Relationships between ramp metering and sprawl

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Abstract

This paper explores impacts of ramp metering on urban land use. A regression-based transportation model is developed to capture changes in accessibility caused by ramp metering on a highway network. A Land Use Change Indicator (LUCI) model is modified to estimate how the spatial distribution of employment and housing would change in response to the redistributed accessibility in five hypothetical urban areas with various initial land use patterns. Accessibility will be improved in almost all areas in a city with ramp metering, but meters affect land use patterns in various ways depending on initial land use conditions. Ramp metering can exacerbate *decentralization*, but not necessarily *sprawl*.

Key words: Ramp metering, Land use, Urban sprawl, Decentralization

1. Introduction

It is generally accepted that accessibility, determined by urban travel costs and the spatial distribution of activities, is an important factor that impacts urban form. Improvements on highways, where over 90% trips are carried in typical US metropolitan areas (Giuliano 1986), can significantly shorten commuting times, and hence redistribute accessibility. Previous studies suggest that highway improvement contributes to suburbanization and urban sprawl (Webster *et al.* 1988). There is a very special form of highway improvement: ramp metering. Previous studies (May and Bogenberger 1999) have demonstrated the effectiveness of ramp metering system in reducing freeway travel times. Some findings suggest that ramp meters also considerably improve traffic conditions on arterial streets due to more carrying capacity on freeways (Haj-Salem and Papageorgiou 1995). The mechanism of ramp metering requires a redistribution of travel time from freeway mainline to entrance ramps. A recent case study on the Twin Cites ramp metering system shows that the system significantly reduces travel times for long-distance travelers while at the same time short-distance travelers are hurt (Levinson et al. 2001). Since it favors people who drive longer, ramp metering may cause more serious sprawl problems than freeway capacity expansion. The relatively low overhead cost further enables cities to deploy system-level ramp control strategies over a short period. For instance, in the Twin Cities, Minnesota metropolitan area, several hundred on-ramp meters were installed in just several years following 1990 when the focus of state transportation policies shift from providing more capacity to better managing existing roads, which immediately changes the traffic conditions on more than seventy percent of all metro freeways.

Sprawl is among the top metro concerns in most US urban areas. Whenever a highway improvement project is put forth, planners, politicians and the general public tend to question its potential impacts on land use patterns and whether it is going to exacerbate urban sprawl. Ramp metering system, though different from traditional capacity expansion projects, is not an exception. In the Twin Cities, sprawl is considered as the chief problem facing the region by 16% of residents according to the 2000 Twin Cities Area Survey, the third after congestion (23%) and crime (17%). Two articles in the local newspaper triggered an extensive public discussion about the relationships between ramp metering and sprawl in 1999, which has significantly affected residents' perception about ramp metering. This, together with observed long delays at entrance ramps, forced the freeway operators to shut down the meters for two months in Fall 2000, and finally switch to a less aggressive metering algorithm. In general, improved speeds on freeway mainline and a ramp delay distribution favoring suburban residents result in the impression that ramp metering encourages commuters to locate their homes further away from activity centers and make longer trips. It is conceivable that ramp metering may lead to decentralization in an urban area. However, this issue needs to be examined more formally. Several other important questions also need to be answered to provide insights for decision-makers and information for the general public. Dose ramp metering exacerbate sprawl? Who are the winners and losers of the activity relocation process due to uneven travel time advantages in a metered freeway system? This study aims to examine the potential land use effects of ramp metering with a spatial interaction model, thus shedding some lights on these research questions. In spatial interaction models, economic activities and transportation networks are separated into aggregated spatial zones, and their relationships studied at this macro level (Lee 1973, De La Barra 1989).

Despite the fact that they are usually loosely structured from a theoretical point of view, spatial interaction models can sometimes serve as useful tools for real-world applications, such as the residential location and retail location model (Hansen 1959) and the land use change indicator model (Robert and Simmonds 1997).

The remainder of the paper is organized into five sections. Section 2 provides some background information and especially defines sprawl, followed by the methodology and models in Section 3. Several hypothetical urban areas with various initial land use patterns are described in Section 4 to which models are applied. Section 5 presents the results in terms of the new land use patterns after the deployment of ramp meters, and a sensitivity analysis on model parameters. Conclusions and discussions are offered at the end of the paper.

2. Background

2.1 What is sprawl?

Sprawl is one of the terms that frequently appear in urban planning. However, it is still a controversial term for which a formal and consistent definition is not available. Therefore, to study whether ramp metering exacerbates urban sprawl, the first step is to define what we mean by *sprawl*. Traditionally, low-density, strip, scattered and leapfrog developments are considered as sprawl indicators. It is hard to distinguish between these developments and economically-efficient discontinuous development (e.g. satellite cities). *"At what number of centers polycentrism ceases and sprawl begins is not clear"* (Gordon and Wong 1985). Ewing (1997) argued in the sprawl debate with Gordon and Richardson (1997):

> *"Wherever one draws the line between sprawl and related forms of development may be challenged unless the choice is (1) quantifiable and (2) related to impacts:*

it is the impacts of development that render development patterns undesirable, not the patterns themselves."

One sprawl indicator is the land use density function. This concept was argued by Ewing (1997) whose definition of sprawl can be shown graphically by Figure 1-1. In this graph, there are few significant centers, low average density and gaps in the urban fabric due to leapfrogging. The pattern itself does not define sprawl, but these leapfrog developments tend to impose high social costs which are avoidable with continuous, higher density developments. *Sprawl is a type of urban developments that induces high social costs in terms of poor accessibility, excessive commuting, infrastructure supply and environmental damages, which can be avoided with more desirable alternatives.* We shall follow this definition of *sprawl* in the remainder of the paper, which can be operationalized by both accessibility measurements and land use density functions.

Ewing's illustration in Figure 1-1 provides a nice graphical representation of a typical *sprawl* pattern based on the verbal definition. Figure 1-2 shows an urban form different from a sprawling one. It is a polycentric pattern with moderate densities and is continuous except for permanent open spaces. Figure 1-3 shows what Gordon and Richardson (1997) consider as a compact pattern. We shall refer to the land use pattern in this last graph as a centralized pattern. Any trend that leads employment/housing density distribution away from this pattern will be referred to as *decentralization*. *Decentralization* does not necessarily imply *sprawl*.

2.2 Ramp metering

Ramp metering was first applied in Detroit, New York and St. Louis in the early 1960s as a peak period freeway traffic management device. Ramp meters limit the flow entering freeways in order to maximize system efficiency. Aside from reducing travel time in the freeway system as a whole, ramp metering also redistributes travel times among different traveler groups. Figure 2 shows travel times with and without ramp metering along a freeway segment on TH169 from I-494 to I-694 in the Twin Cities metropolitan area (Levinson et al. 2001).

It is clear in the graph that longer trips enjoy more benefits from ramp metering than shorter trips. As the travel distance becomes very short, trip travel times actually increase with the presence of ramp metering. This is because travel time saving on the freeway mainline cannot offset the increased delays at entrance ramps for those extremely short trips. In addition, travelers who access the freeway via the first unmetered ramp experience no ramp delay at all, while those entering the freeway via the last metered ramp will be delayed for several minutes on average during the rush hours. This fact provides at least some incentives to locate new developments adjacent to the first unmetered ramp instead of the area close to the last metered ramp, which is a typical inefficient leapfrog development pattern.

