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The Impact of Congestion Pricing Policies on Fuel Consumption, CO2 Emissions and Urban Sprawl

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ABSTRACT

The impacts of anti-congestion policy on urban sprawl, fuel consumption and CO2 emission are analyzed using RELU-TRAN2, a computational general equilibrium (CGE) model calibrated to the Chicago MSA circa 2000. In the model, consumers choose their residential-workplace locations and the fuel economy of their cars, their housing space, labor supply and their consumption of goods and services which entail shopping trips. Consumers also choose their mode and route for each work and non-work trip. The congestion is determined endogenously. Producers, developers and landlords are the other economic agents in the model. We model quasi-Pigouvian tolling of traffic congestion on all roads or only on major roads, versus (in each case) a revenue-neutral fuel tax per gallon of gasoline which increases the monetary cost of travel by 73% on average. The fuel tax reduces gasoline and CO2 by 18%, VMT by 15%, travel time by 11% and improves MPG by 3.3%. We also model a cordon toll for trips entering or crossing the CBD versus a CBD parking tax for trips terminating in the CBD. Under the quasi-Pigouvian toll on all roads or the equivalent fuel tax, residential and job locations become more centralized in the CBD and the City of Chicago, but when only major roads are tolled there is a tendency for job and residence locations (and the implied commutes) to become more localized in the same zone. We find that when the cordon toll is low, jobs leave the CBD and relocate near suburban residences but some jobs move into the CBD under a revenue-equivalent tax on CBD parking. Under low levels of the fuel tax, residential and jobs locations are centralized in the CBD and the City of Chicago, but when the fuel tax becomes higher jobs and residences become more suburbanized.

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1. Introduction[1]

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 or CBD. Although the analytical solution of the monocentric city model yielded many theoretical insights, its applicability remained limited because of its severe assumption about the concentration of jobs in just one place. These early contributions toward the general equilibrium model of a monocentric city included Dixit (1973) and Mills (1972). But these models were not empirical.

The general equilibrium modeling of a polycentric city with dispersed employment is getting more attention recently and again numerical analysis is even more necessary to solve these models. Such models have been developed for linearly shaped hypothetical cities, in which it is assumed that jobs can be endogenously located anywhere in the city. In such models, congestion tolls are studied in Anas and Xu (1999), tolls and the growth boundary are compared in Anas and Rhee (2006), and also in an extension by Ng (2007).

The earliest version of such models was by Anas and Kim (1996), and they included not only traffic congestion but also agglomeration economies which are the cost-savings caused by the market and non-market linkages that make firms locate near each other. They demonstrated that there is a trade-off between agglomeration economies and accessibility. The weaker are the agglomeration economies or the higher the traffic congestion, then the larger is the number of places where jobs concentrate in equilibrium. Tolling the congestion externality has two effects. 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 in and move closer to employees or customers in order to avoid paying higher wages to attract workers to congested job centers.

The purpose of this article is to report the first empirical application of the CGE model RELU-TRAN (Anas and Liu, 2007) to the detailed empirical analysis of congestion pricing policies in the Chicago MSA. RELU-TRAN is in the tradition of the Anas-Xu/Anas-Rhee type models and in Hiramatsu (2010) it has been is extended to deal with a more complete set of choices related to trips. It has also been extended to predict gasoline consumption, emissions of CO2, car VMT and MPG. The model and its calibration are described in more detail in section 2.

We will focus on the quasi-Pigouvian tolling of both local and major roads and of major roads only. Against these benchmarks, we will also model the effects of a tax on gasoline that is revenue neutral with respect to each type of quasi-Pigouvian tolling. We

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will also model the geographically much more limited policies of a hypothetical cordon tolling policy that taxes all trips crossing the cordon in the inbound direction versus a parking tax on all trips terminating inside the cordon. These policies are introduced and discussed in more detail in section 3 and the results are presented in section 4.

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 reduce consumer welfare as long as toll or tax revenues are not redistributed or recycled. The question of recycling is postponed to the next and final draft of this paper. 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 75%. By doing so these policies would achieve reductions in gasoline consumption and CO2 emissions of as much as 18%, in average travel times of 11% and similar gains in VMT reduction. There would also be an MPG increase of about 3-4% or somewhat higher taking into account all rebound effects including those due to congestion reduction and vehicle fuel economy switches.

Our results also shed light on the relative effectiveness of cordon tolling the CBD or the similar policy of imposing a CBD parking tax. First, we show that these policies cannot match the revenue generated by quasi-Pigouvian tolling, at any level of the policy instruments (that is the cordon toll or parking tax). Second, we show that the efficiencies benefits of these policies (without revenue redistribution or recycling) are minor when compared to the benefits of the quasi-Pigouvian tolling. That this is the case despite a highly public transit accessible CBD is disappointing for the proponents of congestion pricing. The result is also disappointing to theoretical examinations of cordon tolling which relied on the assumption of a monocentric city.

Some results from the extant literature

Cordon pricing in the monocentric city in which urban density, traffic congestion and labor supply are endogenous was examined by Verhoef (2005). He showed that cordon pricing captures 94% of the welfare gains from first-best pricing, and that residential population density increased inside the cordon around the CBD (central business district). There are also a number of papers that study the issue purely as a transportation problem, although empirically. These papers ignored the effects of the policies on land use or the urban economy. Akiyama et al. (2004) studied a single-layered cordon, a multi-layered cordon, uniform pricing, and zone pricing in a network model of the Osaka metropolitan area. They showed that a cordon toll or pricing of existing toll roads can achieve the same efficiency gains.

In Fujishima (2007), a non-monocentric analysis, cordon and area tolls are examined in a model where travelers have car or railway choice. Cordon pricing is more efficient than is area pricing, if longer-distance commuting is more prevalent. Residents within the cordoned area increase the most under the area toll, less under first-best pricing and still increase but even less under the cordon toll. Production and employment, increases in the suburbs more than in the center under the cordon and area tolls, and the production is more centralized under the first-best Pigouvian pricing than under the cordon toll.

Modeling gasoline consumption and emissions are one of our purposes in the current paper. Recently, there has been attention paid not only to congestion, but also to greenhouse gas emissions (CO2) from traffic. The congestion pricing policies work indirectly to mitigate the gasoline consumption and the CO2 emissions which are strictly proportional to each other[2]. The gasoline consumption and CO2 emissions in the congested road are highly correlated with the amount of vehicle miles traveled, although this correlation turns negative at high speeds (see Figure 3b in this paper). In addition to the tolls and the gasoline tax, there are alternative policies such as the ones pointed out by Barth and Boriboonsomsin (2007). They estimated CO2 emissions under real world driving conditions, and under steady-state driving conditions as functions of car speed. The difference in CO2 emissions under real world versus steady state driving conditions is caused by differences in the smoothness of driving. By making traffic flow smoother, the CO2 emissions could be reduced at each driving speed.

Proost and Van Dender (2001) compare the impacts of several policies to reduce the gasoline consumption; an air quality policy (regulation of car emission technology), fuel-based policies (minimum fuel efficiency policy and fuel taxes) and alternative transport policies (fuel external cost pricing, cordon pricing, parking charges). The regulation of emission or fuel efficiency levels may reduce emissions, though congestion externalities are hardly affected. The transport policies reduce the congestion and create an environmental benefit at the same time. When the policies are compared, the policy which focuses on the inefficient transportation can lead to larger welfare gains. They summarize that an isolated policy may decrease welfare and an integrated policy is necessary.

Daniel and Bekka (2000) simulate the effects of congestion pricing on the highway network in New Castle County, Delaware. The optimal gasoline tax to improve welfare in Britain and the United States is examined in Parry and Small (2005) who use a very aggregated and simple model. In their model, the total optimal tax is composed of congestion, accidents, air pollution and Ramsey taxes. The authors claim that although the optimal gasoline tax in Britain is higher than in the United States, it is too high in Britain and too low in the United States. If the price elasticity of gasoline consumption is low, then the optimal gasoline tax would be high.

2. The RELU-TRAN CGE Model

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[2] Some other papers scopes the effect of emission on global worming and urban heat island phenomenon. Those papers study the relations of such phenomenon and emission from car (Saitoh et al. (1996)), building (Kikegawa et al. (2006)) and both (Ihara et al. (2008)). Not many papers study the relationship between transportation and the heat island effect. One exception is Saito et al. (2005) that studies the impact of electric vehicle on emission and urban warming.

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 Chicago MSA

Figure 1 shows the 15 zone Chicago MSA in the model. The zones can be grouped into 5 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 (that is Ring 1) complete the rest of the City of Chicago. Ring 3 consists of zones 6-10 which include all of the inner ring suburbs encircling the City of Chicago. Ring 4 consists of zones 11-14, the outer ring suburbs and finally zone 15, a single peripheral zone represents all other exurban areas which are primarily rural in character and include areas of Northwest Indiana and Southeastern Wisconsin.

[FIGURE 1 ABOUT HERE]

All 15 zones are included as possible locations for consumers but those choosing either their residence or job location in the peripheral zone 15 are treated as having partially exited the region. Such consumers can still choose their job or residence location in one of the 14 zones, but the wages they earn or the rents they pay in zone 15 are taken as exogenous and are not adjusted in the general equilibrium the model calculates for the 14 non-peripheral zones. In the base simulation we will report, residents located in the peripheral zone 15 are only 5% of the total.

All intra-zonal trips, that is 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. Inter-zonal trips, that is trips originating in one zone and terminating in another, choose and utilize a path over the inter-zonal road-links of Figure 2 which are 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 2 shows the aggregated inter-zonal road network consisting of 34 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. The model calculates an equilibrium congested travel time for each local road and each one-way inter-zonal link, to be discussed in section 2.2

[FIGURE 2 ABOUT HERE]

2.2 Model structure: consumers, firms, developers

The model is microeconomic in structure and consists of consumers, firms, real estate developers and an abstract public sector that sets road tolls or other tax levies and performs a redistribution of the revenues generated by various policies.

Consumers, firms and developers in the RELU model are treated in sub-models that correspond to different markets: the housing market, the labor market, and the markets for the outputs of industries. In all these markets, consumers and firms are perfectly competitive (price-takers). All consumer decisions involving travel mode and the choice of a travel route on the road network are treated in TRAN, the transportation sub-model. RELU and TRAN are linked sequentially, but are iterated to a fully simultaneous equilibrium (see Anas and Liu, 2007, for a full description of the algorithm).

Consumers in RELU

Consumers in RELU are adults, potentially active in the labor market. Each is either a whole or fractional household. Conclusions about households can be drawn only by pasting together the consumption or other decisions of consumers. Consumers are divided into four groups representing skill levels in the labor market that correspond to quartiles of the income distribution in the calibration of the model. Each consumer makes a set of simultaneously determined utility maximizing decisions consisting of discrete and continuous choices. Consumers are myopic spending the income of each period during that period, neither saving nor borrowing.

The highest-level decision of a consumer is whether to enter the labor market or remain outside the labor market (voluntary (un)employment). An unemployed consumer has an exogenous unearned income that is constant, increasing by skill level. The exogenous unearned income of an employed consumer is supplemented by wage income. Unemployed consumers choose a fictitious job location ("zone 0") and their commute entails zero travel time and cost. Should wages increase (decrease), then consumers are more (less) likely to choose work, rather than non-work.

Discrete decisions common to all consumers are:

(i) *Job-residence location*: Choice of a pair of the MSA's zones as a place of work and place of residence. Each zone is an imperfect substitute in the labor and housing markets. Thus each consumer has an idiosyncratic preference for each one of the 196 (14 by 14) job-residence location pairs. Wages in each zone are determined by the skill level of the consumer (not by industry of employment). The choice of a residence-job location pair (*i,j*) by an employed consumer also determines the consumer's commute as will be discussed in more detail below.

(ii) *Housing type*: There are two housing types representing floor space in single family housing or in a multiple family housing structure. All housing choices occur at the residence zone and are treated as renting.

(iii) *Car-type*: There are five discrete car types differing by fuel economy. Fuel inefficient vehicles are larger, more comfortable and with higher acquisition and maintenance cost. The consumer's utility function has a systematic preference that increases with the comfort, safety and size of the vehicle and an idiosyncratic component for each car-type. Thus the choice of a car-type involves a trade-off between the marginal utility of owning a larger and less fuel efficient vehicle and the higher acquisition, maintenance and operating costs (e.g. gasoline) for such a vehicle. As a result, in the model less fuel efficient vehicles are on average owned by higher-skill-and-income consumers with idiosyncratic variation within each skill-income group.

Choice of continuous variables depends on the above discrete choices (i, j, k, c), where i =1,…,14 are zones of residence, j =1,…,14 are zones of job location where, k = 1,2 are the two housing types and c =1,…,5 are the five car types. Thus, a working consumer faces 1960 discrete bundles to choose from, whereas a non-working consumer faces 140 discrete bundles. In all, each consumer faces 2100 discrete bundles. The conditional choices of the continuous variables depend on the discrete choices as follows:

(i) *Housing quantity*: Given (i, k) the consumer chooses how much housing floor space to rent.

