricing policies is the revenue distribution. Consumers have more budgets to reside in larger space housing and to purchase retail goods. The former effect causes the increment in the housing rents and values. The developer would construct more housing. Since the land amount is limited, this causes the scarce in the land for business and industrial buildings. Therefore, the rents and values increment in these buildings, too. Further more, in the zones where are well developed and lack undeveloped land, the low density building would be demolished to make space for constructing the high density buildings. Under all the policies, the single-family buildings, that are low density, are demolished in the CBD and the City. In the suburban zones, all the buildings increase and the undeveloped buildings are decreases.

Now turning to Table 1(a), the compensative variation per capita increases. We see that consumers who work experience higher utility levels while those who do not work lose utility. The reason is that those who work are more exposed to the higher monetary cost of transportation after road pricing on the one hand, while benefitting from the faster car speeds on the other. Those who do not work experience these effects to a lesser degree because they make shopping trips but have no commutes. The increment in rent and price are the negative effect for both who work and not work and the increment in wage is positive effect only for who work. Note that, roughly speaking, lower income groups lose (gain) a lower utility gain than do higher income consumers. The higher income groups benefit more from reduced congestion and shorten travel time because their wage level and time value are higher than lower income groups. They make more trips for non-work trips and thus benefits from reduced congestion more often. At the same time, since they make more non-work trips than the lower income groups, they hurt more from the monetary expensive trips. For the employed consumers, the benefit exceeds this harm, but opposite for non-work consumers. As mentioned above, wages, rents and retail goods prices are factors that effect on the compensative variation. We see that wages and rents increase under each of the policies. The reason for this is that the revenue distribution gives consumers the additional budget and goods and housing space demand increases. The goods price and the rent would increase. Developers would construct more housing space. Some of those are construct on the vacant land. Some office or industrial buildings are demolished to make space for the housings. This makes the rent increases and the producers substitute labors for the building spaces. Now the wage would increase.

Table 4(a) shows the changes in the driving-related aggregates. Note that, not surprisingly, fuel and emissions of CO2 decrease by larger percentages under the revenue neutral gas tax for QP2 than under QP2. Only the different signs show for the fuel economy by car type. Since fuel tax increase the cost of gasoline directly, consumers have incentive to reduce the fuel consumption and to change car to smaller fuel efficient car. However, not under the quasi-Pigouvian toll which aims to reduce the congestion.

		PT	RN-GAS-TAX	PT-IPT	RN-GAS-TAX
Gas Tax (%)			55.5 (%)		286.6 (%)
Revenue (distributed)		284	284	1,306	1,306
CVEMP ($)	f=1	349	90	380	405
	f=2	411	107	377	428
	f=3	550	136	516	516
	f=4	1,388	351	1,741	1,441
CVUNEMP ($)	f=1	-903	-273	-616	-900
	f=2	-1,417	-524	-1,504	-1,914
	f=3	-1,938	-762	-2,328	-2,874
	f=4	-4,190	-1,802	-5,950	-7,057
(1) CV ($)		244	14	264	97
(2) not distributed Revenue ($)		0	0	0	0
(3) change in value per cap (discounted) ($)		1,149	485	1,701	1,967
(1)+(2)+(3) Welfare		1,393	498	1,965	2,064
wage (%)		8.6	3.4	11.2	13.1
rent (%)		11.6	4.7	16.8	19.1
goods price (%)	r= 4	10.2	4.3	14.6	16.9
travel time (%)	TTT	-2.5	-1.3	-5.3	-5.5
travel cot (%)	TTC	24.0	24.6	114.6	112.9

Table 1 (a): Percent changes in utilities, wages and rents under road pricing policies

		PT	RN-GAS-TAX	PT-IPT	RN-GAS-TAX
Gas Tax (%)			55.5 (%)		286.6 (%)
Job change	CBD	747	2,385	6,215	10,987
	City-ex-CBD	-4,058	2,314	2,275	10,713
	Inner Sub	-5,027	-2,526	-12,385	-15,081
	Outer Sub	9,475	-1,759	5,064	-5,198
	Sum	1,137	414	1,169	1,421
Job % change	CBD	0.1	0.4	1.2	2.0
	City-ex-CBD	-0.5	0.3	0.3	1.3
	Inner Sub	-0.3	-0.1	-0.7	-0.9
	Outer Sub	1.366	-0.254	0.730	-0.749
Residents change	CBD	535	781	3,237	3,755
	City-ex-CBD	-5,940	8,117	14,272	40,296
	Inner Sub	-10,768	-3,713	-27,253	-28,106
	Outer Sub	16,174	-5,184	9,745	-15,944
Residents % change	CBD	1.3	2.0	8.2	9.5
	City-ex-CBD	-0.4	0.6	1.0	2.9
	Inner Sub	-0.5	-0.2	-1.3	-1.3
	Outer Sub	1.5	-0.5	0.9	-1.5