Since most of the ramp meters in the Twin Cities are installed between year 1989 and 1994, using digital orthophotos and new development data of year 1990 and 2000, we are able to create visualization of new developments after the installation of ramp meters at some of these "last-metered-ramp" areas along radial freeways (freeways leading to a CBD, downtown Minneapolis or downtown St. Paul)(see Figure 3). Figure 4 shows that since the deployment of ramp metering, most new developments have taken place at the areas surrounding the first unmetered ramps although there is significant developable land closer to the CBD near the last metered ramp. Similar patterns were found in three of the four areas examined by digital orthophotos. This observed phenomenon could be attributed to ramp metering, or other factors such as easier land acquisition outside the beltway.

The empirical studies and the observations only give us a vague picture of potential impacts of ramp metering on land use. Nevertheless, they provide strong incentives for researchers to pursue a deeper understanding of the issue.

3. Methodology and Models

The analysis is in a theoretical phase and the problem is highly simplified, however, key assumptions will be tested in a sensitivity analysis. Our methodology evaluating how ramp metering affects urban land use patterns consists of the following steps (Figure 5). A regression-based travel time model is first estimated with some empirical data to capture the travel time redistribution caused by ramp metering. An accessibility measure is then used to convert travel time changes to accessibility changes based on the initial land use patterns in all aggregated spatial zones. Finally, a modified land use change indicator (LUCI) model predicts land use changes in terms of employment and residential density distribution.

3.1 Travel time model

A typical transportation model capable of estimating link and trip travel times include a demand analysis module which gives a time-sliced origin-destination (OD) table and a network loading algorithm which loads these demands onto the transportation network. In this study, since travel time data on real-world freeways with and without ramp metering are available directly from field measurements, we are able to estimate a regression model to predict trip travel times. It is assumed travelers will use the shortest path between any OD pair. The following paragraphs explain the regression model.

A bill passed in the 2000 Minnesota Legislature had the Minnesota Department of Transportation shut down all 440 ramp meters in the Twin Cities from October to December 2000 to study their effectiveness. The raw data are average peak hour travel times of 141 freeway OD pairs computed for TH169 and I-94 with (Fall, 1999) and without (Fall 2000) ramp metering based on collected thirty-second loop detector data. Readers interested in the travel time estimation procedure can refer to Levinson *et al.* (2001). Two regression models are specified:

Metering-on travel time:

$$t_{i,j,on} = \alpha + \beta D_{i,j} \tag{1}$$

$t_{i,j,on}$: *travel time from origin i to destination j with ramp metering control;*
α: *ramp delay;*
β: *inverse of freeway mainline speed with ramp metering control;*
$D_{i,j}$: *distance form origin i to destination j.*

Metering-off travel time:

$$t_{i,j,off} = \gamma D_{i,j} \tag{2}$$

$t_{i,j,off}$: *travel time from origin i to destination j without ramp metering control;*
γ: *inverse of average freeway mainline speed without ramp metering control;*
$D_{i,j}$: *distance form origin i to destination j.*

The regression models are estimated and validated and the regression results are summarized in Table 1. Average ramp delay is 2.79 min on TH169 and 1.06 min I-94. se regression results are consistent with what we obtained in a previous field study (Levinson *et al.* 2001), in which ramp delays are estimated to be 2.5min on TH169 and 0.95 min on I-94 based on an input/output queuing analysis. Average travel speed with ramp metering control is 110 km/h on TH169 and 96 km/h on I-94. Average travel speed without ramp metering control is 35 km/h on TH169 and 80 km/h on I-94. These results show that the travel speeds with ramp metering control on different freeways are quite similar while travel speeds without ramp metering differ to a large extent. Ramp delays on different freeways also differ. Considering these, values which will finally be used in the specified model are the averages of the OLS estimates on two freeways.

3.2 Accessibility measure

Accessibility is the product of two measures, a temporal element (e.g. the impedance function of a gravity model applied to the travel time between two points) and a spatial element reflecting the distribution of the activity under question (for instance number of jobs or houses) (Burns 1979, Hanson 1986). It measures the available activities, such as jobs, that can be reached in a given commuting time.

The changes in travel times due to ramp metering are then transformed into accessibility shifts based on a measures of accessibility:

$$A_{i,E} = \sum_j \left[E_j f(t_{ij}) \right] \quad (3)$$

$$A_{i,P} = \sum_j \left[P_j f(t_{ij}) \right] \quad (4)$$

$A_{i,E}$: *accessibility to jobs (employment) from zone i*
$A_{i,P}$: *accessibility to houses(residences) from zone i*
E_j: *number of jobs (employment) in zone j*
P_j: *number of houses (residences) in zone j*
$f(t_{ij})$: *impedance/decay function of travel time between zones i and j*

in which the impedance function for a peak-hour work-trip gravity model estimated for Washington DC (Levinson and Kumar 1995) is used:

$$f(t_{ij}) = \exp(a + bt_{ij}) = \exp(-0.97 - 0.08t_{ij}) \quad (5)$$

t_{ij}: *peak hour auto travel time from zones i to zone j*

With number of zonal opportunities (jobs and houses) in the equations, this measure reasonably describes the likelihood a job/house would be filled by a person according to how easy one can reach it. Accessibility was measured and tested by a series of studies (Handy 1993, Hanson 1987, Levinson 1998, Williams). Both residential accessibility and destination accessibility affect the efficiency of household travel patterns.

3.3 Modified land use indicator model

The original land use change indicator model assumes the availability of the base year population and employment data (Roberts and Simmonds 1997). Another input required by the model is the accessibility in the transportation network for both the base year and the forecast year. Accessibility in the original LUCI model is defined as simply a decay function of travel time without the inclusion of activity opportunities. The model has a logit functional form.

Population:

$$P_i^2 = P \frac{P_i^1 \exp[b(A_{i,E}^2 - A_{i,E}^1))}{\sum_i P_i^1 \exp[b(A_{i,E}^2 - A_{i,E}^1))} \tag{6}$$

P: *the fixed total study area population*
P_i^2: *new zonal population resulting from an accessibility change*
P_i^1: *the initial population of zone i*
b: *the calibrated sensitivity coefficient in accessibility measure, see eqn. (5)*
$A_{i,E}^2$: *the new accessibility to work of zone i*
$A_{i,E}^1$: *the initial accessibility to work of zone i*

Employment:

$$E_i^2 = E \frac{E_i^1 \exp(A_{i,P}^2 / A_{i,P}^1)^b}{\sum_i E_i^1 \exp(A_{i,P}^2 / A_{i,P}^1)^b} \tag{7}$$

E: *the fixed total study area employment*
E_i^2: *new zonal employment resulting from an accessibility change*

E_i^1 : *the initial employment of zone i*
$A_{i,P}^2$: *the new accessibility to house of zone i*
$A_{i,P}^1$: *the initial accessibility to house of zone i*

LUCI is an empirical spatial interaction model. An interpretation of the model is that because of shifted travel times between origins and destinations, some zones become more accessible relative to others in the region. More activities will be attracted to these areas resulting from the increased level of accessibility. Accessibility changes determine the relocation of activities among aggregate zones. The degree of the relocation depends on the calibrated coefficient *b* in the travel time decay function, i.e. people's willingness to travel farther. Aside from accessibility, all other factors in a city that can also influence location choices are assumed to be constant.

