The Welfare Effects of Cordon Pricing and Area Pricing: Simulation with a Multi-regional General Equilibrium Model

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Abstract

This paper analyzes the welfare effects of cordon pricing and area pricing through numerical simulations with a multi-regional general equilibrium model. The toll policies achieve about 60% of the efficiency gains from the Pigouvian congestion tax. Cordon pricing is better if long-distance commuting is prevalent while area pricing is better if city has large central urban area. With the introduction of cordon pricing or area pricing, a toll district becomes more attractive as a residential place but less attractive as a workplace. The toll policies promote short-distance commuting but discourage the use of public transport in toll-free commutes.

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1 Introduction

Cordon pricing and area pricing have attracted the attention of politicians, urban engineers, and recently, some urban economists as second-best policies for the reduction of traffic congestion. Although both cordon pricing and area pricing are sometimes called road pricing, they are different in the following respect: while cordon toll is levied upon automobiles entering a toll area, area toll is levied upon automobile users who travel within a toll area. That is, while cordon toll is levied every time entering the toll district, area toll is imposed on a daily basis and the toll level is fixed regardless of the number of entries made into the toll area in a day. Cordon pricing is implemented in countries such as Singapore and Norway and area pricing is enforced in London.

To my knowledge, urban economists have begun to study cordon pricing only recently. Mun et al. (2003) and Verhoef (2005) analyze the effects of cordon pricing using a monocentric city model. The former focuses on the transport sector, and the latter adopts a general equilibrium approach. Both papers conclude that efficiency gains from cordon pricing are almost the same as those achieved by the first-best pricing. However, this positive result heavily depends on the nature of the monocentric city in the sense that if a toll district contains the CBD, all commuters who live outside the district will pay the cordon toll. Therefore, we need to examine whether cordon pricing remains almost first-best when employment is dispersed. This point is addressed by Mun et al. (2005) focusing on the transport sector. They conclude that cordon pricing is not that efficient in a non-monocentric city as people tend to refrain from making trips that involve passing through the toll gates.

Although there are several papers on cordon pricing, a work on area pricing that I can refer to is conducted by traffic engineers, Maruyama and Harata (2006) who formulate the difference between cordon pricing and area pricing using a transportation network model. One of the main results is that the optimal toll level of area pricing is higher than that of cordon pricing.

This paper analyzes the effects of cordon pricing and area pricing in a city where employment is dispersed. We also adopt a general equilibrium approach, where product, labor, and land markets are considered. Therefore, while population and employment densities at each location are fixed in Mun et al. (2005), they are endogenously determined through interactions of the three markets in our
setting. In this sense, the main purpose of this paper is to investigate effects of the second-best toll policies not only on travel behavior but also on residential and employment distributions. In addition, whether cordon pricing and area pricing can promote the use of public transport or not is an important issue since toll policies usually aim to make car users shift their travel mode to public transport. Thus, in our model, the modal choice between automobiles and railways is incorporated. The analytical model, described in the next section, is based on a multi-regional general equilibrium model developed by Anas and Xu (1999). In their model, a city is composed of a finite number of zones and in each zone, firms produce zone-specific composite goods. Since preference exhibits a love for variety, people consume every zone-specific good and therefore, production takes place in all zones. Moreover, there exist idiosyncratic tastes toward commuting arrangements, which are incorporated by assuming the random utility. Due to these idiosyncratic tastes, a wide variety of commuting patterns including wasteful commuting - commuting from one suburb to another which traverses the central area - can occur at equilibrium. Therefore, we can analyze how shares of each commuting arrangement are changed by the toll policies. This model is well suited for the evaluation of urban policies; thus, this paper is not the first one to use it to analyze the second-best toll policies. Eliasson and Mattsson (2001) analyze cordon pricing with considering modal shifts. However, they do not derive the optimal level of cordon toll, and therefore, do not measure the social welfare of cordon pricing. Safirova et al. (2006) analyze cordon pricing by combining a transportation network model and an extended version of Anas and Xu’s (1999) model. Their model is huge and considers many factors such as time-of-day preferences, route preferences, several types of agents, unemployment, and several kinds of taxes; factors that this paper does not consider. However, they do not analyze the first-best congestion pricing and thereby, the efficiency losses from cordon pricing relative to the first-best policy. Moreover, neither of the two papers analyzes area pricing. This paper analyzes the optimal cordon pricing and the optimal area pricing so that we can compare these two policies. In addition, their efficiency gains are compared with the first-best one so that we can evaluate their effectiveness as a second-best policy.

Since solving the model analytically is not possible, policy implications are obtained through numerical simulations. The main results are as follows. Cordon pricing and area pricing achieve about 60 per cent of the efficiency gains from
the Pigouvian pricing and about half of the efficiency gains from the first-best policy (the Pigouvian pricing + the optimal road investment). A ranking of the two second-best toll policies depends on the spatial structure of a city. Cordon pricing is better than area pricing if a city has many long-distance commuters while area pricing is better than cordon pricing if traffic congestion is mainly caused by residents in the central urban area. With the introduction of cordon or area pricing, a toll area becomes more attractive as a place of residence but less attractive as a place of work. In particular, both cordon and area pricings induce job dispersion even though job centralization is desirable. Therefore, cordon and area pricings cause inefficiencies in location decisions. Cordon and area pricings promote short-distance commuting but discourage the use of public transport in toll-free commutes.

This paper is organized as follows. In Section 2, the analytical model is explained in detail. In Section 3, calibration methods are explained after which simulation results are presented. In the final section, limitations of our analysis and subjects for future research are discussed.

2 The Model

We model a city which comprises three zones, as shown in Figure 1.

![Figure 1: The city structure](image)

The population of the city is fixed and rent revenue is distributed equally among the city residents. Moreover, we assume that if a toll is levied, its revenue is also distributed equally among the city residents. If cordon pricing is implemented, toll gates are set up between zone 1 and zone 2, and between zone 2 and zone 3. People who travel by automobile must pay toll every time they enter zone 2. When
there is no need to distinguish between zone 1 and zone 3, we also call zone 2 the center, and zone 1, 3, the suburb. The total area of each zone is exogenous, which is denoted by $A_i$.