Table 2(a): Effects of road pricing policies on job and residence

		PT time fuel	RN−GAS−TAX	PT-IPT time fuel	RN−GAS−TAX
k=0	CBD	-4.5	-1.9	-7.0	-7.9
k=1	CBD	-4.6	-2.0	-7.1	-8.1
k=2	CBD	1.3	0.9	4.0	4.4
k=3	CBD	2.6	1.0	3.8	4.5
k=4	CBD	3.7	1.4	4.3	4.8
k=0	City-ex-CBD	-2.7	-1.2	-4.2	-5.1
k=1	City-ex-CBD	-1.8	-0.8	-2.6	-3.1
k=2	City-ex-CBD	4.3	2.2	7.3	8.8
k=3	City-ex-CBD	2.4	1.1	3.5	4.2
k=4	City-ex-CBD	3.8	1.5	5.1	6.0
k=0	Inner Suburb	-7.9	-3.4	-10.7	-12.3
k=1	Inner Suburb	3.4	1.5	4.6	5.3
k=2	Inner Suburb	4.0	1.8	5.5	6.4
k=3	Inner Suburb	0.9	0.3	1.1	1.2
k=4	Inner Suburb	2.2	0.8	2.8	3.1
k=0	Outer Suburb	-1.9	-0.7	-2.6	-2.6
k=1	Outer Suburb	6.5	2.3	9.0	9.0
k=2	Outer Suburb	6.7	2.3	9.2	8.9
k=3	Outer Suburb	3.9	1.3	5.3	5.4
k=4	Outer Suburb	4.3	1.7	6.0	6.6

Table 3(a): Effects of road pricing policies on buildings and undeveloped land (Percent change)

		PT	RN-GAS-TAX	PT-IPT	RN-GAS-TAX
Gas Tax (%)			55.5 (%)		286.6 (%)
	Gasoline	-4.6	-2.7	-12.5	-13.3
	VMT	-3.9	-2.1	-9.9	-11.1
	Average GPM	-0.7	-0.6	-2.7	-2.4
	Average FE	0.1	-0.1	0.2	-0.6

Table 4(a): Percent changes in driving related aggregates under road pricing policies

5. Hypothetical Simulation Results.

In this section we experiment the hypothetical simulation in which only auto is the available travel mode. This experiment has a few purposes. First, it is interesting to compare the simulation result with this assumption with the base line simulation as the sensitivity analysis. Second, this simulation gives the insight about the policy impact in the other city where the public transit is less developed. Buyukeren and Hiramatsu (2012) show the importance of the public transit availability in the location choices under the congestion policies. At last, this setting is more compatible with the literatures. For the consumers, changing in the mode choices and the location choices are the important responses among others. In this hypothetical simulation, the mode choice is not changeable and the importance of location choice increases.

Table 1(b) shows that the revenue neutral fuel tax level for QP1 and QP2 increases to 109% and 478%. This implies that QP toll levels increase, too. For one reason, the congestion level is high if only auto is the travel mode. For the other reason, since the consumer cannot change the mode, the same level of the policies are less effective and the externalities are not internalized well. Since the congestion level is high, consumers get more disutility from the congestion, the roads pricing policy improves more CV per person.

The location choice is important response for the consumers. Table 2(b) shows that when travel modes becomes only auto, the location choices are suburbanized in both criterion. This is because city centers are the convenient locations for transit users, but this convenience disappears by assumption. The toll per unit distance is higher in the city than in suburb, because city is more congested. Thus who travel city by auto reacts more than who travel suburb. The consumers who wanted to change the mode to transit and move to city center would move to or stay in suburbs where are less congestion.

6. Conclusions and extensions

Returning to our answer to the basic question posed in the Introduction, we did show that road pricing policies – and especially those applied broadly such as fuel taxation or the Pigouvian tolling of all roads – would indeed cause the centralization of jobs and residences to the City of Chicago from the suburbs. However, Pigouvian tolling of the major roads only could cause suburbanization.

The more implementable alternative road pricing policy Cordon tolling is examined in detail in Anas and Hiramatsu (2012). In that article, we have looked at the location of three cordons and calculated the optimal cordon toll level for each cordon location.

		NO-MODE-PT	RN-GAS-TAX	NO-MODE-PT-IPT	RN-GAS-TAX
Gas Tax (%)		109.4 (%)			478.1 (%)
Revenue (distributed)		706	706	2,958	2,958
CVEMP ($)	f=1	1,210	347	1,586	1,124
	f=2	1,558	441	1,990	1,378
	f=3	2,050	546	2,682	1,687
	f=4	4,339	1,120	5,952	3,570
CVUNEMP ($)	f=1	-2,499	-1,022	-3,144	-4,338
	f=2	-3,870	-1,772	-5,795	-7,514
	f=3	-5,249	-2,494	-8,309	-10,572
	f=4	-11,188	-5,658	-19,395	-23,969
(1) CV ($)		1,066	81	1,211	-235
(2) not distributed Revenue ($)		0	0	0	0
(3) change in value per cap (discounted) ($)		3,859	1,865	7,023	8,205
(1)+(2)+(3) Welfare		4,925	1,946	8,234	7,971
wage (%)		24.9	11.9	42.3	48.8
rent (%)		36.8	16.9	69.0	58.6
goods price (%)	r= 4	28.3	13.8	50.5	59.7
travel time (%)	TTT	-3.6	-1.8	-6.5	-6.6
travel cot (%)	TTC	60.3	60.3	256.2	253.8

Table 1(b): Percent changes in utilities, wages and rents under road pricing policies

