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Abstract

In the urban planning literature, it is frequently explicitly asserted or strongly implied that ongoing urban sprawl and decentralization can lead to development patterns that are unsustainable in the long run. One manifestation of such an outcome is that if extensive road investments occur, urban sprawl and decentralization are advanced and locked-in, making subsequent investments in public transit less effective in reducing vehicle kilometers traveled by car, gasoline use and carbon dioxide emissions. Using a simple core-periphery model of Beijing, the authors numerically assess this effect. The analysis confirms that improving the transit travel time in Beijing's core would reduce the city's overall carbon dioxide emissions, whereas the opposite would be the case if peripheral road capacity were expanded. This effect is robust to perturbations in the model's calibrated parameters. In particular, the effect persists for a wide range of assumptions about how location choice depends on travel time and a wide range of assumptions about other aspects of consumer preferences.

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Lock-in Effects of Road Expansion on CO_2 Emissions: Results from a Core-Periphery Model of Beijing[1]

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1. Introduction

In this paper, we examine the question of whether road investments that cause an urban area to expand peripherally create a lock-in effect so that transit investments that favor the core are not as effective as they would be in the absence of the road investments. Such a lock-in effect is relevant to climate change policy because it results in high CO_2 emissions which become difficult to reverse. The issue is especially important in rapidly growing megacities of the developing countries because these megacities already have high Greenhouse Gas emission levels and high auto ownership growth rates. Therefore, they may be in danger of entering a lock-in pattern.

According to the International Energy Agency (IEA) the world's share of China's and India's combined CO_2 emissions grew from 9.4% in 1990 to 24.4% in 2006 (IEA, 2008). These two populous countries together accounted for 51.8% of the world's total growth of CO_2 emissions over the period. China accounted for almost as much CO_2 emissions as the United States in 2006 (5,607Mt vs. 5,697Mt), and informal reports of the acceleration of this trend suggest that China may have since surpassed the U.S. to become the world's largest emitter of greenhouse gases (GHG).

Local air pollution is an important environmental concern in China. Beijing, China's second largest city, is one of the world's most polluted cities in terms of air quality, although the air quality has improved somewhat after the 2008 Olympics. In Gurjar et al.'s (2008) ranking of ambient air quality in 13 of the world's megacities, Beijing places second for sulfur dioxide (SO2), second for nitrogen dioxide (NO2), and fifth for total suspended particulates (TSP). Similarly, the Millennium Cities Database (MCD, 2001) identifies Beijing as the world's most congested city as measured by average road speed. According to the World Bank (2007), the estimated cost of health damages associated with urban air pollution (i.e., from sickness and premature death) ranges from 1.2 to 3.8% of GDP, making air pollution the costliest pollution problem in China.

The relationship between income growth and suburbanization is well understood theoretically and empirically (e.g. Margo (1992)).[3] The link between income growth and car ownership has been captured by studies spanning many countries (Ingram (1998)). As incomes grow, the demand for discretionary mobility (trips) also increases (Nelson and Niles, 2000), and this causes an increased demand for automobiles. An even higher demand for driving and one that is more than socially optimal arises, because the time delay and fuel consumption externalities of congestion remain un-priced, as congestion

[3] One may see this also in the exposition of the standard theoretical model of the monocentric city of urban economics, applied repeatedly since the 1960s (e.g. Wheaton (1974), Brueckner (2000)). This model, however, has become an anachronism because it assumes that all jobs are located in the center of an urban area.

tolls have not been adopted broadly. Roads are inevitably built to accommodate the growing demand for personal mobility and there are theoretical analyses that support the idea that planners overbuild roads when road travel is underpriced (Krauss et. al.1976; Wheaton, 1978). Excessive road capacity induces even more travel. The automobile dependence summarized above, causes urban areas to sprawl outward and to settle into a dispersed land use pattern. It is widely believed that one side effect of this outward expansion is an increased level of gasoline consumption as well as more emissions of CO_2 that adversely affect global warming.

The pattern of continual urban expansion supported by road building, un-priced congestion and cheap gasoline is generally feared by urban planners to cause long-term unsustainable land use. Because the automobile-oriented pattern favors spread out communities and/or low density suburbs, the urban area becomes less compatible for future public transit investments. Public transit works best in situations of high density corridors where commuters can easily access the transit lines, often referred to as TOD (Transit Oriented Development, Cervero (1993)). Such situations afford enough scale economies induced by land use density, to make the per capita cost of transit investment affordable. In contrast, the automobile fosters a spread out low-density development pattern as car owners reach out to outlying places where land prices and, hence, houses are cheaper and larger homes are more affordable. Then, once such a pattern of land use is locked-in by developments on the ground, modifying the pattern to make it transit-oriented in the future becomes ineffective and costly.

Casual evidence gleaned from knowledge of the history of metropolitan development in the U.S. supports the idea that the lock-in effect may be significant. One way to see this is to compare east coast and Midwestern cities such as New York, Boston and Chicago to Los Angeles or to Phoenix. The former cities developed before the automobile's introduction in the 1920s and much before its widespread use after WWII. These cities, therefore, were organized around public transit corridors initially supported by streetcars fostering a type of transit dependent suburbanization (Warner, 1978). The introduction of the automobile as a new technology for private transportation eventually greatly reduced the intensity with which the transit lines were used, by siphoning development away from transit corridors and farther into outlying areas or areas between transit lines served only by roads. In the case of Los Angeles or Phoenix, both cities developed primarily in the automobile era, although Los Angeles initially went through a period of rail oriented development. As a result, they never got a chance to build urban transit systems that can support high density land use corridors. Because of such a development history, the Los Angeles region is considered by some to be the monster-child of the automobile: a city so sprawled that would not be sustainable should there be a future era of very high energy prices that would make automobile based travel prohibitively expensive.

In the U.S. economists and planners have debated the issue arguing around the edges, and coming to different conclusions about the desirability and sustainability of Los Angeles type of development. Although Los Angeles type lock-in may become common around the world and especially in the rapidly growing and spreading urban areas of the developing countries, it is not clear that this type of urban form is inefficient or unsustainable. The existence of a lock-in effect might be a legitimate concern for supporting transit-oriented development and all would agree that transit does much better in higher density areas and corridors. But there is less agreement on whether the sprawl of Los Angeles type development creates an unsustainable urban form. Some planners have defended the value of having compact cities (e.g. Ewing (1997)), but those who looked at data (Gordon and Richardson, 1989, 1996) have found that the average commuting time in Los Angeles is not unusually high, and that, furthermore, the average commute time in the U.S. as well as in L.A. has remained stable at somewhat above 20 minutes one way since WWII.