However, the accessibility measure used in the original model is a simple function of travel time while opportunities in each spatial unit are not incorporated. In order to apply the accessibility measures described by equation (3) and (4), the model structure needs to be modified. The new model for residential redistribution is:

$$P_i^2 = P \frac{P_i^1 \exp[\frac{b}{\overline{E}}(A_{i,E}^2 - A_{i,E}^1))}{\sum_i P_i^1 \exp[\frac{b}{\overline{E}}(A_{i,E}^2 - A_{i,E}^1))} \tag{8}$$

$\overline{E}$: average zonal employment of the study area

The sensibility of land use to accessibility changes is now $b/\overline{E}$ instead of *b*. Since the employment model has a fractional form relating the accessibility of base year and forecast year, it remains the same. Equation (3), (4), (5), (7) and (8) complete a modified LUCI model.

4. Hypothetical Cities

In order to evaluate the potential impacts of ramp meters on urban form, the transportation regression model, accessibility measure, and the modified LUCI model will be applied together to several hypothetical cities, each of which consists of a transport network and a base year land use pattern. Each scenario city should reasonably reflect reality and not lose its attractiveness as an abstract model. Two hypothetical urban highway networks are proposed (see the first column in Table 2). The network in the first two rows mimics a 1960s urban highway system. The one appearing in the lower three rows represents a typical post-1980s urban highway network with a beltway. Three different land use patterns, constituted by a job density distribution and a housing density distribution are examined, which are monocentric employment pattern, polycentric employment pattern and perfect jobs/housing balance. Empirical data show that the real housing distribution is very close to what is assumed in scenarios 1, 2, 4 and 5, and the real job distribution is somewhere between scenarios 1 and 2 (Clark 1969, Vaughan 1987).

Then, five contrived urban areas are developed with various combinations of highway networks, initial land use patterns, and the deployment of the ramp metering system. Scenario 1 and 2 represent cities without looped freeways. In addition, scenario 1 is a city with all jobs clustered in the city center, while scenario 2 has a perfect job/housing balance. Scenario 3, 4 and 5 represent cities with beltways and they differ in initial land use patterns, namely: polycentric housing distribution, perfect job/housing balance, and polycentric employment distribution. In all five scenarios, highways outside the beltway are not controlled by ramp meters.

The contrived urban areas are then divided into a number of zones. The travel times on the shortest path with and without ramp metering are computed based on the transportation model for each OD pair. Accessibility with and without metering is then derived and used by the modified LUCI model to predict the new land use pattern after the installation of the ramp metering system.

5. Results

The initial (without metering) and the estimated new (with metering) accessibility measurements are summarized in Table 3. Land use patterns in both control scenarios are shown in Table 4. The qualitative marginal effects of the parameters in the transportation model (average ramp delay, travel speed with and without ramp metering) on *decentralization* are summarized in Table 5. The parameters in the transport model were estimated from data collected on two real-world urban freeway segments. Whether these two segments are representative for the whole urban freeway network is unknown without additional observations. Therefore, a sensitivity analysis on these parameters is performed. Overall, the new jobs/housing density distributions are not very sensitive to these parameters. Detailed description of the sensitivity analysis is given in Table 6.

Accessibility is improved with ramp metering for almost all locations in five scenarios (Table 3). The only exception is in scenario 1 the accessibility to jobs actually decreases in areas immediately adjacent to the only job center. In this monocentric case, the increased ramp delays outweigh travel time savings on the freeway mainline for trips originating in these areas, resulting in worse accessibility to jobs. Though almost all commuters are better off in terms of improved accessibility with ramp metering, the benefits have an uneven distribution. Notably, areas just outside the metering system and the traditional CBD will see maximum improvements of accessibility, while the benefits to areas just inside the metering system and suburbs extremely far away from the city center are less obvious. Since land use and transportation choices are made based on relative accessibilities, the uneven distribution of accessibility gains may result in a significant change in the land use pattern. This is confirmed by the results of land use density distributions (Table 4).

The comparison between the before and after density distribution of each scenario reveals the following qualitative impacts of ramp metering:

(a) Ramp metering will slightly increase employment *decentralization*. More jobs will be located further away from areas inside the metering system with evidence from all five scenarios. However this employment redistribution is quite small especially when the initial job/housing distribution is balanced (Scenario 2 and 4). No evidence shows that ramp metering would increase employment *sprawl*. In scenario 1, one cannot see any changes in job density distribution since the LUCI model is unable to explain how nonresidential developments can be introduced into a purely residential area.

(b) Ramp metering influences the residential density distribution (1, 2, 4 and 5) while the degree of the impacts depends on the initial distribution. For a monocentric urban area (scenario 1), the hypothesis that ramp metering exacerbates decentralization in the residential sector is supported. This is a logical outcome of the defined accessibility measures and land use models. The change in the land use is a sprawl type of development since residents are moving away from the jobs, which results in excessive driving. For a polycentric urban area (5), one can again observe the housing decentralization, but this is not sprawl since houses become closer to jobs (compare the housing and the job distribution in scenario 5). The weakest impacts of ramp metering on land use are found when jobs and houses are perfectly balanced (2, 4). Surprisingly, in a polycentric metro area, the traditional downtown becomes more attractive as a residential center with ramp metering, because the accessibility to jobs in the CBD is improved more than the average (2, 3, 4, 5).

(c) It seems from (a) and (b) that, the more jobs and houses are balanced in an urban area, the less the spatial distribution of activities in the area is sensitive to ramp metering. In other words, the urban form is more stable with better job/housing balance.

(d) In general, ramp metering strengthens the existing housing centers and makes them more appealing to residents (1, 2, 4 and 5). A possible explanation is that the level of congestion, which was high around these activity centers, is reduced with the presence of ramp metering

(e) In the DOT beltway study performed by Payne-Maxie Consultants (1980), the conclusion about how new loop freeways in US cities impact land use states *"...given the high level of accessibility that exists in US urban areas, the impact of any single facility (beltway) will be marginal"*. Comparing scenario 2 (no beltway) and 4 (beltway) in this study, we also found a marginal effect of the additional beltway system. Adding a new beltway to the highway network increases the job (population) density in zones where the beltway is located from 2733 (3068) to 2736 (3167) unit per square mile and decreases the job (population) density in CBD from 4312 (5143) to 4295 (4931) unit per square mile.

In summary, under existing employment/housing density spatial distribution in most US urban areas (which are close to a polycentric pattern) ramp metering can drive jobs away from the areas inside the metering system to outer-ring suburbs, but this decentralizing effect is small. No signs of job sprawl have been found in this study. In terms of housing choices, the deployment of ramp metering may (monocentric) or may not (polycentric or balanced job/housing) exacerbate sprawl depending on the initial land use pattern. Places just outside of the boundary of the ramp metering system and the downtown area in a polycentric city are the biggest winners and benefit the most from ramp metering (as seen in all scenarios).

6. Conclusion

Ramp metering is only one of the many factors that can potentially shape urban land use. It is difficult to attribute changes of land use quantitatively to each individual factor because the long-term feature of their impacts make it hard to acquire reliable data to test related hypotheses. The Twin Cities have experienced significant suburban development, including the formation of suburban activity centers and leapfrog residential development in the past decade. However, it is almost impossible to know exactly to which extent the ramp metering system exacerbates the problem. Therefore, we developed a qualitative model in this research to study the impacts of ramp metering on urban sprawl.