		NO-MODE-PT	RN-GAS-TAX	NO-MODE-PT-IPT	RN-GAS-TAX
Gas Tax (%)		109.4 (%)			478.1 (%)
Job Change	CBD	-14,654	-1,078	-23,339	-3,448
	City-ex-CBD	-16,184	297	-26,318	2,196
	Inner Sub	5,029	237	13,205	-755
	Outer Sub	28,699	1,863	40,197	6,388
	Sum	2,890	1,319	3,745	4,381
Job % change	CBD	-2.9	-0.2	-4.6	-0.7
	City-ex-CBD	-2.1	0.0	-3.4	0.3
	Inner Sub	0.3	0.0	0.8	0.0
	Outer Sub	4.0	0.3	5.6	0.9
Residents change	CBD	-1,335	-14	-4,244	-517
	City-ex-CBD	-51,760	-3,746	-95,867	-9,302
	Inner Sub	-422	2,972	18,627	3,720
	Outer Sub	53,517	788	81,484	6,100
Residents % change	CBD	-5.1	-0.1	-16.1	-2.0
	City-ex-CBD	-3.9	-0.3	-7.3	-0.7
	Inner Sub	0.0	0.1	0.8	0.2
	Outer Sub	4.7	0.1	7.2	0.5

Table 2(b): Effects of road pricing policies on job and residence

Appendix A: The RELU-TRAN2 CGE Model

In RELU-TRAN2, the Chicago area is represented by a system of 15 zones and by an aggregation of the major and local road network as shown in Figure 1(a), 1(b). All intra-zonal trips, trips that originate and terminate within the same zone, utilize a congestible *local road* that is an aggregation of the underlying street and minor road system. Trips choose a path over the road- links which are an aggregation of *major roads and highways*, shown in Figure 1(b), and use the intra-zonal local roads for access and egress. Each road link is represented by a capacity used to calculate equilibrium flow congestion which determines equilibrium monetary and time costs on the link.

The economic agents are consumers, firms and real estate developers. RELU treats the housing market, the labor market, and the markets for the outputs of industries including the construction and demolition of buildings. Consumers and firms are competitive in all markets, taking prices as given. Choices of travel route and mode for each trip are treated in TRAN, the transportation sub-model. RELU and TRAN are linked sequentially, but are cycled to a fully simultaneous equilibrium (see Anas and Liu, 2007).

A.I Consumers, producers, developers

Consumers: Consumers in RELU choose among discrete bundles (*i*, *j*, *k*, *c*); *i* =1,...,15 residence zones, *j* =1,...,14 job zones, *k* = 1,2 housing types (single family, multiple family structure), and *c* =1,...,5 car types (the TFI levels of Figure 2). Continuous variables, conditional on each discrete bundle are the housing floor space for (*i*,*k*), labor hours supplied at *j*, shopping trips from *i* to all zones *z*= 1,...14, and the quantity of retailed goods to buy at each *z*. Consumers regard the retailed goods in different zones as imperfect substitutes and all zones are patronized as the consumer's utility exhibiting a taste for variety. Travel time is valued at the wage (an hour of travel foregoes the wage). But commuting time creates some disutility as well, so that the marginal rate of substitution between disposable income and commuting time exceeds the wage.

Formally, each consumer of skill/income level *f* solves (in an inner nest) the utility maximization problem in the retailed goods quantities $\mathbf{Z} = [Z1, Z2, ..., Z14]$, and the housing floor space, *b*. The most-preferred discrete bundle (*i*, *j*,*k*,*c*) is chosen in an outer nest:

$$\underset{\forall(i,j,k,c)}{Max}\left\{\begin{array}{l} \underset{\forall Z_z,b}{Max}\ U_{ijkc|f}=\dfrac{\alpha_f}{\eta_f}\ln\left(\sum_{\forall z}\iota_{z|ijf}(Z_z)^{\eta_f}\right)+(1-\alpha_f)\ln b-\gamma_{1f}G_{ijcf}+\gamma_{2f}m_c+\Lambda_{ijkc|f}+u_{ijkc|f} \\ s.t.:\ \sum_{\forall z}(p_{\Re z}+q_{ijf}g_{izcf})Z_z+bR_{ik}+\Delta_j dg_{ijcf}+K(m_c)=\Delta_j w_{jf}\left(H-\Delta_j dG_{ijcf}-\sum_{\forall z}q_{ijf}Z_zG_{izcf}\right)+M_f \\ H-\Delta_j dG_{ijcf}-\sum_{\forall z}q_{ijf}Z_zG_{izcf}\geq 0\ \ for\ j>0. \end{array}\right\} \tag{A.1}$$

$p_{\Re z}$: mill prices of the retailed goods sold in zone *z*;

R_{ik} : rent of residential floor space;

w_{jf} : wage rate;

M_f : non-wage income;

G_{ijcf}, G_{izcf} : mode and route composite commuting and shopping travel times (from TRAN);

g_{ijcf} and g_{ijzf} : mode and route composite monetary costs of commuting and shopping trips (from TRAN);

q_{ijf} : shopping trips required to buy a unit quantity;

m_c : TFIs of the available car types *c* = 1, 2, …, 5

$K(m_c)$: annualized costs of type-*c* car ownership (acquisition plus maintenance);

H: annual time endowment for work and travel;

d: number of commute days required per year;

$\Lambda_{ijkc|f}$: constant effects of the discrete choice bundle (i, j, k, c);

$u_{ijkc|f}$: idiosyncratic tastes for the choice bundle (i, j, k, c);

$\iota_{z|ijf}$: constant effects of the retail location *z* for type-*f* consumers at residential and job locations *i*, *j*;

η_f : CES parameter controlling the elasticity of substitution among retail locations;

α_f : share of disposable income spent on retailed goods ($1-\alpha_f$ on renting housing);

γ_{1f} : marginal disutility of commuting time;

γ_{2f} : marginal utility of a larger, safer, and more fuel-intensive (higher-TFI) car.