The possible existence and quantification of a lock-in effect induced by road investments can be sorted out with a properly structured simulation model of transportation and land use. In this paper we demonstrate how this can be done by using a simple model, calibrated with data from Beijing representative of the year 2005. Based on the data, Beijing is divided into two areas: the completely built-up urban core (containing about 6.8% of the land) and the periphery. We may think of the core as the equivalent of a Central Business District (or CBD) that is commonly assumed to hold all the jobs in the theoretical analyses that are fashionable in conventional urban economics. Actually, as we will explain in more detail in section 3, the data shows that only 20% of the jobs are in this core, the remaining 80% being distributed in the periphery. Thus, Beijing has little resemblance to a monocentric city. Neither does Beijing look a lot like L.A. where only a few percent of all the jobs are in the downtown. In addition, Beijing – despite the rapid growth of auto ownership in recent past – is not yet a fully auto dependent metropolis. In 2005, only 20% commuted by car, 35% walked or bicycled, while 46% used public bus or subway.

To properly capture the diversity of commuting arrangements in Beijing, we use a discrete choice approach inspired by the general equilibrium models introduced into urban economics by the first author (Anas and Xu (1999), Anas and Rhee (2006)). The model allows workers in Beijing to choose in which of these two areas they will work and in which area they will reside and also whether they will commute by a non-motorized mode (walking and bicycling), public bus or subway, or private automobile. Road travel by buses and cars causes congestion given existing road capacities, thus travel times as well as fuel use are endogenous, because cars consume more (less) fuel per kilometer as congestion reduces (increases) average speed. The core area is completely built up and we assume that the housing supply (measured as aggregate floor space) in this area is equal to the existing stock and unalterable. Hence, in the core the supply of housing is treated as perfectly inelastic. In the periphery, there is plenty of vacant land much of it available for housing development. We assume that the supply of housing in the periphery is perfectly elastic. This choice of assumptions is guided by our limited data as we lack an empirical basis for modeling construction costs and developer behavior in Beijing. Commuters are grouped into quintiles and we use data on wages and rough assumptions of non-wage earnings to construct income levels for each quintile (see Anas, Timilsina, Zheng (2009)). Our treatment of consumer preferences recognizes that the sensitivity to the monetary cost of commuting falls with income, while the sensitivity to travel time rises with income.

How can the model described above generate a lock-in effect with respect to aggregate CO_2 emissions or aggregate gasoline use? The scenario we follow to detect the effect is as follows. We first simulate the base 2005 situation. Next, we assume that a significant highway investment takes place that affects suburb-to-suburb commuting in the periphery. Thus, for example, we increase road capacity in the peripheral area by 20% which increases speed for those residing and working in the periphery, reducing travel time, gasoline consumption and emissions per kilometer, the intensive margin. In the extensive margin, the reduced travel time attracts more residences and jobs to the periphery which, in turn, lowers rents and congestion in the core and increases those relying on the auto mode in both the core and the periphery. The third step is to contrast the above road capacity expansion in the periphery by the alternative of expanding transit service in the core (reducing the transit travel time for core to core commuting by, say, 20%). Doing so works in a way that is much the opposite of the peripheral road expansion. Jobs and residences in the core increase at the expense of the periphery, core housing rents rise and car users in the core become more congested as some bicyclers, walkers and peripheral commuters relocating to the core switch to bus commuting, causing more road congestion for cars due to more buses on the road. Now in the final step, the question we ask is whether the same, larger or lower changes will accrue from the same transit improvement in the core, when that improvement occurs in conjunction with the road capacity expansion examined in step 2. The result is that under a wide range of parameter values, transit improvement is less effective in an urban area that has become more decentralized by road expansion in the periphery. In other words, road expansion in the periphery does, indeed, create a lock-in effect which makes emission reductions from expanding transit service lower than they would be in the absence of the road expansion.

The second section describes the data, the model's assumptions and equations, and the solution procedure for calculating the combined equilibrium of congested road travel and housing market. In section 3 we discuss how the model was calibrated, and in section 4 we describe the simulations that were done to quantify the lock-in effect. In section 5 we examine the robustness of the lock-in effect on emissions by repeating the simulations for alternative values of two parameters, one controlling the elasticity of the demand for peripheral location with respect to road travel time improvements, and the other controlling the commuter's taste heterogeneity. Finally, in section 6, we overview the limitations of the data and explain how more detailed results about lock-in can be obtained with better data that would allow a more sophisticated model.

2. The data and the model

For the purpose of our analysis, the Beijing area was divided into two geographic zones: the core and the periphery. In this definition, the core consisted of the districts of *Dongcheng*, *Xicheng*, *Chongwen*, *Xuanwu* and the periphery of the *Chaoyang*, *Haidian*, *Fengtai*, *Shijing Shan* districts. Table 1 shows the total area of land in the two zones, the net area of land after deducting the land area which cannot be occupied by urban activities (such as water surface or land preserves) and deducting the land already developed in rural villages and small towns. The table also shows the portion of this net land already occupied by housing in each zone, the total quantity of floor space in the years 2000 and 2005, the number of housing units in the year 2005, the average net housing unit densities, and the average structural density in units of square meters of floor space per square meter of land occupied by housing.

We see from Table 1 that the core in Beijing contains only 6.82% of the total land in all eight districts. 21.5% of the 2005 housing units and 18.83% of the total floor space were in the core. The core also contained 23% of the total land taken by housing. No developable land remains in the core zone, redevelopment of the core zone for housing is assumed not likely to happen, and thus all new housing development in the model is to occur in the periphery where undeveloped but developable land is still plentiful. In fact, according to the data between 2000 and 2005, the aggregate housing floor area in the peripheral zone grew by 47.65%, depleting an estimated 10.0% of the periphery's land stock that was available for development in 2000. The housing in the peripheral area is newer and more desirable and has higher density than the older housing in the core.