The results are mixed. Ramp meters' effects depend on the existing land use conditions. If all jobs are clustered in the center of the city, ramp metering will clearly exacerbate sprawl by driving people to live further away from their working destinations. As the job and housing distribution become more balanced in a polycentric pattern where reverse and suburb-to-suburb commuting trips have a larger share, the model suggests that ramp metering will not aggravate sprawl. In this case, although activities still move away from the center of the city, they will relocate to existing secondary activity centers which are more accessible. Accessibilities are improved for almost all areas by freeway ramp metering. In the downtown area, the improvement of accessibility to jobs is more than the average of the entire urban region. Therefore, ramp metering is actually also a tool for rejuvenating old city centers.

Accessibility and the modified LUCI model are two important elements in the qualitative model developed in this study. Accessibility is only one of various factors that affect urban form. Several previous studies draw conclusions that accessibility seems to have insignificant or ambiguous influences on employment and housing spatial distribution in an urban area (e.g. Adams 1999), while others suggest that accessibility changes do have significant distributional impacts (Payne-Maxie Consultants 1980). Nevertheless, the fact that urban regions do not extend infinitely over space indicates that commuting time is a significant factor (Levinson 1996). The fact that the actual commute exceeds the minimum required commute (however defined) indicates that it is not the only factor. Aside from accessibility, crime rates, school quality, tax base, economies of scale are also important factors for residential and business location choices. However, ramp metering should not significantly affect factors other than accessibility. Unlike more sophisticated land use forecasting processes, the modified LUCI model is static and does not consider feedbacks. Therefore, rather than a land use forecast, it only provides indication as to which degree accessibility changes, resulting from ramp meters, affects the land use pattern. Future research can incorporate more formal activity location models. Applying the model to a realistic urban area would also be an interesting future study.

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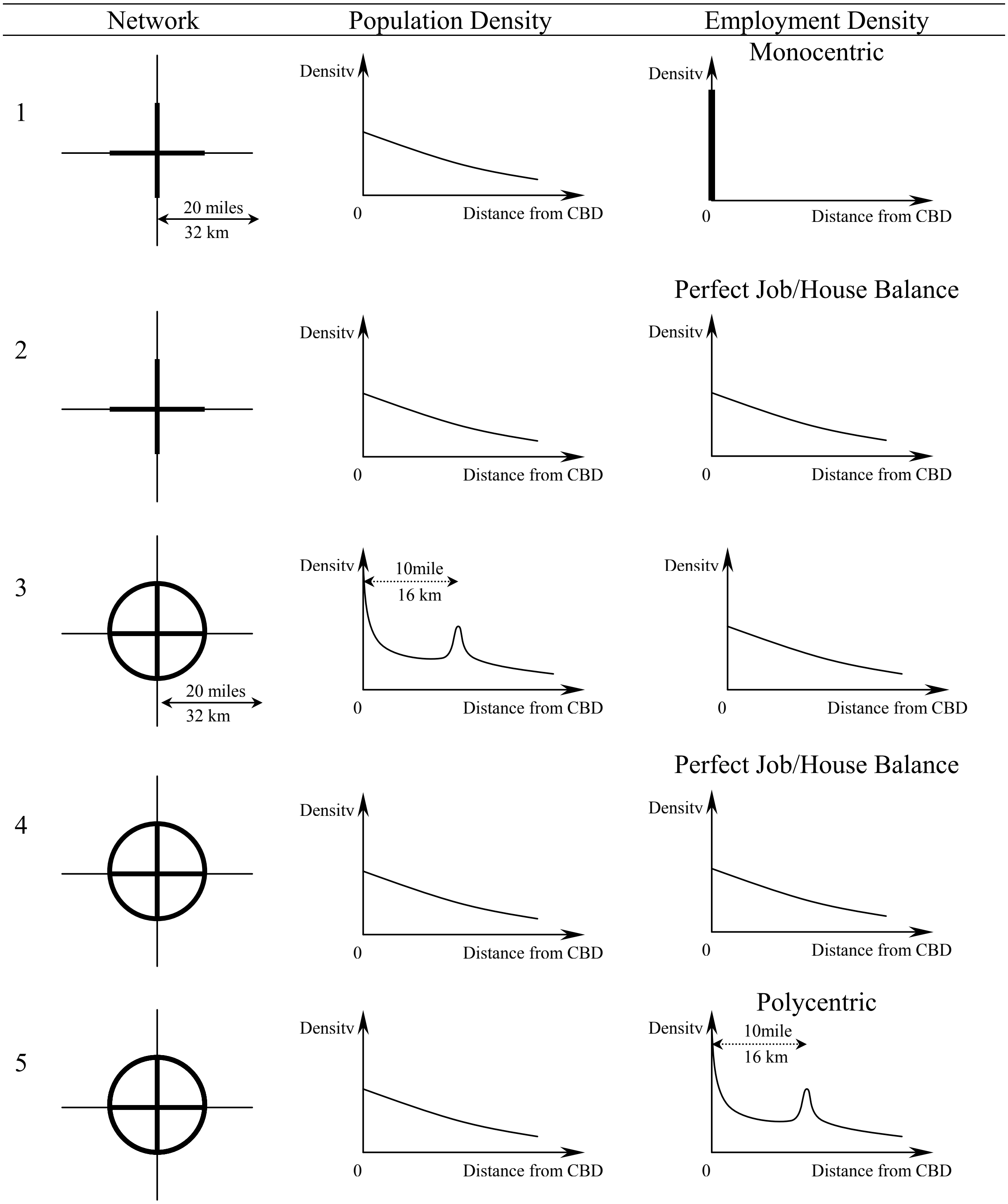
Table 1. Regression Results of Transport Model

Metering Status	Regression Parameters	TH169	I94	TH169+I94	Coefficients in the model
Metering -On	Regression Model	*OLS*	*OLS*	*WLS*	
	α	2.79 (15.8)	1.06 (4.0)	2.55 (15.7)	1.93
	β	0.83 (18.7)	1.00 (17.4)	0.85 (21.2)	0.915
	n (# observations)	105	36	141	
	R^2	0.77	0.90	0.85	
Metering -Off	Regression Model	*OLS No constant*	*OLS No constant*	*WLS No constant*	
	γ	3.18 (102.8)	1.21 (69.4)	3.06 (63.4)	2.20
	n (# observations)	105	36	141	
	R^2	0.99	0.99	0.97	

Note: Numbers in parentheses are t statistics
OLS: Ordinary Least Square
WLS: Weighted Least Square, WLS is used for pooled data of two freeways
All data in regression are peak hour travel time data (14:55pm to 18:10 pm)

Table 2. Five Scenarios



Note: **——** *Highways with ramp metering control*
— *Highways without ramp metering control*

Table 3. Results – Changes in accessibility (with metering – without metering)(Unit: 1mile = 1.6km)