The right side of the budget constraint in Eq. (A.1) is the money income of the consumer who is paid the wage after travel time for commuting and shopping. However, if the consumer chooses not to work (*j* = 0), then $\Delta_j = 0$. Otherwise, for any *j* > 0, $\Delta_j = 1$. The left side of the budget, is the monetary expenditure on retail goods, commuting and housing space and annual costs of car- ownership. The prices of the retail goods are effective prices: the mill price at the retail location plus the monetary cost of the travel from home to the retail location.

In the inner stage (inside the { }in Eq. (A.1)), the Marshallian demands $Z^*_{ijkc|f}$ and $b^*_{ijkc|f}$ are determined. In the outer stage, the consumer chooses the most-preferred discrete bundle (*i,j,k,c*), given the indirect utility function $U^*_{ijkc|f} + u_{ijkc|f}$. By making the usual assumptions about the distribution of the idiosyncratic utilities $u_{ijkc|f}$, the discrete choice probabilities are a nested-logit, with a marginal binary probability for entering the labor market or not (j = 0 if not) and a conditional multinomial logit probability, $P^*_{i,j>0,kc|f}$ for choosing among the bundles ($i, j > 0, k, c$).

RELU connects with TRAN via the mode-and-route-composite trip times and monetary costs, that is the matrices $\left[G_{ijc|f}\right], \left[g_{ijc|f}\right]$. How these composites are determined is descrived next. RELU-TRAN2 does not treat congestion by time of day, and all who use a road, experience the same congested time. Monetary cost depends on car TFI since gas consumption depends on traffic speed determined by congestion, and since TFI is a discrete choice responsive to car acquisition and gas costs, and on car preferences for comfort and safety which increase with income in the indirect utility function. In TRAN consumers make choices of mode of travel (car, mass transit, other) for each trip and choose the route of travel for each car trip, based on the combined monetary cost and travel time of trips (that is generalized cost).

The money cost of car travel depends on the gas price, the car type's TFI, which together with the speed determine gas use. The U-shaped curves of Figure 2 were estimated by fitting a polynomial to the Geo Prizm, the third curve in Figure 2, one of the nine car brands in the study by Davis and Diegel (2004), and then multiplicatively shifting this polynomial up and down for the other values of *m*. The Geo Prizm's polynomial curve is $f(t)m_c$, where m_c=1 and, t=1/s, s being the congestedspeed. Thus:

$$f(t) = 0.12262 - 1.172t^{-1} + 6.413\times10^{-4}t^{-2} - 1.8732\times10^{-5}t^{-3}$$
$$+3.0\times10^{-7}t^{-4} - 2.472\times10^{-9}t^{-5} + 8.233\times10^{-12}t^{-6} \tag{A.2}$$

$pf(t)m_c d$ is the fuel cost of driving a road distance d at speed, s = 1/t, by a car of TFI m_c when the gas price is p . The congested time per mile, t, on a road-link is given by the BPR function: $c_0\left(1+c_1\left(\dfrac{Flow}{CAP}\right)^{c_2}\right)$, where c_1 = 0.15, c_2 = 4, and c_0 is the free-flow (uncongested) travel time per mile. *Flow* is the traffic on the road and *CAP* is the calibrated capacity. Disutility (or generalized cost) on a road-link of length d is $(vot_f)(td) + pf(t)m_c d$, where vot_f is the on-the-road value of time that depends on the consumer's income quartile f.

Producers : The four RELU industries are: (a) agriculture, (b) manufacturing, (c) business services, and (d) retail. Goods in the same industry produced in different zones are variants of the same good, the Armington (1969) assumption. Consumers buy all variants of the retail good by shopping them where they are produced. All non-retail outputs are used as intermediate inputs in producing the other goods. Each industry also uses primary inputs which are business capital, space in commercial and industrial buildings and labor from each of the skills groups (income quartiles) of the working consumers. All outputs including retail can be exported to other regions from any of the MSA's zones.

Production functions are constant returns to scale and all firms are perfectly competitive profit maximizers. Under constant returns, the number of firms being indeterminate, the model finds aggregates specific to zone and industry. The first three industries supply their outputs to meet demand from exports and from other firms, while retail trade output is shopped or exported. Formally, for industry r located in zone j, the cost minimization problem is:

$$\underset{[L_f],[B_k],[Y_1],\ldots,[Y_{\Re}]}{Min} \quad \rho K + \sum_{f=0}^{F} w_{jf} L_f + \sum_{k=0}^{\aleph} R_{jk} B_k + \sum_{s=1}^{\Re}\sum_{n=0}^{\Im'} \left(p_{sn} + \sigma_s g_{nj}\right) Y_{sn} \tag{A.3}$$

with target output

$$X_{rj} = A_{rj} K^{\nu_r} \left(\sum_{f=0}^{F} \kappa_{f|rj} L_f^{\theta_r}\right)^{\frac{\delta_r}{\theta_r}} \left(\sum_{k=0}^{\aleph} \chi_{k|rj} B_k^{\zeta_r}\right)^{\frac{\mu_r}{\zeta_r}} \prod_{s=1}^{\Re} \left(\sum_{n=0}^{\Im'} \upsilon_{sn|rj} Y_{sn}^{\varepsilon_{sr}}\right)^{\frac{\gamma_{sr}}{\varepsilon_{sr}}}.$$