TABLE 1: Core versus periphery land, housing and densities (Beijing, *circa* 2005)

Zone	Total land (sq-km)	Developable vacant land (sq-km)	Land in housing (sq-km)	Housing Units	Housing floor area (mill. m-sq)	Floor, land per housing unit (m-sq)		Gross structure Density
Core in 2000,2005	93.39	0	39.62	760,000	49,498,880	65.13	52.14	1.25
Periphery in 2000	1275.93	424.28 (*)	89.10	1,876,286	144,473,981			
in 2005	1275.93	284.63 (*)	131.56	2,770,370	213,318,490	77.00	47.49	1.62
construction 00-05 (% change 00-05)		− 42.46 (− 10.00%)	+42.46 (+47.65%)	+ 894,084 (+47.65%)	68,844,509 (+47.65%)			

Table 2 presents the distribution of a random sample of workers in 2005.[4] The displayed distribution is by three aggregated modes of commuting which are non-motorized (walking and bicycling), public motorized (bus or subway) and private automobile; and by the location of the commuter's residence and job as core or periphery. The data in Table 2 shows that a little more than 79% of the jobs are located in the periphery and only a little more than 20% in the core. 25% of the residences are in the core and thus the core has a higher gross residential density than a gross job density. 15% of the commutes are in the "reverse commuting" direction from residences in the core to jobs in the periphery, while 10% are from the periphery to the core. 64% of the commutes originate and terminate within the periphery.

From these descriptions of the data, Beijing does not resemble much the monocentric city typically studied by urban economists. Its core area, while similar in size to an American CBD, is about equally residential as it is commercial, and contains a much higher percentage of the total residential population than most American CBDs now contain. However, since a lot of income growth is expected in China's future and there is a lot more room for car ownership to increase, it is reasonable to assume that the periphery will develop fast (as it did in the 2000-2005 period) and that as these trends continue, many core residents may gravitate increasingly to peripheral housing over time.

[4] This survey was conducted by the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Science, in Beijing, during August and September of 2005. The primary benefit of this sample is a pair of matched records, indicating where each worker works and lives. We are grateful to Siqi Zheng who provided this data with financial support from the World Bank.

Table 3 shows the one-way average travel times and distances of commuters by mode of travel and by the four residence-job location arrangements.

TABLE 2: Percentage distribution by mode of commuting and residence-workplace location (Beijing, *circa* 2005)

Residence →	***Core***	***Core***	***Periphery***	***Periphery***		
Workplace →	***Core***	***Periphery***	***Core***	***Periphery***		
Commute mode ↓						
Walk, bicycle +	*188*	*315*	*183*	*1242*	**1928**	46.24%
Bus or Subway	*152*	*240*	*161*	*899*	**1452**	34.82%
Car +	*94*	*80*	*77*	*539*	**790**	18.94%
	434	**635**	**421**	**2680**	**4170**	
	10.40%	15.23%	10.10%	64.27%		100.00%

TABLE 3: Average travel times and distances by mode of travel and commuting arrangement (Beijing *circa* 2005)

		Workplace			
		Core		***Periphery***	
Walk or bicycle		One-way travel time (min)	One-way distance (km)	One-way travel time (min)	One-way distance (km)
Residence	***Core***	33.66	*2.26*	39.36	*10.75*
	Periphery	42.81	*11.51*	37.44	*11.45*
Public bus or subway					
Residence	***Core***	32.77	*2.96*	37.65	*9.75*
	Periphery	41.34	*9.93*	35.93	*11.18*
Car+					
Residence	***Core***	34.71	*2.53*	39.14	*9.40*
	Periphery	43.09	*11.42*	33.92	*10.26*

2.1 The demand for commute mode, housing and location

We assume that the consumer's direct utility function is the log-of-Cobb-Douglas:

$$U_{ijm|f} = \alpha_{ijm|f} + \left(1-b_f\right)\ln z_{ijm|f} + b_f \ln h_{ijm|f} - \beta w_f \ln G_{ijm} + u_{ijm|f}, \tag{1}$$

where b_f is the share of income after commuting that the consumer spends on renting housing floor space, $h_{ijm|f}$, and where $z_{ijm|f}$ is consumption of goods other than housing. The subscript *f* denotes the income quintile of the commuter. The choice bundle is denoted by (i, j, m) where *i* is the location of the residence, *j* the location of the workplace, and *m* the mode of commuting. G_{ijm} is the travel time from *i* to *j* via mode *m*. In βw_f, w_f is the average wage in the *f* income quintile, and $\beta > 0$, is to be calibrated. The marginal disutility of time in the model is $\beta w_f (G_{ijm})^{-1}$ which increases with the wage rate of the commuter.[5] Finally, the last term in the utility function, $u_{ijm|f}$, is an additive idiosyncratic utility that varies among the commuters for each (*i* ,*j* ,*m*) and is independently and identically distributed in the population of commuters of income quintile *f*. Housing floor space and "other consumption" are treated as continuous variables. Thus given any discrete choice (*i* ,*j* ,*m*), the values of $\alpha_{ijm|f}, G_{ijm}, u_{ijm|f}$ and the monetary cost of a commute g_{ijm} are fixed for the consumer. Then for each (*i* ,*j* ,*m*), the consumer maximizes (1) with respect to the budget constraint,

$$z_{ijm|f} + R_i h_{ijm|f} = y_f - Dg_{ijm} \tag{1'}$$

where R_i is the annual rent per square meter of housing floor space in location *i* where residence is taken. The annual disposable income after the monetary commuting cost is $y_f - Dg_{ijm}$, where g_{ijm} is the monetary cost of a two-way daily commute (fare for public transit and fuel cost for cars) from a residence in location *i*, to a job in location *j*, via mode *m*. y_f is the annual income, and *D* is the number of commuting days per year. Maximizing (1) with respect to (1'), the quantity of floor space demanded is

$$h_{ijm|f}(R_i) = b_f \frac{y_f - Dg_{ijm}}{R_i} \tag{2}$$

Then, the indirect utility of the commuting arrangement (*i* ,*j* ,*m*) is

$$U^*_{ijm|f} = \alpha_{ijm|f} + \ln\left(y_f - Dg_{ijm}\right) - b_f \ln R_i - \beta w_f \ln G_{ijm} + u_{ijm|f} \tag{3}$$

In the next stage, the consumer compares the indirect utilities and chooses the most-preferred commuting arrangement (*i* ,*j*, *m*). The assumption that the i.i.d idiosyncratic utilities are Gumbel distributed, yields a multinomial logit model that describes the choices of the population of consumers. It is a dodecanomial logit since there are 2 possible residence locations (core, periphery), the same also being possible work locations, and three possible modes of travel. Since all of these options (*i* ,*j* ,*m*) are available to all commuters, there are 12 combinations from which the commuter chooses. Then, the probability that (*i* ,*j* ,*m*) will be most-preferred by a type *f* commuter is