The one-way trip distance to pass through zone $i$ is given by its diameter, that is, $d_i = 2 \sqrt{A_i/\pi}$. For intra-zonal travel, the trip distance is $d_i/2$. The modes of transport that people can use are automobiles and railway. We label the travel mode of automobile [resp. railway] by 1 [resp. 2]. The travel time (minutes per kilometer) of a trip by a travel mode $m \in \{1, 2\}$ in zone $i$ is given by $g^m_i = g^m_i(F^m_i, T^m_i)$ where $F^m_i$ denotes the total daily traffic by the travel mode $m$ in zone $i$ and $T^m_i$ denotes the amount of land allocated to the travel mode $m$ in zone $i$. In particular, we specify the travel time functions as follows:

$$g^1_i = \sigma_{0i} \left\{ 1 + \alpha_{1i} \left( \frac{F^1_i}{\sigma_3 K^1_i} \right)^{\sigma_2} \right\},$$

(1)

$$g^2_i = c_i,$$  

(2)

where $K_i$ is road capacity per hour in zone $i$ and $c_i$ is a positive constant. We assume that the road capacity is a linear function of $T^1_i$: $K_i = b_1 T^1_i$. Note that since $g^2_i$ does not depend on the number of passengers, there is no congestion externality in railway. Also, railway does not use land.\textsuperscript{1} In our model, people who travel from zone 1 to zone 3 and vice versa must traverse zone 2 (i.e., detour is not considered). Hence, the total travel time of a round trip by a travel mode $m$ from zone $i$ to zone $j(\neq i)$ is

$$g^m_{ij} = g^m_i d_i + g^m_j d_j + 2 \sum_{k=i+1}^{j-1} g^m_k d_k.$$  

(3)

The last term is dropped, except when $i = 1$ and $j = 3$. The total travel time of an intra-zonal round trip by a travel mode $m$ is

$$g^m_{ii} = g^m_i d_i.$$  

(4)

For later use, we define $G^m_{ij}$ as

$$G^m_{ij} = \begin{cases} g^m_{ij} & \text{if } i = j \\ g^m_{ij} & \text{otherwise} \end{cases}.$$  

(5)

\textsuperscript{1}If we consider underground, this assumption is not so unrealistic.
2.1 Production

In each zone, the differentiated composite good is produced under a constant returns to scale technology. The production function in zone \( i \) is

\[
X_i = EL_i^\delta Q_i^\mu, \tag{6}
\]

where \( E \) is the scale parameter, \( L_i \) denotes the aggregate labor inputs, \( Q_i \) denotes land inputs, and \( \delta + \mu = 1 \). Since the technology exhibits constant returns to scale, the equilibrium number of firms in a zone is indeterminate. Let \( p_i, w_i, \) and \( R_i \) be the mill price of the goods produced in zone \( i \), the wage rate in zone \( i \), and the land rent in zone \( i \), respectively. Then, free entry in each zone ensures that the following zero profit conditions are satisfied at equilibrium\(^2\):

\[
\forall i, p_i = \frac{w_i^\delta R_i^\mu}{E^{\delta \mu}}. \tag{7}
\]

2.2 Consumption

We assume that households can choose different travel modes depending on whether they travel within one or more zones. For example, a household in the center can choose railway for trips within the center and automobile for trips to the suburb. Their utility depends on consumption of composite goods, lot size, leisure, and random terms. To buy a zone-specific composite good, people have to travel to where it is produced incurring a travel cost. In other words, households have to bear the shopping cost to consume the composite goods. The utility function of households who reside in zone \( i \), commute to zone \( j \), and use a travel mode \( m \) for intra-zonal trips and a travel mode \( n \) for inter-zonal trips (in short, households with the home-work-modes quaternary \((i, j, m, n)\)) is

\[
U_{ij}^{mn} = \frac{1}{\rho_1} \ln \left\{ \alpha \left( z_{ij}^{mn} \right)^{\rho_1} + \beta \left( h_{ij}^{mn} \right)^{\rho_1} + \gamma \left( l_{ij}^{mn} \right)^{\rho_1} \right\} + \varepsilon_{ij} + \varepsilon_{ij}^{mn}, \tag{8}
\]

where

\[
z_{ij}^{mn} = \left\{ \sum_{v=1}^{3} \left( z_{ij}^{mn} \right)^{\rho_2} \right\}^{1/\rho_2}. \tag{9}
\]

\(^2\)See Appendix A for the expressions of the conditional input demands.
\(z_{ij}^{mn}, h_{ij}^{mn}, \text{ and } l_{ij}^{mn}\) denote the quantity of the composite good produced in zone \(v\), lot size rented in zone \(i\), and leisure, respectively. We assume that \(\alpha + \beta + \gamma = 1\) and \(0 < \rho_2 < 1\). The latter assumption implies that the marginal utility at \(z_{ij}^{mn} = 0\) is infinite for all \(v\). Thus, people consume the composite good of all of the zones. This leads to residential and employment densities reaching their peak in zone 2 since households can save the most in terms of the shopping cost in that area. Therefore, as Anas and Xu (1999) point out, an agglomeration occurs even if we do not assume increasing returns to scale technology. The term \(\varepsilon_{ij}\) [resp. \(\varepsilon_{ij}^{mn}\)] is Gumbel distributed random variable, which represent idiosyncratic tastes to the home-work pair \((i, j)\) [resp. the home-work-modes quaternary \((i, j, m, n)\)]. We assume that \(\varepsilon_{ij}\) and \(\varepsilon_{ij}^{mn}\) satisfy the conditions which are compatible with the nested logit model.\(^3\)

The budget constraint of city residents with the home-work-modes quaternary \((i, j, m, n)\) is

\[
\sum_{v=1}^{3} p_{v} z_{ij}^{mn} + R_{i} h_{ij}^{mn} = w_{j} (H - l_{ij}^{mn}) - T C_{ij}^{mn} - T S_{ij}^{mn} + \frac{\sum_{i=1}^{3} R_{i} A_{i}}{N} + \frac{R V_{\tau}}{N} - h, \tag{10}
\]

where \(H\) is endowment in units of times, \(N\) is the number of households in the city, \(R V_{\tau}\) is toll revenue, and \(h\) is head tax. \(T C_{ij}^{mn}\) [resp. \(T S_{ij}^{mn}\)] is the travel cost for commuting [resp. shopping], which is represented as follows:

\[
T C_{ij}^{mn} = \begin{cases} 
 w_{j} g_{n}^{m} + \tau_{m} \phi_{ij} & \text{if } i = j \\
 w_{j} g_{n}^{m} + \tau_{m} \phi_{ij} & \text{otherwise}
\end{cases} \tag{11}
\]

\[
T S_{ij}^{mn} = \theta \left\{ w_{j} g_{n}^{m} + \tau_{m} \phi_{ij} \right\} z_{ij}^{mn} + \sum_{v \neq i} \left\{ w_{j} g_{n}^{m} + \tau_{m} \phi_{iv} \right\} z_{ij}^{mn}, \tag{12}
\]

where \(\theta\) is the number of shopping trips required to buy one unit of zone-specific composite good, and \(\tau_{m}\) is toll. It is assumed that toll is not levied on railway passengers: \(\tau^{2} = 0\). The term \(\phi_{ij}\) reflects the fact that the number of times toll is paid differs among trips. In cordon pricing, \(\phi_{ij}\) is defined as the \((i, j)\)th element of the following matrix:

\[
\phi = \begin{pmatrix}
0 & 1 & 2 \\
1 & 0 & 1 \\
2 & 1 & 0
\end{pmatrix}.
\tag{13}
\]