p_{sn} is the price of the output in industry s produced at zone n and $\hat{p}_{snj}$ is the delivered price paid by purchasing producers located at j. ρ is the exogenous price of business capital (the real interest rate), w_{jf} are hourly wage rates and R_{jk} are rents per unit of floor space. K is business capital with cost-share ν_r. The first group of inputs, L_f, with collective cost share δ_r is labor. The industry hires all skills and the elasticity of substitution between any two skills is $1/(1-\theta_r) > 1$. f = 0 stands for labor hired outside the Chicago MSA. The second group of inputs, B_k, are buildings with cost share μ_r and elasticity of substitution $1/(1-\zeta_r)>1$. k = 0 stands for floor space rented outside the region, and k = 3, 4 are commercial and industrial buildings. The cost-share of industry r for the intermediate inputs received from basic industry s is γ_{sr} and the elasticity of substitution for the sth group of intermediate inputs is $1/(1-\varepsilon_r)>1$. n= 0 stands for intermediate inputs from outside the region. Coefficients $\kappa_{f|rj},\chi_{k|rj},\upsilon_{sn|rj}=0$ allow specifying input-specific biases including the case of zero values to rule out specific inputs. For example, suppose that businesses do not use residential buildings. We would set $\chi_{k|rj}$ =0 when k stands for residential building. The scale factors, A_{rj}, are constants that we vary by industry and location to capture place-specific Hicks-neutral productivity effects.

Developers: Developers in RELU are based on a perfect foresight model of building conversions with idiosyncratic cost uncertainty (Anas and Arnott, 1993). A developer either owns land and each period decides whether to construct a particular floor space type which is one of the residential or non-residential buildings; or owns a building and each period decides whether to demolish or not the building. Construction each of the four buildings is treated as an industry and so is demolishing each building and these industries like all the others in the model, make use of primary and intermediate inputs. The developers' decisions are made under perfect foresight about land and floor prices and idiosyncratic shocks to the financial and non-financial cost of construction and demolition. It takes one period for these decisions to be taken and realized with the idiosyncratic shocks occurring during the period. Therefore, in the beginning of each period, the probability of constructing a particular floor space (building) type and the probability of demolishing an existing building are determined by profit maximization under idiosyncratic cost uncertainty and given by logit models A.4a and A.4b:

$$Q_{i0k}(V_{i0},V_{i1},...,V_{i\aleph})=\frac{\exp\left(\Phi_{i0}\tilde{\Pi}_{i0k}\right)}{\exp\left(\Phi_{i0}\tilde{\Pi}_{i00}\right)+\sum_{s=1...\aleph}\exp\left(\Phi_{i0}\tilde{\Pi}_{i0s}\right)} \qquad \text{(A.4a)}$$

$$Q_{ik0}(V_{i0},V_{ik})=\frac{\exp\left(\Phi_{ik}\tilde{\Pi}_{ik0}\right)}{\exp\left(\Phi_{ik}\tilde{\Pi}_{ik0}\right)+\exp\left(\Phi_{ik}\tilde{\Pi}_{ikk}\right)} \qquad \text{(A.4b)}$$

Q_{i0k} is the probability that a type k building will be constructed on a unit amount of land in zone i, while Q_{ik0} is the probability that a type k building will be demolished. V_{i0} is the market price of a unit amount of land and V_{ik}, k=1,...,4 are the unit prices of floor space of each type. $p_{\Re+k,i}$ is the cost of construction of a unit amount of type-k floor space in zone i, and $p_{\Re+4+k,i}$ the cost of demolishing a unit amount of type-k floor space. $Ci0k$ is the nonfinancial cost of constructing a square foot of type-k floor space and C_{ik0} the non-financial cost of demolishing it, with C_{ikk} the non-financial cost of keeping type-k floor space unchanged. m_{ik} is the type-k building's structural density in zone i, that is square feet of floor space per square feet of lot size. ρ is the interest rate. The coefficients $\Phi_{i0},\Phi_{i1},...,\Phi_{i4}$ are the idiosyncratic cost dispersion parameters for land and each building type respectively.

A.II The market equilibrium conditions

Rental real estate markets: The excess demand for floor space vanishes for each residential and each commercial type of building in each zone:

$$\sum_f N_f \sum_{cj} P_{ijkc|f} b_{ijkc|f} - S_{ik} q_{ik} = 0 \qquad \text{(A.5a)}$$

for k = 1,2 (residential buildings), and

$$\sum_r B_{k|ri} - S_{ik} q_{ik} = 0 \qquad \text{(A.5b)}$$

for k = 3,4 (commercial buildings). N_f is the number of consumers of each type, S_{ik} is the stock building floor space of each type, $P_{ijkc|f}$ are the consumer's choice probability functions and $b_{ijkc|f}$ are the Marshallian demand functions for floor space, $B_{k|ri}$ is the industry's aggregate demand for commercial floor space, and q_{ik} is the probability function that a unit floor space will be rented than kept vacant.

Labor Markets: The annual excess demand for the labor hours of each skill group f, summed over the industries vanishes in each zone:

$$\sum_r L_{f|rj} - N_f \sum_{ikc|f}\left(H - dG_{ijfc} - s_{ijf}\sum_Z Z_{z|ijcf} G_{izfc}\right) P_{ijkc|f} = 0 \qquad \text{(A.6)}$$

where $L_{f|rj}$ are the industries' demands functions for labor, $P_{ijkc|f}$ are the consumer's choice probability functions and $Z_{z|ijcf}$ are the consumer's Marshallian demand functions for the retail good while the parenthesis contains the labor hours supplied annually by a consumer after time allocated to shopping and commuting.