[5] The marginal disutility of travel time increases with travel time but at a decreasing rate. It is reasonable to suppose that it should increase at an increasing rate, although most econometric studies have specified it as being constant or increasing at a decreasing rate. In any case, the results of this paper do not depend on the second derivative.

$$P_{ijm|f} = \frac{\exp\lambda\left[\alpha_{ijm|f} + \ln\left(y_f - Dg_{ijm}\right) - b_f \ln R_i - \beta w_f \ln G_{ijm}\right]}{\sum\limits_{\ell=1,2}\sum\limits_{k=1,2}\sum\limits_{n=1,2,3} \exp\lambda\left[\alpha_{\ell kn|f} + \ln\left(y_f - Dg_{\ell kn}\right) - b_f \ln R_\ell - \beta w_f \ln G_{\ell kn}\right]},\text{[6]} \qquad (4)$$

satisfying $\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{m=1}^{3} P_{ijm|f} = 1.$ The coefficient, λ, is the dispersion parameter of the model that controls sensitivity to the non-idiosyncratic utility which appears in the brackets. As $\lambda \to 0,$ choices are driven purely by the idiosyncratic utilities and commuters choose randomly regardless of rent, travel time and monetary travel cost. At the other extreme, as $\lambda \to +\infty$, the idiosyncratic utilities lose their importance, and all will choose the same alternative, that is the one with the highest value in the bracket. The elasticity of (4) with respect to the own monetary cost and the own time cost of a trip by mode *m* and between *i* and *j* are:

$$\eta_{P_{ijm|f}:g_{ijm}} = -\lambda\left(\frac{Dg_{ijm}}{y_f - Dg_{ijm}}\right)(1 - P_{ijm|f}), \qquad (5a)$$

$$\eta_{P_{ijm|f}:G_{ijm}} = -\lambda\beta w_f (1 - P_{ijm|f}), \qquad (5b)$$

$$\eta_{P_{ijm|f}:R_i} = -\lambda b_f (1 - P_{ijm|f}). \qquad (5c)$$

2.2 The supply side: housing stock adjustment

We now turn to the supply side of the core and periphery housing markets. We will assume that the core housing supply is perfectly inelastic. This assumption is supported in part by the fact that in Beijing's core area there is virtually no vacant land. In the periphery, we assume that the supply of housing is perfectly elastic which is supported by the fact that the supply of undeveloped land available for housing is quite large. This means that the rent of peripheral housing will be taken as exogenous.

At equilibrium, the floor space markets in the core and the periphery must clear. By the above assumptions, market clearing means that given, S_{1b}, the supply (stock) of housing in the core, and R_{2b}, the exogenous rent in the periphery, the market will determine $R_{1b}, S_{2b},$ the rent in the core and the supply (determined by the demand) in the periphery.

[6] We use the simultaneous multinomial logit rather than the nested logit model. In the sequel, it may be thought that the IIA property of the logit model would affect our results. But this is not true as our results will be driven by the fact that there is substitution between transit and auto in mode choice and much more so in the cities of developing nations.

$$\sum_{f=1,...,5} N_f \left(\sum_{j=1,2} \sum_{m=1,2,3} h_{1jm|f}(R_{1b}^*) P_{1jm|f}(R_{1b}^*, R_{2b}) \right) - S_{1b} = 0, \tag{6a}$$

$$\sum_{f=1,...,5} N_f \left(\sum_{j=1,2} \sum_{m=1,2,3} h_{2jm|f}(R_{2b}) P_{2jm|f}(R_{1b}^*, R_{2b}) \right) - S_{2b}^* = 0. \tag{6b}$$

By the nature of the problem, the solution procedure is sequential. Given the core's stock, (6a) is solved for the core's rent, and then given this rent in the core, the supply of housing in the periphery is calculated directly from (6b).

2.3 Congestion externalities, fuel use and CO_2 emissions

The aggregate daily commutes by mode are next calculated as follows, given the number of commuters N_f in quintile f:

$$T_{ijm} = \sum_{f=1}^{5} N_f P_{ijm|f}. \tag{7}$$

Then, the sum of motorized vehicle traffic $(m = 2, 3)$ in car-equivalent units, is obtained as:

$$T_{ij} = \phi_2 T_{ij2} + \phi_3 T_{ij3}, \tag{8}$$

where ϕ_2, ϕ_3 are the inverse ratios of vehicle occupancies (car-equivalent buses per bus person-trip, and fractional cars per person-trip by car respectively). (8) converts person trips to car equivalent vehicular trips. Given aggregate road capacities, Z_{ij}, the congested round trip travel time per trip is then calculated from the Bureau of Public Roads type of congestion function,

$$G_{ij3} = c_0 \left(1 + c_1 \left(\frac{T_{ij}}{Z_{ij}} \right)^{c_2} \right) d_{ij3}, \tag{9}$$

where d_{ij3} are the given round-trip distances by car in kilometers that remain fixed in the model (Table 3). Car speed then is calculated as $\hat{s}_{ij3}$:

$$\hat{s}_{ij3} = \frac{d_{ij3}}{G_{ij3}} = \left\{ c_0 \left(1 + c_1 \left(\frac{T_{ij}}{Z_{ij}} \right)^{c_2} \right) \right\}^{-1}. \tag{10}$$

The fuel expenditure in liters of gasoline per kilometer (assuming a vehicle efficiency of unity) is calculated from the following statistically verified equation reported by Davis and Diegel (2005) (see Figure 1)[7],

$$f(\hat{s}_{ij3}) = (3.78541178/1.6093)\times\ [0.122619-0.0117211\times(\hat{s}_{ij3})+0.0006413\times(\hat{s}_{ij3})^2$$
$$-0.000018732\times(\hat{s}_{ij3})^3+0.0000003\times(\hat{s}_{ij3})^4-0.0000000024718\times(\hat{s}_{ij3})^5+0.000000000008233\times(\hat{s}_{ij3})^6\ ]. \quad (11)$$