\(^3\)Specifically, we assume that \(\varepsilon_{ij}\) and \(\varepsilon_{ij}^{mn}\) satisfy the following conditions: (i) \(\varepsilon_{ij}\) and \(\varepsilon_{ij}^{mn}\) are independent for all \((i, j)\) and \((m, n)\), (ii) \(\varepsilon_{ij}^{mn}\) is i.i.d. Gumbel distributed, and (iii) \(\varepsilon_{ij}\) is distributed so that \(\max_{(m, n)} l_{ij}^{mn}\) is Gumbel distributed. For more detail, see Ben-Akiva and Lerman (1985).
For example, $\phi_{13} = 2$ because people who travel from zone 1 to zone 3 enter zone 2 on their way to and from zone 3. If the government introduces area pricing, people who travel by automobile in zone 2 must pay a fixed toll regardless of the number of entries made into zone 2. Therefore, in area pricing, households who reside in zone 2 must pay toll whenever they use their automobiles unlike in cordon pricing. Thus, it would be reasonable to think that it is difficult to implement area pricing without giving a discount to residents in a toll district. Indeed, in London’s case, residents in the toll area receive a 90 per cent discount. Following London’s example, we also assume that in the case of area pricing, the residents in zone 2 are entitled to a 90 per cent discount. Therefore, if we consider area pricing, $\phi$ is replaced by the following matrix:

$$
\phi' = \begin{pmatrix}
0 & 1 & 1 \\
0.1 & 0.1 & 0.1 \\
1 & 1 & 0
\end{pmatrix}.
$$

The city residents’ choice of the home-work-modes quaternary $(i, j, m, n)$ maximizes (8) subject to (10). See Appendix A for the expressions of the Marshallian demands and the systematic component of the indirect utility.

Households compare all 36 home-work-modes quaternaries $(i, j, m, n)$ and choose the most preferable one. Their choice structure involves two steps. In the first step, they choose a home-work pair $(i, j)$ and then decide on which mode to use for intra-zonal travels and inter-zonal travels simultaneously. Due to the assumptions about $\epsilon_{ij}$ and $\epsilon_{mn}^{ij}$ stated above, the probability of households choosing the home-work pair $(i, j)$ and the conditional probability of households choosing the modes pair $(m, n)$, given the home-work pair $(i, j)$, are described as

$$
\psi_{ij} \equiv \Pr \left( \max_{(m,n)} U_{ij}^{mn} \geq \max_{(k,l)} U_{ij}^{kl}, \forall (k, l) \neq (i, j) \right) = \frac{\exp \lambda_1 S_{ij}}{\sum_{(k,l)} \exp \lambda_1 S_{kl}},
$$

$$
\psi_{mnij} \equiv \Pr \left( U_{ij}^{mn} \geq U_{ij}^{uv}, \forall (u, v) \neq (m, n) \right) = \frac{\exp \lambda_2 V_{ij}^{mn}}{\sum_{(u,v)} \exp \lambda_2 V_{ij}^{uv}},
$$

where $V_{ij}^{mn}$ is the systematic component of the indirect utility and $S_{ij} = \frac{1}{\lambda_2} \ln \sum_{(m,n)} \exp \lambda_2 V_{ij}^{mn}$. $\lambda_1^{-1}$ [resp. $\lambda_2^{-1}$] is the dispersion parameter for the distribution of $\epsilon_{ij}$ [resp. $\epsilon_{ij}^{mn}$]. $S_{ij}$ is called the logsum variable, which is the expected maximum utility for households.

\[\text{However, we will also analyze the cases of different discounts as a sensitivity analysis.}\]
choosing the home-work pair \((i, j)\). The probability of households choosing the home-work-modes quaternary \((i, j, m, n)\) is \(\Psi_{ij}^{mn} = \psi_{mnij}\).

### 2.3 Transport

We do not consider trip-scheduling issues. Thus, the number of trips by a travel mode \(m\) from zone \(i\) to zone \(j\) is given by

\[
F_{ij}^m = \begin{cases} 
N \sum_{v} \Psi_{ij}^{mv} + \theta N \sum_{(v,s)} \Psi_{is}^{mv} & \text{if } i = j \\
N \sum_{u} \Psi_{ij}^{um} + \theta N \sum_{(u,s)} \Psi_{is}^{um} & \text{otherwise}
\end{cases}
\]  

(17)

The first term is the number of commuting trips and the second term is the number of discretionary trips. Thus, the total daily traffic by a travel mode \(m\) in zone \(i\), defined earlier, is now formulated explicitly:

\[
F_i^m = F_{ii}^m + \sum_{j \neq i} (F_{ij}^m + F_{ji}^m) + 2 \sum_{k=1}^{i-1} \sum_{l=i+1}^{3} (F_{kl}^m + F_{lk}^m). 
\]

(18)

For zone 1 and zone 3, the last term is dropped out.

In each zone, the amount of land for road is determined arbitrarily by the government and is financed by the head tax. Hence, the government budget constraint is

\[
\sum_{i=1}^{3} R_i T_i^1 = Nh.
\]

(19)

### 2.4 General Equilibrium

In each zone, there are three markets: the product market, labor market, and land market. Therefore, in total, there are nine market clearing conditions to be satisfied at equilibrium:

\[
\forall k, X_k - N \sum_{i,j,m,n} \Psi_{ij}^{mn} z_{ijk} = 0 \quad \text{Product market,} \quad (20)
\]

\[
\forall k, L_k - N \sum_{i,j,m,n} \Psi_{ik}^{mn} \left( H - G_{ik}^{mn} - \theta \sum_{v} z_{ikv} G_{iv}^{mn} - l_{ik}^{mn} \right) = 0 \quad \text{Labor market,} \quad (21)
\]

\[
\forall k, A_k - T_k^1 - N \sum_{i,j,m,n} \Psi_{ki}^{mn} h_{ki}^{mn} - Q_k = 0 \quad \text{Land market.} \quad (22)
\]
2.5 Welfare

We define social welfare as follows:

\[
SW(\tau^1, \mathbf{p}, \mathbf{R}, \mathbf{w}, \mathbf{Y}) \equiv E \left[ \max_{(i,j,m,n)} (V^m_{ij} + \epsilon_{ij} + \epsilon^m_{ij}) \right] = \frac{1}{\lambda_1} \ln \left( \sum_{(i,j)} \exp \lambda_1 S_{ij} \right),
\]

(23)

where \(\mathbf{p}, \mathbf{R}, \mathbf{w}, \) and \(\mathbf{Y}\) are the vectors of mill price, land rent, wage rate, and full endowment income, respectively.\(^5\) The government determines the toll level so that (23) is maximized, subject to (7), (19), (20)-(22), and the household’s utility maximization problem. It is not possible to explicitly find the optimal condition for the second-best toll level. Thus, in the following section, we derive numerical solutions. We also evaluate welfare change by using equivalent variation (EV). However, since the utility in this model has the random terms, we define EV using the logsum variables (Morisugi and Ohno, 1995). Let \((\mathbf{p}^{w_0}, \mathbf{R}^{w_0}, \mathbf{w}^{w_0}, \mathbf{Y}^{w_0})\) be the equilibrium prices without toll policy and \((\mathbf{p}^w, \mathbf{R}^w, \mathbf{w}^w, \mathbf{Y}^w)\) be the equilibrium prices with toll policy. The EV of households who reside in zone \(i\) and commute to zone \(j\) satisfies the following relation:

\[
S_{ij}(\tau^1, \mathbf{p}^w, \mathbf{R}^w, \mathbf{w}^w, \mathbf{Y}^w) = S_{ij}(\mathbf{p}^{w_0}, \mathbf{R}^{w_0}, \mathbf{w}^{w_0}, \mathbf{Y}^{w_0} + EV_{ij}).
\]

(24)

We simply aggregate \(EV_{ij}\) by \(EV = \sum_{(i,j)} N_{ij} EV_{ij}\), where \(N_{ij}\) is the number of households choosing the home-work pair \((i, j)\) at no toll equilibrium.