Output Markets: Letting Ξ_{ri} be the exogenous export demands, the excess demand in each basic industry (agriculture, manufacturing, business services) must vanish in each zone:

$$\sum_{ns} Y_{ri|ns} + \Xi_{ri} - X_{ri} = 0, r = 1,2,3, \qquad \text{(A.7)}$$

where $Y^*_{ri|ns}$ are the demands functions for intermediate inputs . X^*_{ri} is the output of industry *r* in zone *i.* For retail:

$$\sum_f N_f \sum_{nskc} P_{nskc|f} Z_{i|nscf} + \Xi_{4i} - X_{4i} = 0, \qquad \text{(A.8)}$$

where the summations are the aggregate shopping demands of the consumers.

Construction and demolition: Construction and demolition of each type of floor space is treated as an industry. Then, the output is simply

$$X^*_{4+k,i} - S_{i0} Q^*_{ik} = 0, \textit{ for } r = 5,...,8, \qquad \text{(A.9)}$$

where S_{i0} is the stock of vacant developable land in the beginning of a period.

Zero- profit conditions of producers: By free entry, in each period a zero-profit equilibrium exists for each industry in each zone. Then, output prices are found from input prices:

$$p_{rj} = \frac{\rho^{v_r}}{A_{rj} \delta_r^{\delta_r} \mu_r^{\mu_r} v_r^{v_r} \left(\prod_{s=1}^{\Re} \gamma_r^{\gamma_r} \right)} \left(\sum_{f=0}^{F} \kappa_{f|rj}^{\frac{1}{1-\theta_r}} w_{jf}^{\frac{\theta_r}{\theta_r - 1}} \right)^{\frac{\delta_r(\theta_r - 1)}{\theta_r}} \left(\sum_{k=0}^{\aleph} \chi_{k|rj}^{\frac{1}{1-\varsigma_r}} R_{jk}^{\frac{\varsigma_r}{\varsigma_r - 1}} \right)^{\frac{\mu_r(\varsigma_r - 1)}{\varsigma_r}}$$
$$\times \prod_{s=1}^{\Re} \left(\sum_{n=0}^{\Im'} \upsilon_{sn|rj}^{\frac{1}{1-\varepsilon_{sr}}} \hat{p}_{sn|rj}^{\frac{\varepsilon_{sr}}{\varepsilon_{sr} - 1}} \right)^{\frac{\gamma_{sr}(\varepsilon_{sr} - 1)}{\varepsilon_{sr}}} \qquad \text{(A.10)}$$

The foregoing RELU equations which are solved for the output prices, wages, floor rents and industry outputs, that is for $p_{ri}, w_{jf}, R_{jk}, X_{ri}$ given the vacant land stocks S_{io} from the previous period and given the composite over modes and routes congested travel times and monetary costs from TRAN ($\left[G_{ijc|f} \right], \left[g_{ijc|f} \right]$). From a RELU equilibrium, commuting and shopping trips are calculated and entered into TRAN. RELU and TRAN are thus linked in a loop which is cycled to a fully simultaneous and accurately calculated equilibrium (see Anas and Liu, 2007).

Zero- profit conditions of developers: Developers are competitive so that land and floor assets are bid up to a level where expected economic profits are zero at the beginning of each period, which is expressed by Eq. (A.11a) and (A.11b) for land and each floor space type respectively:

$$V_{i0} = R_{i0}$$
$$+ \frac{1}{\Phi_{i0}} \ln \left\{ \exp \Phi_{i0} \frac{1}{1+\rho} V_{i0} + \sum_{s=1...4} \exp \Phi_{i0} \left[\frac{1}{1+\rho} \left(V_{is} - p_{\Re+s,i} \right) m_{is} - C_{i0s} \right] \right\} \qquad \text{(A.11a)}$$

$$V_{ik} = \omega_{ik} \left(R_{ik} \right)$$
$$+ \frac{1}{\Phi_{ik}} \ln \left\{ \exp \Phi_{ik} \left(\frac{1}{1+\rho} V_{ik} - C_{ikk} \right) + \exp \Phi_{ik} \left[\frac{1}{1+\rho} \left(V_{i0} \frac{1}{m_{ik}} - p_{\Re+4+k,i} \right) - C_{ik0} \right] \right\} \qquad \text{(A.11b)}$$

R_{i0} is the rent on land and $\omega_{ik}\left(R_{ik}\right)$ is the expected rent on type-*k* floor space which reflects the probability that the floor space may remain vacant during the period.

Stationary-state construction-demolition cycle: In stationary equilibrium, for each type of building, the flow of demolished floor space equals that constructed so that the stock of each building type in each model zone remains stable in each year. There are, therefore, $\Im\aleph$ such equations in each model zone:

$$S_{ik} Q_{ik0}(V_{ik}, V_{i0}) = m_{ik} S_{i0} Q_{i0k}(V_{i0}, V_{i1}, ..., V_{i\aleph}) \qquad \text{(A.12a)}$$

Meanwhile, in each model zone, the total amount of land, J_i *Ji* , is given. Hence the land taken up by each real asset type including land that remains vacant, must add up to J_i .

$$\sum_{i=0,1,...,\aleph} \frac{1}{m_{ik}} S_{ik} = J_i . (m_0 \equiv 1) \qquad \text{(A12.b)}$$

A.III Welfare analysis

The aggregate welfare gains, *W*, from cordon tolling are measured by,

$$W = \sum_{f=1,...,4} \left(N_{fe}(CV_{fe}) + N_{fu}(CV_{fj}) \right)$$
$$+ \sum_{\forall i} \sum_{k=0,1,...,4} \left((S_{ik} V_{ik})_{POST} + (S_{ik} V_{ik})_{PRE} \right) + TOLLS \qquad \text{(A.13)}$$

TOLLS is the aggregate revenue from the tolls, the middle term of summations are the change in aggregate real estate values, *POST* (*PRE*) referring to the values after (before) the tolls, and the first summation is the aggregate consumer welfare in the form of the sum of all the CVs (compensating variations), the subscripts *e* (*u*) referring to a consumer in (out of) the labor force and *f* to the income quartile (cum skill level) of the consumer. The compensated variations are calculated as the amount a consumer would pay for the increase (require as an offset for the decrease) in expected utility that the cordon toll policy would confer on a consumer in each group after the policy goes into effect.