The monetary fuel cost per passenger (including fuel taxes) is next calculated from,

$$g_{ij3} = \phi_3 \times p_F \times e \times f(\hat{s}_{ij3}) \times d_{ij3}, \quad (12)$$

and e is the vehicle inefficiency factor.[8] We will also calculate CO_2 emissions in grams/km of car travel by taking the exponential of a polynomial equation that predicts log-CO_2 as a function of the speed in miles per hours (Barth and Boriboonsomsin, 2007), plotted in Figure 1 alongside the fuel consumption equation (11):

$$\begin{aligned} CO_{2ij3} &= \exp[7.613533 - 0.138655\times(\hat{s}_{ij3}) + 0.003915\times(\hat{s}_{ij3})^2 \\ &-0.00004945\times(\hat{s}_{ij3})^3 + 0.0000002386\times(\hat{s}_{ij3})^4]/1.6093 \end{aligned} \quad (13)$$

2.4 The combined equilibrium of congested road traffic and the housing market

The model's equilibrium is calculated according to a procedure described in the following steps:

1. (a) Set the initial value of the aggregate car-equivalent traffic for each residence-workplace pair, $\left[T_{ij}\right]$, and call it $\left[\hat{T}_{ij}\right]$; (b) Set the initial core-rent $\hat{R}_1$.
2. Calculate the four auto travel times, $\left[G_{ij3}\right]$, from $\left[T_{ij}\right]$, using the congestion function, equation (9), the speeds from equation (10), the fuel requirements from equation (11), and the monetary travel costs g_{ij3}, from equation (12).

[7] This equation presented by Davis and Diegel (2004) calculates fuel use in gallons/mile from speed in miles/hour. We converted the equation to the liters/km version by making the three required adjustments incorporated into (11). First, the speed in kilometers/ hour is divided by 1.6903 km/mile in order to get the speed in miles/hour. This is then used in the original equation to predict gas consumption in gallons/mile. Then, the result is multiplied by 3.785 liters/gallon to get fuel use in liters/mile and, lastly, that result is divided by 1.6903 to get the fuel use in liters/km.

[8] The monetary cost of travel depends also on the car's fuel inefficiency level. However, we have formulated the model as if everyone uses a standard efficiency vehicle since we could find no data on how car fuel inefficiency varied by income or other factors in Beijing . From Davis and Diengel (2004), a fuel efficiency of unity (e = 1 in equation (11)) corresponds roughly to a Geo Prizm.

3. Solve equations (6a) to find R_1 and then calculate S_2 from (6b).

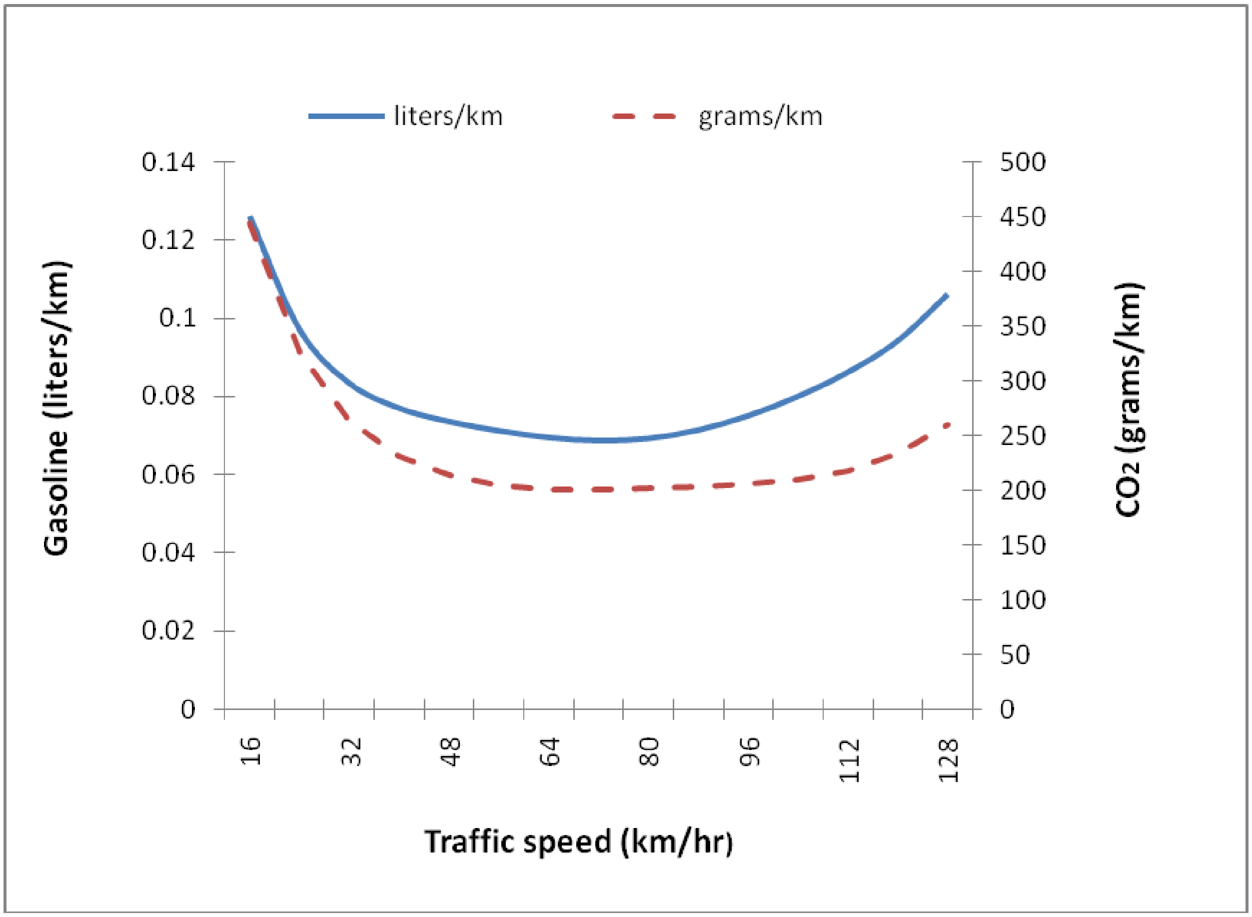
4. (a) If $\frac{\left|\hat{R}_1 - R_1\right|}{\left(\hat{R}_1 + R_1\right)/2} < 1\times10^{-8}$, stop and declare convergence; or (b) if $\frac{\left|\hat{R}_1 - R_1\right|}{\left(\hat{R}_1 + R_1\right)/2} \geq 1\times10^{-8}$, continue iterating by returning to step 1, with the R_1 from step 3 replacing the $\hat{R}_1$ in step 1.