2.6 First-best Policy

For comparison, we analyze the first-best case in which the congestion externalities are fully internalized and road capacity in each zone is optimized. Since the travel time of automobile is increasing in the total traffic, there are congestion externalities in automobile traffic (there is no such externality in railway traffic). To internalize the congestion externalities, the government needs to levy OD-specific Pigouvian congestion taxes which are equal to the value of congestion externalities. Specifically, the Pigouvian congestion tax \(\tau^1_{kj}\) that is levied on automobile trips from

\(^5\)See Appendix A for the definition of the full endowment income.
zone $k$ to zone $l$ is given by
\[ \tau_{kl}^1 = N \sum_{i,j,m,n} \psi_{ij}^{mn} w_j \left( \frac{\partial G_{ij}^{mn}}{\partial T_k^1} + \theta \sum_{v=1}^3 z_{ijn}^{mn} \frac{\partial C_{ij}^{mn}}{\partial T_k^1} \right). \] (25)

When we consider the Pigouvian congestion tax, a new household budget constraint is formulated in which $\tau^1$ is replaced by $\tau_{ij}^1$ and $\phi$ is replaced by the identity matrix. The amount of land allocated to road in each zone is determined so that the marginal benefit of investment is equal to its marginal cost. Since the travel time function is homogeneous of degree zero in its inputs, we do not need to care about indirect effects of the road investment on non-transport markets if the congestion externalities are fully internalized. Hence, the first-best amount of land for road in zone $k$ satisfies
\[ -N \sum_{i,j,m,n} \psi_{ij}^{mn} w_j \left( \frac{\partial G_{ij}^{mn}}{\partial T_k^1} + \theta \sum_{v=1}^3 z_{ijn}^{mn} \frac{\partial C_{ij}^{mn}}{\partial T_k^1} \right) = R_k. \] (26)

Since the travel time function of automobile is homogeneous of degree zero with respect to $F_{i}^1$ and $T_{i}^1$ and road construction exhibits constant returns to scale, it is well known that the investment cost is exactly financed by revenue from the congestion tax.

The first-best policy is characterized by the Pigouvian congestion tax (25) and the optimal road investment rule (26). However, since road capacities are not optimized in the second-best policies, we also consider a case in which the planner levies the Pigouvian congestion tax but does not optimize the road capacities. We call this policy the Pigouvian pricing.

3 Numerical Analysis

3.1 Calibration

In our model, there are many parameters to be calibrated: $\alpha, \beta, \gamma, \rho_1, \rho_2, \theta, E, \mu, \delta, \{\sigma_0\}, \{\sigma_1\}, \{\sigma_2\}, \{\sigma_3\}, b, \lambda_1, \lambda_2, H, N, \{A_i\}, \{c_i\}, \{T_i\}$. The calibrated values of each parameter are shown in Table 1. To set parameter values that are as realistic as possible, we assume that the toll policies are enforced in an actual city and use data of the city. Since the 2000 Kyoto-Osaka-Kobe person-trip survey provides sufficient data for calculating the important figures such as the shares of each commute.
pattern, we chose the Osaka city in Japan, where road traffic congestion is severe, to serve as the center.\(^6\) Two suburbs adjoining the center are set as in Figure 2. The values for \(\lambda_1\) and \(\lambda_2\) are adjusted so that the simulated shares of each commute pattern and automobile shares in each commute type would resemble the actual data (see Tables 2 and 3). Since the travel time is symmetric, our model cannot reproduce the asymmetry of automobile shares between commutes from the suburb to the center and vice versa. The parameters of the travel cost functions such as \(c_i\) and \(T^i\) are calibrated so that an automobile is faster than the railway in the suburb but slower in the center (see Table 4).\(^7\) Since the Walras Law holds in our model, we normalize the product (mill) price in the center to one. The figures such as EV are converted to the monetary values with the assumptions that hourly wage in the center at no toll equilibrium is $24. Calibration method of each parameter is explained in Appendix B.

\(^6\)According to 2007 Road Traffic Census of Japan, the Osaka city is the third worst city in Japan in terms of travel speed of automobile.

\(^7\)It is interpreted that the travel time of the railway includes access time (travel time from origin to station), egress time (travel time from station to destination), and waiting time at stations. Since the density of stations is smaller and service frequency is lower in the suburb, the travel speed is slower in the suburb.
Figure 2: Three zones

Table 1: Parameter Values

<table>
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<tr>
<th>(a)</th>
<th>(\beta)</th>
<th>(\gamma)</th>
<th>(\rho_1)</th>
<th>(\rho_2)</th>
<th>(E)</th>
<th>(\delta)</th>
<th>(\mu)</th>
<th>(\theta)</th>
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<td>(A_2)</td>
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<td>(T_{22}^1)</td>
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<td>(\sigma_{12})</td>
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### Table 2: Commute pattern share (%)

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<th>Data</th>
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<td>Center→Center</td>
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<td>Center→Suburb</td>
<td>9.7</td>
<td>4.6</td>
</tr>
<tr>
<td>Cross commuting</td>
<td>4.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Note: Cross commuting is defined as commuting from one suburb to another.

### Table 3: Automobile share in commute trips (%)

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suburb→Suburb</td>
<td>57.2</td>
<td>75.1</td>
</tr>
<tr>
<td>Center→Center</td>
<td>38.1</td>
<td>27.6</td>
</tr>
<tr>
<td>Suburb→Center</td>
<td>46.6</td>
<td>16.7</td>
</tr>
<tr>
<td>Center→Suburb</td>
<td>46.5</td>
<td>41.5</td>
</tr>
<tr>
<td>Cross commuting</td>
<td>44.6</td>
<td>38.8</td>
</tr>
</tbody>
</table>

### Table 4: Travel speed (miles/h)

<table>
<thead>
<tr>
<th></th>
<th>Suburb</th>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>Railway</td>
<td>17</td>
<td>21</td>
</tr>
</tbody>
</table>
Table 5: Simulation results