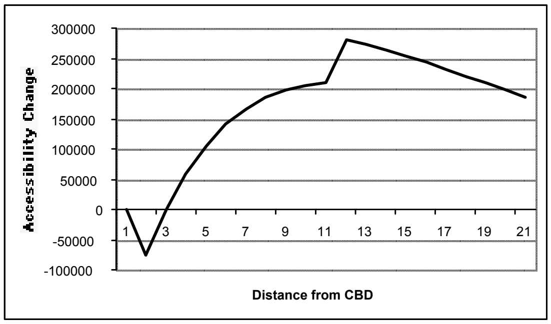
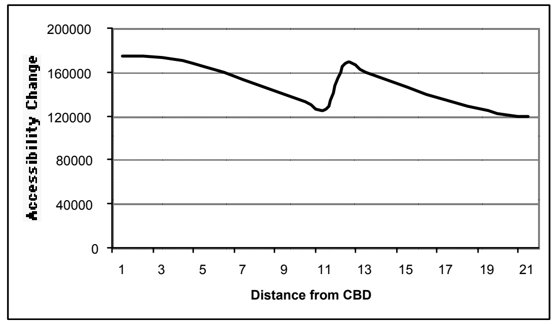
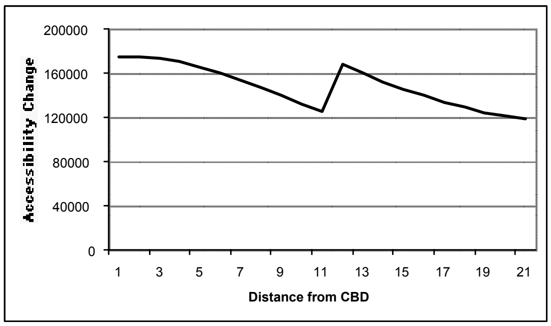
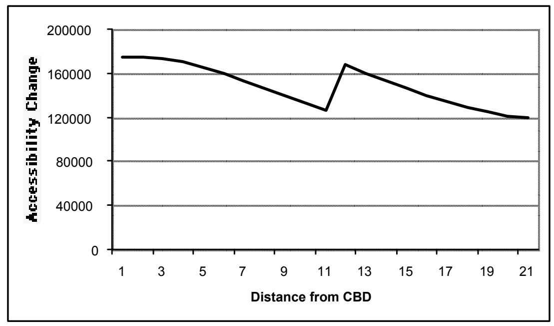
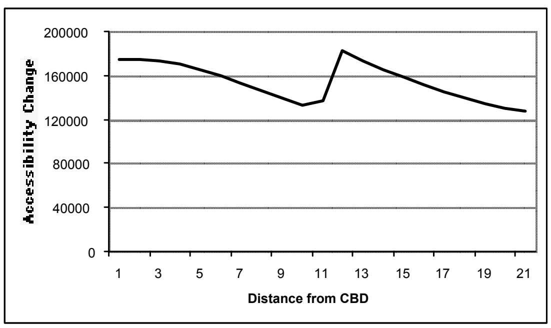
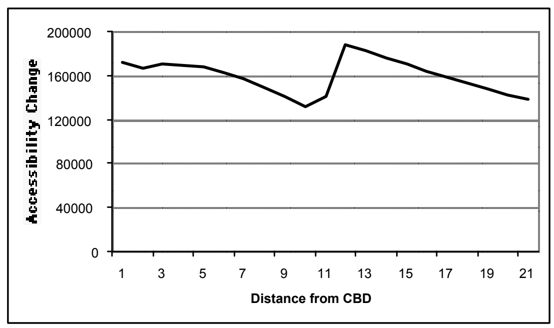
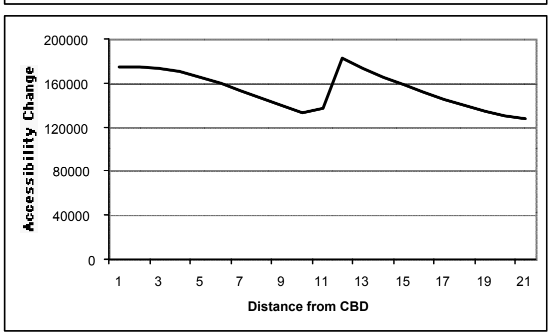
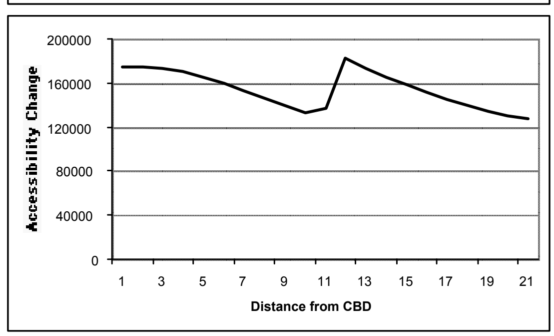
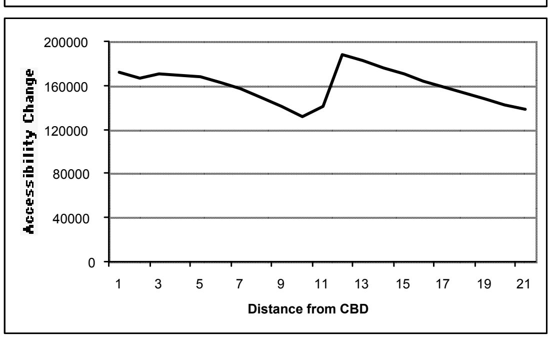
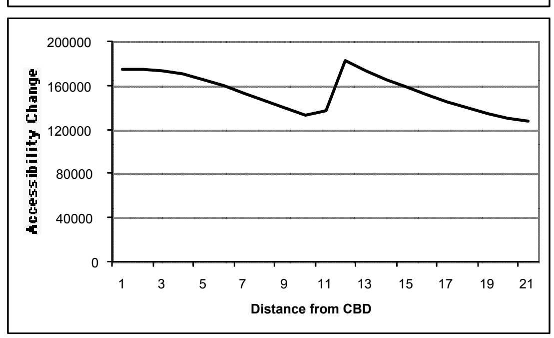
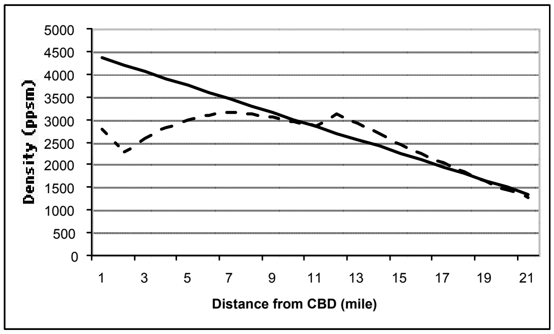
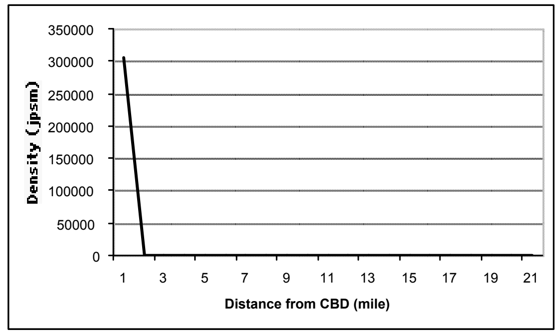
Scenario	Accessibility to Jobs	Accessibility to Houses
1		
2		
3		
4		
5		

Table 4. Results - Job/Population Density with/without Ramp Metering (Unit: 1mile = 1.6km)

Scenario | Population Density | Employment Density

1





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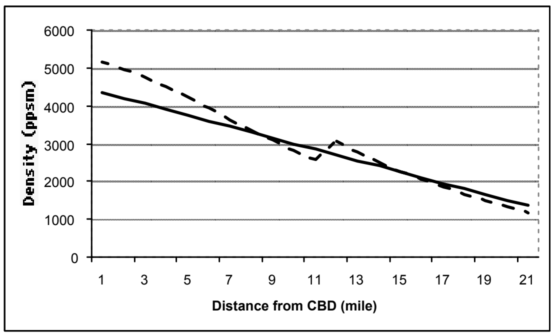