5. Calculate the choice probabilities P_{ij2}, P_{ij3}, from equation (4), and $\left[T_{ij2}\right]$, $\left[T_{ij3}\right]$, from equation (7), and $\left[T_{ij}\right]$ from (8).

6. (a) If $\Delta \equiv \max\limits_{\forall\ (i,j)}\left(\frac{\left|\hat{T}_{ij} - T_{ij}\right|}{\left(\hat{T}_{ij} + T_{ij}\right)/2}\right) < 1\times10^{-8}$, stop and declare convergence; or (b) If $\Delta \geq 1\times10^{-8}$, continue iterating by returning to step 1, with the $\left[T_{ij}\right]$ from step 6 replacing the $\left[\hat{T}_{ij}\right]$ in step 1.

7. After convergence, calculate various aggregate outputs such as housing stock in the periphery, person trips by mode, vehicle kilometers traveled by car, fuel consumption, carbon emissions, rents and the aggregate value of consumer surplus by income group (see below).

Figure 1: Relationship of fuel consumption and CO_2 emissions with vehicle speed



2.5 Welfare and other performance measures

Important outputs of the model are the per-capita expected utility measure for each income group. As is well known from the properties of the logit model, the expected utility of income group *f* is:

$$E\left[\max_{\forall(i,j,m)}\left(U^*_{ijm|f}\right)\right]=\frac{1}{\lambda}\ln\left(\sum_{i=1,2}\sum_{j=1,2}\sum_{m=1,2,3}e^{\lambda U^*_{ijm|f}}\right). \qquad (14)$$

3. Calibration

The model was calibrated by first expanding the distribution of choices shown in Table 2 to the population of 2005 workers in Beijing. The travel distances and times from Table 3 were replicated by calibrating the road capacities in the congestion function (9) so that congested travel times and speeds for cars given by (9) and (10), agreed with those given or implied in the data. Then, the parameters λ, β and b_f in the utility function were set in such a way that, given the observed hourly wage rates, and the observed choice frequencies from the sample, the elasticity of the choice probabilities with respect to monetary travel cost, travel time and rent, given by (5a)-(5c), after being weighted by the choice probabilities, gave the numbers shown in Table 4. Then, the constant effects $\alpha_{ijm|f}$ were calculated so as to replicate the observed choice frequencies for each mode-residence location-job location combination.

Table 4 shows that the own elasticity of the choice probability with respect to monetary cost, and with respect to rent decrease with income, as should be the case, using the principle that the lower is the income share of an expenditure the lower is the price elasticity with respect to the corresponding good. The own elasticity of the choice probability with respect to travel time is increasing with income, reflecting the fact that the value of time is increasing with income or with wage. Given a reasonable guess for the rent of floor space in the periphery as 425 RMB per sq. meter of floor space, the rent in the core was calculated in such a way that, given all the previous calibration results, the calibrated model for the 2005 base situation replicated the observed floor space stocks in the core and in the periphery, while generating reasonable consumption of floor space per worker in both the core and the periphery. The core rent that achieved this result was 705 RMB/sq. meter of floor space.

TABLE 4: Calibrated values of the model's elasticities by income. $\lambda_f = 1, \ \beta = 0.25.$

Income quintile	Wage RMB/hr w_f	Income RMB/year y_f	Housing Cost share b_f	Average elasticity of choice probability with respect to own		
				Monetary cost η_{fg}	Travel time η_{fG}	Rent η_{fR}
1	6.61	20,814	0.50	-0.0266	-1.3592	-0.4113
2	8.47	37,242	0.45	-0.0133	-1.7959	-0.3817
3	10.56	49,009	0.40	-0.1200	-2.2573	-0.3420
4	12.66	61,145	0.35	-0.0061	-2.4747	-0.2737
5	23.59	115,510	0.30	-0.0035	-4.8413	-0.2463

4. Lock-in effects of road expansion

As explained in the Introduction, the purpose of the article is to quantify the "lock-in effects" of expanding road transportation. However, a clear definition of "lock-in effects" needs to be developed first. To do so, we first describe the following procedure of comparative equilibrium simulations which illustrates the lock-in concept, and then we generalize to the definition.

1. *Base run*: We compute a base equilibrium, representative of the 2005 conditions. In fact, from the calibration of the model described in section 3, the base equilibrium replicates exactly the observed 2005 data.

2. *Transit improvement on base*: The transit travel time in the core zone is reduced by a certain percentage (ignoring the cost of doing so) and the changes induced by this policy are calculated. In particular, we focus on changes from the base in: (i) traffic speed; (ii) housing supply in the periphery; (iii) aggregate VKT (car kilometers traveled); (iv) aggregate fuel consumed by cars; (v) aggregate carbon emissions from cars; (vi) aggregate rents; (vii) expected utilities by income quintile.

3. *Road improvement on base*: The base highway capacity in the peripheral zone is increased by a certain percentage (ignoring the cost of doing so) and the changes in (i) to (vii) (see 2 above) are calculated relative to the base.

4. *Transit improvement in conjunction with road improvement on base*: The road capacity improvement in the periphery (step 2) and the transit travel time reduction (step 3) are introduced together. The transit travel time in the core is reduced by the same percentage as in step 2, and the road capacity is increased by the same percentage as in step 3, and the changes in (i)-(vii) induced by this combined policy relative to the base are calculated.

The results of the above simulations will be used to detect whether a "lock-in effect" exists according to the following definition.