<table>
<thead>
<tr>
<th></th>
<th>No Toll</th>
<th>First-best</th>
<th>Pigouvian Tax</th>
<th>Cordon</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV ($/wkr/year)</td>
<td>1004</td>
<td>887</td>
<td></td>
<td>551</td>
<td>428</td>
</tr>
<tr>
<td>DATT (h/day/people)</td>
<td>10.09</td>
<td>9.85</td>
<td>9.86</td>
<td>9.95</td>
<td>9.98</td>
</tr>
<tr>
<td>Toll Revenue ($/wkr/year)</td>
<td>0</td>
<td>4084</td>
<td>3694</td>
<td>1810</td>
<td>1496</td>
</tr>
<tr>
<td>Toll ($)</td>
<td>0</td>
<td>9.64</td>
<td>9.41</td>
<td>9.78</td>
<td>9.67</td>
</tr>
<tr>
<td>Wage ($/h)</td>
<td>24.4948</td>
<td>24.017</td>
<td>23.77412</td>
<td>23.4185</td>
<td>23.9728</td>
</tr>
<tr>
<td></td>
<td>-0.14215</td>
<td>0.017003</td>
<td>-0.72068</td>
<td>-0.5815</td>
<td>-0.055</td>
</tr>
<tr>
<td>Rent ($/sq.ft/year)</td>
<td>0.8811</td>
<td>6.5767</td>
<td>6.548196</td>
<td>6.57085</td>
<td>6.6227</td>
</tr>
<tr>
<td></td>
<td>-0.03766</td>
<td>-0.0285</td>
<td>-0.02056</td>
<td>-0.00585</td>
<td>0.0071</td>
</tr>
<tr>
<td>Speed of a car (miles/h)</td>
<td>18.1172</td>
<td>14.1693</td>
<td>18.71271</td>
<td>15.18668</td>
<td>15.45422</td>
</tr>
<tr>
<td></td>
<td>18.98311</td>
<td>15.2913</td>
<td>18.5716</td>
<td>15.2135</td>
<td>18.4659</td>
</tr>
<tr>
<td></td>
<td>-0.0121</td>
<td>0.0218921</td>
<td>0.009</td>
<td>0.162961</td>
<td>-0.0011</td>
</tr>
<tr>
<td>Job Density (worker/acre)</td>
<td>1.1528</td>
<td>15.7587</td>
<td>1.132484</td>
<td>16.12569</td>
<td>16.01393</td>
</tr>
<tr>
<td></td>
<td>-0.02032</td>
<td>0.366991</td>
<td>-0.01414</td>
<td>0.255234</td>
<td>0.0164</td>
</tr>
</tbody>
</table>

Note: DATT is daily average travel time.
3.2 Simulation Results

Simulation results are summarized in Table 5. Efficiency gains from the Pigouvian congestion tax without [resp. with] the optimization of road capacities are $887 [resp. $1,004] per worker per year. Efficiency gains from cordon pricing [resp. area pricing] are $551 [resp. $428] per worker per year. The ratio of the efficiency gains from cordon pricing to those from the Pigouvian pricing is approximately 62 per cent. Thus, our simulation results agree with the conclusion of Mun et al. (2005) that cordon pricing is not that efficient when employment is dispersed. The optimal cordon toll [resp. area toll] is $9.64 [resp. $12.41]. Area pricing is less efficient than cordon pricing. In Section 3.3, we will discuss what factors are important for a ranking of the second-best toll policies.

3.2.1 Spatial distributions of residence and employment

The main purpose of this paper is to look at how the spatial distributions of residence and employment are changed by the toll policies. Table 6 shows the changes of residential and working populations in the center induced by each policy. In all the toll policies, increases in travel costs strengthen the tendency of households to move to the center where the most savings on travel costs can be achieved. However, the magnitude of the population shifts is significantly different in each policy (see Table 6). In area pricing, automobile users who live in the center are given favorable treatment for all types of trips since they obtain the discount. On the other hand, in the first-best policy, all types of travels are tolled impartially in the sense that the toll levels are equal to the values of congestion externalities. Thus, area pricing increases the attraction for the center more strongly, and the magnitude of the population shift induced by area pricing is larger than that induced by the first-best policy. In cordon pricing, on the other hand, automobile users who live in the center do not receive a favorable treatment. Both automobile commuters in the suburb and in the center have to pay the toll when they go out from their zone while they do not have to pay it when they remain in their zone. Therefore, it becomes more beneficial for them to work in the zone of residence. However,

---

8The simulation program is written in Matlab. The program calculates the endogenous variables iteratively until residuals of (7), (20), (21) and (22) are less than $10^{-12}$. The optimal cordon toll and area toll are found by a grid search since closed-form formulae for these do not exist.
as we can see in Table 5, wage rate is higher in the suburb than in the center.\textsuperscript{9} As a result, continuing to live in the suburb is not so disadvantageous as compared with other policies, and the magnitude of the population shift induced by cordon pricing is the lowest of the four policies.

Table 6: Population shifts from the suburbs to the center

<table>
<thead>
<tr>
<th></th>
<th>First Best</th>
<th>Pigou</th>
<th>Cordon</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Population</td>
<td>12,032</td>
<td>8,758</td>
<td>1,080</td>
<td>28,653</td>
</tr>
</tbody>
</table>

The change in employment distribution is well explained by the changes in product demand in each zone since the toll policies directly affect the shopping costs. If the increase of demands for products in the suburb is larger than the increase of demands for products in the center, we can argue that working population will shift from the center to the suburb. In cordon pricing, the intra-zonal shopping cost of automobile users decreases; however, inter-zonal shopping costs increase. Therefore, most of the households tend to consume more products from their zones than those from other zones.\textsuperscript{10} Overall, the total demands for products of each zone increase since the demand from the other zones constitutes only a small fraction of the total demand. However, the increase in the aggregate demand for the suburban product is larger than the increase in the aggregate demand for the central product since the population of the suburb is larger than that of the center. In area pricing, the same is true for suburban automobile users. That is, intra-zonal shopping cost decreases but inter-zonal shopping cost increases. However, both intra-zonal and inter-zonal shopping costs decrease for automobile users in the center thanks to the discount. As a result, they decrease the consumption of products in the center and increase the consumption of suburban products to enjoy the benefits of variety. Thus, the total product demand increases in the suburb but decreases in the center. Therefore, in both cordon pricing and area pricing, the increase of production in the suburb is larger than that in the center, which

\textsuperscript{9}Since the suburb is larger than the center, land inputs of firms become also larger in the suburb than in the center. On the other hand, total labor supply is larger in the center than in the suburb. These two factors make the marginal productivity of labor be higher in the suburb than in the center.

\textsuperscript{10}The shoppers using the railway for both intra- and inter-zonal shopping increase their consumption of products from all zones.
implies that the increase of employment in the suburb is also larger. Note that since the aggregate demand for the central product decreases in area pricing, the magnitude of job dispersion is larger in area pricing than in cordon pricing (see Table 6). In the first-best policy (and the Pigouvian pricing), the mechanism is rather simple: Automobile users reduce consumption of products from all zones while railway users increase the consumption of products from all zones due to the income effects. Whether aggregate demand increases or decreases is determined by the balance between the number of automobile shoppers and railway shoppers. In our simulations, aggregate demand decreases [resp. increases] in the suburb [resp. center]. Thus, employment is centralized, which is identical to the result obtained in Anas and Xu (1999). Therefore, cordon pricing and area pricing induce job dispersion even though job centralization is desirable.

The above argument is summarized in the following:

\textbf{Result 1} Cordon pricing and area pricing induce the agglomeration of the residential population and the dispersion of the working population. The change of the employment distribution is opposite to the first-best one. The magnitudes of the population shifts induced by area pricing is larger than those induced by cordon pricing.

We have seen that cordon and area pricings cannot achieve the first-best outcome not only because they cannot fully internalize the congestion externalities but also because they cause the inefficiency in the location decisions of the agents. But how important is the latter factor? To address this issue, we consider the first-best toll policy given by (25) under the constraint that the shares of each commuting arrangement \( \psi_{ij} \) are fixed at the levels induced by the second-best policies and see the efficiency losses from the first-best case. Then, we obtain the results that the efficiency losses when \( \psi_{ij} \)'s are fixed at the levels induced by cordon pricing [resp. area pricing] are $112 [resp. $97] per worker per year. Hence, we can conclude that the efficiency losses due to the location effects are not negligible.