(ii) *Labor hours*: Given (i, j), the consumer chooses how many hours to supply at j.

(iii) *Shopping trips*: Given i, the consumer chooses the quantity of retailed goods to buy at z=1,…,14, and the number of trips required to make those purchases are determined according to calibrated fixed rates per unit of the retailed good. Goods purchased at alternative retail locations are imperfect substitutes and all retail locations are patronized because the consumer's utility incorporates a taste for location variety in shopping.

An important aspect of the consumer is the trade-off in the utility function between work, leisure and travel. Leisure is fixed and that the remaining time is allocated between working hours (labor supply) and travel which includes both commuting (assumed to occur once per work day) and endogenously determined discretionary non-work trips to buy the retailed goods. Travel time of any purpose is valued at the wage rate since an extra hour of travel means that one hour less in wages will be earned. It is also assumed that commuting time creates some disutility. Thus, the marginal rate of substitution between disposable income and commuting time exceeds the wage.

Formally, each consumer of skill/income f maximizes utility in the continuous variables $\mathbf{Z} = [Z_1, Z_2, ..., Z_{14}]$ and b; and the discrete bundles (i, j, k, c),where i is residence location, j is job location, k housing and c car type:

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

Given are the prices of goods retailed in *z*, $p_{\Re z}$, the rent of residential floor space, R_{ik}, the wage rate , w_{jf}, non-wage income, M_f, mode-and-route- composite shopping travel times, G_{izcf}, and commuting times, G_{ijcf}, mode-and-route- composite monetary costs of commuting and shopping trips, g_{ijcf} and g_{ijzf}, the quantity shopped per trip, c_{ijf}, the fuel inefficiencies (gallons per mile) of the available car-types m_c, the annual time endowment available for work and travel, *H*, the number of days per year, *d*, for which a commute is required. $\Lambda_{ijkc|f}$ are constant effects associated with the discrete choice bundle (i,j,k,c) and $u_{ijkc|f}$ are the idiosyncratic tastes. $\iota_{z|ijf}$ are constant effects that reflect the attractiveness of a retail location *z* to consumers of type *f* located at residence-job locations *i*, *j*. η_f in the CES sub-utility defined over retail locations is related to the elasticity of substitution among the retail locations, and α_f is the share of the disposable income spent on purchasing retailed goods and $1-\alpha_f$ the share that will be spent on renting housing. γ_{1f} is the marginal disutility of commuting time and γ_{2f} the marginal utility of a larger, safer but less fuel-efficient car. The right side of the budget constraint is the money income of the consumer who is paid a wage per hour of labor supplied after all travel time (for commuting plus shopping). If the consumer chooses not to work by choosing *j* = 0 in the outer stage, then $\Delta_j=0$, and the consumer has no wage-income. 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 car-ownership costs, $K(m_c)$. The prices of the retail goods are the prices at the retail location plus the monetary cost of the travel from home to the retail location.

In the inner stage (inside { }), given the discrete choice bundle (*i, j, k, c*) determined at the outer stage, the consumer chooses the optimal quantities of the retailed composite goods to shop from each retail location *z*, (vector **Z** =**[** $Z_1,Z_2,...,Z_{14}$]); and the residential floor space b to rent. This results in the Marshallian demands $Z^*_{ijkc|f}$ and $b^*_{ijkc|f}$. At the outer stage, the consumer chooses the most-preferred (*i, j, k, c*), given the indirect utility function $U^*_{ijkc|f}+u_{ijkc|f}$ from the inner stage. The discrete choice probabilities have the nested-logit structure, where a marginal probability describes the binary choice of entering the labor market versus not participating in the labor market. The conditional multinomial logit probability, $P^*_{i,j>0,kc|f}$, describes the distribution of employed consumers of type *f* 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 $\left[G_{ijc|f}\right], \left[g_{ijc|f}\right]$. RELU-TRAN2 does not treat traffic congestion by time of day, so all who use a road experience the same congestion. The monetary cost, on the other hand, does depend on car-type since gasoline consumption depends on traffic speed determined by congestion, and since car-type is a discrete choice that depends on car acquisition and operating costs and on car preferences which vary with income.

Consumers in TRAN

(i) *Mode choice*: For each residence-job-car bundle (*i*, *j*, *c*), the consumer of type *f* chooses a travel mode for each trip (whether for commuting or for shopping) that are determined in RELU. There are three modes of travel. m =1 (car), m =2 (public transit) and m = 3 (other, mostly non-motorized). The third applies largely to intra-zonal trips especially in the suburbs. When the consumer chooses auto for a trip, it is assumed that she uses her chosen car-type, *c*. Both systematic and idiosyncratic generalized costs are considered in the choice of mode.

(ii) *Route choice*: For car trips, the consumer chooses the route from trip-origin zone *i* to trip-destination zone *j* with the minimum round-trip generalized cost over the road network. As in mode choice, the systematic and idiosyncratic generalized costs of the available routes are considered. The consumer takes as given the speed of travel on each road-link on that route since speed is determined by traffic congestion which is the ratio of the trip volume using the link and the link's capacity. As the ratio increases, traffic slows down. Thus, the travel time on each link is endogenously determined at equilibrium. All car-types are assumed to cause the same congestion on each other. The generalized cost of travel on a link is a weighted sum of the monetary cost and the value of travel time. This value of time is exogenous and increasing by skill-income group. The monetary cost depends on vehicle type (hence on fuel economy) and on the cost of gasoline. Figure 3a plots the U-shaped speed versus fuel consumption curves estimated by Davis and Diegel (2004) for nine actual car models. Figure 3b shows the band of fuel versus speed relationships enveloped by the model's five car types.

[FIGURES 3a, 3b ABOUT HERE]

These relationships were obtained by fitting a polynomial curve to the Geo Prizm in Figure 3a and then multiplicatively shifting this polynomial. Consumers can determine their monetary expenditure on operating a car by choosing their car-type in RELU (as we saw), and by choosing routes that are faster or slower in TRAN. Consumers with lower (higher) values of time are more likely to prefer monetarily cheaper (faster) routes and this together with their preference for car-size and the level of car acquisition costs relative to their income determines their fuel economy and gasoline consumption

The gallons/mile versus miles/hour polynomial curve is $\mathrm{f(s)}m_c$, where:

$$\begin{aligned} \mathrm{f}(s) &= 0.12262 - 1.172 + 6.413\times10^{-4}s^2 - 1.8732\times10^{-5}s^3 \\ &+3.0\times10^{-7}s^4 - 2.472\times10^{-9}s^5 + 8.233\times10^{-12}s^6 \end{aligned} \tag{2}$$

$p_F\mathrm{f}(s)m_c d$ is the fuel cost of driving a road distance d at speed, s, using a car of fuel efficiency level m_c when the price of a gallon of fuel is p_F. The speed is calculated as $s = \dfrac{1}{Time}$, where d is the road distance and *Time* the congested time it takes to travel one mile. *Time* is given by a BPR type congestion function $Time{=}c_0\left(1+c_1\left(\dfrac{Flow}{CAP}\right)^{c_2}\right)$. *Flow* is the aggregate volume of traffic on the road and *CAP* is the road's capacity (assumed constant all along the road). The generalized cost of traveling a road of length d is $gcost_{fc} = (vot_f)(\dfrac{d}{s}) + p_F\mathrm{f}(s)m_c d$, where vot_f is the value of time in route choice that depends on the consumer's income indicated by f.

Firms

RELU includes four industries. They are: (a) agriculture, (b) manufacturing, (c) business services, and (d) retail. Production functions are constant returns to scale and all firms producing in the same zone and industry are perfectly competitive profit maximizers in input and output markets, charging the same price and paying the same wages and rents. Goods in the same industry produced in different zones are variants of the same good. As explained earlier, consumers buy only the retail good by shopping it in every zone, that is by buying all the variants. All variants of a good are also used as intermediate inputs in the production of the other goods except for the retail good which is produced by the input of the other goods, but is not itself an input in the production of other goods. In addition each industry uses primary inputs which are business capital, space in commercial and industrial buildings and labor from each of the skill groups (income quartiles) of the working consumers. All outputs can be exported to other regions from any zone where they are produced.

Developers

Our treatment of developer behavior is based on Anas-Arnott (1991) which has been adapted to RELU. Developers are agents that incorporate the activities of landlords (who rent out floor space), investors who buy and sell real estate and contractors who either construct or demolish buildings. Unlike firms and consumers who are myopic, developers operate with perfect foresight about the future and are risk neutral profit maximizers. In this article, the model is implemented as a stationary state or long run equilibrium model, and developers therefore, operate with perfect foresight of this stationary state. Time is view in discrete periods consisting of five years in duration. There are no transactions costs in buying and selling real estate. In the beginning of each period, a developer is the owner either of vacant land in some zone or of either residential or commercial or industrial buildings. Developers in the same zone who own vacant land face the same construction cost for constructing one of the building types, but they are horizontally differentiated by idiosyncratic costs around the common cost. It is assumed that the idiosyncratic cost draw of each developer for constructing each type of building and for just keeping the land vacant is determined towards the end of each period.

When these costs are determined the developer decides whether to continue to hold the land vacant or whether to construct a particular building type, given the per-square-foot construction cost of floor space in such a building. At the beginning of the period when the uncertainty about the idiosyncratic costs has not been resolved, the developer values the vacant land asset at the expected maximum profit the land would fetch from the most profitable construction or doing nothing at the end of the period. Similarly, developers who start the period owning a particular type of building have common systematic costs of demolition and idiosyncratic costs around the common systematic cost that are revealed near the end of the period. Again, they decide whether to demolish or not at the end of the period, while in the beginning of the period they value the building asset knowing only the expected value of the profit maximizing action (whether to demolish or not). Developers being perfectly competitive, asset prices for vacant land and for each type of building are determined in the beginning of each period so that the expected profit that can be realized during that period, including net rental income from leasing out the property is zero.

2.3 Model structure: general equilibrium

The relevant markets are the labor market for each labor skill level in each zone (56 equations consisting of 14 zones by 4 skill levels), the residential rental market for each residential building type (single-family and multiple-family) in each zone (28 equations, that is 14 by 2), the business rental market for commercial and industrial buildings (28 equations, that is 14 by 2), and the good markets for each industry and zone (that is 56 equations, 4 industries by 14 zones). Solving these equations determines the rental price (per square foot) of each type of floor space in each zone, the hourly wage for each skill level in each zone and the output price for each industry in each zone.

Additional equilibrium processes are the determination of congestion on every link of the major road network as well as the local congested travel time in each zone on the local roads. This allows the calculation of speeds and then of congested travel times and of travel monetary costs from zone to zone in TRAN, that are then entered into RELU to calculate the demands of the consumers (since travel time reduces the time available for work and thus determines the disposable income of the consumers), and the demand for intermediate inputs by firms.

Since the developers' behavior is assumed to be stationary in the aggregate in each zone and for each type of building and vacant land, the asset prices for building and land make all expected economic profits zero so that developers earn only normal profits, while stocks, rents and values are stationary by the construction flow of the floor space of each building type equaling the demolition flow of the floor space of the same building type. An exogenous change would change the long run equilibrium stocks that prevailed, but would also change the rates of demolition and construction necessary to maintain the stocks at a stationary level.

2.4 Calibration of the Model

The model's calibration is evaluated by certain key elasticity measures and the marginal rate of substitution between commuting time and disposable income. The values of these relationships are for the year 2000 Chicago MSA data and are shown in Table 1. It is important to put these numbers in the context of the literature where the same relationships have been estimated by others.

[TABLE 1 ABOUT HERE]

The elasticity of location demand with respect to commuting time has been estimated in the 1970s by Charles River Associates (1972), Lerman (1977), Atherton (1975), Train (1976). A survey of the literature which includes their own estimates is given by Anas and Chu (1984). They reported that: "*The in-vehicle time elasticity ranges from -0.36 to -1.40 for transit and from -0.55 to -1.77 for the drive-alone mode. Out-of-vehicle time elasticities range from* -0.23 to -2.7 for transit and are -0.42 in the CSI model. *Train and CRA do not report out-of-vehicle time elasticities for the auto mode*." As shown in Table 1, our workers' travel time elasticity of location demand in RELU-TRAN2 ranges from -0.544 to -0.619 and is in the range of the above estimates.

It is reported in Anas and Arnott (1993) 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 to 1980, are -0.554, -0.516 and -0.683 respectively. In our model, the rent elasticity of housing demand cannot be larger than -1, because of the functional form of the utility function, and ranges from -1.38 to -1.95. Our elasticity combines two aspects of the demand for housing: the demand for housing size as floor space which has elasticity of -1, and the number of consumers who demand housing at a particular location which has elasticity that ranges from -0.38 to -0.95. Housing demand at a particular location is the product of these two quantities. Thus our elasticity is higher than that in Anas and Arnott (1993), who estimate a model in which the size effect is fixed.

Kimmel and Kniesner (1998) studied US household data for the period from 1983 to 1986. Their wage elasticity of labor supply (hours worked) is +0.51. In our model, the consumer makes more non-work trips when the wage increases (because of the income effect for shopping normal goods), and this reduces the labor supply.