Definition of "lock-in": *A lock-in effect exists with respect to a particular indicator, if highway improvements in the periphery cause such changes in location and land use patterns that a transit improvement in the core cannot achieve as beneficial a level for that indicator that it would have achieved if the same transit improvement had occurred in the absence of the highway improvement.*

4.1 The effect of road expansion in the periphery

For a representative simulation that can reveal lock-in effects with the calibrated model, we assumed that in step 2, highway capacity for periphery-periphery commuters (i.e. Z_{22}) is increased by 20%. The direct effect of this is to lower congestion in the periphery and thus increase the speed and lower the travel time of commuters who reside and work in the periphery. This can be seen directly from equations (9) and (10), while (11) and (12) show that the benefit of the speed improvement is lower fuel use and lower CO_2 emissions per km of travel, because the base speed is quite low and on the initial rapidly falling segment of the curves. An indirect effect of the particular road expansion is that the attractiveness of residing and working in the periphery is increased relative to the attractiveness of the other commuting arrangements. Because of this, some commuters in the other arrangements switch to residing and working in the periphery. For example, a commuter who resided in the periphery prior to the capacity improvement but worked in the core, can switch his job to the periphery; or one who already worked in the periphery but reverse commuted from the core can switch his residence to the periphery; or one who resided and worked in the core can switch both residence and job to the periphery. All these switches amount to reducing the congestion in the core as well as in the periphery. The result is that travel times in the core decrease because speeds in the core increase. Because speeds in the core increase, fuel consumption per km and CO_2 emitted per km both decrease. Meanwhile, speed in the periphery increases because of the 20% increase in road capacity; and because speed increases, fuel per km, and CO_2 per km both decrease. Table 5 shows these per km. results. In addition, as shown in the second column of Table 6, since more commuters now reside in the periphery, the stock of housing floor space increases by 0.96%. Also seen in the same table is the impact of the road expansion in the periphery on the aggregates of travel time by auto, vehicle kilometers by auto, fuel use by auto, and carbon emissions from autos. Each of these aggregates increase. Rent in the core decreases, since the improved peripheral travel times reduce the demand for residing in the core. Aggregate rent decreases. The expected utility of each income quintile increases. This welfare improvement reflects the benefits of lower travel times, lower rents in the core and more consumers locating in the periphery where rent is lower than in the core and, hence, a larger housing size can be afforded.

TABLE 5: Effects of the improvements on the intensive margins (per kilometer) of travel by car

		Base		Road expansion in periphery (Z_{22} increased 20%)		Transit improvement in core (G_{112} decreased 20%)		Road expansion in periphery and transit improvement in core	
		j=1	*j=2*	*j=1*	*j=2*	*j=1*	*j=2*	*j=1*	*j=2*
Speeds (km/hr)	*i=1*	*4.37*	*14.41*	*4.41*	*14.55*	*4.14*	*14.72*	*4.19*	*14.86*
	i=2	*15.90*	*18.15*	*16.18*	*19.52*	*16.09*	*18.33*	*16.30*	*19.71*
Trips by car	*i=1*	149,270	147,460	149,400	147,900	118,870	148,540	119,900	148,900
	i=2	122,450	842,820	122,700	1,008,700	122,730	842,720	123,000	1,000,730
Fuel (liters/km)	*i=1*	*0.2238*	*0.1351*	*0.2233*	*0.1343*	*0.2267*	*0.1333*	*0.2261*	*0.1325*
	i=2	*0.1270*	*0.1165*	*0.1259*	*0.1111*	*0.1260*	*0.1158*	*0.1250*	*0.1104*
CO_2 (grams/km)	*i=1*	888.12	481.51	885.41	478.24	903.30	474.13	889.98	470.98
	i=2	448.26	405.83	443.79	383.73	444.42	402.69	440.03	380.83
Car km/trip	*i=1*	5.06	18.80	*Unchanged from base*		*Unchanged from base*		*Unchanged from base*	
	i=2	22.84	20.52						

4.2 The effect of improving public transit trip times in the core

In step 3, we simulate the effect of improving public transit travel times for those residing and working in the core. The results are shown in column 3 of Table 6. Note that doing so would induce commuters who reside and work in the core to switch to buses from driving but also from the walking and bicycling mode. As a result, although public transit travel times are improved exogenously, the travel times of car users can increase if sufficiently more commuters switch from walking and bicycling to buses than from driving to buses, because buses create congestion (see (8) and (9)). It is indeed the case, however, that auto travel times within the core do decrease because of many non-motorized commuters switching to public transit. In the other commuting arrangements auto speeds increase since some marginal commuters switch to residing and working in the core in order to take advantage of the lowered bus commute times there. Rents in the core increase and the aggregate floor space consumption in the periphery decreases by 3%. The direction of change in aggregate trips by auto, travel time, vehicle kilometers, fuel and CO_2 are down, opposite of what was observed when roads in the periphery were expanded. The expected utility of each income quintile increases but generally not as much as in the case of the peripheral road improvement.

TABLE 6: Effects of the improvements on the aggregates

	Base	**Road expansion in periphery** (Z_{22} increased 20%)	**Transit improvement in core** (G_{112} decreased 20%)	**Road expansion in periphery and transit improvement in core**
Car person trips $,10^6$	1.2620	1.4287	1.2329	1.3991
Car travel time (hours) $,10^6$	1.4939	1.5966	1.4523	1.5539
Vehicle kilometers $,10^7$	1.3497	1.5450	1.3423	1.5363
Fuel used by cars (liters) $,10^6$	1.6653	1.8257	1.6365	1.7950
CO_2 emitted by cars (grams) $,10^9$	5.8732	6.3916	5.781	6.2697
Core rent (RMB/m.sq)	705	686.56	759.25	738.73
Aggregate rent (RMB) $,10^9$	1.2571	1.2567	1.2569	1.2565
% change in peripheral housing	n/a	+0.0096	– 0.0298	– 0.0190
Expected utility 1	*10.2140*	*10.2413*	*10.2236*	*10.2512*
2	*10.4546*	*10.4812*	*10.4175*	*10.4982*
3	*10.4254*	*10.4662*	*10.4692*	*10.5096*
4	*11.8830*	*11.9129*	*11.9062*	*11.9364*
5	*11.7065*	*11.7695*	*11.7692*	*11.8318*

4.3 Simultaneous road expansion in the periphery and transit improvement in the core

The last column of Table 6 shows the results of step 4 where the improvements of steps 1 and 2 (road expansion in the periphery, transit improvement in the core) are introduced simultaneously. These results compared to those of step 1 and 2 indicate the lock-in effect. While the transit improvement reverses in part the increase in auto trips, auto vehicle kilometers, fuel and CO_2 emissions, caused by the road expansion, each of these measures remains above the level to which improving only transit had reduced them. The same is true for the rent in the core which remains at a lower level than that it had reached when only transit was improved.

In the case of the road expansion in the periphery, the housing stock in the periphery had increased by almost 1%. In the case of transit improvement in the core, the peripheral housing stock had shrunk by 3%. When core transit improvement occurs in the presence of peripheral road expansion, the peripheral stock shrinks by 2% less than 3%. Therefore, this result too indicates that transit is less effective in reducing peripheral development when transit improvements are accompanied by road expansion. Of course, introducing both policies together, gives a higher welfare level for each income group, than introducing only one policy at a time.