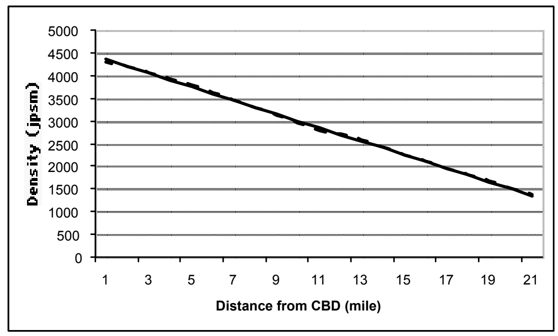

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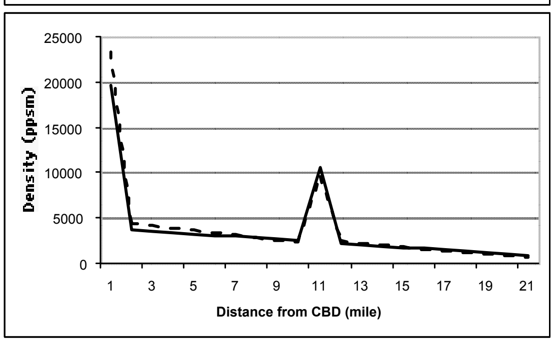

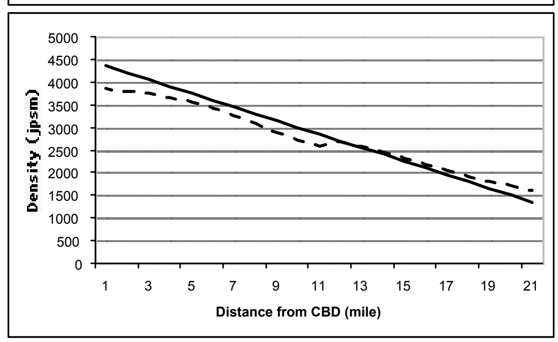

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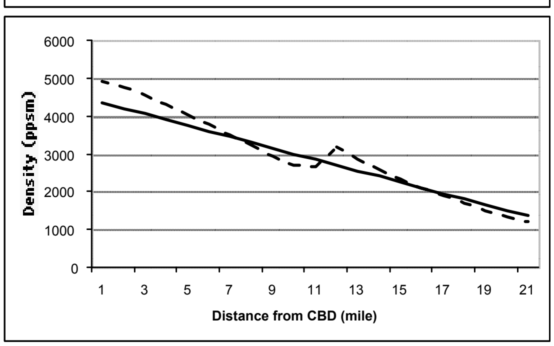
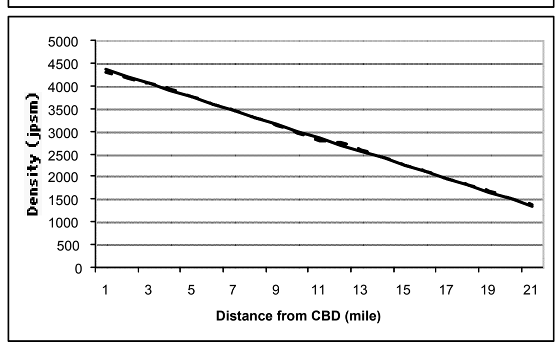
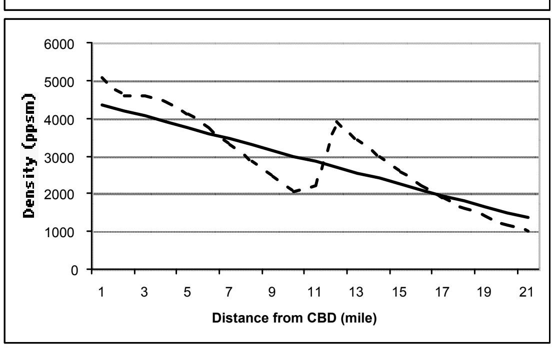
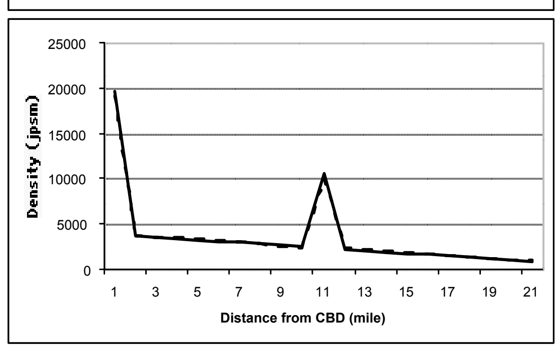




5





—— Before (Density without ramp metering control)   – – – After (Density with ramp metering control)

Table 5. Marginal Effects of Transport Parameter Changes on Decentralization

Chang of Parameters	Effects	Chang of Parameters	Effects
+ Ramp delay	+	- Ramp delay	-
+ Metering-off speed	-	- Metering-off speed	+
+ Ramp-on travel speed	++	- Metering-on speed	--

Note: + weak positive relationship, ++ strong positive relationship;
- weak negative relationship, - - strong negative relationship.

Table 6. Sensitivity analysis on parameters in the transport model

Scenario 1 is chosen as the object of the sensitivity analysis because its density changes are the most significant. The sensitivity analysis shows that the results not sensitive to the parameters in the transportation model.

Distance from CBD (mile)	Base Case Results	Ramp Delay +10%	%change	Ramp Delay -10%	%change	Travel Speed Ramp Off +10%	%change
0	2777	2793	1%	2759	-1%	2953	6%
1	2282	2227	-2%	2340	3%	2354	3%
2	2585	2528	-2%	2644	2%	2608	1%
3	2825	2769	-2%	2883	2%	2808	-1%
4	2997	2943	-2%	3052	2%	2949	-2%
5	3100	3050	-2%	3151	2%	3033	-2%
6	3140	3094	-1%	3186	1%	3064	-2%
7	3124	3084	-1%	3165	1%	3049	-2%
8	3062	3027	-1%	3098	1%	2993	-2%
9	2964	2934	-1%	2994	1%	2906	-2%
10	2838	2812	-1%	2863	1%	2792	-2%
11	3129	3147	1%	3109	-1%	3092	-1%
12	2908	2926	1%	2890	-1%	2887	-1%
13	2686	2702	1%	2669	-1%	2679	0%
14	2464	2479	1%	2449	-1%	2470	0%
15	2248	2262	1%	2234	-1%	2264	1%
16	2038	2050	1%	2025	-1%	2062	1%
17	1836	1847	1%	1824	-1%	1866	2%
18	1642	1652	1%	1632	-1%	1676	2%
19	1457	1466	1%	1448	-1%	1492	2%
20	1280	1288	1%	1272	-1%	1316	3%