In Anas and Arnott (1993), the elasticity of housing floor space supply with respect to rent is +0.1016 and +0.1136 for single-family and multiple–family housing respectively. In our model the corresponding values are +0.0991 and +0.23. Thus our single-family housing is similarly elastic with theirs, but our multiple-family housing supply is more elastic than theirs. This elasticity measures the percent of existing housing stock that will be put on the market to be rented (than being kept vacant) by the landlords. Our +0.23 estimate for multiple family housing is almost the same as that reported for by Anas (1982) for the Chicago MSA using 1970 data.

DiPasquale and Wheaton (1994) report that the long run price elasticity of the aggregate housing stock is in the +1.2 to +1.4 range. 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 (supply measured in value terms) in United States for 1950 to 1994 ranges from +1.6 to +3.7. Green et al. (2005) report a price elasticity of housing supply in the Chicago MSA for the period from 1979 to 1996 as +2.48. But their estimate is not significantly different from zero. Their housing supply is defined as the number of housing units for which building permits were issued, multiplied by 2.5 (the average household size), divided by the population. Our elasticity of housing construction measures what percent of the land available for construction will be developed into type *k* building (housing) if the asset price of type *k* building rises. This elasticity ranges from +0.03 (for single-family housing in the city) to +0.68 (for multiple-family housing in the suburbs).

One of the reasons why our elasticity of construction is so small is that many of our modeled zones are urbanized and there is not much land left to be developed. The area covered by the Chicago MSA in Green et al. (2005) covers a broader area than do our modeled zones. It is also the case that by the year 2000, our modeled zones had become more developed than they were during their period, and the available land would have decreased significantly. Also, the definition of our elasticity of construction is different than theirs, because they measure how much an increase asset price would increase building permits multiplied by the population that would use the newly constructed housing, whereas our elasticity measures the percent by which the developed land would increase.

There are two additional assumptions that could be affecting our elasticity in real estate variables. First, is that our building structural density (in floor space per unit of land), is constant by building type and zone. But, average structural density in our model zones is not constant and can change over time by demolishing low structural density buildings and constructing higher structural density buildings, for example. But, if the building's floor space amount 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 +5.27, where their 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, that could be affecting our low elasticity of stock, is the equilibrium condition that the construction and demolition flow of each building stock in each zone is equalized by the real estate market being in stationary equilibrium. In reality, the construction flow would be larger than demolition and stock in a growing economy.

The above discussion suggests that 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. This suggests that it might be better to evaluate the reasonableness of our housing supply elasticity by actually simulating the model in a comparative static exercise, and observing how the housing stock responds in quantity. In such a comparative statics exercise (Hiramatsu, 2010), we simulated a simple urban growth scenario, in which we increased the total population and the net exports by 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. Both single and multiple family housing stocks increase by less than the 10% population growth and the average floor space per person decreases. The industrial and commercial buildings also increase in the city and in the suburbs. The rate of increase is more in the city than in the suburbs, but not as high as the rate of increase 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 commercial buildings are also constructed in the suburbs. Thus the building stocks respond reasonably with respect to the increase of the population and net exports. Accordingly, the rents and values of each building type change in a normal way. In the city, the rent of single family housing increases by more than 10%, because the supply decreases. The other building rents also increase since demand increases by more than supply does. Both rent and value increase more for those building types and locations where the demand increases more and the supply increases less. In this way we conclude that the building markets, including stocks, rents and values, respond reasonably under the calibrated elasticities of the model.

3. Alternative congestion pricing policies: Road tolls, cordon tolls, fuel taxes and parking taxes

The model calculates only two externalities of traffic congestion. The first is the time delay caused by the volume of traffic (that is, congestion delay) and 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 3b. The model calculates these two externalities on each mile of road for both major roads (links of the model's highway network) and local roads (intra-zonal links), 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 (a) a quasi-Pigouvian congestion toll (that varies by type of road and is charged on each model road link), (b) a per gallon fuel tax, (c) a cordon toll paid by car traffic crossing into zone 3 (the CBD), and (d) a parking tax per trip, paid by all car trips terminating in zone 3.

Quasi-Pigouvian tolls versus fuel tax

A first-best Pigouvian tolling policy would perfectly internalize both externalities over the entire network. 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 congestion indirectly. Because congestion and fuel consumption are not perfectly correlated, the fuel tax cannot be as efficient a policy as the congestion toll.

The Pigouvian tolls we calculate measure the excess time delay imposed by each car-trip on all other car-trips 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. 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 *MRS* 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. A second reason that congestion tolls in RELU are quasi-Pigouvian is that consumers can save fuel not only by switching to faster routes 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 car type. Again, we assume that road authorities do not tax by car type, but know only the average car on each road and set a toll that is common to all vehicles.

Under the fuel tax all car traffic pays the same per gallon of gasoline. As explained our quasi-Pigouvian tolls ignore the fact that a car's fuel economy affects the fuel externality it causes. The gasoline tax takes the fuel externality by car-type into account because cars with lower fuel economy would consume more gasoline and thus pay higher fuel taxes. Thus, on the one hand, the gasoline tax does a better job than the quasi-Pigouvian toll of creating an incentive for trips to be made with vehicles that have higher fuel efficiency. On the other hand, the gasoline tax does a poorer job of internalizing the delay externality 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 is directly proportional to the delay caused by congestion and reduces the time-delay externality more effectively.

Cordon toll versus parking tax

In practice, congestion tolling has been implemented by tolling only the most congested places of an urban area that is the CBDs, as in the cordon charging schemes (CCS) implemented for downtown London and the City of Stockholm. The London CCS was imposed in 2003 on the vehicles driving through or parking inside the cordon between 7:00 am and 6:30 pm of work days. Beevers and Carslaw (2005a, 2005b) examine London's CCS, observing higher speeds in and near the cordon Although emissions are decreased inside the cordon, the effect is weaker in the inner ring road which is outside the cordon, or emissions may have even increased there (Leape (2006)).

Equity effects of road pricing using the proposed congestion-charging scheme for Stockholm are discussed by Eliasson and Mattsson (2006). Results show, for example, that high income groups and residents in the central area are affected the most, since they pay often. But, by using the toll revenues to improve public transportation, women and low income groups benefit the most. The initial travel patterns and revenue usage are important factors in the formulation of an appropriate congestion policy.

The most congested area in Chicago is the CBD that corresponds roughly to our model zone 3. For our cordon toll policy we select the major roads that allow entry into the CBD and calculate a uniform toll that all car traffic will pay when entering (but not when exiting) zone 3. We can optimize this cordon toll by maximizing an appropriate welfare measure or calculate it to get revenue equivalence with another policy. Our downtown parking tax is similar to the cordon toll in the sense that both target the CBD. But while the parking tax reduces congestion by discouraging trips that terminate in the CBD, the reduced congestion actually encourages more through traffic. It therefore has an ambiguous total effect on congestion in the CBD. On the other hand, the intra-CBD trips are discouraged by the parking tax but not by the cordon toll.

Effects of 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 in the choice of route. As an example of this, a commuter who passes through the CBD could be induced to travel around the CBD and thus avoid the cordon toll. As many others choose the same behavior, the roads circumventing the CBD would get more congested, as the roads going into the CBD get less congested. Another example is that a quasi-Pigouvian congestion toll would increase the monetary cost of travel. This would induce consumers with low values of time to choose longer routes which entail lower tolls. Commuters with higher time values would prefer to pay the higher fuel taxes and travel on the routes that became faster.

A second 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 third 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 fourth margin of adjustment would be to change the destination and number 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 the adjustments discussed above can be accomplished in the short and medium terms because they do not require changing a job or residence location which require longer term adjustments. Some examples of residence location changes would be for a CBD-worker who commutes into the cordon to move his residence into the CBD, reducing housing size at the same time in response to the higher CBD rents. Such a choice would be typical of those who either strongly dislike using transit, or those who reside in suburban areas that are transit inaccessible. Others may indeed switch to transit but in order 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 inside the cordon and employing many employees who drive into the cordon 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 so as to lower the tolls and taxes incurred by its employees. But the CBD may attract more firms if enough consumers are willing to locate residence within the CBD or switch to transit, because such shifts could increase the supply of labor within the CBD sufficiently so as to cause wages to go down. Meanwhile, though such shifts would also induce demolishing commercial real estate to replace it with residential which would drive up commercial rents per square foot indirectly inducing firms to leave the CBD.

Moving out of the CBD would also entail higher costs of procuring certain intermediate inputs (for manufacturers or business service providers) or less accessibility to customers (for a retailer). These considerations imply that no strong conclusions can be made about whether a cordon toll policy entails the revival or decline of certain real estate markets within the cordon. 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. Meanwhile, the results are also influenced by how the toll or tax revenues are distributed.

In practice, it may not be infeasible to toll all roads. In realistic schemes only major roads are proposed for tolling, while local roads would remain untolled. 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 in the model) 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 would be the fuel tax on highly congested roads that take longer time to go through. On the other hand, the fuel tax would be expensive where drives consume more fuel. Hence drivers would feel that the fuel tax is too high on long distance and slower routes. Under both policies, it would not be very helpful for drivers to make detours since all roads would be impacted.

The most important difference between the two policies is that the quasi-Pigouvian toll removes the externality of congested roads, but that the fuel tax does not. A second important difference is that, the quasi-Pigouvian toll is the same for any types of vehicle on the same road, but the fuel tax paid increases by the fuel diseconomy of the vehicle.

4. The impacts of the policies

We examine the impacts of the four policies on consumer utilities, population and job location patterns, urban sprawl (defined as aggregate land under development) and variables related to driving such as trips, VMT (vehicle miles traveled by cars), MPG (average miles per gallon, that is average fuel efficiency), aggregate fuel consumption and CO2 emissions.

Our comparisons rely on revenue-neutrality that is after all markets have adjusted to the simulated policy, the aggregate tax or toll revenue raised by each policy is the same. Quasi-Pigouvian tolls are endogenously determined so that the average private cost plus the toll paid on each road add up to the marginal social cost of travel on each road. For the other policies there is no equivalent formula that can be used to find the right level of the policy instrument. Instead, under these policies the level of the fuel tax, cordon toll or parking tax can be varied until an objective is maximized.

One could maximize the sum of consumer utilities weighted by arbitrary weights assigned to each income group, but the weights are arbitrary and obviously affect the results. Alternatively, one could maximize a monetary measure of consumer surplus that is the aggregation of the consumer surplus of all the consumers. The problem with this approach is that in RELU the utility function is not of Gorman form (that is the marginal utility of income is not constant within an income group and varies by income group). Therefore, the consumer surplus measure is not uniquely determined. Approximate measures of consumer surplus can be computed by dividing the consumer surplus of each consumer with the consumer’s marginal utility of income, but since this marginal utility is not constant, thus the constructed consumer surplus is not an exact measure of welfare.

In large part also, the welfare maxima and the comparison across policies depend on how each policy’s aggregate revenue is redistributed or recycled. For example, alternative Pareto efficient outcomes can be calculated depending on how this redistribution is made. To avoid these pitfalls, we make revenue neutral comparisons of the policies proceeding as follows. We gradually increase the policy instrument (fuel tax rate, parking tax or cordon toll), and stop when the revenue from each policy is equalized to the revenue from quasi-Pigouvian tolling.

We tested three quasi-Pigouvian tolls: (i) the quasi-Pigouvian toll for time delay and fuel consumption on all major roads only; (ii) the quasi-Pigouvian toll for time delay and fuel consumption on all roads; and (iii) the limited quasi-Pigouvian toll for time delay and fuel consumption on the three major road links entering the CBD. The last policy is similar to the cordon toll, in which the same three road links in (iii) are tolled uniformly.

The annual per capita revenue (that is revenue per RELU consumer whether the consumer is paying the toll or not) from the three quasi-Pigouvian tolling policies (QP) are: (QP-i) \$277.60, (QP-ii) \$1173.11 and (QP-iii) \$25.67. In the case of QP-i, the tolls paid average at about 19 cents per mile and range from \$2.04 to -\$0.098. The subsidy occurs because there are major road links in suburban areas where traffic moves so fast that the fuel consumption externality can be reduced by a slight subsidy that would increase congestion slightly. This can happen because of the U-shaped fuel/mile versus speed relationship in Figure 3b. On average, under QP-i, 92.5% of the average toll is due to the time delay externality and the remaining 7.5% is due to the excess fuel consumption externality. In the case of (QP-ii), 5.33% of the congestion externality is due to excess fuel consumption.

The fuel tax is always levied on all travel as a per gallon tax. We express it as a percentage of the gasoline price which is exogenous to the model. The fuel tax rate that that is revenue neutral with QP-i is 146% and the rate that achieves revenue neutrality with QP-ii is 227%. Since, fuel tax revenue is inverse U-shaped there can be two revenue neutral fuel tax rates. The revenue peak of the fuel tax rate occurs at a rate of 1100% (\$2709.01 per capita), but we could not find another revenue neutral tax rate within the range we examined (from 0% to 1500%). Since the fuel price elasticity of fuel consumption is small (-0.0899), even if the fuel tax rate increases greatly, the fuel consumption decrease only moderately.