5. Sensitivity analysis of the lock-in effect on emissions

We now wish to see the robustness of the lock-in effect we have found, in the face of parameter perturbations. In this respect, we will focus on CO_2 emissions only, which is the main issue of interest. In order to properly design the sensitivity analysis we must first note the fact that the results in Table 5 have illustrated two important processes. One is the fact that suburban road expansion causes more peripheral commuting, more suburban housing consumption, whereas improving transit in the core has the opposite effects. The transit improvement policy in fact increases auto congestion in the core because of an increase in bus capacity to accommodate commuters that were non-motorized prior to the transit improvement. But despite this higher auto congestion which decreases speed and increases emissions per km., overall emissions decrease because less people commute by driving in the core. In the context of lock-in, this is advantageous because it reduces auto dependence. The results described above are consistent with the belief of planners that more road expansion causes suburbanization, sprawl and more emissions, while transit improvement in the core increases central densities and reduces sprawl. The policy message is that transit development in the core is preferable to suburban road expansion from the point of view of reducing lock-in effects. To see how much sprawl and decentralization of jobs and residences is caused by road expansion, we need to turn to the effect of the elasticity (5c) of the choice probability (4) on the propensity of commuters to take advantage of the lower travel times caused by the road expansion. This elasticity is governed by the coefficient β in the indirect utility function (3). The higher is this coefficient, the bigger the response of the commuter population to the time saving induced by the road improvement in the periphery. Therefore, in Table 7, β was varied from zero to 1.5 in order to see the effect on CO2 emissions in each case. For each value of β, the base simulation and the three improvement simulations were repeated. The results show that the transit improvement in the core does not do as well when it is accompanied with the road improvement in the periphery (except in the case of $\beta = 0$, when commuters do not care about travel time). Therefore, the road improvement has the effect of locking-in a higher level of emissions.

TABLE 7: Effect of value of time on aggregate CO_2 emissions (in 10^9 grams)

β	**Base**	**Road expansion in periphery** (Z_{22} increased 20%)	**Transit improvement in core** (G_{112} decreased 20%)	**Road expansion in periphery and transit improvement in core**
0	5.4274	5.0448	5.4274	5.0448
0.25	5.8732	6.3916	5.7581	6.2697
0.50	5.9800	6.7959	5.6762	6.4535
0.75	5.9575	6.9002	5.7030	6.5324
1.00	5.9077	6.9168	5.7952	6.6348
1.25	5.5591	6.9065	5.8617	6.6954

A second sensitivity analysis is done by decreasing (increasing) the value of the taste heterogeneity coefficient λ, which as shown in (5a)-(5c) decreases (increases) all of the elasticities. In general, as already noted in section 2, the effect of a lower λ is less sensitivity of location choices to any of the prices or other terms in the utility function. This lowered sensitivity arises because the spread of the idiosyncratic tastes increases and, therefore, so does the weight of idiosyncratric utilities in the utility function. Therefore, with a lower λ, commuters become less likely on average to relocate to take advantage of the travel time saving benefits of a suburban road expansion or of a transit improvement in the core. The results of the repeated simulations for each value of λ are shown in Table 8. It is shown that if taste heterogeneity is not extremely high (as long as $\lambda > 0.25$ in the table), then the lock-in effect is present and quite pronounced. In each of these cases, the presence of the road improvement weakens the ability of the transit improvement to reduce emissions.

TABLE 8: Effect of taste heterogeneity on aggregate CO_2 emissions (in 10^9 grams)

λ	**Base**	**Road expansion in periphery** (Z_{22} increased 20%)	**Transit improvement in core** (G_{112} decreased 20%)	**Road expansion in periphery and transit improvement in core**
0.10	10.6980	10.4820	10.6260	10.4140
0.25	8.1134	8.0241	7.9995	7.9126
0.50	6.8036	7.0010	6.6729	6.8666
0.75	6.2392	6.6334	6.1135	6.5013
1.00	5.8732	6.3916	5.7581	6.2697
1.50	5.3814	6.0311	5.2899	5.9342

6. Concluding remarks

In this study we examined possible transportation infrastructure lock-in effects in Beijing. Using a simple core-periphery model of Beijing, we have demonstrated that suburban road expansion in a setting resembling that of Beijing in 2005 would induce higher suburbanization, higher welfare gains and more fuel consumption and emissions. The core transit improvements, on the other hand, would create the opposite effects by drawing population to the core and reducing suburbanization, although they are also welfare improving. While the core transit improvement increases congestion (by drawing many non-motorized commuters to buses), it does at the end achieve less suburbanization, higher core densities and lower emissions and fuel consumption. This is a good policy because it reduces auto dependence and emissions but it comes at the expense of lower welfare gains when compared to the road expansion. However, the gains would not be as big in an urban area that has already undergone considerably more suburbanization due to suburban road expansion. Therefore, we concluded that road expansion does lock-in a pattern of land use and location choices that are less malleable to future emission improvements to be achieved by transit improvements in the core. Generalizing this finding we would indeed conclude (with the usual reservations and caution) that L.A.-type sprawl indeed locks-in a long-term high aggregate emission level.

The model we used is relatively simple, reflecting the limited data. The model would be much more incisive and relevant if it were dynamic reflecting the durability of housing. We did not embark on this path due to lack of data on construction costs in Beijing. The dynamic model would be used to perform an analysis of sequenced road and transit improvements. This can be done by supposing – as has happened historically in the case of L.A. – that road expansion is undertaken for many years, resulting by new construction in a low density pattern of buildings on the ground, expensive to alter once built. Transit improvements undertaken in later years would then be shown to be less effective, than if the same improvements were undertaken earlier in time, when the low density pattern of buildings is less entrenched. That is, the longer lasts an era of highway expansion, the more locked-in becomes the level of fuel consumption or emissions induced by that expansive highway era.

A second important extension of our simple model concerns the fact that we treated the benefits of road and transit improvements, neglecting the cost side. Should transit and road improvements be undertaken with local funds, such as taxes on land rent increases etc. then the results may change considerably and would depend closely on what types of taxes were used to finance road or transit improvements. Again we could not do such an analysis because of lack of data.

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