Appendix B: Data and calibration

Deciding on the model's parameters was a mixture of fixing some at reasonable values and calibrating others so that the elasticity relationships concerning location demand, housing demand and supply and the labor market are within ranges of estimates in the literature. We first discuss the data sets used to calibrate, then how the calibrated model fit the data, and lastly the model's calibrated elasticity relationships.

Data: A variety of data sets were utilized to calibrate RELU- TRAN1. Travel times and work trips from residences (origins) to workplaces (destinations) by income and by mode of travel (car, mass transit and non-motorized) came from the year 2000 Census Transportation Planning Package (CTPP). From the CTPP jobs by zone of workplace, and estimates of wages by place of work were also determined. Non-work trip frequencies from residence location trip origins were estimated from the Home Interview Survey for the Chicago MSA. Residential housing stock is from the year 2000 Census, and non-residential building stock and floor space prices from COSTAR data. Residential housing prices and rents for floor space in single and multiple family housing were inferred by an imputation procedure that used the Public Use Micro Sample data. The land use files of the Northeastern Illinois Planning Commission were used for the vacant developable land and land use by building type in each model zone and from that the structural density of buildings by type was constructed as a zone- average floor area per acre. The industries and inter-industry trade-flow relationships were obtained by following the IMPLAN's economic modeling system as were also expenditure shares by intermediate input categories. Car costs are from the American Automobile Association (AAA, 2005) and the Bureau of Transportation Statistics (RITA).

The model's fit to the data: Since RELU-TRAN2 is an extension of RELU-TRAN that includes choice among five car-types differing by TFI (Figure 2) and precise calculations of gasoline use, VMT, MPG and speed, it required a calibration adjustment that draws on additional data. Data targets for RELU-TRAN2 to be matched as closely as possible by the calibration were constructed. The RTAMS (2000)[3] data were used to target the number of jobs and residents by zone, the work-trip pattern by mode of com- muting and the average travel speed. The VMT, gas use and MPG targets are from the Illinois Travel Statistics (IDOT, 2000). The targeted car distribution by TFI was constructed from the NHTS (2001). Table B2 shows how well the calibrated model fit the targets.

Elasticities: Table B1 shows the key calibrated elasticities and values of time calculated from the model's predicted equilibrium for the year 2000. Here, we discuss how these elasticities compare to values from the relevant literature and if they differ we explain why.

Our MRS between disposable income and commuting time from the choice of job-residence is higher than the wage rate because of our specification of the consumer's utility: the consumer gives up the wage for commuting, but there is also disutility from the commuting time. This specification ignores that a consumer's dislike for hours spent at work may be higher than his dislike of commut- ing, which would result in a value of time lower than the wage. It is consistent with recent empirical evidence that the value of time in commuting exceeds the wage rate due to job market frictions (Van Ommeren and Fosgerau, 2009).

The elasticity of location demand with respect to commuting time was estimated in the 1970s by Charles River Associates, Inc. (1972), Atherton et al. (1975), Train (1976), and Lerman (1977). The in-vehicle time elasticity ranged from -0.36 to -1.40 for transit and from 0.55 to 1.77 for the drive-alone mode. The out-of-vehicle time elasticity ranged from -0.23 to -2.7 for transit. As shown in Table B1, our workers' travel time elasticity of location demand in RELU-TRAN2 ranges from -0.54 to -0.62 and is in the range of these estimates.

Anas and Arnott (1993) found that the average rent elasticity of housing demand, the rent elasticity of white households and the rent elasticity of non-white households in the Chicago MSA for 1970–1980 were -0.55, -0.52 and -0.68 respectively. In our model, the rent elasticity of housing demand is more negative than -1, because of the functional form of the utility function, and ranges from -1.38 to -1.95. But our elasticity combines two margins, one is the demand for housing floor space and the other the number of consumers who demand housing. Thus our elasticity is higher than that in Anas and Arnott (1993), who estimate a model in which the demand for housing in the first margin is inelastic.

Kimmel and Kniesner (1998) studied nationwide US data for the period 1983–1986. Their nationwide average wage elasticity of labor supply (hours worked) is +0.51. In our case, the model is at the metropolitan level and an average elasticity can be calculated for each zone and each income-skill level as the increase in labor hours per consumer times the number of consumers wishing to work at a zone. Table B2 shows the average wage elasticity of labor supplied to the City of Chicago versus the

[3] Regional Transportation Assets Management System (RTAMS) http://www. rtams.org/ui/homepage.asp contains an aggregated version of the year 2000 CTPP data for the Chicago MSA.

suburbs. These wage elasticities of labor supply decrease with income-skill group, and are lower for suburban zones.