Revenue from the cordon toll or the parking tax at the revenue peaks is less than the revenue from the quasi-Pigouvian toll (i) and (ii) for any level of toll or fee. We use the revenue of the limited quasi-Pigouvian toll (QP-iii), to define the revenue neutral level of the cordon toll. Since the cordon's revenue is an inverse U-shaped function of the cordon toll per crossing, there are two revenue neutral cordon tolls, one on each side of the cordon's revenue peak. Between these two, the one on the ascending portion of the revenue curve is closer to the quasi-Pigouvian toll than is the one on the descending portion. These two revenue neutral cordon tolls are \$1.49 and \$29.39. The cordon revenue-peak occurs at \$ 11 yielding annual per-capita revenue of \$ 93.76. The two revenue neutral parking fees are \$ 2.24 and \$24.67 with the peak at \$ 10 yielding an annual per-capita revenue of \$64.95.

We now turn to discussing the impacts of the policies. In doing so, it is convenient to group the global pricing policies together separately from the more geographically limited policies together. The global policies are the Quasi-Pigouvian tolling on major roads (QP-i) and on all roads (QP-ii) and the fuel tax (FT), while the more limited policies are the quasi-Pigouvian tolling of the major roads entering the CBD, the cordon toll (CT) and the Parking tax (PT). The comprehensive policies major impacts are summarized in Table 2, while the geographically limited policies are shown in Table 3. Figures 4, 5 and 6 each consisting of six panels show effects on important variables as the intensity of each toll or tax is increased for the CT, PT and FT policies.

4.1 Quasi-Pigouvian tolling and the revenue-equivalent fuel tax

The results are shown in Table 2. Revenues under the three policies are the same but are not recycled. Hence, not surprisingly, each policy reduces the average utility level of each skill level and for both workers and non-workers. But, what is important here is to note that utility is decreased more by the fuel tax than under the corresponding quasi-Pigouvian tolling. Thus, the fact that the fuel tax is less efficient is borne out despite the fact that our Pigouvian tolls are not first-best.

Rents and wages are decreased by all of these policies and the reason is that the tolls or fuel taxes without re-distribution, have sizeable income effects. As disposable income is decreased, consumers cut back on the demand for housing which reduces equilibrium rents. Consumers also cut back and on the demand for other goods that they shop. This reduces the retail prices of goods and, in turn, the demand for labor is reduced. Meanwhile, since the faster travel and the fewer trips induced by the tolls or taxes frees up more time for work, labor hours supplied increases. The combined effect of a higher labor supply and lower labor demand is lower wages. Note that the Pigouvian toll on major roads only QP-i is the least comprehensive policy. It therefore has smaller income effects on average, resulting in smaller percentage decreases is wages and rents. This can be observed from Table 2 which shows a roughly 75% increase in the average monetary cost of travel under QP-ii or its equivalent fuel tax, but a much smaller 15% increase Under QP-i and a 50% increase under its equivalent fuel tax. The underlying behavior is that when only the major roads are tolled consumers can partially avoid the tolls on major roads by increasing the localization of their jobs, shopping and residences in the same zone, thus increasing the share of intra-zonal to inter-zonal trips. This avoidance strategy is less effective when all roads are subjected to Pigouvian tolling or under the equivalent fuel tax. Similarly, gasoline consumption, CO2 emissions, travel time, all decreases less (and speed increases less) under QP-i than under QP-ii. Under all policies consumers switch on the margin to more fuel efficient vehicles (the rebound effect's prerequisite) but the improvement in the design fuel economy is rather small. Nevertheless, because of the improvement in speed and the reduction in car VMT, significant reductions in gasoline consumption and emissions are realized. Since consumer can avoid some of the fuel tax by driving more efficient vehicles, but cannot equally well avoid the quasi-Pigouvian toll by doing so, fuel economy improves more under QP-i rather than under its equivalent fuel tax. But the greater congestion reduction (speed improvement) under QP-ii, causes fuel economy to improve more than under its equivalent fuel tax.

Next we look at the effects on the location of jobs, residences and the aggregate land consumption. These are shown at the bottom of the Table 2. In this regard, QP-i under which only the major roads are tolled has interesting effects. This policy's impact is avoided in diverse ways. Jobs decentralize from the CBD and the City of Chicago to the suburban zones, while residents centralize from the suburbs to the CBD and the City of Chicago. Both types of changes are consistent with the relationships between firms and workers or retailers and shoppers in RELU. On the one hand, when the cost of travel is increased by tolling the major roads, some consumers switch to transit which entails in part moving closer to the center of the MSA where transit is more accessible, or move closer to the center but continue to commute and shop by car traveling shorter distances than before. On the other hand, some consumers are less willing to do so if they highly value suburban housing, for example. In that case, firms must move closer to them reducing the travel distance and/or allowing intra-zonal travel that avoids the tolls. Under the other policies, however, intra-zonal travel substituted for inter-zonal travel is not as effective (as we have already noted) and as a result, many more consumers switch to transit and centralize, so much so that suburban jobs themselves following customers and employees become more centralized as well. It is especially noteworthy that the number of jobs in the CBD greatly increases (as does also the number of residences but less so) since switching to public transit which generally serves the Chicago CBD very well makes downtown jobs much more attractive for workers wishing to avoid the tolls or fuel taxes. A result of the centralization is that undeveloped land in the suburbs increases (urban sprawl decreases), as excess floor space in the suburbs decreases by net demolition, while floor space per consumer decreases both by consumers moving to the city where densities are higher and also by the income effect of the toll or tax that reduces the demand for housing size.

[TABLE 2 ABOUT HERE]

4.2 Cordon tolling and the parking tax

Table 3 compares the three geographically limited policies. These are the toll paid by all trips including through traffic coming into zone 3 (the Chicago CBD) or cordon toll policy (CT), and the tax paid per trip terminating inside the CBD and therefore parking there, or the parking tax policy. The third policy QP-iii is quasi-Pigouvian tolling applied to each major road crossing into zone 3, including though traffic. Because the CT policy is made revenue equivalent to QP-iii, these two policies (CT and QP-iii) have virtually identical effects in all respects. Therefore, we will focus on the comparison of CT and PT. Since the CBD contains only about 10% of the regional jobs and since trips crossing the CBD are also a fraction of the total, the two policies have much milder effects and mostly fractional percentage impacts on equilibrium utilities, wages, rents and driving related variables than did the more comprehensive policies of FT and QP-i, QP-ii.

One interesting result is that the population and job distribution effects of the CT and PT policies are qualitatively different. Under the cordon toll, the jobs decreased by 7,648 in the CBD (that is inside the cordon), increasing by 1,247 in the rest of the City of Chicago and by 6,346 in the suburbs. Meanwhile, residents decreased by 245 in the CBD, decreased by 1,321 in the rest of the City of Chicago and by 1,566 in the suburbs. Under the parking tax, the changes were smaller. Jobs decreased by only 499 in the CBD, increased by 599 in the rest of the City of Chicago, and decreased by 182 in the suburbs. Residents increased by 89 in the CBD, increased by 182 in the city and decreased by 271 in the suburbs. Thus the metropolitan area becomes somewhat more suburbanized under the cordon toll, but becomes somewhat more centralized under the parking tax.

As noted earlier, there are two key differences between the parking tax and the cordon toll. One is that the through traffic does not pay the parking tax but pays the cordon toll (in fact through traffic by commuters and shoppers pays the cordon toll twice as each such round trip crosses the cordon in both directions). The other difference is that intra-

CBD car trips pay the parking tax but not the cordon toll. A trade-off arises because the parking tax directly reduces congestion in and near the CBD that is contributed by car trips terminating in the CBD, but this encourages more through traffic which causes a rebound in congestion. A consumer who resides outside the cordon but either works or shops in the CBD, can avoid or reduce the effect of the cordon toll by moving his residence into the CBD or by choosing a job and shopping outside the CBD. But in the case of the parking tax, only choosing a job outside the CBD would work to avoid the tax. Meanwhile, both the cordon toll and the parking tax can be avoided by switching CBD-bound trips from car to transit. *Why then do CBD jobs decrease by more than 7600 under the cordon toll but by a much smaller 499 under the parking tax? We are still investigating the reasons.*

[TABLE 3 ABOUT HERE]

5. Remaining work

In the next and final draft of the paper we will make several improvements. One is that Tables 2 and 3 will be improved by focusing on variables that are not currently shown such as transit trips, intra-zonal versus inter-zonal trips, retail industry's job locations, the average floor space per consumer and job. Also, in the case of Table 3 we will focus on a different set of variables describing changes within the CBD rather than in the rest of the region.

Also, in the next and final draft the policies will be compared under alternative redistribution of their revenues.

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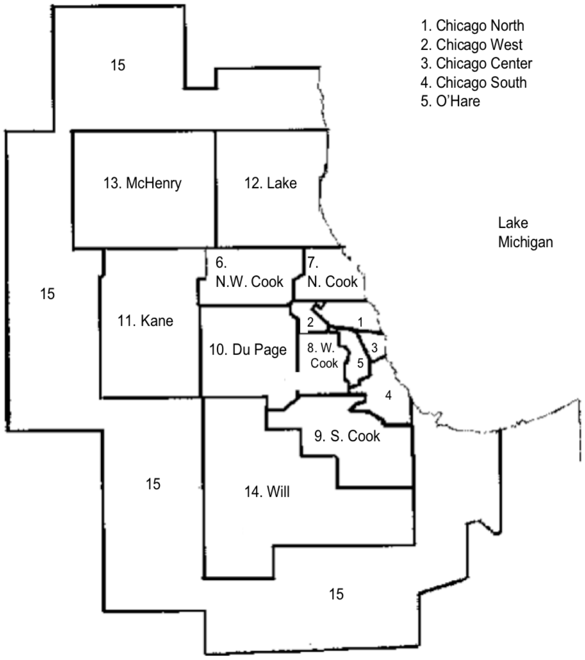

FIGURE 1: RELU-TRAN zones for Chicago MSA

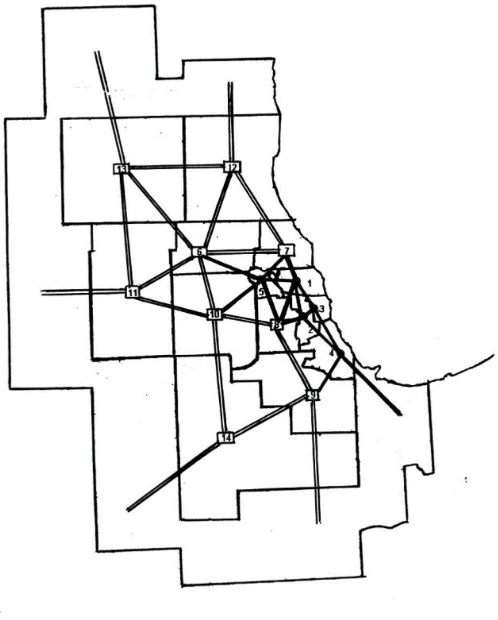

FIGURE 2: Network of major roads in RELU-TRAN2

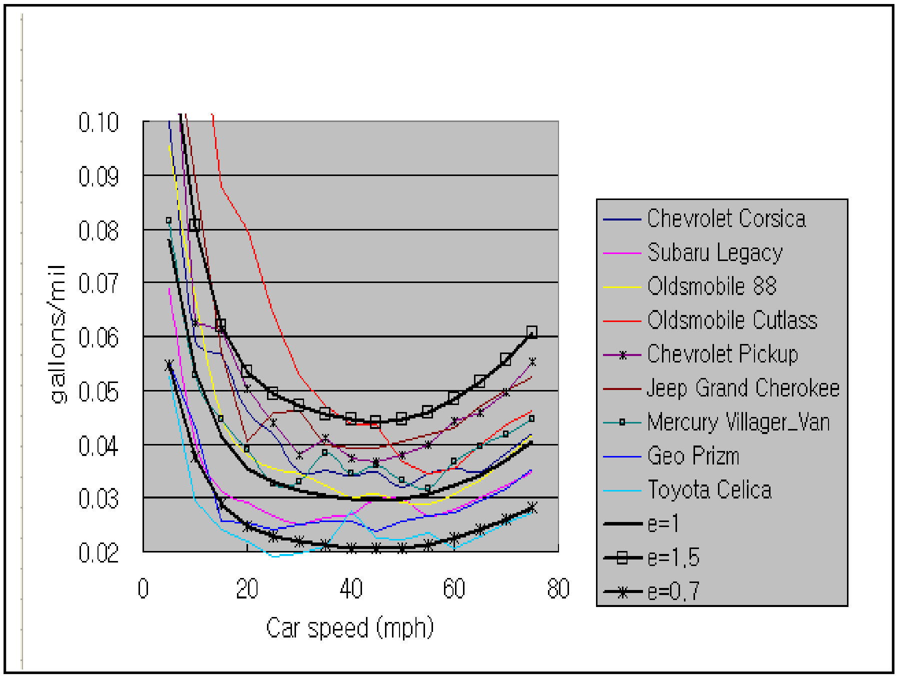

FIGURE 3a: Fuel intensity versus speed in nine car model (Source: Davis and Diegel (2004))