\footnote{That is, in the suburb, the number of shoppers using automobiles is larger than that of shoppers using the railway and the opposite is true in the center. This is robust as long as the speed of travel of the railway is faster in the center than in the suburb.}

\footnote{In what follows, several important findings will be summarized as Result. However, we should note that those findings are obtained by numerical simulations under specific values of parameters.}
3.2.2 Commuting patterns

Shares of each commuting arrangement are shown in Table 7. In the first-best policy and the Pigouvian pricing, the shares of commuting for the center (intra-central commuting and commutes from the suburb to the center) increase reflecting the result that employment is centralized. On the other hand, by the same reasoning, the shares of commuting for the suburb decrease. In cordon pricing and area pricing, the shares of intra-zonal commutes increase because people can avoid the toll in those commuting arrangements. In other words, cordon pricing and area pricing make people have their workplace near their home. In area pricing, reverse commuting (work trips from the center to the suburb) also increases due to the discount.

**Result 2** Cordon pricing and area pricing promote intra-zonal commuting. Area pricing also fosters reverse commuting.

**Table 7: Commuting patterns (%)**

<table>
<thead>
<tr>
<th></th>
<th>No Toll</th>
<th>First-best</th>
<th>Cordon</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suburb → Suburb</td>
<td>43.3</td>
<td>42.7</td>
<td>45.0</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>-0.6</td>
<td>1.7</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Center → Center</td>
<td>17.0</td>
<td>17.8</td>
<td>17.6</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.6</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Suburb → Center</td>
<td>26.0</td>
<td>26.2</td>
<td>24.6</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>-1.4</td>
<td>-2.3</td>
<td></td>
</tr>
<tr>
<td>Center → Suburb</td>
<td>9.7</td>
<td>9.5</td>
<td>9.2</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>-0.2</td>
<td>-0.5</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Cross Commuting</td>
<td>4.0</td>
<td>3.8</td>
<td>3.6</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>-0.2</td>
<td>-0.4</td>
<td>-0.3</td>
<td></td>
</tr>
</tbody>
</table>

3.2.3 Car shares in commute trips

Automobile shares in each commute pattern are shown in Table 8. Since there is no externality in railway trips, automobile shares should be decreased for all commuting flows. Indeed, in the first best policy and the Pigouvian pricing, automobile shares decrease for all the commuting patterns. However, whether or not the second-best toll policies promote the use of the railway depends upon
the type of commuting flow. In cordon pricing, the automobile shares increase in intra-zonal commutes that are exempt from the toll. In area pricing, the automobile shares in intra-suburb work trips which are exempt from the toll increase as in cordon pricing. However, the situation is different for the commuting flows starting from the center. Although the automobile share in intra-center commuting slightly decreases, the automobile share in reverse commuting increases due to the discount.\footnote{This result is compatible with the Transport for London’s report that the use of underground across and in Central London decreased after area pricing was introduced (Transport for London, 2005).} This is one of the important factors that make area pricing less efficient than cordon pricing because the reverse commuting affects the travel time both in the center and in the suburb. Indeed, in the first-best case, the car share in reverse commuting decreases by 15.8 per cent. However, we should note that area pricing has this inefficiency only when the discount is high as we will see in the section of sensitivity analysis.

\textbf{Result 3} Cordon pricing and area pricing discourage the use of public transport in commutes that are exempt from toll.

\begin{table}[h]
\centering
\caption{Automobile shares in commute trips (\%)}
\begin{tabular}{lcccc}
\hline
 & No Toll & First-best & Cordon & Area \\
\hline
Suburb $\rightarrow$ Suburb & 57.2 & 45.7 & 59.1 & 58.8 \\
 & -11.5 & 2.0 & 1.6 \\
Center $\rightarrow$ Center & 38.1 & 31.3 & 40.6 & 37.8 \\
 & -6.8 & 2.5 & -0.2 \\
Suburb $\rightarrow$ Center & 46.6 & 30.6 & 34.3 & 31.5 \\
 & -16.0 & -12.3 & -15.1 \\
Center $\rightarrow$ Suburb & 46.5 & 30.7 & 34.4 & 47.7 \\
 & -15.8 & -12.1 & 1.2 \\
Cross Commuting & 44.6 & 21.4 & 26.4 & 30.7 \\
 & -23.2 & -18.2 & -13.9 \\
\hline
\end{tabular}
\end{table}
3.3 Sensitivity Analysis

3.3.1 Discount

We argued in Section 3.23 that a prime source of the inefficiencies which is specific to area pricing is that the car share in reverse commuting increases due to the discount for car users living in the center. Therefore, it is natural to expect that this inefficiency will be mitigated if the discount is lowered. Tables 9 and 10 show changes in car shares and population shifts induced by area pricing for several discounts respectively. As expected, the automobile share in reverse commuting decreases when the discount is low. However, when the discount is low, not only the working population but also the residential population disperse, which becomes another source of the inefficiencies. Hence, the government faces the trade-off when it lowers the discount and Figure 3 shows that abolishing the discount is not efficient. Furthermore, we can see that in our base simulation, area pricing cannot achieve the efficiency gains which are larger than cordon pricing even if the discount is allowed to change.

Figure 3: Efficiency gains from area pricing for several discount rates
Table 9: Automobile shares in commute trips (%)

<table>
<thead>
<tr>
<th></th>
<th>No Toll</th>
<th>Area (0%)</th>
<th>Area (50%)</th>
<th>Area (90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suburb → Suburb</td>
<td>57.2</td>
<td>58.3</td>
<td>58.7</td>
<td>58.8</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.6</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Center → Center</td>
<td>38.1</td>
<td>26.2</td>
<td>30.2</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>-11.9</td>
<td>-7.9</td>
<td>-0.2</td>
<td></td>
</tr>
<tr>
<td>Suburb → Center</td>
<td>46.6</td>
<td>37.5</td>
<td>33.1</td>
<td>31.5</td>
</tr>
<tr>
<td></td>
<td>-9.0</td>
<td>-13.5</td>
<td>-15.1</td>
<td></td>
</tr>
<tr>
<td>Center → Suburb</td>
<td>46.5</td>
<td>36.2</td>
<td>40.5</td>
<td>47.7</td>
</tr>
<tr>
<td></td>
<td>-10.4</td>
<td>-6.1</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Cross Commuting</td>
<td>44.6</td>
<td>37.3</td>
<td>32.9</td>
<td>30.7</td>
</tr>
<tr>
<td></td>
<td>-7.3</td>
<td>-11.7</td>
<td>-13.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Population shifts from the suburbs to the center

<table>
<thead>
<tr>
<th></th>
<th>Area (0%)</th>
<th>Area (50%)</th>
<th>Area (90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Population</td>
<td>-30,607</td>
<td>-6,804</td>
<td>28,653</td>
</tr>
</tbody>
</table>

3.3.2 Cordon vs. Area

When the government chooses one between cordon and area pricings, it may be convenient to have a guideline which is related to the spatial structure of a city. Although cordon pricing is more efficient than area pricing in the base case, each policy has its advantage. Comparing (13) and (14), we can argue that cordon pricing is better than area pricing in the sense that cordon pricing levies higher toll to longer distance commuting (that is, $\phi_{12} < \phi_{13}$ but $\phi'_{12} = \phi'_{13}$), while area pricing is better than cordon pricing in the sense that area pricing levies toll on intra-zonal central trips (that is, $\phi'_{22} \neq 0$ but $\phi_{22} = 0$). Therefore, one natural conjecture is that cordon pricing is likely to be better in a city which has many long-distance commuters while area pricing is likely to be better in a city where traffic congestion is mainly caused by households living in the central urban area.