In Anas and Arnott (1993), the elasticity of housing floor space supply with respect to rent is +0.10 and +0.114 for single-family and multiple-family housing in the Chicago MSA. It is the percent of stock that will be offered for rent by the landlords (than kept vacant). Our corresponding values are +0.099 and +0.23. While our single-family housing is similarly elastic, our multiple-family housing supply is more elastic than theirs.

The methodology used in the literature to estimate the supply elasticity of housing is not robust. There are important data- driven or definitional differences between any two studies. DiPasquale and Wheaton (1994) report that the long run price elasticity of the aggregate housing stock of +1.2 to +1.4. Blackley (1999) reports that the construction elasticity ranges from +1.0 to +1.2, and that the long-run price elasticity of new housing supply (in value terms) for 1950–1994 ranges from +1.6 to +3.7 Green et al. (2005) report a price elasticity of housing supply in the Chicago MSA for 1979–1996 as +2.48, but not significantly different from zero. Their supply is the number of housing units for which building permits were issued, multiplied by 2.5 (aver- age household size), divided by the population. They cover a bigger region than does our model. By 2000, our region was more developed than during their period, and the available land would have decreased significantly. The definition of our elasticity of construction is different than theirs and measures the percent by which the construction flow would increase. In addition, there are two assumptions that could be affecting our elasticity in real estate variables.

First, is the assumption that our building structural density (in floor space per unit of land), is constant by building type and zone. Our average structural density is not constant, however, and changes over time by demolishing low structural density and constructing higher structural density buildings. If the building's floor space could be directly chosen by the developer, the stock could be more elastic when the building value increases. This would be especially true in the zones where the vacant land is scarce. Smith (1976) reports that the price elasticity of density is þ5.27, where density is the number of dwelling units built on a unit land area, from Chicago MSA cross-section data between 1971 and 1972. The second assumption is the equilibrium condition that the construction and demolition flow of each building stock in each zone is equalized in stationary equilibrium. In reality, the construction flow would be larger than demolition and stock in a growing economy.

This suggests that it is better to evaluate the reasonableness of our housing supply elasticity by simulating the model in a comparative static exercise, observing how the housing stock responds. In Hiramatsu (2010), an urban growth scenario is simulated, in which the total population and the net exports are increased 10%. The vacant land stock decreases in both the city and the suburbs. The single family housing stock decreases in the city and increases in the suburbs. The multiple family housing stock increases in both the city and the suburbs, and increases more in the suburbs than in the city. The single and multiple family housing stock increases less than the 10% population growth and the average floor space per person decreases. Indus- trial and commercial floor space also increase in the city and suburbs. The increase is higher in the city, but not as high as that of the housing stock. In the city, where the available land is limited, some single family housing is demolished and multi- family housing, industrial and commercial buildings are constructed. In the suburbs where there is plenty of land, both single and multiple family housing is constructed. Industrial and com- mercial buildings are also constructed in the suburbs. Thus the building stocks respond reasonably with respect to the increase of population and net exports. In the city the rent of single family housing increases by more than 10% as the supply decreases. The other building rents also increase since demand increases by more than supply does. We conclude that the building markets, including stocks, rents and values, respond reasonably under the calibrated elasticities.

Consumers	Income quartiles			
	1	2	3	4
MRS (disposable income, commute time) ($/h/day)	12.257	20.934	35.91	92.625
Elasticity of location demand with respect to commuting time	-0.618	-0.606	-0.612	-0.546
Elasticity of housing demand with respect to rent	-1.949	-1.756	-1.568	-1.378
Elasticity of labor supply in city with respect to city wage	2.818	2.168	1.694	1.199
Elasticity of labor supply to suburbs with respect to wage in suburbs	1.602	1.352	0.973	0.626
Developers	**Building type**			
	1 Single family	2 Multi family	3 Commercial	4 Industrial
Elasticity of Elasticity of floor space supply with respect to rent (short-run)	0.099	0.23	0.268	0.138
Elasticity of Elasticity of construction flow with respect to asset value				
Overall	0.052	0.421	0.42	0.074
City	0.033	0.056	0.261	0.04
Suburbs	0.053	0.681	0.452	0.079
Elasticity of Elasticity of demolition flow with respect to asset value				
Overall	-1.612	-0.982	-0.176	-0.523
City	-0.055	-0.528	-0.346	-0.667
Suburbs	-1.719	-1.375	-0.073	-0.465
Elasticity of Elasticity of floor space stock with respect to asset value				
Overall	0.0535	0.0147	0.0054	0.0087
City	0.001	0.0068	0.0064	0.0079
Suburbs	0.0672	0.0218	0.0048	0.0092

TABLE B1: Calibrated Elasticities in RELU-TRAN2 (Chicago, MSA)

Data items	Source	Percent (%) over- under-prediction (average absolute value % error)	Calibration Target
Region wide car-VMT (mill.mi/day)	IDOT (2000)	-3.9	137.9
Interstate car-VMT (mill.mi/day)		-16.1	39
Other car-VMT(mill.mi/day)		0.9	98.9
Fuel use by cars (mill.gall./day)		-5.2	6.51
MPG by cars (mi./gall.)		1.3	21.2
Employed residents by zone		6.10%	
Jobs by zone		4.90%	
Work trips by origin-to-destination	RTAMS (2000)	5.90%	
Work trips by car origin-destination		6.10%	
Distribution of car TFI levels	NHTS (2001)	5.30%	

Table B2 Fit of the calibrated RELU-TRAN2 to targets constructed from data.

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