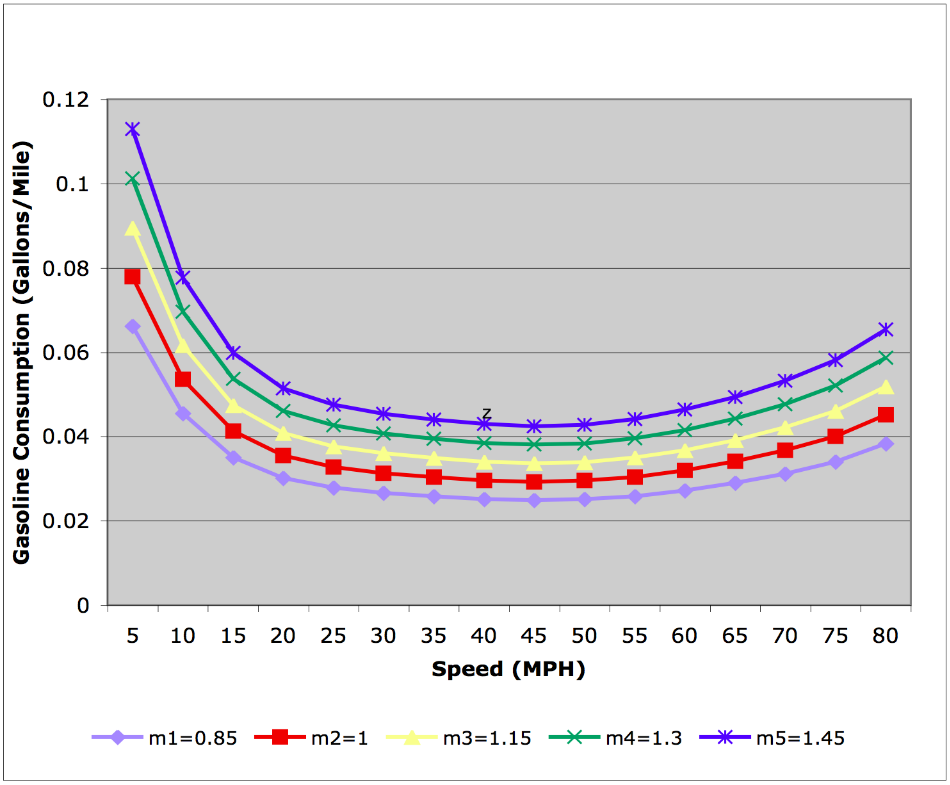

FIGURE 3b: Band of gasoline intensity and speed for the range of cars in RELU-TRAN2