Distance from CBD (mile)	Base Case Results	Travel Speed Ramp Off -10%	%change	Travel Speed Ramp on +10%	%change	Travel Speed Ramp On -10%	%change
0	2777	2607	-6%	2575	-7%	3016	9%
1	2282	2224	-3%	2146	-6%	2437	7%
2	2585	2583	0%	2460	-5%	2721	5%
3	2825	2871	2%	2717	-4%	2939	4%
4	2997	3076	3%	2906	-3%	3087	3%
5	3100	3197	3%	3028	-2%	3168	2%
6	3140	3242	3%	3084	-2%	3189	2%
7	3124	3222	3%	3083	-1%	3158	1%
8	3062	3148	3%	3034	-1%	3084	1%
9	2964	3033	2%	2944	-1%	2977	0%
10	2838	2889	2%	2825	0%	2846	0%
11	3129	3167	1%	3158	1%	3091	-1%
12	2908	2926	1%	2938	1%	2873	-1%
13	2686	2687	0%	2714	1%	2654	-1%
14	2464	2451	-1%	2490	1%	2437	-1%
15	2248	2224	-1%	2270	1%	2227	-1%
16	2038	2006	-2%	2056	1%	2022	-1%
17	1836	1798	-2%	1849	1%	1825	-1%
18	1642	1601	-2%	1652	1%	1637	0%
19	1457	1415	-3%	1463	0%	1456	0%
20	1280	1239	-3%	1283	0%	1283	0%

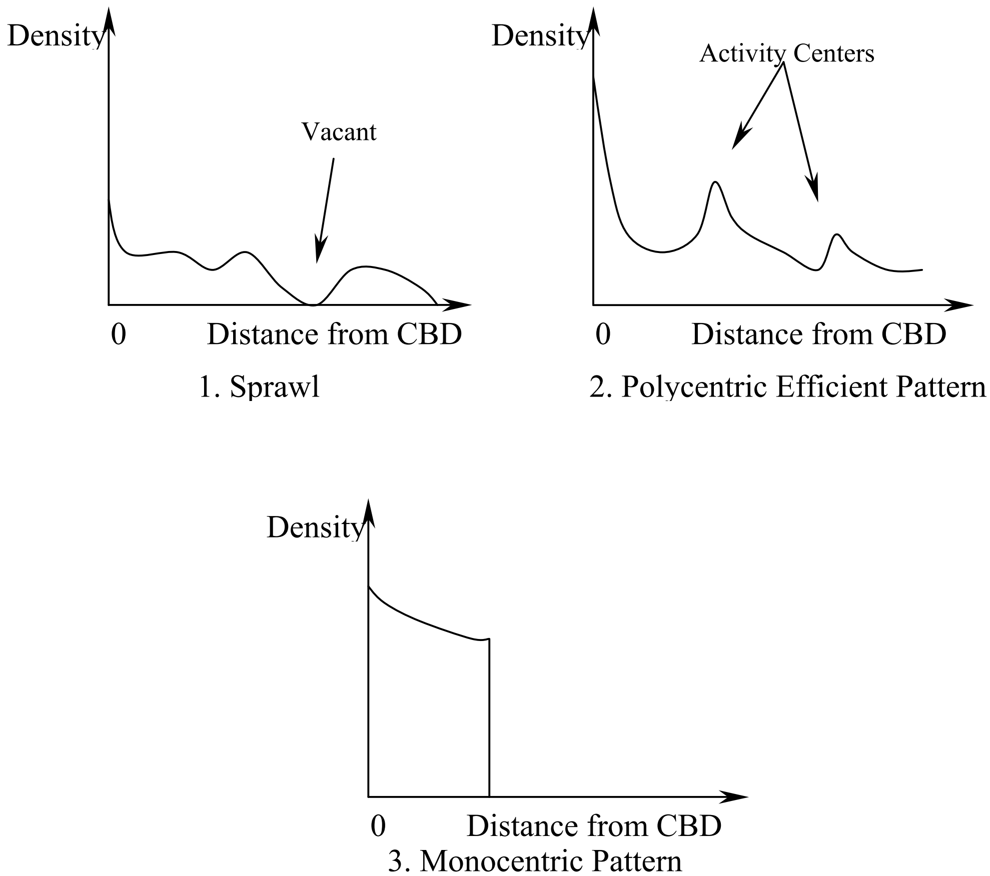


Figure 1. Definition of Sprawl and Decentralization
(prototypes of the graphs from Ewing(1997) Gordon and Richardson (1997))