To address the point for cordon pricing at first, we change $\lambda_1$ which represents the dispersion of the idiosyncratic tastes for the commuting arrangements. $\lambda_1$ is a
key parameter which affects the commuting patterns.\(^{14}\) If \(\lambda_1\) is lowered, people stick to their idiosyncratic tastes more strongly, so share of a commuting arrangement which gives low (systematic) utility will increase. Table 11 shows shares of each commuting flow in the city where \((\lambda_1, \lambda_2) = (12, 14)\) at no toll equilibrium together with those of the base city where \((\lambda_1, \lambda_2) = (18, 20)\). As we can see, the city where \(\lambda_1 = 12\) has a larger number of long-distance commuters than the base city. Table 12 shows the efficiency gains from cordon and area pricings when \((\lambda_1, \lambda_2) = (12, 14)\). The efficiency gains from cordon pricing are higher than the base case. Hence, as is expected, the advantage of cordon pricing can be exploited more fully in a city where long-distance commuting is prevalent. On the other hand, the efficiency gains from area pricing are lower than the base case. The main reason is that the share of the reverse commuting is higher, which will be a prime source of the inefficiencies as we saw in Section 3.23. As a result, the ratio of the efficiency gains from cordon pricing to those from area pricing increases from 1.29 to 1.33.

Next, to address the point for area pricing, we increase \(A_2\), the area of the center, from 221 to 350. With this change, the relative size of the center increases and as a result, the shares of commuting flows starting from the center also increase. We measure the congestion externalities caused by households living in the center by their total payment of the Pigouvian congestion tax evaluated at the no toll equilibrium. Then, the fraction of the congestion externalities caused by households living in the center, that is, \(\sum_{(i,j,m,n)} \Psi_{mn}^{ij} \tau_{ij} / \sum_{(i,j,m,n)} \Psi_{ij} \tau_{ij}\), increases from 0.19 to 0.24 with the change of \(A_2\). Therefore, compared with the base city, traffic congestion is attributed more largely to households living in the center. In this setting, we can find a percentage discount under which area pricing is more efficient than cordon pricing as opposed to the base case (Table 13).

From the above observations, we can position cordon pricing as a policy for urban sprawl.\(^{15}\) If the main problem of a city is excessive dispersion of the spatial structure and the average commuting time is too long, cordon pricing will work. On the other hand, if the main problem of a city is excessive amount of car trips made by residents in the central urban area rather than urban sprawl, a congestion

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\(^{14}\)Note that as \(\lambda_1\) approaches 0, each commuting arrangement is chosen with equal probability, while as \(\lambda_1\) approaches \(\infty\), the commuting arrangement that brings about the highest utility is chosen with a probability of 1.

\(^{15}\)Using Anas and Xu’s (1999) model, Anas and Rhee (2006, 07) analyze the welfare effects of urban boundaries which is one of the anti-sprawl policies.
tax on trips within the central urban area is highly necessary and therefore, area pricing will work. To summarize, the guideline can be written as follows:

**Result 4** In a city where long-distance commuting is prevalent, cordon pricing is better than area pricing. On the other hand, in a city which has large central urban area, area pricing with an appropriate discount is better than cordon pricing.

### Table 11: Commuting patterns (%)

<table>
<thead>
<tr>
<th></th>
<th>Base case ((\lambda_1, \lambda_2) = (18, 20))</th>
<th>((\lambda_1, \lambda_2) = (12, 14))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suburb → Suburb</td>
<td>43.3</td>
<td>37.0</td>
</tr>
<tr>
<td>Center → Center</td>
<td>17.0</td>
<td>15.4</td>
</tr>
<tr>
<td>Suburb → Center</td>
<td>26.0</td>
<td>27.5</td>
</tr>
<tr>
<td>Center → Suburb</td>
<td>9.7</td>
<td>12.5</td>
</tr>
<tr>
<td>Cross Commuting</td>
<td>4.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

### Table 12: EV ($/worker/year)

<table>
<thead>
<tr>
<th></th>
<th>Base case ((\lambda_1, \lambda_2) = (18, 20))</th>
<th>((\lambda_1, \lambda_2) = (12, 14))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordon</td>
<td>551</td>
<td>566</td>
</tr>
<tr>
<td>Area</td>
<td>428</td>
<td>424</td>
</tr>
<tr>
<td>Pigou</td>
<td>887</td>
<td>842</td>
</tr>
<tr>
<td>First-best</td>
<td>1,004</td>
<td>891</td>
</tr>
</tbody>
</table>

### Table 13: EV ($/worker/year)

<table>
<thead>
<tr>
<th></th>
<th>Base case (A_2 = 221)</th>
<th>(A_2 = 350)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cordon</td>
<td>551</td>
<td>509</td>
</tr>
<tr>
<td>Area (50%)</td>
<td>428</td>
<td>512</td>
</tr>
<tr>
<td>Pigou</td>
<td>887</td>
<td>822</td>
</tr>
<tr>
<td>First-best</td>
<td>1,004</td>
<td>965</td>
</tr>
</tbody>
</table>
4 Discussion

We analyzed cordon and area pricings by using Anas and Xu’s (1999) model and found that their efficiency gains are about 60 per cent of the efficiency gains from the Pigouvian pricing and about half of the efficiency gains from the first-best policy due to the fact that cordon and area pricings cause the inefficiencies in the location decisions and the modal choices. In particular, it is important to note that the impact of the inefficiencies in the location decisions is not negligible. It was also argued that a ranking of the second-best toll policies depends on the spatial structure of a city. If the city has many long-distance commuters, cordon pricing is likely to be better. On the other hand, if the congestion externalities are mainly caused by residents in the central urban area, area pricing is likely to be better.