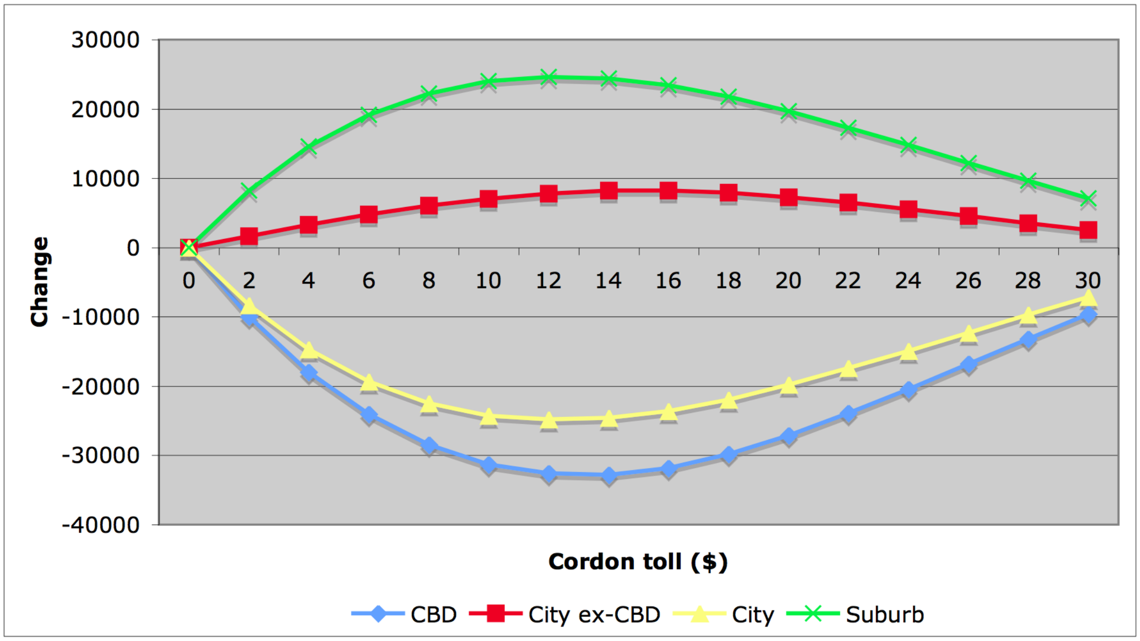

Figure 4 (a) Job location under the cordon toll

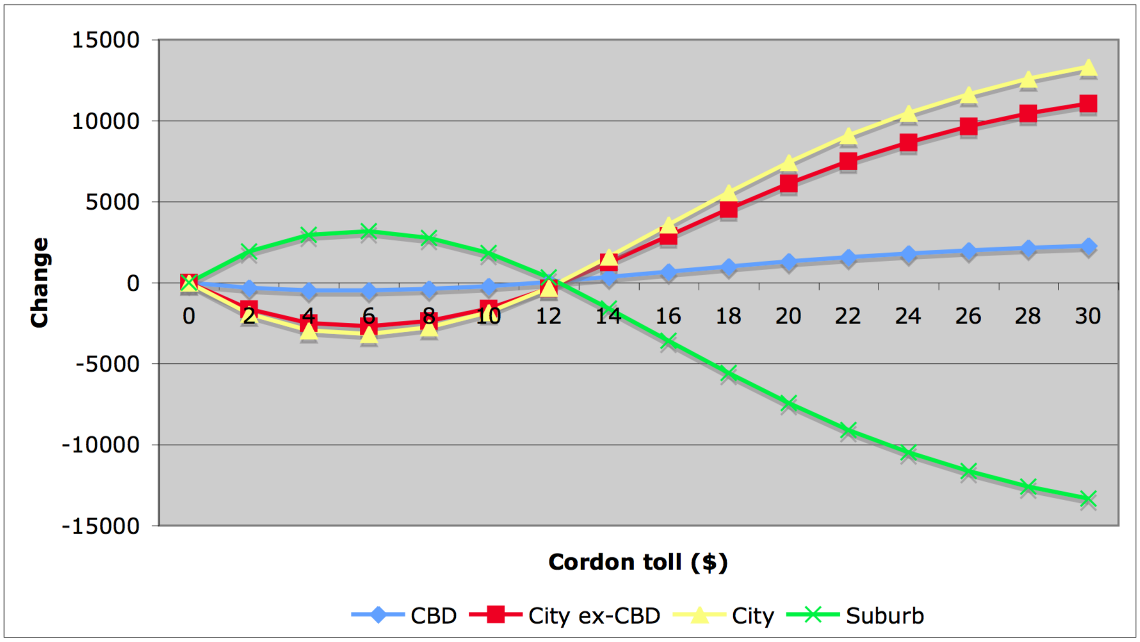

Figure 4 (b) Residence location under the cordon toll

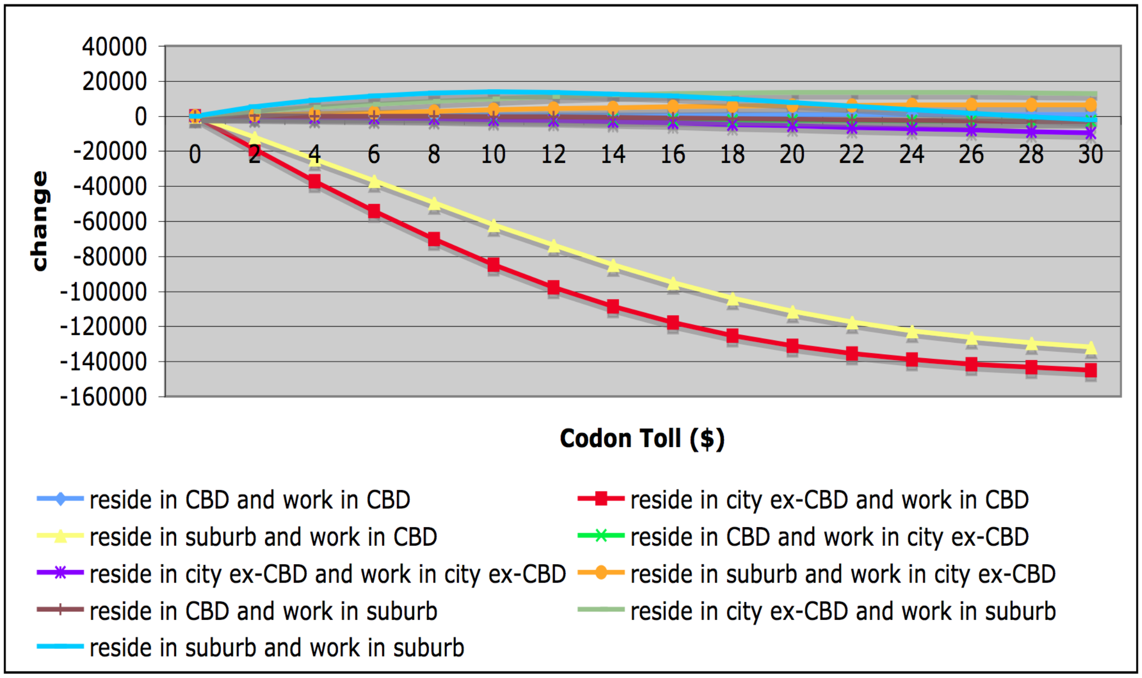

Figure 4 (c) Commuters by car under the cordon toll

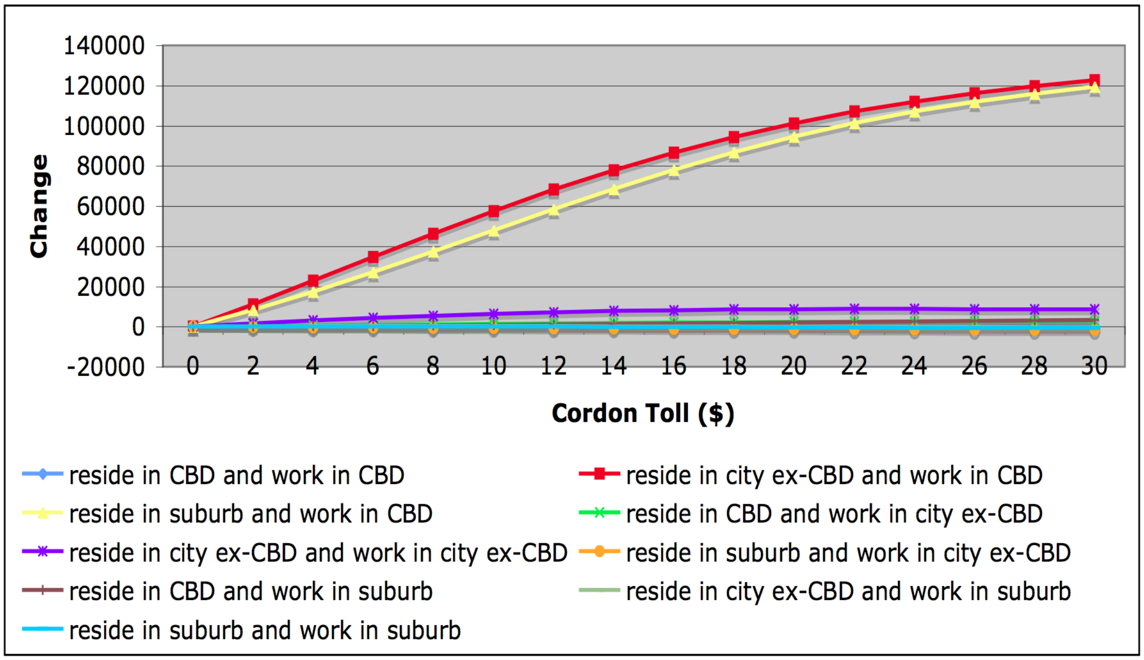

Figure 4 (d) Commuters by public transport under the cordon toll

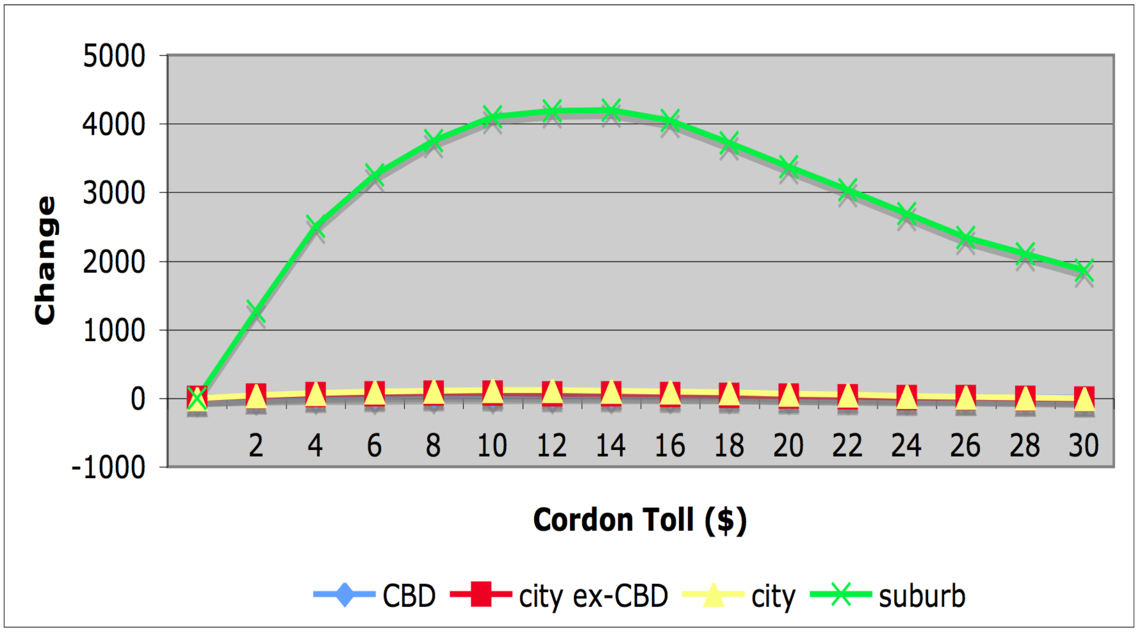

Figure 4 (e) Undeveloped land under the cordon toll

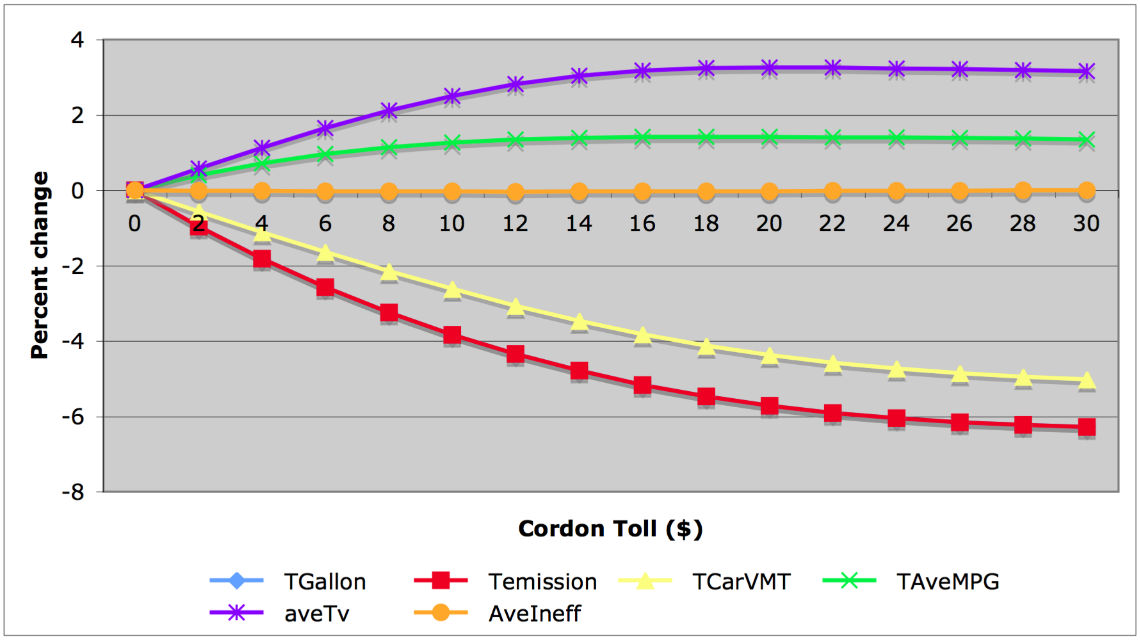

Figure 4 (f) Changes under the cordon toll

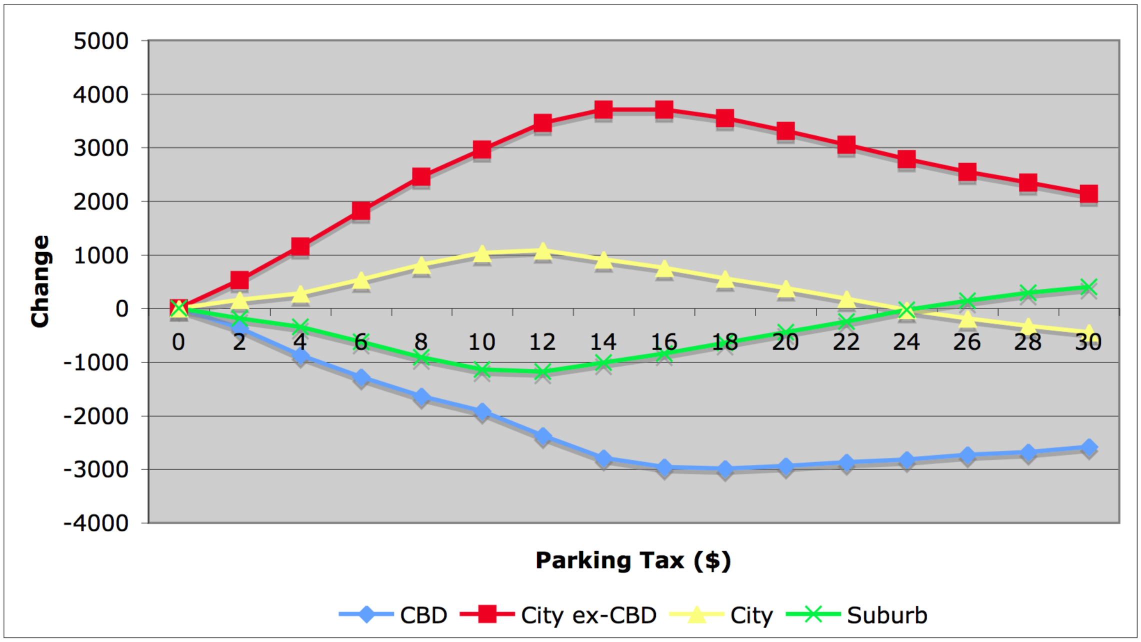

Figure 5 (a) Job locations under the parking tax

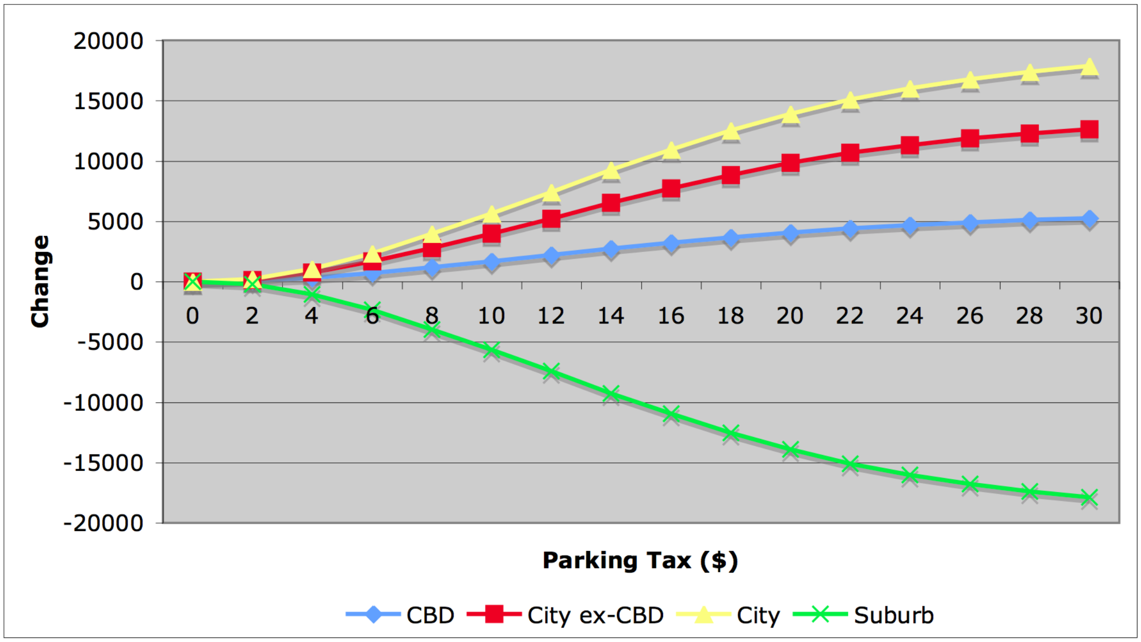

Figure 5 (b) Residential location under the parking tax

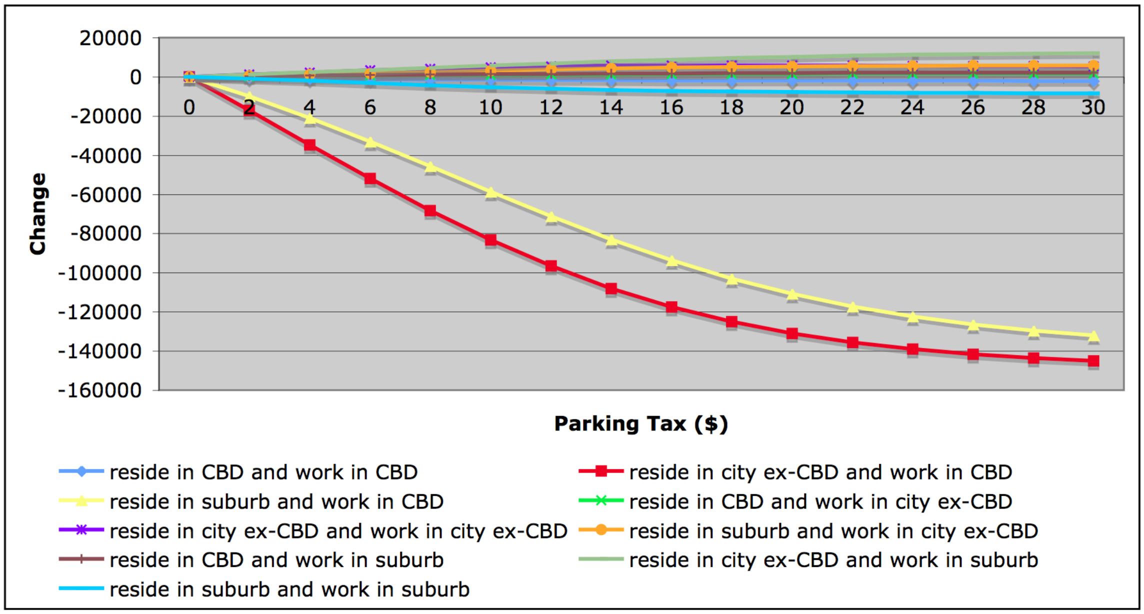

Figure 5 (c) Commuters by car under the parking tax

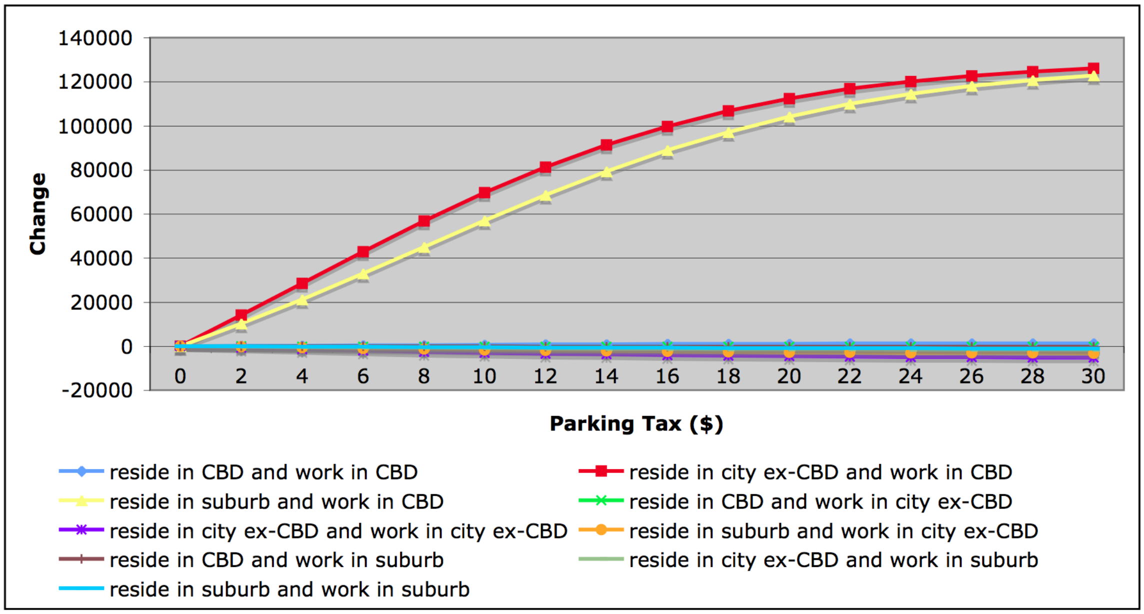

Figure 5 (d) Commuters by public transit sit under the parking tax.