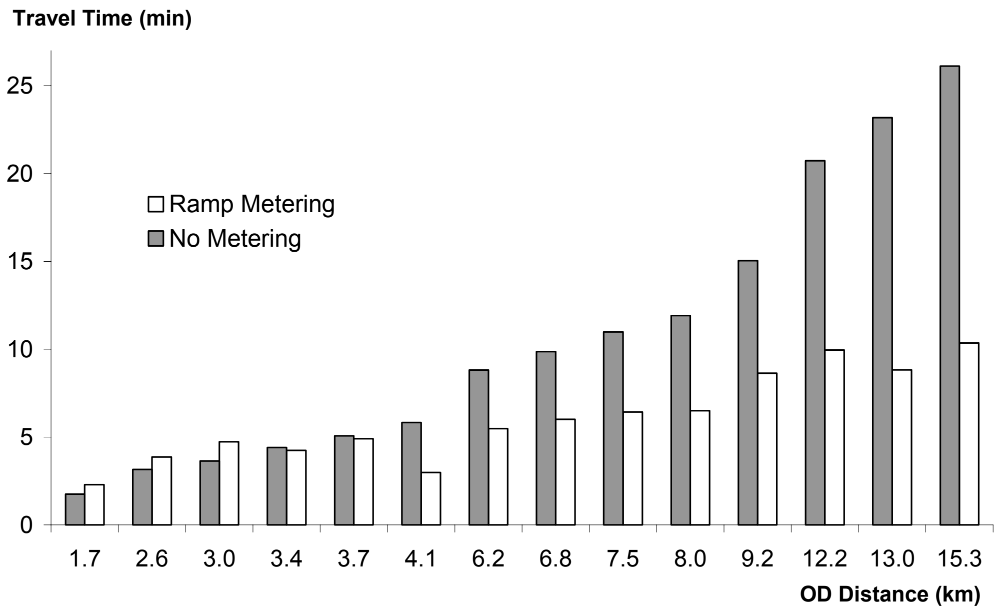


Figure 2. Travel Time: Ramp Metering vs. No Ramp Metering

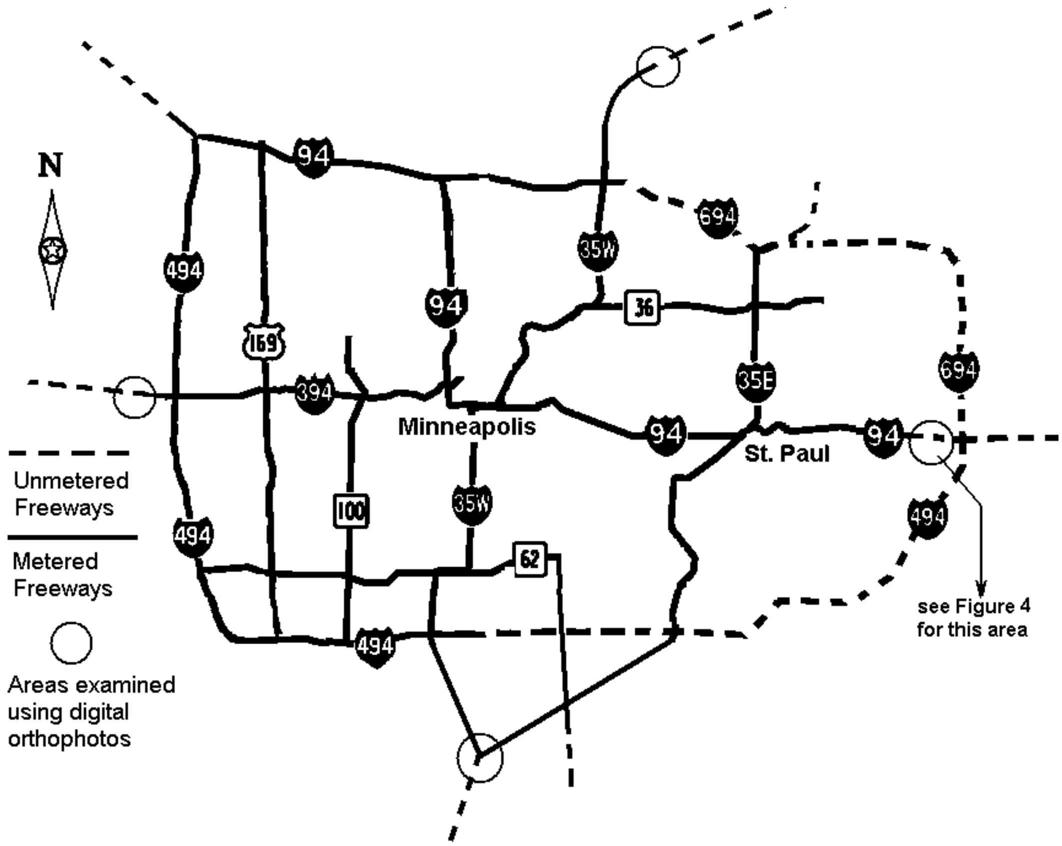
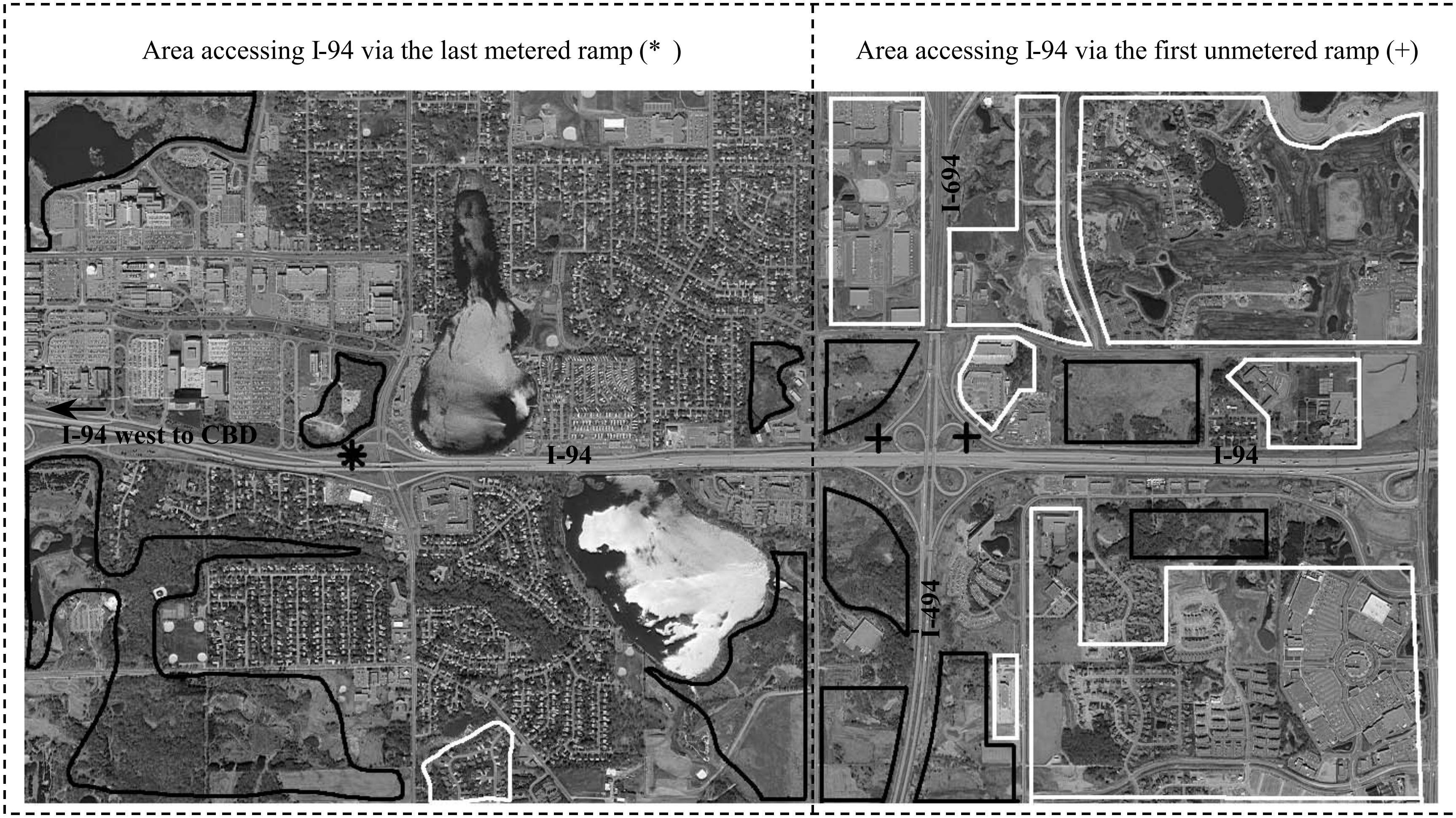


Figure 3. Ramp Metering Deployment Map in Minneapolis/St. Paul, MN
Source: Minnesota Department of Transportation, Metro Traffic Management Cente4, 2001



Areas bounded by black lines: developable lands in 2000
Areas bounded by white lines: new developments between 1990 and 2000

Figure 4. Area photograph: I-94, I494 and I-694, Twin Cities, MN

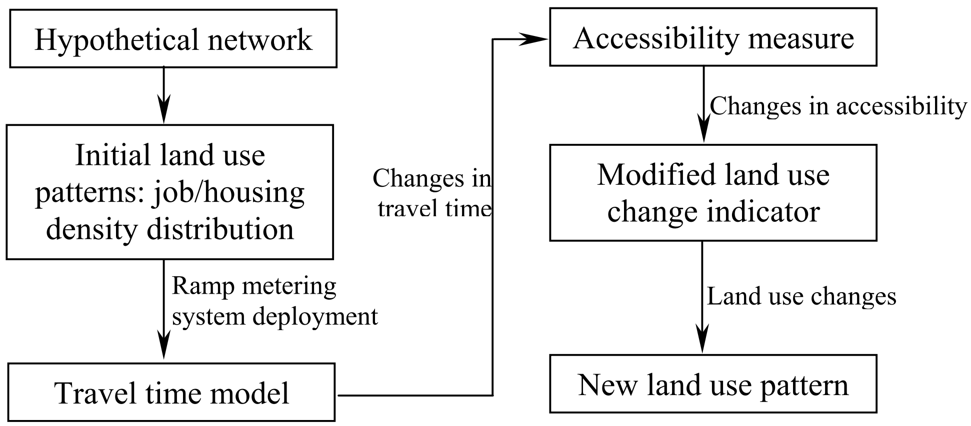


Figure 5. Flowchart of the modeling process