However, there are several limitations in our analysis, which should be the subjects for future research. First, when policy makers implement cordon pricing or area pricing, they need to decide not only the toll level but also the area of a toll district. In our discrete space model, we need to increase the number of zones to cope with the optimal area of the toll district. Second, one important problem of cordon and area pricings is that congestion in the fringe areas of the toll district increases. We ignored this point since detour travel was not considered. Third, to reproduce the asymmetry between the commutes from the suburb to the center and vice versa, we need to consider trip-scheduling issues. These are particularly important when we consider area pricing since people can curtail expenditure on the area toll by making several trips together in one day instead of making each trip on separate days. Fourth, in our analysis, land was not efficiently allocated to transportation except the first-best case. However, since it is difficult to derive an explicit formula for a second-best land allocation to transport, multidimensional grid search (investments plus toll) is required to analyze the land allocation issues. Therefore, it may be better to use a simpler model when we address the road investment issues. Fifth, we assumed that there is no externality in the railway. Generally though, public transport has both negative externalities (congestion) and positive externalities (the Mohring effect). In particular, if the negative externalities are larger, modal shift from automobiles to the railway does not always improve welfare. Moreover, as a substitute for automobiles, buses are also important. Since automobiles and buses cause the same road congestion externalities, analysis
would be more complex. Sixth, we simply assumed that the toll revenues are equally distributed to city residents. However, in the actual cases, the toll revenues are usually required to reinvest in the transport sector (Santos and Fraser, 2006). Finally, while changes in travel behavior occur in short-run periods, the time frame for which changes in residential and employment distributions actually occur will be quite long. However, our model is static, so it does not distinguish between short-term and long-term. To address this issue, we need a dynamic model.

Appendix A

The conditional input demands are given by

\[ L_i = \frac{\delta p_i X_i}{w_i}, \quad (27) \]
\[ Q_i = \frac{\mu p_i X_i}{R_i}. \quad (28) \]

The Marshallian demands for goods, lot size and leisure, and the systematic component of the indirect utility are in order:

\[ z_{mn}^{ij} = \alpha \left( 1 - \rho_1 \right)^{1-\rho_1} \left( P_{mn}^{ij} \right)^{1-\rho_1} \left( P_{ij}^{mn} \right)^{1-\rho_2} \left( p_{mn}^{ij} \right)^{1-\rho_2} \frac{1}{\rho_2-1} Y_{ij}^{mn}, \quad (29) \]
\[ h_{ij}^{nm} = \beta \left( 1 - \rho_1 \right)^{1-\rho_1} \left( P_{ij}^{nm} \right)^{1-\rho_1} \frac{1}{\rho_1} Y_{ij}^{mn}, \quad (30) \]
\[ l_{ij}^{mn} = \gamma \left( 1 - \rho_1 \right)^{1-\rho_1} \left( P_{ij}^{mn} \right)^{1-\rho_1} \frac{1}{\rho_1} Y_{ij}^{mn}, \quad (31) \]
\[ V_{ij}^{mn} = \ln \frac{\gamma_{ij}^{mn} Y_{ij}^{mn}}{P_{ij}^{mn}}, \quad (32) \]

where

\[ p_{mn}^{ij} = \begin{cases} p_v + \theta \left( w_j s_{iv}^n + w_{iv} \phi_{iv}^n \right) & \text{if } i = v \\ p_v + \theta \left( w_j s_{iv}^n + \phi_{iv}^n \right) & \text{otherwise}, \end{cases} \quad (33) \]
\[ P_{ij}^{mn} = \left( \sum_{v=1}^{3} \left( p_{mn}^{ijv} \right)^{\rho_2} \right)^{\frac{1}{\rho_2}}. \quad (34) \]

\(^{16}\)As Parry and Bento (2001) point out, the use of the toll revenue is also important when considering other taxes.
\[ PI_{ij}^{mn} = \left\{ \alpha^{1-\rho_1} \left( P_{ij}^{mn} \right)^{\rho_1} + \beta^{1-\rho_1} R_i^{\rho_1} + \gamma^{1-\rho_1} w_j^{\rho_1} \right\}^{\rho_1-1} \]  
\[ Y_{ij}^{mn} = w_j H - TC_{ij}^{mn} + \frac{\sum_{i=1}^{3} R_i A_i}{N} + \frac{RV_T}{N} - h. \]

\( P_{ij}^{mn} \) is the CIF price of the goods produced in zone \( v \) for households with the homework-modes quaternary \((i, j, m, n)\). \( PI_{ij}^{mn} \) can be interpreted as price index. In Anas and Rhee (2006), \( Y_{ij}^{mn} \) is called full endowment income.

Appendix B

In this appendix, it is explained how the values of each parameter are determined.

\( A_i \)'s are set to the areas of each zone in Figure 2. \( N \) is set based on the total number of automobile and railway commutes in one or more of the three zones. Since \( F_i^{mn} \) is on a daily basis and the travel time is in units of minutes, \( H = 24 \times 60 = 1,440 \).

The values of \( \theta, \alpha, \beta, \gamma, \rho_2, E, \mu, \delta \) are based on the values chosen in Anas and Rhee (2006).

The value for \( \rho_1 \) is calculated from a formula for the price elasticity of housing demand, which is given by

\[ \frac{\partial h_{ij}^{mn}}{\partial R_i} \left. \frac{R_i}{K_{ij}^{mn}} \right|_{I} = \frac{1}{\rho_1 - 1} + \frac{R_i A_i}{NY_{ij}^{mn}} - \frac{\rho_1}{\rho_1 - 1} \frac{R_i h_{ij}^{mn}}{Y_{ij}^{mn}}. \]

\( \frac{R_i h_{ij}^{mn}}{Y_{ij}^{mn}} \) is set to the expenditure share of housing, which is calculated from the 2004 National Survey of Family Income and Expenditure. Housing expenditure is calculated as \( \text{House owner-ship rate} \cdot \text{Imputed rent} + (1 - \text{House owner-ship rate}) \cdot \text{Rent} \).

\( \frac{R_i A_i}{NY_{ij}^{mn}} \) is computed as \( \text{The housing expenditure} \times \frac{\text{Lot size}}{3 \text{ Inhabitable area in Japan}} \) divided by GDP per month. Tiwari and Hasegawa (2000) and Horioka (1988) estimate the price elasticity of Japanese housing demand. Elasticities of demand for owner-occupied housing are -0.38 in Tiwari and Hasegawa (2000) and -0.8 in Horioka (1988). Tiwari and Hasegawa (2000) also estimate the elasticity of demand for private rental housing, which is -0.33. In our simulation, we take a value of approximately -0.52.

Matsui and Yamada (1998) estimate the parameters of the BPR functions of automobiles, using the 1994 Japanese Road Traffic Census data. The authors distinguish
five categories of roads and offer five sets of estimates. We assign a different set of
the estimates to the suburb and the center (see Table 1).\textsuperscript{17} The value for $T_1$ is set
to the road area in Osaka city, which is obtained from the 1999 Dōro Tōkei Nenpō
(Yearbook of Road Statistics). For the road area in the suburb, we assume that the
ratio of road area to the total area is 10 per cent above the ratio in the center. $b_1$ is
calculated as the road capacity in Osaka city divided by the road area in Osaka city.
The road capacity is computed as the trip generation and attraction in Osaka city
divided by average congestion rate of local roads in Osaka city. The trip generation
and attraction is available in the 2000 Kyoto-Osaka-Kobe person-trip survey and
the average congestion rate is computable from the 1994 Road Traffic Census. $c_2$
is set to the average hourly speed of the railway in Osaka city, which is computed
using the website of a train route finder. For the suburb, we assume that it is 20 per
cent below the central level.

References

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\textsuperscript{17}The values for the suburb are the estimates of national highways, principal prefectural roads
and principal major city roads with more than four lanes. The values for the center are the estimates
of prefectural roads and major city roads with more than four lanes.