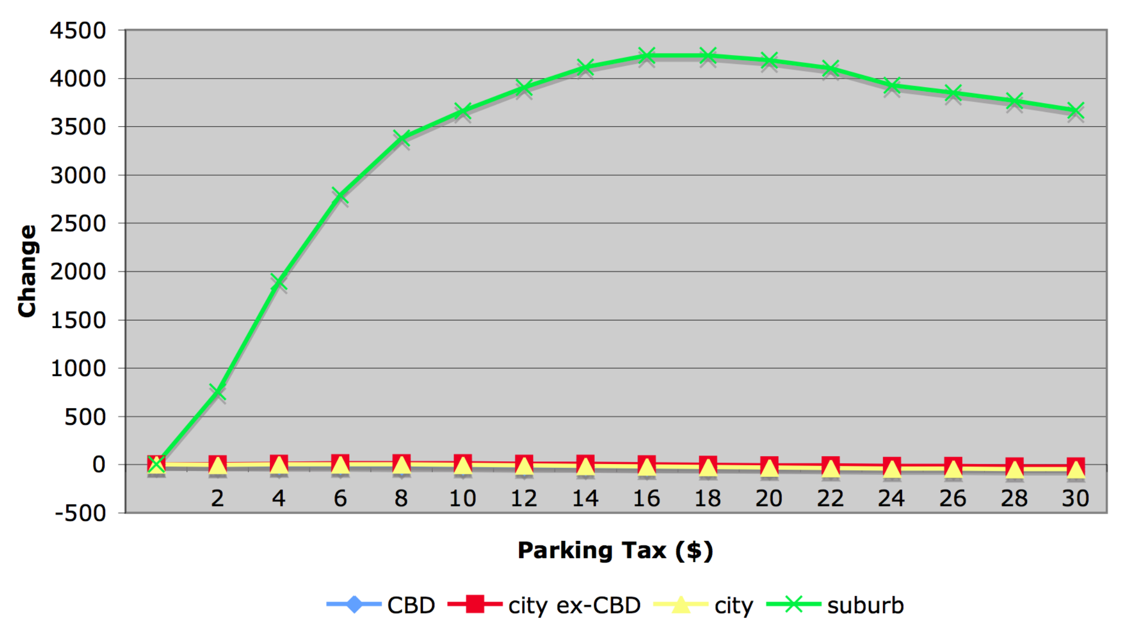

Figure 5 (e) Undeveloped land under the parking tax

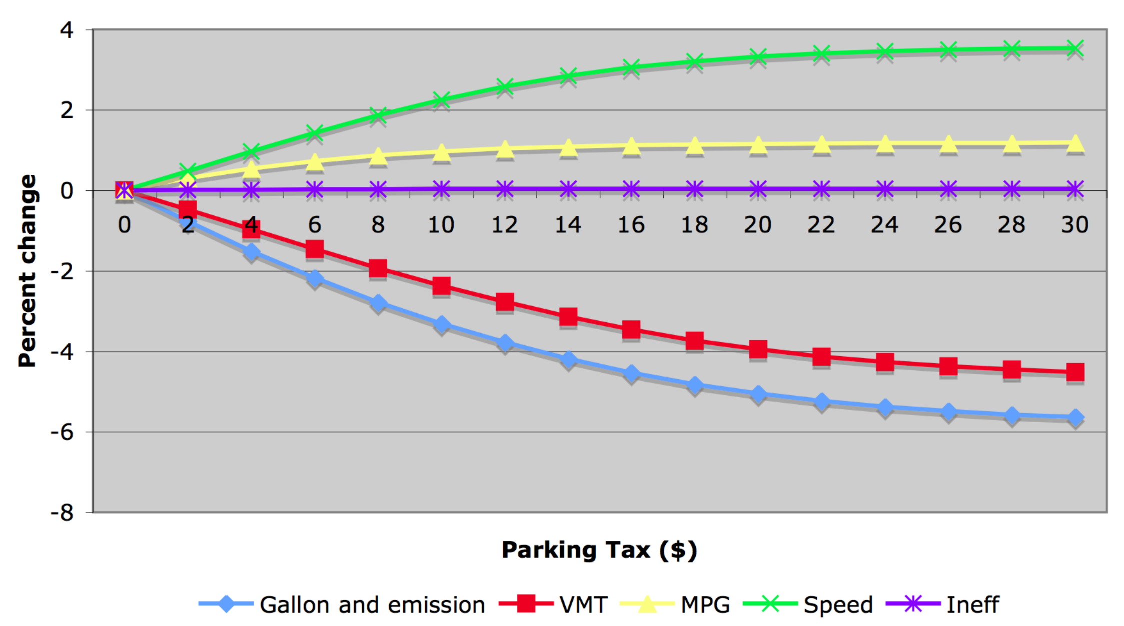

Figure 5 (f) Changes under the parking tax

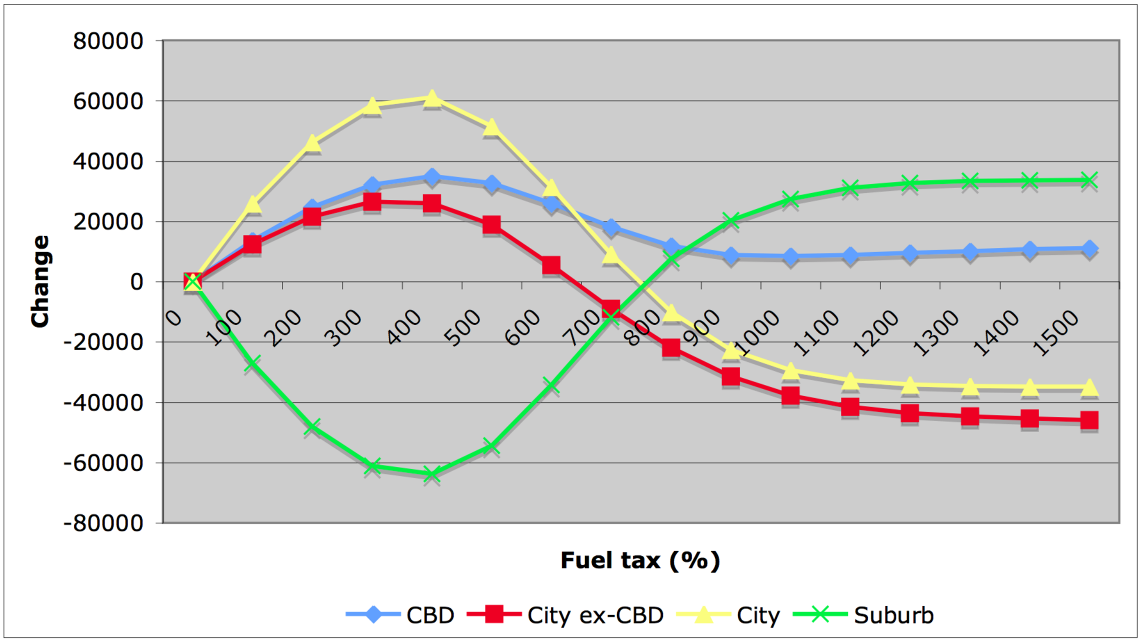

Figure 6(a) Job locations under the fuel tax.

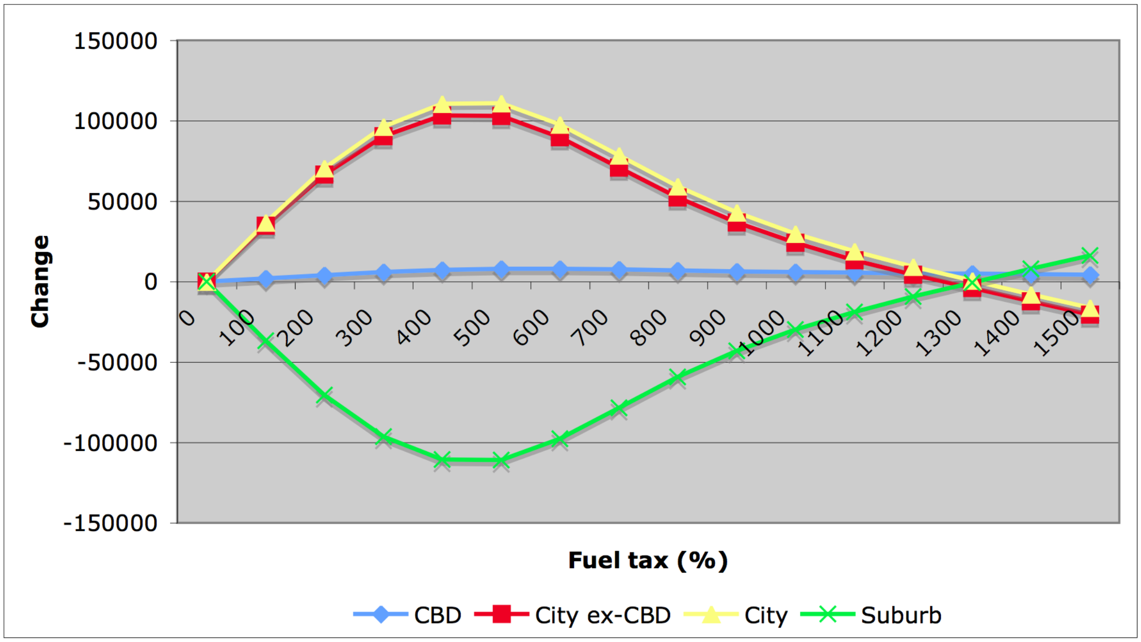

Figure 6(b) Residential location under the fuel tax.

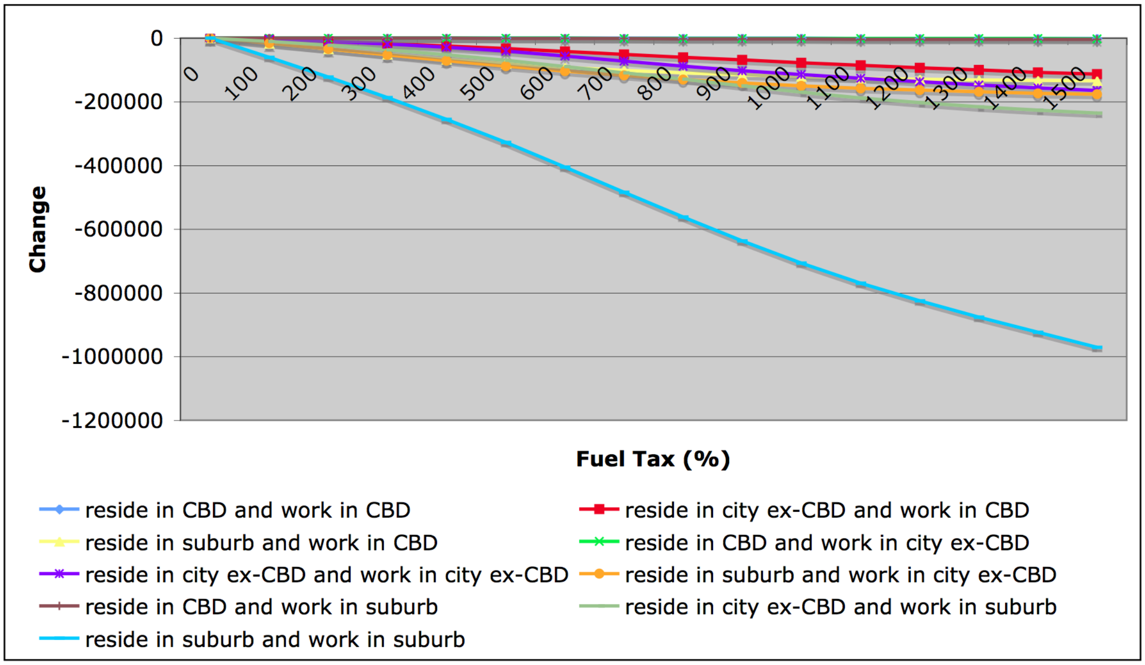

Figure 6(c) Commuters by car under the fuel tax

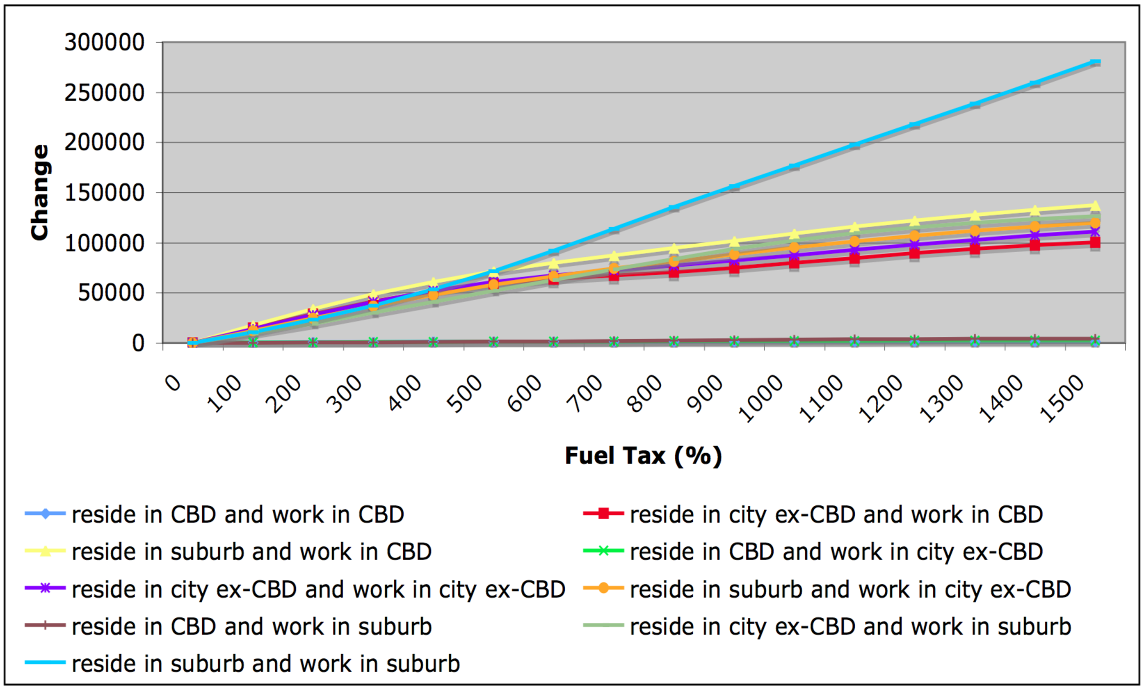

Figure 6(d) Commuters by public transit under the fuel tax

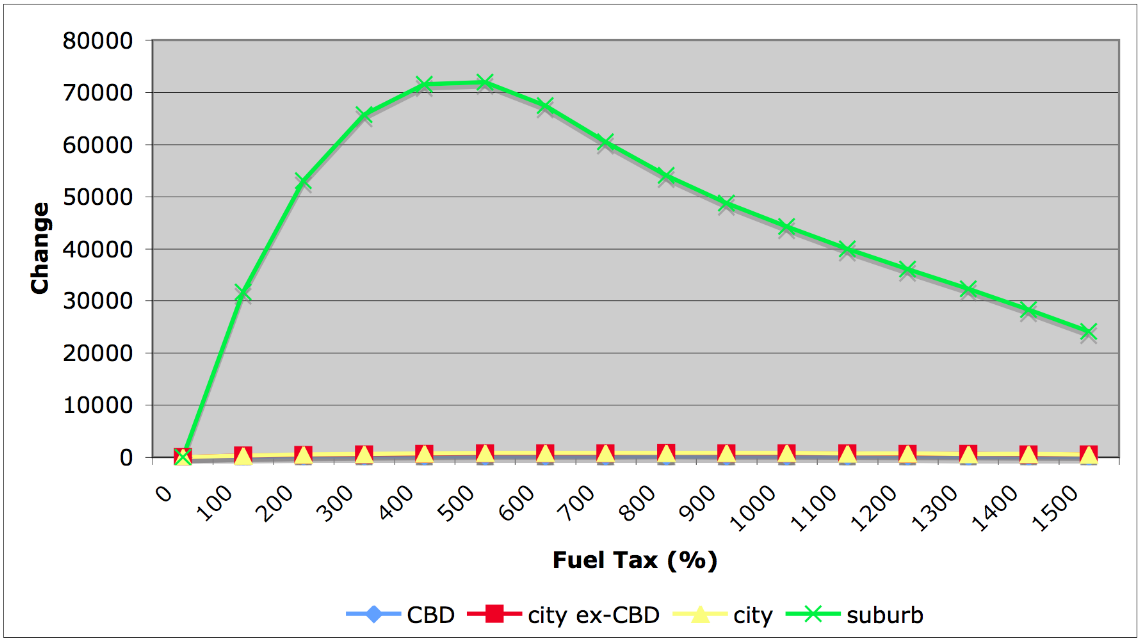

Figure 6(e) Undeveloped land under the fuel tax

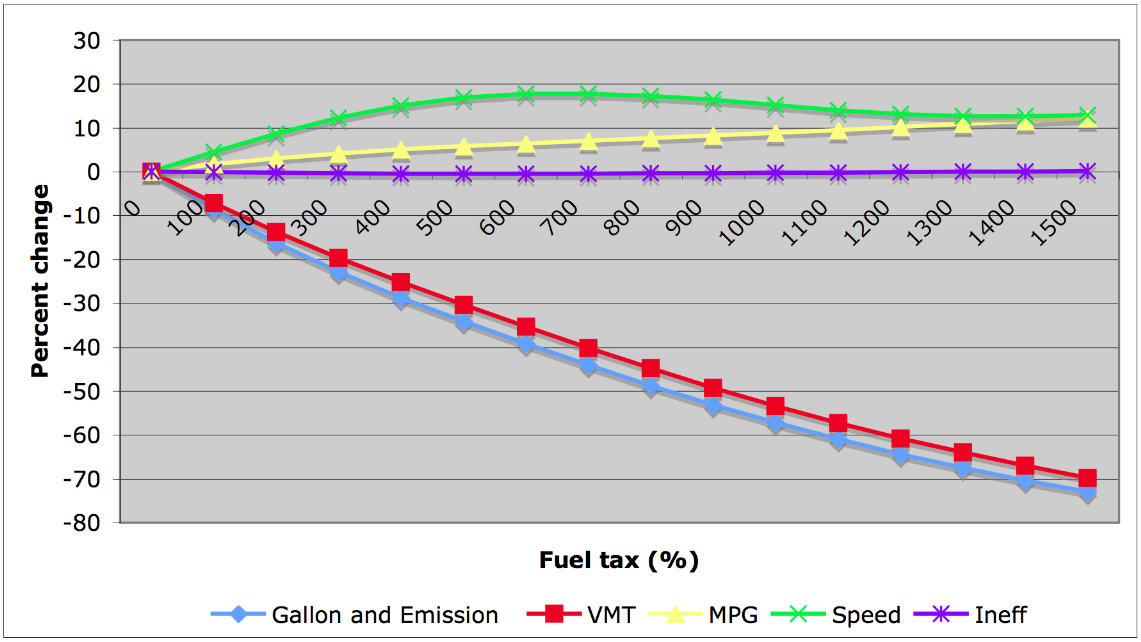

Figure 6(f) Changes under the fuel tax.

Consumers	**Income quartiles**			
	1	2	3	4
MRS (*Disposable income, Commute Time*) ($/hour/day)	12.295	21.056	36.204	93.215
Elasticity of location demand with respect to commuting time	-0.619	-0.602	-0.607	-0.544
Elasticity of housing demand with respect to rent	-1.95	-1.76	-1.57	-1.38
Elasticity of labor supply with respect to wage	3.83	2.93	2.1	1.32
Developers	**Building Type**			
	1 Single family	**2 Multi-family**	**3 Commercial**	**4 Industrial**
Elasticity of floor space supply with respect to rent (*Short-run*)	0.0991	0.23	0.268	0.138
Elasticity of construction flow with respect to asset value				
Overall	0.0521	0.421	0.420	0.0744
City	0.0335	0.0564	0.261	0.0396
Suburbs	0.0526	0.681	0.452	0.0785
Elasticity of demolition flow with respect to asset value				
Overall	-1.612	-0.982	-0.176	-0.523
City	-0.0550	-0.528	-0.346	-0.667
Suburbs	-1.719	-1.375	-0.073	-0.465
Elasticity of floor space stock with respect to asset value				
Overall	0.0535	0.0147	0.00542	0.00872
City	0.00102	0.0068	0.00643	0.00786
Suburbs	0.0672	0.0218	0.00480	0.00922
Driving				
Gasoline Consumption (CO2 Emissions) with respect to fuel price (Base Fuel Price is $1.90)	-0.0899			
VMT with respect to fuel price	-0.0721			
MPG with respect to fuel prie	-0.0180			

TABLE 1: Calibrated Elasticities in RELU-TRAN2 (Chicago, MSA)

		Major roads QP-i	**Fuel tax 145.9%**	**All roads QP-ii**	**Fuel tax 226.8%**
Revenue per consumer ($)		277.60	277.60	1,173.11	1,173.11
		% changes		**% changes**	
Utility (workers by skill level)	1	-0.457	-0.983	-1.367	-1.373
	2	-0.393	-0.798	-1.099	-1.114
	3	-0.333	-0.671	-0.907	-0.937
	4	-0.230	-0.466	-0.599	-0.644
Utility (non-workers by skill level)	1	0.054	0.244	0.443	0.334
	2	0.049	0.206	0.386	0.278
	3	0.042	0.194	0.365	0.260
	4	0.031	0.167	0.313	0.223
Wage by skill level ($/hr)	1	-5.590	-11.316	-15.667	-15.112
	2	-5.627	-11.303	-15.711	-15.098
	3	-5.630	-11.325	-15.750	-15.140
	4	-5.591	-11.305	-15.736	-15.119
Rent by building type ($/sq.ft.)	1	-2.931	-5.998	-8.426	-8.179
	2	-2.203	-4.136	-6.247	-5.619
	3	-2.531	-5.826	-8.295	-7.803
	4	-2.710	-6.212	-8.596	-8.321
Gasoline and CO2		-7.031	-12.265	-17.112	-18.084
Vehicle (car) miles traveled (VMT)		-5.579	-10.200	-13.633	-15.312
Average on-the-road fuel economy (MPG)		1.562	2.354	4.198	3.383
Average car speed		4.726	6.469	10.763	9.683
Average design fuel economy		-0.064	-0.207	-0.056	-0.309
Total travel time		-4.997	-8.187	-11.208	-11.325
Total monetary cost (including tolls or taxes)		15.560	50.358	74.776	73.081
		Changes		**Changes**	
Distribution of jobs	CBD	-289	19,041	12,484	27,071
	City ex-CBD	-4,939	17,079	5,112	23,388
	City	-5,228	36,120	17,596	50,459
	Suburb	4,607	-37,570	-19,721	-52,469
Distribution of residences	CBD	622	2,930	3,885	4,590
	City ex-CBD	5,833	50,103	40,343	73,876
	City	6,455	53,033	44,228	78,466
	Suburb	-6,455	-53,033	-44,228	-78,466
Undeveloped land (acres)	CBD	29	44	80	58
	City	231	352	602	474
	City ex-CBD	261	396	682	533
	Suburb	15,441	42,695	53,210	57,233

Table 2. Comparison of the Effects of the quasi-Pigouvian toll on major roads (QP-i), and its revenue neutral fuel tax; and the quasi-Pigouvian toll on all roads (QP-ii) and its revenue neutral fuel tax.

		Limited QPT (iii)	CT $1.494	PF $2.235
Revenue per cap ($)		$25.67	$25.67	$25.67
		% change		
Utility (workers by skill level)	1	-0.037	-0.038	-0.022
	2	-0.030	-0.031	-0.014
	3	-0.023	-0.023	-0.007
	4	-0.012	-0.012	0.003
Utility (non-workers by skill level)	1	0.010	0.011	0.011
	2	0.009	0.010	0.012
	3	0.008	0.010	0.011
	4	0.007	0.008	0.009
Wage by skill level ($/hr)	1	-0.543	-0.567	-0.373
	2	-0.565	-0.589	-0.378
	3	-0.544	-0.566	-0.372
	4	-0.513	-0.534	-0.352
Rent by building type ($/sq.ft.)	1	-0.209	-0.222	-0.139
	2	-0.201	-0.212	-0.105
	3	-0.312	-0.335	-0.098
	4	-0.131	-0.145	-0.129
Gasoline and CO2		-0.716	-0.722	-0.863
Vehicle (car) miles traveled (VMT)		-0.413	-0.416	-0.534
Average on-the-road fuel economy (MPG)		0.306	0.308	0.332
Average car speed		0.426	0.427	0.539
Average design fuel economy		-0.008	-0.009	0.009
Total travel time		-0.576	-0.585	-0.503
Total monetary cost (including tolls or taxes)		1.471	1.469	2.208
		change		
Distribution of jobs	CBD	-7,337	-7,648	-449
	City ex-CBD	1,067	1,247	599
	City	-6,270	-6,401	151
	Suburb	6,217	6,346	-182
Distribution of residences	CBD	-229	-245	89
	City ex-CBD	-1,329	-1,321	182
	City	-1,559	-1,566	271
	Suburb	1,559	1,566	-271
Undeveloped land (acres)	CBD	11	12	-4
	City	20	20	3
	City ex-CBD	31	31	0.
	Suburb	832	871	900

Table 3. The results of the limited quasi-Pgouvian toll (QP-iii), its revenue neutral cordon toll (CT), and its revenue neutral parking tax (PT).